Remote Sensing and the Kyoto Protocol: A Review of Available and Future Technology for Monitoring Treaty Compliance

Ann Arbor, Michigan, USA, October 20-22, 1999

Workshop Report

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I. INTRODUCTION

1.1. Background

The Kyoto Protocol to the United Nations Framework Convention on Climate Change contains quantified, legally binding commitments to limit or reduce greenhouse gas emissions to 1990 levels and allows carbon emissions to be balanced by carbon sinks represented by vegetation. The issue of using vegetation cover as an emission offset raises a debate about the adequacy of measurement and monitoring methodologies, and of current and planned remote sensing systems and data archives to both assess carbon stocks/sinks at 1990 levels, and monitor the current and future global status of those stocks. These concerns and the potential ratification of the Protocol among participating countries is stimulating policy debates and underscoring a need for the exchange of information between the international legal community and the remote sensing community.

On October 20-22 1999, two working groups of the International Society for Photogrammetry and Remote Sensing (ISPRS) joined with the University of Michigan (Michigan, USA) to convene discussions on how remote sensing technology could contribute to the information requirements raised by implementation of and compliance with the terms of the Kyoto Protocol. The meeting originated as a joint effort between the Global Monitoring Working Group and the Radar Applications Working Group in Commission VII of the ISPRS, co-sponsored by the University of Michigan. The meeting was attended by representatives from national government agencies and international organizations and academic institutions.

Some of the key themes addressed were:

- Legal aspects of transnational remote sensing in the context of the Kyoto Protocol;
- A review of current and future remote sensing technologies that could be applied to the Kyoto Protocol;
- Identification of areas where additional research is needed in order to advance and align remote sensing technology with the requirements and expectations of the Protocol.
- The bureaucratic and research management approaches needed to align the remote sensing community with both the science and policy communities.

1.2. Remote Sensing and the Kyoto Protocol

While global inventory of all six greenhouse gases covered by the Kyoto Protocol is an overarching requirement and a daunting task, it was recognized by the workshop participants that, at present, the remote sensing community is best equipped to address CO_2 and CH_4.

Within the context of the Kyoto Protocol (see Annex III), Article 10 was recognized as a key driver, in which contributions can be made to provide systematic observations and data archives in order to reduce uncertainties in the global terrestrial carbon budget. Specific contributions can be made to supporting national and international networks and observation programs, especially for above-ground biomass, and for assessing trends and shifts in land cover. The importance of Article 3 and Article 12 (the Clean Development Mechanism) of the Kyoto Protocol were recognized, and that Earth Observation can help support national accounting of Afforestation, Reforestation and Deforestation (ARD) under these articles.

Also relevant is that countries shall, by the first commitment period (2008-2012), report in a transparent and verifiable matter their CO_2 equivalent emissions of greenhouse gases. Another milestone is 2005, by which countries shall have made "demonstrable progress" towards achieving their assigned emission limitation and reduction commitments under the Protocol (Article 3).

The group reviewed a large number of remote sensing instruments and categorised them according to how they might be best applied to support the Kyoto Protocol. The primary emphasis was on satellite based technologies - although some aircraft platform based sensors were also discussed.

II. SOME LEGAL CONSIDERATIONS ABOUT REMOTE SENSING

One initial topic addressed during the workshop was the legal implications of using remote sensing technology for treaty verification, within the context of international laws, policies and remote sensing treaties (e.g. UN Principles Relating to Remote Sensing of the Earth from Outer Space and international Space Law Treaties including the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies). International air law was examined as well, citing the Chicago Convention of 1944.

A few points of relevance were acknowledged:
- Airborne remote sensing activities fall under the jurisdiction of international aviation law, which, among others, provides that airborne sensing activities be performed with the consent of the state being surveyed.
- Spaceborne remote sensing activities can be performed without the permission of the sensed state - although there are some restrictions any state may sense the entire Earth from outer space.
- Air law and space law make no distinction between passive and active sensing techniques.

However the UN Principles Relating to Remote Sensing of the Earth from Outer Space, which is not a binding Treaty, but a Statement from the United Nations to which many countries agree, provides, that:
- Remote sensing activities should be carried out for the benefit and in the interests of all countries, taking into particular consideration the needs of the developing countries (Principle II);
- Remote sensing activities should include international co-operation and technical assistance (Principles V and VIII);
- When one country acquires data over another country, the sensed country should have access to the data on a non-discriminatory basis and at reasonable cost terms (Principle XII).

In short, if a survey is performed from outer space, states can legally collect data useful for the purposes stated in the Kyoto Protocol, and these data should also be made available to the sensed state. However, it is not clear, if the data collected can be used to *compel* a state to comply with the protocol when it has not expressly agreed to permit verification. This issue has not been addressed in the text of the relevant Treaties.

In conclusion, remote sensing technology should be viewed as a tool in support of the Kyoto Protocol and its signatories, rather than an instrument for treaty policing. After all, the UN Principles provide that remote sensing activities should be carried out *in the spirit of international co-operation and for the benefit and in the interests of all countries.*

III. OVERVIEW OF REMOTE SENSING TECHNOLOGY CAPABILITIES

3.1. Applying Remote Sensing to the Kyoto Protocol

A concern with the Kyoto Protocol is the current imprecise definition of a "forest", which, in terms of ecosystem type, canopy cover, minimum area of interest etc., will have significant implications on the applicability of remote sensing technology to the treaty (Skole and Qi, paper #5). The IPCC is currently examining the implications of different forest definitions for the Protocol and is also evaluating the merits of a more quantitative approach to land cover monitoring which would focus on carbon and biomass as a basic unit of measurement. While some of these issues will be addressed at the 6th Conference of the Parties (COP-6) in The Hague (NL) in November 2000, there is a need for the remote sensing community to provide a synopsis of what Earth observations can do relative to the land cover issues as they are stated now.

In this context, five areas were identified where remote sensing technology may be applied, partly or fully, toward facilitating the treaty:
- Provision of systematic observations of relevant land cover (Art. 5, Art. 10);
- Support to the establishment of a 1990 carbon stock baseline (Art. 3);
- Detection and spatial quantification of change in land cover (Art. 3, Art. 12);
- Quantification of above-ground vegetation biomass stocks and associated changes therein (Art. 3 Art 12);
- Mapping and monitoring of sources of anthropogenic CH_4 (Art. 3, Art. 5, Art. 10);

3.1.1. Provision of systematic observations of relevant land cover

Article 5:1 of the Kyoto Protocol states that " Each Party included in Annex I shall have in place, no later than one year prior to the start of the first commitment period, a national system for the estimation of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol." Article 10 (d), in turn, states that countries shall "Co-operate in scientific and technical research and promote the maintenance and the development of systematic observation systems and development of data archives to reduce uncertainties related to the climate system, [and] the adverse impacts of climate change...".

Providing systematic, repetitive observations of large areas is potentially one of the strengths of remote sensing technology, and one where it can provide substantial support to the protocol on a long-term basis. Remote sensing data are, however, generally not acquired in a systematic manner, except locally over specific study sites and regional scale analysis of archived data are often complicated by variations in seasonally, sensor characteristics, viewing geometry etc., which introduce biases and uncertainties in the interpretation of the results. This is typically valid for most operational sensors, both optical and microwave, thereby undermining the usefulness of the data. It is recognized that dedicated and systematic acquisition strategies, focusing on obtaining regional coverage on a repetitive basis, would significantly improve the usefulness of remote sensing data, not only in the context of the Kyoto Protocol, but also in a broader scientific framework.

Although global or regional scale projects, such as the Landsat Pathfinder, TREES (Achard *et al.* 1997), GRFM/GBFM (Rosenqvist *et al.* 2000) and IGBP DIS (Belward *et al.* 1999), have existed for a long time, it is recognized that a federated approach having common goals and thematic definitions will be required to effectively support the Kyoto Protocol. Such an effort is currently underway within the framework of the Global Observations of Forest Cover (GOFC) Pilot Project (Ahern *et al.* 1998), under the auspices of CEOS.

Passive Optical (Multi-spectral and Panchromatic) Systems

Spaceborne optical systems have been in operation since 1972 and thematic mapping applications are generally past their initial research stages. However, while results for numerous land cover mapping applications have been presented over the years, they are often site specific and focused on a particular science objective. The feasibility of identifying the thematic classes directly applicable to the Kyoto Protocol remains to be confirmed, and in some cases, further investigated.

While panchromatic systems are of limited use for thematic mapping of vegetation, multi-spectral systems, in particular sensors which include mid-infrared bands such as Landsat TM, ETM+ and SPOT HRVIR, are well suited for this purpose. High resolution data will be required for the delineation of fragmented forest lands and smaller patches of forest. Coarser resolution sensors such as NOAA AVHRR and SPOT VEGETATION are frequently used in combination with high resolution sensors for continental and global scale mapping (Mayaux *et al.* 1998, Eva *et al.* 1999, Richards *et al.* 2000)

Currently available optical systems are generally capable of acquiring data at local, regional, and global scales and in a timely and regular manner. Cloud cover, smoke and haze, however put limitations on data availability, particularly in the tropical zone. The problem can be somewhat overcome with the coarse resolution sensors which have a higher temporal repeat-cycle, thereby enabling the creation of weekly or monthly mosaics compiled from cloud free pixels.

Active Microwave Systems (SAR)

The current suite of orbiting SAR systems all operate with a single-band and a single polarization, which to a large extent limit their usefulness for thematic mapping of vegetation Classification accuracy with SAR, however, increases notably with the inclusion of additional bands and polarizations, and with multi-temporal data acquisitions. Very good results can also be achieved when optical and microwave data are combined. While multi-band/polarimetric and interferometric radar systems are not yet available in a space-borne mode, they are available on aircraft platforms and could be used for local to regional scale applications.

A major limitation of radar systems, with respect to vegetation mapping, is their sensitivity to surface topography which limits their application to flat or gently undulating terrain. Radar data are also subject to speckle, which on one hand enables techniques such as radar interferometry, but reduces the effective ground resolution (typically by a factor 3-4, thus providing an effective resolution in the order of 50-100 metres for current spaceborne systems). For ultra-wide band radar systems, however, the speckle problem is absent. The advantage of radar systems is their all-weather capability, which assures image acquisitions independent of cloud cover and daylight, thereby enabling timely and reliable acquisitions at local, regional and global scales. It should however be noted that radar systems are not "weather independent" as hydrologic conditions on the ground such as; wet, flooded, or snow covered soil affect the radar signal.

Active Optical Systems (LIDAR)
LIDAR systems are only just recently being explored for vegetation mapping. At the time of this writing, NASA's Vegetation Canopy LIDAR (VCL) is the only LIDAR system planned for orbit in the near future. VCL is an active infrared laser altimeter which will make soundings of the vegetation canopy, providing unprecedented information on the structure of the Earth's forests and land surfaces by directly observing vegetation canopy height, forest vertical and spatial distribution, and ground topography at high resolution (Dubayah *et al.* 1997, Blair *et al.* 1999). VCL is however not an imaging instrument. It will collect data in a series of samples, along the flight path. As such the production of thematic products from VCL is, as of yet, unproven. However, using VCL data in combination with other spatially extensive data, such as optical/multispectral or SAR, holds a significant potential.

3.1.2. Support to the establishment of a 1990 carbon stock baseline

According to Art. 3:4 of the Kyoto Protocol, each Annex I country shall "provide data to establish its level of carbon stocks in 1990 and to enable an estimate to be made of its changes in carbon stocks in subsequent years". However, Art. 3:5 of the Protocol also states that Annex I countries "undergoing the process of transition to a market economy" may, under certain circumstances, "use a historical base year or period other than 1990 for the implementation of its commitments" under Art. 3. Hence, baselines formulated after 1990 may, for certain countries, be considered.

Nevertheless, as it can be expected that the year 1990 will be the dominant base year, the selection of potential sensors to be used to support the establishment of this base line will to the largest extent be limited to those in operation during that year.

Passive Optical (Multi-spectral and Panchromatic) Systems
Among the high resolution optical sensors, only Landsat TM and SPOT HRV were in operation in 1990. The use of high resolution data for compiling a regional-global 1990 land cover map to support the establishment of the carbon stock baseline is possible - albeit expensive. It is feasible at a national level, especially for smaller countries or regions. Archives of Landsat TM and MSS, and SPOT HRV exist and could be used for this purpose.

The use of coarse resolution data is also feasible, although spatial resolution issues for many areas would limit its utility. A Global Land Cover map from 1992 has been generated from NOAA AVHRR data within IGBP DIS and archives of NOAA AVHRR data exist for the required time period (Belward et al. 1999, Townshend *et al.* 1994, Esters *et al.* 1999). In order to be useful, however, the land cover classes used need to be re-defined and adapted to classes relevant to the Kyoto Protocol.

Active Microwave Systems (SAR)
No orbital active microwave systems were in operation in 1990 and the use of SAR data to support a 1990 baseline would thus in general not be feasible. SAR data could however possibly be useful for quantification of component biomass (leaves, branches, stems) of the extensive areas of woodlands that occur throughout Australia, Africa and South America, for which the establishment of a 1990 baseline could be supported.

For non-1990 baseline countries in the tropical and boreal zones of the Earth, continental scale (100 m resolution) JERS-1 L-band SAR mosaics from 1995-96, generated within the GRFM/GBFM projects (Rosenqvist *et al.* 2000), can be used to support the establishment of a mid-1990's carbon baseline.

Active Optical Systems (LIDAR)
Not feasible. No data available.

3.1.3. Detection and spatial quantification of change in land cover

In the first commitment period (2008-2012) this application primarily concerns the detection and spatial quantification of afforestation, reforestation and deforestation (ARD) activities, and changes resulting from fire. While the accounting of land cover change is initially limited to that caused by human activity, disturbances and changes due to natural causes also need to be identified. In the second and subsequent commitment periods, accounting will also include other types of land use change.

Article 3:3 of the treaty states that "The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article...".

Article 3.4 also mentions that "additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories" will be accounted for in the second and subsequent commitment periods.

Article 12 furthermore defines a "clean development mechanism", which in principle stipulates the conditions for "carbon trading" between countries. This, in turn, would require verifiable measurements of ARD, should LULUCF projects (Land Use, Land Use Change and Forestry) be accepted under the terms of the clean development mechanism.

While the articles above concern measurements of carbon stocks and changes therein, a first important step is the identification and quantification of the areas subject to ARD. In combination with up-to-date *in situ* data and relevant allometric models, changes in biomass (carbon) stocks may be estimated.

In order to detect ARD activities, image acquisitions on a repetitive basis will be required, preferably annually and performed during a specific season, in order to minimise the effects of seasonal artefacts in the data. A spatial resolution better than the minimum area of interest - still to be defined - will be required for this task.

Passive Optical (Multi-spectral and Panchromatic) Systems

Optical systems are sensitive to parameters related to the structure and closure of the vegetation canopy, (e.g. canopy projected cover (CPC) and leaf area index (LAI)) which are affected during ARD activities and fire. Detection and spatial quantification of deforestation (D) activities, which bring about the removal of the forest canopy, is the most straight-forward part of the three ARD components, and both panchromatic and multi-spectral remote sensing data are deemed useful for this task. High resolution systems will be required to detect partial deforestation activities, such as selective logging and thinning. Reforestation (R) is more difficult to detect, as it represents a gradual change from non-forest to forest, spanning several years. Afforestation (A) events, which can be expected to take place in relatively small patches outside the "forest" areas will be most difficult to detect of the ARD components. Multi-spectral systems are however sensitive to growth parameters such as APAR (absorbed photosynthetically active radiation), which peaks during the regeneration stages, thus indicating the location of potential R and A areas after the trees are large enough. High resolution multi-spectral systems will be required for both R and A, but repetitive (annual) measurements will be essential. Persistent cloud coverage in some areas constitutes a major obstacle. Nevertheless, the simple identification that ARD activities have taken place over time can be achieved (Justice *et al.* 1996) and is a valid contribution in the context of the protocol

Active fire events can be detected in an operational manner both at global (Dwyer *et al.* 1998, Grégoire *et al.* 1998, Stroppiana *et al.* 1999) and regional scale (Barbosa *et al.* 1999, 1998) by coarse resolution optical sensors, which provide daily coverage. Spatial quantification of the burnt areas can thereafter be assessed with the use of high resolution sensors. The World Fire Web network provides near-real time information on global fire activities using NOAA AVHRR data (Pinnock and Grégoire, 2000).

Active Microwave Systems (SAR)

Microwave sensors are particularly sensitive to detecting changes between images acquired at different times, even in areas of topographic terrain, provided that the viewing geometry is kept the same. Instruments operating with long wavelengths (L-band or longer) are more suitable for forest related monitoring than short wavelength sensors (C-band or shorter) as the L-band signals interact with the forest at branch and trunk level, while the main interaction at C-band occurs with the canopy. Rough soil and herbaceous vegetation may, in the latter case, be confused with forest. Multi-baseline interferometry, however, even at C-band may be used to separate the contributions of ground and canopy for many forest types (Treuhaft and Siqueira 2000). Tomographic multi-baseline approaches (Reigber and Moreira, in press) will also play an important role in separating ground and volume contributions, and therefore will apply to detecting change in forest area.

Since SAR image acquisitions are independent of cloud cover, it is possible to accurately plan the timing of the data takes, thus optimising the conditions to detect change in the land cover. While it is possible to use short wavelength band SAR systems for the detection and spatial quantification of deforestation (D) events, the use of single polarization C-band data has proven to be problematic as forest and non-forest areas cannot always be differentiated. Still, interferometric C-band tandem data, in particular the phase coherence, may under certain circumstances constitute a valuable source of land cover type information (Treuhaft *et al* 1996, Wegmüller *et al.* 1997). If limited to single polarization data sets, the detection and quantification of deforested (D), reforested (R) and afforested (A) areas is best addressed using longer wavelength band SAR systems, which are more sensitive to the range of biomass associated with forests.

Active fires are not possible to detect with microwave systems as the smoke plumes are invisible to the radar. Burn scars however, may be detected in cases where the fire has caused substantial change to the structure of the forest (Antikidis *et al.* 1997) and can be detected from SAR for several years after the burn.

Polarimetric SAR and polarimetric interferometric systems (Cloude and Papathanassiou 1998) will improve the capabilities for ARD monitoring (Kellndorfer et al. 1998) and at least three such systems are currently planned for the near future: ALOS (L-band), Envisat (C-band) and Radarsat-2 (C-band). The LightSAR (L-band) mission has been halted, but NASA is currently studying alternative mission concepts.

Active Optical Systems (LIDAR)

As long as imaging LIDAR systems are unavailable, detection of ARD activities and burn scars will be limited to those areas actually sampled by the VCL. As such, the feasibility of using LIDAR to address ARD events for extensive areas is, as of yet, unproven. However, LIDAR should have the ability to repeatedly characterise structural attributes at specific locations or collect sample sets in known ARD areas which could prove useful (Blair *et al.* 1999).

3.1.4. Quantification of above-ground vegetation biomass stocks and associated changes therein

The possibilities of making direct estimations of biomass stocks from space is naturally of prime interest in the context of Articles 3 and 12, above.

Passive Optical (Multi-spectral and Panchromatic) Systems

Direct measurements of total above ground forest biomass stocks or changes in such is not feasible with (passive) optical systems. However, indirect estimations of biomass change is possible to a limited extent using vegetation indices based on photosynthetically active radiation (PAR) or through indirect relationships with, for example, mid infrared reflectance data. PAR measurements have been routinely made using multi-spectral sensors and may be combined with environmental data and forest growth models to predict NPP (net primary production) which is presented in terms of units of carbon [e.g. kgC /ha/yr] (Asrar *et al.* 1984, Tucker and Sellers 1986, Prince *et al.* 1995). Future perspectives in this domain through the exploitation of multi-angular measurements, e.g. from the MISR instrument, also offer a significantf potential (Martonchik *et al.* 1998).

Active Microwave Systems (SAR)

The application of radar systems to measure and detect changes in above-ground biomass stocks is an active area of research and development. There was general agreement among the workshop participants, that currently available radar satellite systems (ERS-2 and Radarsat-1), which operate with single channel C-band, are not well suited for biomass estimation, since the signals saturate at low biomass levels. Although C-band sensitivity to biomass up to almost 100 t/ha in certain circumstances may be achieved by fixed-baseline and dual-pass interferometric techniques (Askne *et al.* 1997, Santoro *et al.* 1999, Treuhaft *et al.* - paper 8), the accuracy is largely dependent on factors such as the baseline distance and surface conditions, and more R&D is required before the technique may become operational with single band data. Polarimetric interferometry at L- and C-band, however, is a field of research which holds a certain potential for biomass monitoring (Cloude and Papathanassiou 1998, Treuhaft and Siqueira 2000)

L-band SAR, with a biomass saturation level of 60-100 tons/ha (Dobson *et al.* 1992, Imhoff 1995), may be useful for coarse biomass estimates in regeneration areas (A and R components). There are currently no L-band SAR systems in orbit (JERS-1 failed 1998), but a polarimetric L-band system is planned for the ALOS satellite (due for launch in 2002) and could be well suited to address biomass issues in the context of the Kyoto Protocol. Interferometric coherence by L-band SAR is yet to be investigated.

While the biomass levels approachable by L-band SAR are still way below those of mature forests, which vary between 100 - 600 t/ha, longer wavelengths, together with polarimetric and/or interferometric techniques, can be used to push the biomass saturation levels forward and to improve accuracy (Dobson *et al.* 1992, Imhoff 1995).

Aircraft based radar sensors having full multi-band, polarimetric, and interferometric capabilities currently exist and have proven capable of detecting biomass in a wide range of forests up to 200 tons/ha dry above ground biomass (Ranson *et al.* 1997), primarily due to the long wavelength P-band channel. No space-borne P-band SAR system has been launched up-to-date, mainly due to unresolved ionospheric effects associated with low frequency radars. These effects, which are functions of the total electron content (TEC) in the ionosphere, result in deformation and polarimetric rotation of the signal (Kim and van Zyl, 1999; Ishimaru *et al.* 1999). It has however recently been shown that polarimetric (Faraday) rotation may be corrected for by using a fully polarimetric system (Freeman *et al.* 1998), while other ionospheric artefacts may be reduced to acceptable levels by accurate timing of the data acquisition (early dawn) when TEC is at minimum (Siqueira *et al.*, paper #10). Physical constraints in instrument design, relating to minimum antenna dimensions, can be by-passed at the expense of a lower (50-100 m) ground resolution (Freeman et al. 1999).

Lower frequency SAR systems (VHF band) are probably the most useful for direct measurement and mapping of biomass. In this frequency band, the forest trunks act as Rayleigh scatterers and accordingly has a linear relationship between radar amplitude and stem volume. The VHF-band sensitivity to surface slopes is much less than at higher frequencies, and can to a large extent be corrected for (Smith and Ulander 2000). Recent studies have shown that these frequencies are capable of accurately measuring biomass above 100 tons/ha (dry above ground biomass). Results from the aircraft based CARABAS (20-90 MHz; Ulander et al. 1998), deployed in temperate and boreal forests in Europe, and the BioSAR system (80-120 MHz, Imhoff et al. 2000), deployed in the neo-tropics, have shown that biomass measures can be accurately derived (within ± 10% of field measures) for forests between 100 and 500 tons/ha (actual saturation levels for the BioSAR and CARABAS systems have yet to be determined). These systems show great promise for local to regional applications using aircraft. However, the deployment of space-based VHF/UHF sensors may not be technically feasible due to ionospheric interference with the signal and has yet to be explored (Ishimaru *et al.* 1999). Alternative platforms may also be considered, including long endurance stratospheric airships (UAV) which are not subject to ionospheric distortions. Such platforms will in the near future have an endurance of 6 months to 5 years, through use of combinations of solar cell and fuel cell technologies.

The possibility of using UHF and VHF radar for routine forest biomass measurement is very real. Technological advancements are eliminating many of the obstacles that previously limited the development of UHF and VHF systems and orbital systems may be possible in the near future. In order to take advantage of the potential of these systems, , the scientific community needs to make the appropriate frequency allocation requirements known to the International Telecommunications Union (ITU) and the World Radio Conference (WCR) so that some part of the spectrum can be set aside for remote sensing purposes.

Active Optical Systems (LIDAR)

Combined with allometric models (models linking biomass to measurable parameters such as tree height) the data collected by VCL should be capable of helping it make accurate measures of above ground biomass based on vegetation structure and canopy height measures. Combined with spatially extensive data, such as optical or SAR imagery, interpolation of biomass estimates between VCL sample points could be used to provide local, specific site, biomass estimates. As mentioned previously, it remains to be seen how such data will be applied over large areas.

A limitation of LIDAR is that species/genera cannot be discriminated and yet wood density - and hence biomass - may vary considerably between different species of similar height and similar age. Environmental factors also affect biomass/height relationships.

3.1.5. Mapping and monitoring of certain sources of anthropogenic CH_4,

Article 3:1 of the Kyoto Protocol states that " The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts..." , "with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012". Hence, the Kyoto Protocol relates to all six greenhouse gases listed in Annex A, including CH_4, which is the second of the two greenhouse gases, apart from CO_2, considered relevant in the context of this report.

Although it may well be included in paragraph 3.1.1. above, mapping and monitoring of certain sources of anthropogenic CH_4 is here listed separately, as it is not generally related to forestry or to forest change. Apart from livestock management - which is not considered feasible to monitor by remote sensing - CH_4 is also emitted as a result of anaerobic conditions in open water bodies following extended inundation. Typical anthropogenic sources of CH_4 include irrigated rice paddies, aquaculture (e.g. fish- and shrimp cultivation) and hydroelectric reservoirs.

Quantification of global biomass burning patterns and burnt area will also help to close uncertainties in CH_4 emissions from vegetation fires.

Passive Optical (Multi-spectral and Panchromatic) Systems

Detection and spatial quantification of open water bodies such as aquaculture and hydroelectric reservoirs can be performed by single date high resolution optical sensors. Rice paddies may also be identified in a single date, although repetitive measurements during the growth season are recommended in order to be able to separate it from other agricultural crops and to monitor the water regime - the key factor triggering the CH_4 emissions. However, cloud cover will, in the latter case, constitute an obstacle to obtaining the relevant multi-temporal data.

Active Microwave Systems (SAR)

SAR data can be used to map the three CH_4 sources referred to above. SAR data is particularly suitable for multi-temporal monitoring of irrigated rice, as regular acquisitions can be performed irrespectable of the cloud conditions. Both C-band and L-band SAR have been used to map rice growth (Le Toan et al 1997, Rosenqvist 1999) and it is now deemed possible to perform this in an operational way, using current sensors (ERS-2 and Radarsat-1) as well as sensors planned in the near future (ALOS PALSAR, ENVISAT ASAR, Radarsat-2).

Active Optical Systems (LIDAR)

The feasibility of using LIDAR to address this issue is not currently known.

3.2. Summary of Remote Sensing Instruments

Below follows a brief summary of historical, operational and near future spaceborne remote sensing platforms and sensors of potential relevance to the information needs of the Kyoto Protocol. The list is by no means complete, but it gives a sense of the range of instruments available. For specifications on sensor characteristics, reference should be made to the relevant Internet pages, which can be obtained by undertaking a web search.

[Passive] Optical (Panchromatic/Multi-spectral) Systems - Fine Resolution

Spatial resolution 1 - 250 metres.
Temporal re-visit time ~ 14-45 days (depending on the resolution/swath width).
Landsat TM, ETM+ and MSS, USA, 1972 - present.
SPOT HRV, HRVIR, France/Sweden/Belgium, 1986 - present.
JERS-1 OPS, Japan, 1992 - 1998.
IRS PAN, LISS and WiFS, India, 1995 - present.
ADEOS AVNIR, Japan, 1996 - 1997.
CBERS CCD and IR-MSS, Brazil/China, 1999 - present.
IKONOS, USA, 1999 - present.
EOS-AM MODIS, ASTER, MISR, USA/Japan, 1999 - present.
EO-1 ALI and Hyperion, USA, planned launch Oct. 2000.
ALOS AVNIR-2 and PRISM, Japan, planned launch 2002.

[Passive] Optical (Panchromatic/Multi-spectral) Systems - Coarse Resolution

Spatial resolution 250 m - 1 km.
Temporal re-visit time daily - weekly.
NOAA AVHRR, USA, 1970's - present;
ERS ATSR, ATSR-2, Europe, 1991 - present;
SPOT VEGETATION, France/EU/Sweden/Belgium, 1998 - present;
ADEOS OCTS, Japan, 1996 - 1997.
CBERS WFI, Brazil/China, 1999 - present.
EOS-AM MODIS, USA, 1999 - present.
ADEOS-II GLI, Japan, planned launch 2000.
ENVISAT MERIS, AATSR, Europe, planned launch 2001.

Active Microwave Systems (SAR)

Spatial resolution 3 - 100 metres.
Temporal re-visit time ~ 14-45 days.
SEASAT (L-band HH pol.), USA, 1976.
SIR-A;B;C (L-HH; L-HH; X,L,C) USA,1981;1984; 1994.
Almaz (S-band HH pol.), Russia, 1992-1993.
ERS AMI (C-band VV pol.), Europe, 1991 - present.
JERS SAR (L-band HH pol.), Japan, 1992 - 1998.
Radarsat-1 (C-band HH pol.), Canada, 1995- present.
ENVISAT ASAR (C-band polarimetric), Europe, planned launch 2001.
Radarsat-2 (C-band polarimetric), Canada, planned launch 2001.
ALOS PALSAR (L-band polarimetric), Japan, planned launch 2002.

Active Optical Systems (LIDAR)

Spatial resolution - [VCL] 25 metres (non spatial extensive)
Temporal re-visit time - [VCL] 2 weeks.
Height accuracy - [VCL] < 1 m.
Vegetation Canopy LIDAR - VCL (optical laser altimeter), USA, planned launch Sept. 2000.

3.3. *In Situ* Data

For all applications evaluated in section 3.1 above, up-to-date, quantifiable, *in situ* data are needed for reliable use of the remote sensing data and for thematic validation. A thematic product derived from remote sensing data, be it a land cover classification, carbon stock estimate or a "simple" ARD change map, has no value or credibility unless its accuracy can be reliably assessed and quantified. Although collection of field data generally is a painstaking, time consuming and expensive endeavour, the relevance of *in situ* data cannot be overly emphasised.

In any operational monitoring effort using remote sensing technology performed in support to the Kyoto Protocol, systematic collection of *in situ* data should be performed as an integral part of the undertaking.

An important component of estimating biomass (for ground truth purposes) is the development of allometric equations. A key concept is that allometric equations may be similar for a number of genera at any one site (although may vary between genera) as growth and biomass allocation is dictated largely by prevailing environmental conditions. By harvesting species of ‘key’ genera along environmental gradients, a generalised suite of allometric equations may be generated for local to global application. As an example, allometric equations for tropical regenerating forest genera are similar for both Africa and South America. Cost effective and efficient methods of quantifying component biomass in the field also need to be developed further.

IV. FUTURE ACTIONS

4.1. Research topics

From the discussion in the previous section, it is clear that while remote sensing technology is the only technology which can provide global scale data acquisition schemes and comparable data sets, it can not yet be considered operational in more than a handful applications, relevant to the Kyoto Protocol. In part, this may be due to a lack of knowledge of the specific thematic requirements posed by the treaty - which are still to be defined. Nevertheless, the outer boundaries that comprise the measurement requirements are to a large extent known already. Furthermore, it is important to acknowledge that research should not be limited to only fulfilling the requirements of the Kyoto Protocol. It should also address the larger context of global change and measures that reduce uncertainties in estimating the terrestrial carbon budget. The Kyoto Protocol, in this respect, should constitute a minimum requirement. The following areas of research were identified by the workshop participants:

Optical and SAR data fusion
While both optical and microwave technologies have their specific advantages and disadvantages, fusion of the two technologies can be expected to hold a great potential for enhanced thematic mapping and biomass estimation,. Both technologies have co-existed for almost a decade but surprisingly little definitive work has occurred to take advantage of the potential of data fusion.

VCL and synergy with other sensors
The Vegetation Canopy LIDAR (VCL) holds a specific potential for concrete contributions to the Kyoto Protocol, in particular to estimations of above-ground biomass. VCL will be able to collect samples which to a large extent resembles *in situ* data, characterising canopy structure and canopy height. A first research topic should be focused on developing adequate allometric models for a variety of ecosystems (forest types), from which above-ground biomass can be derived.

A second research topic related to the VCL is synergy with other, spatially extensive, sensors. As VCL will only provide data in a sampled manner, extrapolation between VCL sample points should be attempted in synergy with optical or SAR data, or a combination of both. JERS-1 SAR mosaics at high resolution (100 m) covering the entire tropical and boreal belts of the Earth (Rosenqvist *et al.* 2000) for instance provide a potential for fusion, as do regional coverages of Landsat or SPOT sensor data.

Interferometric, polarimetric and/or multi-frequency SAR applications

SAR interferometry has recently indicated a potential for enhanced biomass sensitivity, even for short wave C-band, which with traditional intensity techniques saturate at very low biomass levels (Askne *et al.* 1997, Santoro *et al.* 1999, Treuhaft *et al.* - paper 8). Interferometric C-band techniques also show enhanced capabilities in distinguishing forested and non-forested areas. Interferometric applications should be explored further, and if possible, with other frequencies.

Airborne SAR campaigns and the Shuttle Imaging Radar missions (SIR-C) have shown the potential of polarimetric SAR applications for enhanced thematic sensitivity and vegetation structure. With the forthcoming launch of ENVISAT, Radarsat-2 and ALOS (all polarimetric), efforts should be made to develop and enhance polarimetric techniques and to align them with the requirements posed by the Kyoto Protocol, and other international global change issues.

Multi-frequency SAR applications is also an area which largely has been overlooked, despite the fact that ERS-1 (C-band), Radarsat-1 (C-band) and JERS-1 (L-band) have co-existed for several years. As with the polarimetric issue above, airborne SAR campaigns and the Shuttle Imaging Radar missions (SIR-C) have shown the potential of multi-band SAR, but the issue should be explored further.

Spaceborne P-band applications

Ionospheric interference with the radar signal at low frequencies generally prevent the operation of such sensors from space. P-band (~ 70 cm wavelength) is the lowest frequency possible to operate from an orbital platform, in which the ionospheric effects can be corrected for by the use of a fully polarimetric system (Siqueira *et al.*, paper 10). Although a spaceborne P-band system is yet to be launched, airborne P-band SAR data have a proven sensitivity to above ground biomass up to some 200 t/ha (Ranson *et al.* 1997), which is a significant improvement compared to today's operational C-band and L-band systems. It is recommended that research be dedicated to investigating the use of polarimetric P-band for biomass estimations and characterisation of vegetation structures in a variety of forest ecosystems, initially by the use of available airborne platforms. It is furthermore recommended that the necessity of a spaceborne P-band platform in the context of terrestrial carbon assessment be investigated not only in a scientific perspective, but also at political and administrative levels.

Low frequency SAR

Low-frequency (VHF and UHF band) radar holds a certain potential for biomass determination on a local to regional scale. While low-frequency radar data have been demonstrated to be free of saturation characteristics up to as much as 400 t/ha (Imhoff *et al.* 1998, 2000, Ulander *et al.* 1998), there are several research questions still to addressed. Further tests of low frequency radar systems should be made to fully explore their capabilities for biomass retrieval and for potential for soil penetration. Experiments need to be carried out where the number of test sites are expanded to include forests that are fully representative of the worlds forests, particularly including mixed forest and rainforest areas. The possibility of combining VHF and UHF band data with LIDAR and/or optical data should also be explored, as well as the feasibility of alternative platforms with long endurance.

Field measurements and networking

Establishment of adequate, global scale, data bases of ground truth data is considered essential for the success of using remotely sensed data in support of the Kyoto Protocol. Allometric models linking biophysical parameters and forest biomass should also be developed. The distribution, geolocation accuracy, revision frequency, biophysical parameters to be measured, etc., should be standardised and managed as a part of an international effort, such as e.g. within IGOS or the CEOS GOFC projects.

4.2. Access and affordability

Over the last two decades there has been a revolution in the way information about the environment is acquired, processed and stored. This centres around the use of computer technology in all stages of data collection and manipulation, and the ability to spatially integrate, interrogate and analyze the nature of the relationships that exist for co-located information. Remote sensing, geographic information systems (GIS) and global positioning systems (GPS) have had a tremendous impact on the way local, regional and global information about the environment is acquired and analyzed.

The major characteristics of ‘geographic information’ is that the feature or object in question can be accurately located, its dimensionality captured, is capable of being measured and adequately described. Given that attributes about objects are obtained through remote sensing, it is important that the processed or interpreted information is stored systematically, so that it can be interrogated and translated from one measurement framework to another and linked with other relational data for mapping and modeling real world scenarios. GIS provides such an environment. The connectivity afforded by these systems is important because an understanding of sustainability requires not only an interdisciplinary approach, but also the integration of information derived from a variety of sciences which span the physical and human disciplines.

The effectiveness of decision-support systems for biomass estimation, for example, within spatial information technologies is jeopardised by problems related to *operational* constraints including the accessibility, affordability and timeliness and *infrastructure* constraints related to poor management, inadequate staffing and lack of training opportunities within responsible environmental agencies. Appropriate government policies and institutional frameworks need to be introduced to address these constraints and to facilitate research, training and education.

Accessibility and affordability should be addressed through agreed international protocols that ensure the open exchange of remotely sensed data between all countries and agency users. Timeliness depends on the actual information requirements and the frequency and type of data being sought. Information needs can most effectively be addressed by accessing both optical and radar remote sensing for vegetation, biomass and vegetation change analysis.

Strengthening institutional infrastructure capabilities of countries and organisations can best be addressed through collaborative technology transfer programs in which the ideas, skills and operational procedures necessary to utilise remote sensing and spatial information technologies are shared with the potential adopters of this methodology. The success of any technology transfer program depends on the level of provision included in the program for training skilled personnel. Failure to give due attention to the training and education needs that accompany the implementation and use of this technology will limit not only its adoption but also the quality of its application. It is obvious that technically advanced nations in which the expertise for using remote sensing for biomass estimation need to be become involved in sharing the necessary data, skills and operational procedures with those countries wishing to upgrade their national capability for using advanced remote sensing technology.

V. SUMMARY AND RECOMMENDATIONS

5.1. Summary

The state-of-the-art of the remote sensing technology in the context of the information requirements raised by the implementation of, and compliance with, the Kyoto Protocol were assessed. A large number of remote sensing sensors and applications were reviewed and it could be concluded that remote sensing technology as such, with its inherent advantages and current limitations, may be used to contribute to meeting some critical and strategically important information needs of the Protocol. The greenhouse gases considered relevant in the context of remote sensing were CO_2 and CH_4. The areas where the technology may contribute significantly to the information needs of the Protocol are listed below. Relevant articles of the Kyoto Protocol are given within parenthesises.

- Provision of systematic observations of relevant land cover (Art. 5, Art. 10);
- Support to the establishment of a 1990 carbon stock baseline (Art. 3);
- Detection and spatial quantification of change in land cover (Art. 3, Art. 12);
- Quantification of above-ground vegetation biomass stocks and associated changes therein (Art. 3 Art 12)
- Mapping and monitoring of certain sources of anthropogenic CH_4 (Art. 3, Art. 5, Art. 10);

A number of areas where increased research activities - primarily focused to solving the specific needs posed by the Protocol - were identified.

- Optical and SAR data fusion
- VCL and synergy with other sensors
- Interferometric, polarimetric and/or multi-frequency SAR applications
- Spaceborne P-band applications
- Low frequency SAR
- Field measurements and networking

However, while it has been shown above that the technological capacity to support the Kyoto Protocol to a large extent exists, it is recognized that there is a lack of commitments from the international civilian space agencies to ensure that adequate remote sensing data will be collected, even during the first commitment period. This lack of commitments is in turn partly linked to a lack of explicit demands from policy makers in the environment arena.

It is furthermore recognized that in order to significantly improve the usefulness remote sensing data on a regional scale, the establishment of dedicated and systematic satellite acquisition strategies which focus on obtaining regional coverage on a repetitive basis, would be required. If pursued by international space agencies and other satellite operators, such dedicated observation plans would provide consistent archives useful for both ARD monitoring within the Kyoto context, as well use in a broader scientific framework.

The issue of accessibility and affordability of geographic information along with the need for training were also raised and it was recommended that these issues be addressed through agreed international protocols that ensure the open exchange of remotely sensed data and training to all.

The legal aspects of utilising remote sensing technology in the context of the Kyoto Protocol were reviewed briefly, and it can be concluded that, while there are no obvious legal impediments to prevent global acquisitions of remote sensing data from outer space, it was deemed unlikely that the data could be used to compel a state to fulfil certain obligations unless the state itself expressly had consented to satellite monitoring. The issue of treaty verification is not addressed in the Protocol.

5.2. Recommendations

Although political in nature, the global impact of the Kyoto Protocol on technical and scientific issues of relevance to the remote sensing community is considerable and unprecedented. Issues related to the protocol, in particular to afforestation, reforestation and deforestation (ARD) activities, will affect the work of the scientific community for years to come. Consequently, it is recommended that a considerable part of international remote sensing research activities be focused and aligned to fulfil the specific information needs posed by the Kyoto Protocol, and in a broader context, the needs relating to full carbon accounting and an improved understanding of the terrestrial carbon budget. Research topics of specific relevance, not only relate directly to remote sensing but also to the need for adequate *in situ* information, have been identified above.

Credibility and international acceptance of any methodology proposed as a result of research into the terrestrial carbon budget are paramount. As such, the roles of the IPCC and international science programmes and entities, such as IGBP, IHDP, WCRP, IUFRO and IIASA, in providing scientific guidance to the Kyoto Protocol, and to encourage dialogue, are duly recognized. Dialogue with other national and international entities, such as the World Bank, GEF and national development agencies will also be essential for capacity building and technology transfer.

The ISPRS, being an international organisation without national bias, can play a significant role in this context. It is therefore proposed that the ISPRS, in particular Commission VII (Resource and Environmental Monitoring), for its next mandate period, 2000-2004, forms a dedicated Kyoto Task Force with the aim of promoting and stimulating remote sensing research and development aligned with the topics identified above. It is here acknowledged that harmonising international efforts is essential. Therefore the activities recommended by this group should be performed in the context of the terrestrial carbon initiative of the IGOS partnership, and co-ordinated closely with the CEOS GOFC Pilot Project, which is considered to be of particular importance and relevance in this context.

VI. ACKNOWLEDGEMENTS

On behalf of the ISPRS, the workshop organisers would like to thank all the participants of the October 1999 workshop for their participation and valuable contributions. We would also like to thank Dr. Fawwaz Ulaby and the University of Michigan for their kind offer to host this workshop.

VII. ACRONYMS

ARD - Afforestation, Reforestation and Deforestation
CEOS - Committee on Earth Observation Systems
FAO - Food and Agriculture Organization of the United Nations
GEF - Global Environment Facility
GBFM - Global Boreal Forest Mapping project
GOFC - Global Observations of Forest Cover
GRFM - Global Rain Forest Mapping project
IGBP - International Geosphere Biosphere Programme
IGOS - the Integrated Global Observation Strategy
IHDP - International Human Dimensions of Global Change
IIASA - International Institute for Applied Systems Analysis
IPCC - Intergovernmental Panel on Climate Change
ISPRS - International Society for Photogrammetry and Remote Sensing
IUFRO - International Union of Forest Research Organizations
LIDAR - Laser Infrared Detection And Ranging
SAR - Synthetic Aperture Radar
UNFCCC - United Nations Framework Convention on Climate Change
VCL - Vegetation Canopy LIDAR
WCRP - World Climate Research Programme

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Appendix I

Workshop Agenda and List of Participants

AGENDA

Remote Sensing and the Kyoto Protocol: A Review of Available and Future Technology for Monitoring Treaty Compliance

October 20-22, 1999 University of Michigan
Ann Arbor (MI), USA

Session 1 Remote Sensing Implications of the Kyoto Protocol		
Paper No.	***Topic***	***Panel Speaker***
	Welcome address	Fawwaz Ulaby Vice President for Research University of Michigan
N.A.	The Global Carbon Cycle	Compton Tucker University Maryland
1	Land Use Change and Forestry Implications of Global Change - Public Policy	Alan Belward DG JRC European Commission
N.A.	The Kyoto Protocol Viewed from the US signatory	Dan Reifsnyder U.S. Department of State
N.A.	Remote Sensing and International Law - Using Satellites for Verification under the Kyoto Protocol	Steven A. Mirmina Office of General Counsel NASA Headquarters
2	Ground Measurements, Remote Sensing and Biomass Estimation in the Australian Context.	Richard Lucas University of New South Wales Philip Tickle Bureau of Rural Sciences
Open Floor Discussions		
3	The Integrated Global Observation Strategy - IGOS	John Townshend University of Maryland
4	CEOS GOFC Project requirements for forest biomass and structure measurements: a role for low-frequency SAR?	Frank Ahern Canada Centre Remote Sensing

Session 2 The Potential of Contemporary Platforms		
Paper No.	***Topic***	***Panel Speaker***
5	Optical Remote Sensing for Monitoring Forest and Biomass Changein the Context of the Kyoto Protocol	David Skole Jiaguo Qi Michigan State University
N.A.	Capabilities of today's SAR Systems for Biomass Monitoring.	Craig Dobson University of Michigan
6	Potential Contributions of the Vegetation Canopy LIDAR Mission to the Kyoto Protocol	Ralph Dubayah University of Maryland
N.A.	Remote Sensing for Global Carbon Cycle Scienc	Diane E. Wickland Earth Science Enterprise NASA Headquarters
Open Floor Discussions		
Session 3 **Theme: "Direct Mapping of Biomass - Low Frequency Radar Systems"**		
7	Monitoring Biomass Using Polarimatric Multi-Frequency SAR	Anthony Milne University of New South Wales
8	The Vertical Structure of Vegetated Surfaces from Interferometric and Polarimetric Radar Data	Robert Treuhaft NASA Jet Propulsion Laboratory
9	Biomass Redtrieval in Very Dense Forest using low-VHF-band SAR	Lars Ulander Swedish Defence Research Establishment - FOA
N.A.	VHF Radar Measurement of Tropical Forest Biomass: Some Early Results from the BioSAR Deployment in Panama	Marc L. Imhoff NASA Goddard Space Flight Center
10	Challenges Associated with Spaceborne Low-Frequency for Achieving the Goals of the Kyoto Protocol	Paul Siqueira Anthony Freeman NASA Jet Propulsion Laboratory
Plenary Session Panel Discussions		

List of Registered Participants

Frank Ahern, Canada Centre Remote Sensing (Canada)
Alan Belward, DG JRC, European Commission (E.U.)
Kathleen Bergen, Environmental Research Institute of Michigan (U.S.A.)
Charles Brown, University of Michigan (U.S.A.)
Daniel Brown, University of Michigan (U.S.A.)
Richard Cicone, ISciences (U.S.A.)
Craig Dobson, University of Michigan (U.S.A.)
Yuhan Dong, University of New South Wales (Australia)
Ralph Dubayah, University of Maryland (U.S.A.)
Fernando R. Echavarria, U.S. Department of State (U.S.A.)
Alaa El-Rouby, University of Michigan (U.S.A.)
Alfred De Gier, ITC (The Netherlands)
Brian Hornbuckle, University of Michigan (U.S.A.)
Marc L. Imhoff, NASA Goddard Space Flight Center (U.S.A.)
Josef Kellndorfer, Envisense (U.S.A.)
Richard Lucas, University of New South Wales (Australia)
Anthony Milne, University of New South Wales (Australia)
Steven A. Mirmina, NASA Headquarters (U.S.A.)
Leland Pierce, University of Michigan (U.S.A.)
Jiaguo Qi, Michigan State University (U.S.A.)
Dan Reifsnyder, U.S. Department of State (U.S.A.)
Ake Rosenqvist, DG JRC, European Commission (E.U.)
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Paul Siqueira, NASA Jet Propulsion Laboratory (U.S.A.)
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Appendix II

Workshop Paper 1

Land Use Change and Forestry Implications of Global Change Public Policy

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1. Introduction

By the beginning of the 19^{th} century Jean Baptiste Joseph Fourier had already developed his suggestions that the Earth's atmosphere traps heat (citations as early as 1807 can be found, but the first separate publication is Fourier, 1824). By the end of the 19^{th} century, Svante Arrhenius had published work on the likely effects of coal burning on atmospheric CO_2 concentration and subsequent warming (Arrhenius, 1896). At the end of the 20^{th} century we are now in a position where the political agenda is adapting to scientific advance. Nowhere is this more clearly seen than in the formulation of public policy concerning the global environment. More than 400 multilateral environmental treaties are currently listed in the IUCN's database (CIESIN 1998), most of which are the results of scientific advance in various environmental fields. This paper examines just one of these, the UN Framework Convention on Climate Change (UNFCCC) and in particular the Kyoto Protocol to this Convention.

2. The Kyoto Protocol to the UNFCCC

The United Nations Framework Convention on Climate Change adopted in 1992 (UNFCC 1992) has the objective of "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner".

The Kyoto Protocol to the UNFCCC (UN 1997) contains legally binding commitments to either reduce or limit the emissions of six greenhouse gases (GHG). The six GHG covered by the Protocol are CO_2, CH_4, N_2O, HFCs, PFCs and SF6. The Protocol contains agreed targets for the Annex B countries including the European Union (EU). Collectively the Annex B countries have agreed to a 5% reduction on 1990 emission levels of all six GHG. The EU collectively negotiated its commitment to reduce yearly emissions by 8% compared to 1990 levels within the commitment period 2008 – 2012.

The Protocol requires national systems for verification reporting and accountability based on guidelines for GHG inventories provided by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 1996). Because of the collective negotiation the EU must collectively report and the European Commission is required by Council Decision to take "steps to promote comparability and transparency of national inventories and reporting" (EC 1999 a).

The reports must provide country specific emission estimates and removal estimates for seven measurement categories (1. Energy, 2. Industrial Processes, 3. Solvent and other product use, 4. Agriculture, 5. Land use Change and Forestry, 6. Waste and 7. Other).

To comply with Article 5 of the Kyoto Protocol the national reporting systems for sinks and sources must comply with the guidelines set out by the Intergovernmental Panel on Climate Change (IPCC). The IPCC recognises the uncertainties in the reporting structures and is constantly working to improve these.

Of particular note are the difficulties surrounding implementation and compliance with those Articles referring to the use of biological sources and sinks, especially to "measure changes in carbon stocks resulting from human-induced land-use change and forestry activities (Article 3)".

Within the EU15 greater consistency in reporting these changes is desirable. And interpretation of the clean development mechanism (Article 12) by certain parties to the convention call for world-wide assessment of changes in land use, especially afforestation, deforestation and reforestation (WBGU 1998).

A global perspective is also implicit in Article 10 of the Protocol. To comply with this article parties must ***"provide systematic observation and the development of data archives to reduce uncertainties related to the climate system".***

The spirit of this Article is international collaboration, rather than unilateral commitment. The Subsidiary Body for Scientific and Technological Advice recommended a draft decision on research and systematic observation that was adopted by the fourth Conference of the Parties (COP) at Buenos Aires in 1998. The text of the draft decision includes the following article:

"#7. Urges Parties to actively support national terrestrial networks including observational programmes to collect, exchange and preserve terrestrial data according to the Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS) climate priorities."

Understanding the climate is a task for all parties to the FCCC but one in which the more advanced and wealthy have something of an obligation to lead. European responsibility in this context is clearly recognised in the Commission document "Preparing the implementation of the Kyoto protocol", COM(1999)230 of 19 May 1999 (EC 1999c).

This states ***"With respect to the international context, the EU could consider enhancing the capabilities to monitor the global environment. In particular, monitoring systems attuned to changes in carbon sources and sinks globally need to be further developed. Information technologies including networks of measurement sites and satellite observation systems represent indispensable sources of data, which can be exploited for the benefit of monitoring and verification of implementation of the obligations under the Kyoto Protocol. The well-developed European technical and scientific capabilities could provide a strong foundation for such an expanded monitoring role."***

In this context European space agencies and related organisations met informally in May 1998 and 1999 at the invitation of the European Commission to examine the implications various European policies have for space activities (EC 1999c).

The meetings concluded that our understanding of Earth science and space techniques has progressed to the point where we can move from scientific investigations to systematic quantitative monitoring of the environment at a global level. Furthermore the group concluded that Europe should strengthen the environmental information input to the policy making, development and implementation processes. European partners are exploring this through the development of the Global Monitoring for Environment and Security (GMES) concept (EC1999c).

3. A GMES framework

GMES must provide information and services that help the EU and others, such as our trading partners and development beneficiaries to implement the Kyoto Protocol and to verify compliance with the terms of the Protocol. Strategically too the ability to assess the compliance of others should not be ignored.

World wide inventory of all 6 GHG for all seven categories is a daunting task. The range of observations required embraces both resource inventories and ***in situ*** measurements and thus remains firmly in the national domain. Nevertheless particular elements of the Protocol do call for global observations, notably the capacity to determine land use change and forestry activities in countries other than the Annex B States (Article 3 and the Clean Development Mechanism Article 12), and the global observations needed to comply with Article 10.

Measurements of agriculture, land use change and forestry are central to the idea of incorporating biological source and sinks into national inventories as set out in the Protocol. These categories imply inventory of two GHG, CO_2 and CH_4. Better understanding of the sources and sinks of these two gases is also central to improving our knowledge of the global carbon cycle (Article 10). Of course under Article 10, the uncertainties also call for quality data sets describing oceanic sinks/sources and for atmospheric data too.

The accounting and monitoring of CO_2 and CH_4 in the context of the Articles identified above are a clear focus for GMES. This accounting and monitoring must be performed in accordance with IPCC guidelines. GMES will provide methods for accounting and monitoring will provide supplemental information both for inventory preparation and for verification and will identify trends and shifts in the parameters inventoried.

4. Measurement requirements and products

In a first phase GMES will target Agriculture and Land use Change and Forestry because

a) These are the areas with a deal of uncertainty in reporting and in need of improvement and harmonisation,
b) There is a clear national, EU15 and global information requirement.
c) The technology and methodology are already ripe for this work,

In dealing with these categories the key measurements required are “area” and “biomass” (the latter implying biomass estimates prior to conversion of land use and/or biomass burning, and/or annual growth rates).

Comprehensive global measurements of area and biomass cannot easily be achieved by conventional means. Concerns for national security and national sovereignty, the lack of appropriate institutional infrastructures, and technological and scientific constraints will all limit access by “third parties”.

The spatial and temporal dimensions of spaceborne Earth observations are such that they have the potential for global observation of these parameters, often daily and over a range of wavelengths suited to the study of terrestrial surfaces. Though a recent innovation in terms of the time scales relevant to climate change, Earth observing satellites can now provide observations going back to 1972 (and even beyond with the declassification of early military satellite imagery). A daily global record is also available from 1981 to the present from the Global Area Coverage archives of the AVHRR data.

The creation of global land cover maps with known accuracy was demonstrated by the International Geosphere Biosphere Programme's DISCover project (Belward ***et al***, 1999), and the use of statistically conditioned samples to provide quantitiative estimates of changes in these cover types is growing too (Richards ***et al.*** 1999).

Scientific advances are leading to optimal spectral indices to determine biophysical variables such as the fraction of absorbed photosyntheticaly active radiation (FAPAR) (e.g., Gobron ***et al.*** 1999). Unlike previously established indices (e.g., the widely used Normalised Difference Vegetation Index) the FAPAR has direct biological significance and can be directly used in biological models to help in the calculation of important ecological variables such as Net Primary Productivity. This will become a feature of GMES as space systems implement the technologies highlighted by such research.

However, even with today's technologies quasi-operational systems measuring area and changes in the areas of the parameters covered by Article 3 are possible. These are listed in Table 1.

The requirements articulated through Article 10 call for products in addition to the basic accounting and inventory work, especially global data sets related to oceanic and atmospheric observations. These are listed in table 2.

5. GMES information system

GMES must bridge the gaps from data to information and from information to knowledge. UNEP’s Earthwatch strategic framework for environmental observing, assessment and reporting (UNEP 1999) provides an overview of this process. This emphasises the point that

“the whole chain of environmental information flow must be included. From observing, monitoring and other data collection, through assessment, modelling and other value-added data processing, to delivery of reports and other information products to priority groups of users, including decision-makers and the general public”.

Table 1. GMES serving Article 3 of the Kyoto Protocol

IPCC inventory category	GMES version 0.0 product
4. Agriculture	
C) Rice Cultivation	Maps of S.E. Asia rice production. Available now
D) Agricultural Soils	The European Soil Bureau products
E) Prescribed Burning of Savannahs F) Field burning of Agricultural residues	Fire map, documenting monthly global fire activity for 1992-93. Available now. Near-real time global fire detection (number of fires, location and time). Australia, North America, most of Amazonia, Europe, West and Central Africa, South East Asia available now, Boreal zone of Russia and Southern Africa available by end of 2000. Annual estimates of global burnt area (ha) from 1981 to present at coarse resolution (8 km). Analysis of same with reference to land cover and population as indicator of environmental stress/land cover change. Africa available now, global data available for 1990, figures for 1991-94 available by January 2000, full history available by 2001. 1-km resolution map of global burnt area (ha) from VEGETATION data. Prototype available mid 2000. GMES partners (CNES, SNSB and CTIV) approached to produce operational monthly estimates of global burnt area. Quantitative estimates of burnt biomass (tdm/ha). Available end 2001.
5. Land Use Change and Forestry	
A) Changes in Forest and other woody biomass stocks	Uniform baseline maps of global tropical forest resources in digital and hardcopy formats. Available now. Quantitative figures documenting forest resources (in ha) and forest losses (in ha/yr), accompanied by accuracy estimates (in % for each continent / region). Global figures available now, continental and regional estimates of deforestation rates available mid 2000. Global monthly estimates of the fraction of absorbed photosynthetically active radiation. Prototype products from SeaWiFS available now. Simulations from MERIS available now. GMES partner ESA has installed the MERIS index in their operational ground segment for use one ENVISAT is launched. Forest inventory maps at 200m resolution (in four classes) for substantial parts of the EU15. Hard copy and digital data available now.
B) Forest and grassland conversion	Mapped location of the most important sites of active deforestation (hotspots). Available now.
C) Abandonment of managed lands	Global map of land cover at 1 km resolution for the year 2000, from vegetation data. Available end 2001, accuracy assessment complete end 2002. Follow-on maps will be used to determine conversion, as too could comparison with standards such as IGBP

Table 2. GMES serving Article 10 of the Kyoto Protocol

Global maps of sea surface biomass (mg chlorophyll.m-3) at 9 km resolution from the defunct CZCS (1979-1986), OCTS (Oct.'96 to June '97) and the operating SeaWIFS (since Oct.1997). Available now.
Prototype product of sea surface biomass at 2 km resolution for coastal areas from SeaWIFS available now. An operational processing chain for SeaWIFS has been implemented at the ME Unit including the algorithm to retrieve Vegetation Index for land. Extension to global mapping (10-days, monthly, seasonal and annual composites) in the 1st half of 2000.
Table 2. continued
Global maps of depth-integrated primary production (mg carbon.m-2)at 9 km and 2km (coastal areas) resolution for SeaWIFS and OCTS for the 2nd half of 2000. Algorithm already available and in preparation for MERIS data (ENVISAT PI project).
Quantitative assessment and mapping of most important marine productive waters and their variability with time by the end of 2000 (time series analyses over 3 1/2 years of SeaWIFS).
Estimation of 'new production' (directly linked to the biological pump, i.e. sequestration of carbon to deeper oceanic layers)starting by 2001 with SeaWIFS and newly launched sensors (MODIS, MERIS, GLI). Quantitative assessment and mapping of marine carbon sinks and sources by the end of 2001 and 2002. Retrospective mapping for previous years and trend analyses (variability in the "sink/source" term) by the end of 2002.

Specific objectives of a global environmental information system as identified by UNEP are

- to keep policy-makers informed of the global environmental situation, particularly where it threatens human health and well-being and environmental sustainability
- to provide adequate scientific information on the global environment assembled, integrated and organised so that the current status and trends can be summarised for each necessary global report
- to provide the basis for integrated assessments of the global environment
- to measure the effectiveness of management actions
- to maximise participation in all parts of the environmental information system.

The Tropical Forest Information System (TFIS), developed by the JRC satisfies these objectives, but of course for only one single environmental variable - the state of the world's tropical forests. This system allows users to combine up to date tropical forest maps and deforestation statistics derived from satellite imagery with other sources of information, ranging from spatial data sets such as global digital elevation models, to anecdotal information, such as local newspaper reports documenting specific deforestation events. The system is being developed so that it runs models of deforestation risk. The success of the TFIS is in no small part due to the fact that it is installed directly in the headquarters of those responsible for implementing environmental policy (in this case DG Environment). Yet it is maintained and updated by the scientists making the measurements and analysing the data (the JRC). The next logical development of the TFIS is to transfer it to a World Wide Web based system. This will allow access (where appropriate) from the general public, and will allow the directorates general to place systems in the field, thus using TFIS for project management in an operational sense.

6. International framework

An operational GMES will be an explicit contribution to the international effort. The Integrated Global Observing Strategy (IGOS; IGOS 1999)is one current focus for co-operation in this field, and the IGOS Partnership (space agencies grouped in CEOS, the G3OS sponsors group, the programme offices of all three Global Observing Systems, two international research programmes, IGBP and WCRP and major national agencies funding global change research grouped in the International Group of Funding Agencies (IGFA)).

The IGOS (http://www.igospartners.org/) unites the major satellite and ground-based systems for global environmental observations of the atmosphere, oceans and land, in a framework that delivers maximum benefit and effectiveness in their final use. The overall concept is set out by Townshend and Williams (1998).

It is also axiomatic that GMES cannot become operational without international acceptance. (Article 5 of the Protocol demands this). Interaction with the IPCC and SBSTA through the Conference to the Parties is an essential part of this.

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Workshop Paper 2

Ground Measurements, Remote Sensing and Biomass Estimation in the Australian Context

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Abstract

Spatial data sets that quantify both the biomass and biomass increment of forests and woodlands are required by Australia to better quantify carbon emission estimates associated with land use change and forestry. Such datasets, although currently existing, are largely in the form of a) extrapolations from available vegetation maps or limited networks of plot data, which are often biased towards commercial forests, or b) surfaces generated using relationships between biomass surrogates (e.g., basal area, volume) and climate and/or remotely sensed data. In all cases, these approaches at mapping biomass/biomass increment have been limited by the lack of reliable and consistently-derived field measurements and inappropriate scaling-up mechanisms. For these reasons also, the potential of new technologies (e.g., laser altimetry, polarimetric radar) for quantifying biomass has not been fully realized.

This paper recommends a range of options for providing reliable estimates of both the biomass and biomass increment at landscape to national scales that are unlikely to place excessive demands on available resources. These include:

a) The formulation of generalized allometric equations, relating tree size to component biomass, that can be applied within selected environmental envelopes.
b) The development and standardization of scaling-up mechanisms that fully utilize laser altimetry, large-scale photography/videography and radar and are supplemented by field measurements appropriate for calibrating multiple sources of remotely sensed data.
c) The use of generalized process models that use climate, soils, terrain and remotely sensed data to predict the growth rates and allocation of biomass to different plant components.
d) The expansion and re-designing of the existing national network of permanent plots to quantify long-term changes in the biomass and biomass increment of forests and woodlands.

Finally, an inventory and monitoring framework is proposed that involves a systematic national grid of multi-stage and multi-phase sampling based around a range of airborne observations and ground-based double sampling and observations by a range of spaceborne sensors.

1. Introduction

The requirement for many countries to generate national spatial datasets of vegetation biomass and biomass increment is relatively recent, and is largely in response to international agreements that oblige signatory countries to fully document net annual carbon emissions from all sources, including land use change and forestry.

Australia, as a signatory to both the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, is in a unique position in that it is the only OECD (Organization for Economic Co-operation and Development) country to report significant losses of carbon dioxide (CO_2) associated with land use change. The large contribution of land use change to national carbon emissions became apparent in the 1990 National Greenhouse Gas Inventory (NGGI), which Australia is obliged to compile and update under the UNFCCC. In the recent revision for 1990 (Australian Greenhouse Office, 1999), an estimated 90 million tonnes (Mt) of carbon dioxide equivalent (CO_2-e) were emitted through land use change, largely through clearance of vegetation biomass. This emission represented approximately 23 % of Australia's total 1990 emissions of 385 Mt CO_2-e. In 1996, emissions had reduced to an estimated 63 Mt CO_2-e, or 15 % of Australia's total emissions (419 Mt CO_2-e).

To calculate emissions associated with land use change, spatial data sets on soil carbon, the areas of vegetation cleared and regenerating, the biomass of the pre-cleared vegetation and the biomass increment of regenerating vegetation are all required. Furthermore, spatial data sets on the area of vegetation thickening in Australia are also now considered important. Caused by several factors, that include a reduction in fire frequency, thickening leads to an increase in vegetation density of both live and dead woody biomass (Archer, 1995; Idso, 1995). Recent estimates, although still uncertain, suggest that vegetation thickening in Queensland alone represents a carbon sink of approximately 100 Mt CO_2-e yr^{-1} (Carter ***et al***., 1998; Burrows ***et al***., 1998). Leemans and Zuidema (1995) also indicate that thickening is not unique to Australia and worldwide may account for a significant proportion of the missing carbon sink that has been identified in global CO_2 circulation models.

The provision of more reliable data, particularly relating to the area of vegetation cleared and regenerating, has been largely responsible for the reported reduction in emissions associated with land use change (Australian Greenhouse Office, 1999). For example, the estimates of the areas of changing land cover were refined recently by comparing time-series of Landsat sensor data over the period 1990 to 1995 for the Intensive Land Use Zone (Kitchen and Barson, 1998; Bureau of Rural Sciences, 1999). However, even with these improvements, Australia still expresses considerable uncertainty associated with emissions and removal in the land use change and also forestry sectors. The Australian Greenhouse Office (1999) currently estimates this uncertainty at between 20 and 60 percent and attributes this largely to the lack of spatial datasets on the biomass (carbon) content of pre-cleared vegetation and the biomass increment of regenerating vegetation.

In this context, the objectives of the paper are to

a) briefly review current approaches to mapping the biomass of vegetation in Australia,
b) identify a range of techniques that already show promise in providing efficient, cost-effective and reliable field estimates of biomass and biomass increment, and
c) propose mechanisms for scaling-up such estimates from site to national levels.

The paper purposely avoids detailed discussion in relation to spaceborne optical and radar sensors as this topic is covered in other papers. Instead this paper focuses on narrowing the gap between field data and satellite remote sensing. The use of such sensors for regional mapping of biomass and biomass increment is, however, fully recognized.

2. Current approaches to estimating biomass

Forests, as defined by the Australian National Forest Inventory (Montreal Process, 1997), cover approximately 157 million hectares (20 percent) of the Australian continent and are divided into closed forest (4.6 million ha), open forest (34.9 million ha), woodlands (104.5 million ha), mallee (11.8 million ha) and plantations (1.0 million ha). The net area available for timber production (excluding plantations) is estimated to be approximately 13.3 million ha, 50 % of which is in public tenure.

A number of approaches to estimating the biomass and biomass increment of these forests and woodlands have been proposed. The simplest has been to group structural classes within existing vegetation maps and to associate each group with the best available estimate of biomass or biomass increment. An alternative strategy has been to assign biomass or biomass increment estimates to the distribution of vegetation as modeled using biogeographic information, climate surfaces, soils data and, in some cases, remotely sensed data. Some limitations to these approaches are apparent.

- The maps generated are often lacking in consistency and inclusiveness of all vegetation types.
- Within mapped classes, the vegetation is often assumed to be in a mature state whereas, in reality, a range of regeneration and degradation stages may exist. The growth of vegetation at all stages of regeneration will also vary in response to different soil and climate regimes.
- The quantity of available biomass estimates is far lower than the number of vegetation classes defined and the estimates used are rarely representative of the class with which they are associated.
- Most estimates of biomass and biomass increment are derived using a limited set of allometric equations, timber volume, mean/periodic annual increment and wood density data obtained from public commercial forests, which comprise less than 10 % of Australia's total forest cover. In many cases, little

> consideration is given to the below ground biomass and non-commercial biomass components (i.e., leaves, branches), and non-commercial and understorey species are seldom acknowledged. For the majority of forests outside of public tenure, few data are available to estimate biomass or biomass increment.

An alternative approach for mapping biomass that has been widely adopted in Australia has been to relate field estimates of biomass surrogates (e.g., basal area) to remotely sensed data from optical satellite sensors such as the Landsat Thematic Mapper (TM) and NOAA Advanced Very High Resolution Radiometer (AVHRR). For example, the Queensland Department of Natural Resources (QDNR) generated a multiple non-linear regression model that predicted tree basal area as a function of the Normalized Difference Vegetation Index (NDVI), calculated from AVHRR visible and near infrared data, and mean annual temperature, as derived from climate surfaces. Above and below ground biomass were then estimated for the Australian continent at 1 km spatial resolution using this model and relationships established between biomass and stand basal area, as derived using data from published Australian studies. The calibration to basal area was then based on field measurements of mature forest canopies. A similar approach was adopted by Kuhnell ***et al***. (1998) whereby relationships between Foliage Projected Cover (FPC) and both Landsat TM NDVI and channel 5 mid infrared data were developed initially. FPC was then related to basal area and subsequently to biomass. While results using both methods have shown promise, it is well recognized that the relationships derived are only applicable to vegetation in a mature state and the reliability of the techniques for estimating the biomass of regenerating woodlands is uncertain.

The acquisition and use of time-series Landsat sensor data for land cover change assessment by both Federal and State agencies has provided an incentive for focusing on these data sets. However, a recognized limitation of optical data is that the two-dimensional structure of vegetation is observed and only indirect relationships with woody biomass may be obtained (Harrell ***et al***. 1997). Microwave sensors, that provide information on the three-dimensional structure of vegetation, are being considered but only by a few agencies.

3. Alternative approaches to quantifying biomass and biomass increment.

In this paper, several approaches that facilitate estimation of both the biomass and biomass increment at landscape to national scales are identified. These approaches can improve the reliability and quantity of field measurements of biomass and biomass increment and/or operate as appropriate mechanisms for scaling-up to the landscape or even to national scales. It is believed that all of these approaches are cost effective and do not place excessive demands on resources.

These approaches include: the formulation of generalized allometric equations that can be applied within selected environmental envelopes; the use of a range of field measurements; large-scale photography/videography; laser altimetry and airborne radar for purposes of scaling-up; the advancement of generalized process models that use climate, soils, terrain and remotely sensed data to predict the growth rates and allocation of biomass to different plant components, and the expansion and re-design of the existing national network of permanent plots, including the establishment of a national grid of sample sites to quantify long-term changes in the biomass and biomass increment of forests and woodlands.

3.1 Allometric equations

To provide comprehensive sets of allometric equations for carbon budgeting purposes, cost-efficient techniques for sampling the component biomass of woody vegetation need to be adopted. The following sections outline some of these techniques and then propose the formulation of generic allometric equations that can be adjusted according to the environmental conditions that prevail.

3.1.1 Optimizing the formulation of allometric equations

Allometric equations which relate commonly measured properties of trees (e.g., diameter) to above and/or below ground biomass components (e.g., leaves, branches, stems), are currently the most effective and efficient method for estimating stand biomass. These equations are typically applied to plot data in order to generate estimates of stand biomass from measurements of tree size. Such plot-based estimates are frequently used to support the quantification of biomass using, for example, remotely sensed data or growth models.

Allometric equations for Australian forests species are, however, scarce, as considerable effort and expense is involved in obtaining the biomass data required for their formulation. As an example, the ratio method of sampling biomass (Snowdon, 1992), which is traditionally used in Australia, typically involves felling trees (for above ground biomass) and/or excavating roots (for below ground biomass). The separate components of the entire tree (i.e., leaves, branches, bole, fine roots and coarse roots) are then weighed wet and sub-samples weighed dry to obtain wet:dry mass ratios from which the dry biomass of the tree can be calculated. To obtain an allometric equation for a particular species, several trees across a diameter range need to be felled and/or excavated and their biomass estimated, adding considerable cost to the whole exercise.

The lack of allometric equations, and the expense of generating new equations, represents a major obstacle to the establishment of an effective biomass inventory and monitoring system in Australia as few stand biomass data can be generated using traditional methods such as ratio sampling. This also raises the real concern that the potential of existing and new technologies (e.g., laser altimetry, radar) for biomass estimation is unlikely to be fully realised due to the lack of accurate estimates of stand biomass that can be used for calibration and validation purposes.

A number of biomass sampling techniques are, however, available that may significantly reduce the cost of harvesting and physical effort in the field. These techniques, which include double regression sampling, importance sampling and randomised branch sampling (RBS), which provide unbiased estimates of biomass that are comparable to those obtained using the ratio method. Many of these techniques are also used in combination.

Double regression sampling uses individual branches as sampling units (Attiwill, 1962; Harrington, 1979). On individual trees, the first step involves developing regression equations between the dry weight and diameter of the primary branches. These regressions are then used to estimate the dry weight of the crown by measuring the diameters of all primary branches. The estimated dry weight of the crown is then regressed against the diameter of the trunk at a selected diameter above ground level to develop regressions for the dry weight of the whole tree.

Importance sampling is a technique based upon Monte Carlo Integration of definite integrals and is a continuous analogue to sampling with probability proportional to size (pps). Sampling with pps randomly selects elements from a known population based on their size or some other auxiliary information relating to each element. Elements that are larger, and therefore contribute more to the estimation of the parameter of interest, are given higher probabilities of selection (Valentine ***et al***., 1984). This technique is particularly useful for sampling the biomass of the larger woody components (stems and branches) and, where applied, only a few disks need to be retrieved for biomass estimation

Randomised Branch Sampling (RBS) is also based on probability theory and uses the technique of Monte Carlo Integration to provide unbiased estimates of the biomass of tree components (above ground), and their variances (Gregoire ***et al***., 1995). RBS is often applied to estimate the biomass of the crown (leaves and small branches), whilst IS is used for estimating the biomass of the larger woody components. The selection of branches is based on probability roughly proportional to the biomass of the leaves/twigs on the branch. An estimate of the amount of foliage on the entire tree is obtained by dividing the sample weight of the terminal segment by the unconditional selection probability of reaching the segment. The variance is estimated by selecting multiple paths although it should be recognized that the same path may be selected. The resulting estimate is usually very precise and unbiased. Studies in Australia have indicated that between 5 and 10 paths need to be followed and the same number of end branches are required to estimate the biomass of the smaller crown elements. Even so, the number of samples is partly dependent upon the size and form of the tree.

The advantages of all three techniques are that the cost of harvesting is reduced considerably as fewer samples need to be taken for analysis and wet weighing of tree components is unnecessary. Although research is continuing in this area, more studies are required to confirm the optimal technique for sampling Australian species. It should be noted that similar methods for optimising the sampling of below ground biomass (e.g., relationships with phloem cross sectional area) have also been devised and should also be investigated.

3.1.2 Allometric equations for estimating component biomass

Many of the allometric equations that exist for Australian tree species do not estimate the biomass of all trees from measurements of tree size, particularly those that are generated for commercial purposes. Such equations are, however, considered essential for scaling up-purposes as optical and radar data (see later discussion) can be related to different components of the biomass. Furthermore, knowledge of the different partitioning of biomass to different plant components greatly assists the validation, calibration and refinement of models that predict biomass allocation. Perhaps some of the most useful equations for this purpose, which serve as examples, are those generated by Burrows ***et al***. (1999) where, for several Eucalyptus species, the circumference at 30 cm has been related to the biomass of different components (leaves, branches, trunks; Table 1). The derivation of equations that estimate component biomass is therefore advocated.

Table 1: Allometric equations for estimating the component biomass of ***Eucalyptus melanaphloia*** (intact woodland). These equations are of the form ln y = a + ln x where y represents biomass (kg) and x is the stem circumference at 30 cm.

Component	n	a	b	R^2
Branches	22	-5.554	2.344	0.925
Total (above ground)	22	-2.809	1.922	0.939
Stem	22	-3.327	2.006	0.91
Bark	22	-3.685	1.685	0.869
Wood	22	-3.428	1.979	0.916
Trunk	22	-2.873	1.761	0.9
Capsules	20	-9.985	1.932	0.619
Leaf	22	-3.491	1.259	0.806
Dead wood	18	-10.664	2.767	0.809
Lignotuber scrap	6	-28.906	6.305	0.711
Lignotuber trunk	10	-5.339	1.976	0.933
Lignotuber total	10	-5.747	2.116	0.922

3.1.3 Generic allometric equations

In Australia, the few allometric equations that exist are often used, perhaps inadvertently, to estimate the biomass of species of the same genus at a particular site. However, several studies have indicated that this may be a reasonable approach as similar allometric equations have been reported ***for E. calophylla*** and ***E. marginata*** in south-west Western Australia (Hingston ***et al***., 1981), ***E. miniata*** and ***E. tetradonta*** in the Northern Territory (Werner, 1988) and ***E. crebra*** and ***E. melanphloia*** in central Queensland (Burrows ***et al***., 1999; Figure 1). Senelwa and Sims (1998), in a study of 2-5 year old plantation eucalypts (***E. globulus***, ***E. nitens***, ***E. ovata***, ***E. regnans*** and ***E. saligna***), also reported that the allometrics did not differ significantly. These observations therefore suggest that a single equation for several like-species (similar lifeforms) may be sufficient to estimate above ground and potentially below ground biomass. Therefore, the approach recommended is that further harvesting of species should take place at a number of key sites to assess the similarity of allometrics between species.

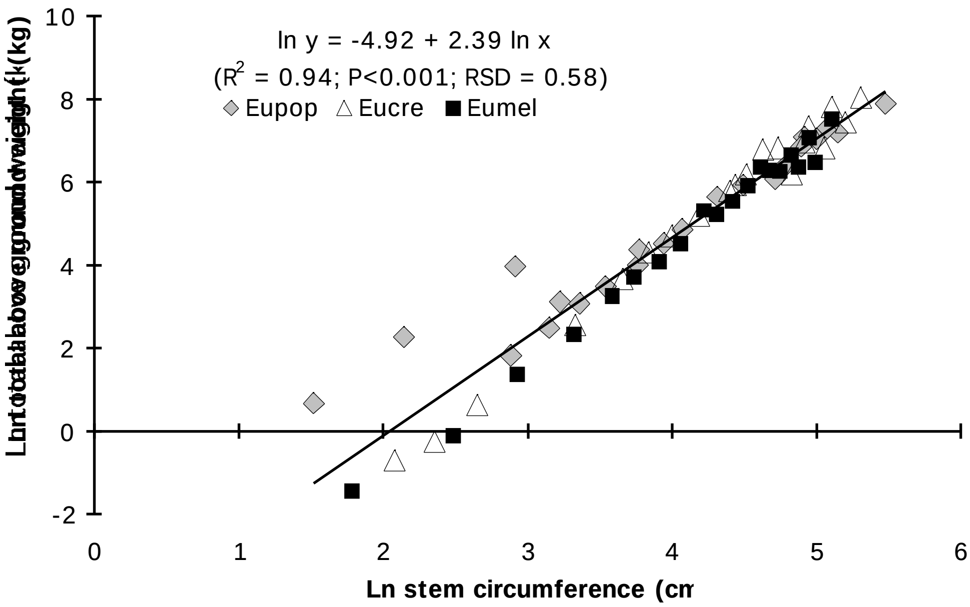

Figure 1. Lognormal regression of stem circumference (cm) measured 30 cm above ground vs total aboveground weight (kg) for ***Eucalyptus crebra*** (Eucre), ***E. melanophloia*** (Eumel)and ***E. populnea*** (Eupop) combined data. (Independent regressions for each species were not significantly different, P> 0.05; Burrows ***et al***., 1999).

3.1.4 Harvesting along environmental gradients

A limitation of allometric equations existing for Australian forests is that they have been derived from, and are therefore only applicable, to particular species within an environmental envelope. For example, equations generated for highly productive ***Eucalyptus obliqua*** forests at wet sites in Tasmania are unlikely to provide a reasonable estimate of stand biomass when applied to ***E. obliqua*** woodlands at dry, lower productivity sites in western Victoria. This is because the form, size and dimension of trees of similar diameter will be markedly different because of the extremes in growth environments. This changing architecture of many tree species is particularly evident in Australia where noticeable environmental gradients exist. Therefore, where allometric equations are applied to the same species across an environmental gradient, the assumptions used to fit the original regression models are often violated which leads to errors in the estimation of total above ground, below ground and component biomass.

A recommended solution is to establish a set of generalised allometric equations by harvesting key generic species (e.g., ***Eucalpytus obliqua*** in south east Australia, ***E. miniata*** in the Northern Territory or ***E. populnea*** in Queensland) along environmental gradients (e.g., water balance). These equations could be formulated by first harvesting a few widespread species at the extremes of their environmental gradients (e.g., along a water balance, soil fertility or temperature gradient) and then at intermediate sites along these gradients. Although such a harvesting exercise would be costly using traditional ratio sampling methods, the use of more efficient sampling techniques (e.g., a combination of Importance Sampling and RBS) would reduce the investment substantially.

The appropriate equations would be applied by relating environmental conditions at a new site to those associated with one of several generalised equations. Such conditions may include soil (as derived from national soil maps or modelled from terrain data) and climate (as derived from local weather stations or generated using ESOCLIM software (Hutchinson, 1989), for example).

3.2 Mechanisms for scaling-up

The previous sections have dealt with the need to improve the reliability and cost-effectiveness of biomass sampling schemes at the individual tree level and site level. Opportunities for scaling-up tree-level measurements to landscape levels are discussed in this section. Techniques discussed include the use of field measurements, laser altimetry, large-scale photography/videography and radar.

3.2.1 Field measurements

Traditionally, ground measurements of above ground biomass (including above ground NPP) that may be used to calibrate remotely sensed data or growth models, have come from existing forest mensuration data sets collected for an entirely different purpose. In most cases such plots cover 0.01-0.25ha in area, and as mentioned previously, often rely on a poor selection of allometric equations to derive biomass values. In addition, these plots are often poorly geo-referenced, rarely account for the spatial heterogeneity at the landscape scale, and cannot generally be considered as being representative “ground truth” for the interpretation of remotely sensed data.

An additional factor that is also often overlooked is the fundamental mis-match between the spatial and temporal scales, of the ground data being used to calibrate remotely sensed data. (e.g., using data collected from a 10 x 10 m plot to calibrate 30 m Landsat TM data). This gap between “ground truth” and remotely sensed information becomes even greater when coarse spatial resolution data or global productivity models, with pixels sizes ranging from 250 m and 1 km, are applied (Running, 1999).

For direct field measurements there are a number of potential options. One of the most effective (i.e., in terms of data quality) ground sampling schemes is a nested sampling approach such as a systematic spatial cluster design (Fortin ***et al***. 1989). Such a scheme allows for varying the sampling intensity for different attributes depending upon ease and cost of measurement. This nested sampling design also allows information to be generated on zones of influence and types of spatial patterns (Cohen ***et al***., 1999, Running ***et al*** 1999; Fortin ***et al***., 1989). While such an approach for field data collection generates very high quality data, it comes at a high cost.

The trade-off with any sampling scheme is the need for accuracy and precision verses time and cost. There is an argument that, for the purposes of calibrating and validating remotely sensed data over local, regional, national and global scales, it is better to sample in more locations but to sample less at each location. This approach is not, however, cost-effective if only ground measurements are used due partly to the expense of travelling between sites. A more efficient and cost effective alternative for calibrating “course” scale (>25m) remotely sensing is to use large-scale aerial photography and laser altimetry systems within a multi-stage and multi-phase sampling environment that includes cluster sampling as described above. Before detailing the actual sampling strategy, it is worth undertaking a brief review of the remote sensing technologies of large-scale photography and laser altimetry that allow us to make a number of individual tree level measurements equal to that taken from the ground. A number of old and new technologies are available to enhance our capacity to generate ground quality data more cheaply than direct ground surveys. Furthermore, these data can be used for calibrating a range of coarse spatial resolution remote sensing platforms.

3.2.2 Large-scale aerial photography

The application of large-scale photography (less than 1:5000 scale) has, since the 1960s been recognized as a valuable tool for bridging the gap between ground measurements and medium scale Aerial Photo Interpretation (API). This approach has demonstrated the capacity to create measured data (i.e., individual tree measurements) at a fraction of the cost of collecting the same information from the ground (Spencer and Hall, 1988, Pitt, 1997, Tickle ***et al*** 1998). With the use of Differential GPS, analogue and digital camera/video systems now have the capacity to collect information at plot scales that are commensurate to the spatial resolution of satellite sensors, while maintaining the ability to undertake individual tree measurements.

The most efficient way of utilizing large-scale photography is within a two-phase (double sample) sampling scheme with regression or ratio estimation (Bonnor, 1975). In practice this simply means that for a subset of the photo-plots a ground sample is selected (systematically or randomly) and either the same variable, or surrogate variable is measured on the ground to establish a relationship between the two samples. The objective is to either identify any bias in the photo measurement (e.g. a systematic under-estimate of the number of trees) or to establish relationships between variables such as tree height and diameter, the latter of which is difficult or impossible to measure from photography. Given the strength of relationships found within the double sample, the number of photo-plots and ground plots can be optimised according to precision of estimates and cost.

3.2.3 Laser Altimetry

Over the last 15 years a number of studies have shown that airborne laser altimetry systems also have enormous potential to improve our estimate of forest structure and biomass (Nelson ***et al***, 1984 and 1987, Nilsson, 1994, Jacobs, 1993, Ritchie, 1996, Naesset, 1998, Tickle ***et al***, 1998 and Means, 1999). All of these studies have shown that laser altimetry systems in both small footprint (Blair, 1999) and large footprint (Blair, 1999b) have the capacity to measure the height and vertical structure of forests at least as well as ground measurements in most forest types.

Until recently, most of the laser technology was only available in non-commercial, research aircraft. Now, however, there are numerous commercial systems offering small footprint, multiple return laser systems in profiling and scanner form. All such systems have integrated inertial navigation systems, and many have analogue and digital camera systems coincident with the laser system.

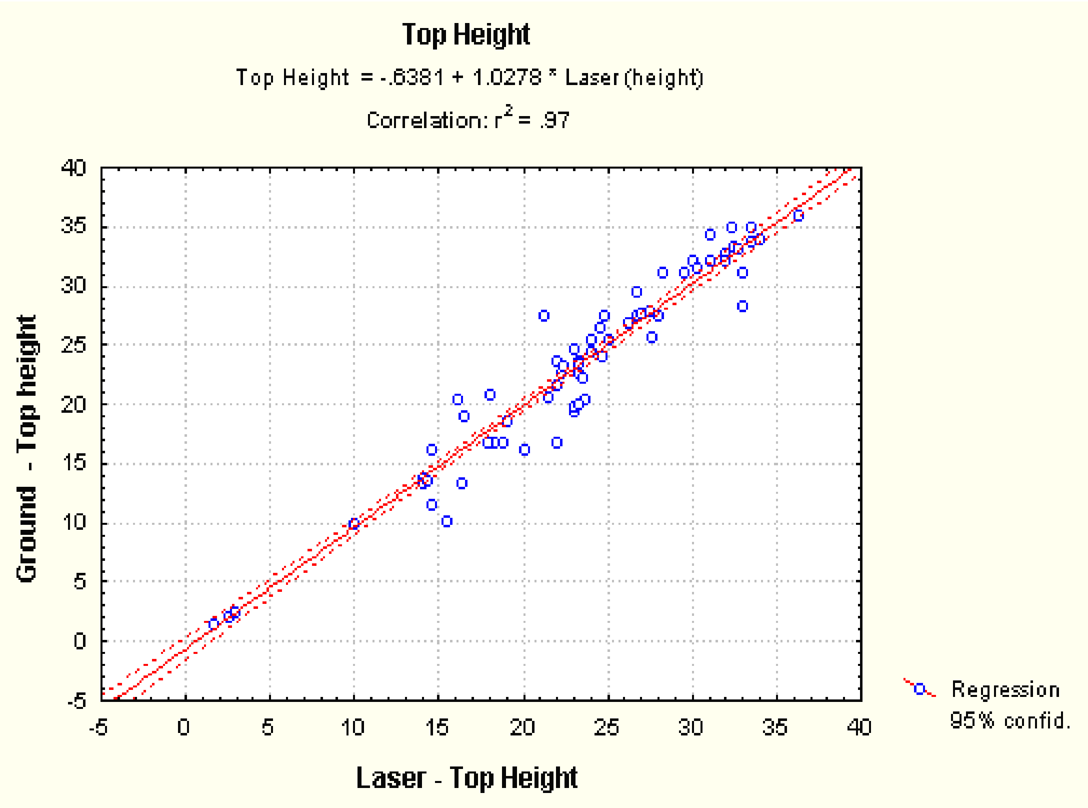

Figure 2: The relationship established between ground measured tree height and laser measured height from Tickle et al (1998).

Given this integrated technology, there is the capacity to undertake detailed individual tree level interpretation from large-scale photography (eg species, growth stage, stocking, disturbance), and precise measurements of tree height (in addition to ground elevation), canopy density and vertical structure) using the laser systems (Figure 2).

By coupling such data with appropriate field measurements (double samples) to establish, for example, height/diameter and allometric relationships, basic data for the estimation of biomass can be collected at a fraction of the cost. The inclusion of a large number of airborne survey sites into the site-specific database would therefore increase the efficiency and cost effectiveness of the inventory and monitoring system. These samples would also provide a permanent record of site-specific conditions for future analysis.

3.2.4 Airborne Synthetic Aperture Radar

Radar technology has been poorly investigated in Australia despite recognition of its potential for quantifying biomass in other countries. This is due to a number of reasons, including the poor availability of allometric equations for biomass estimation, particularly those that do not consider the different components of the biomass.

As indicated earlier, allometric equations that estimate component biomass are considered essential for the interpretation of Synthetic Aperture Radar (SAR) as microwaves of increasing wavelength interact with different components of the biomass. In particular, microwave energy at X band (wavelength of ~3.5 cm) and C band (~5.6 cm) is particularly sensitive to surface scatterers which, in the case of vegetation, include leaves, twigs and smaller branches of the canopy layer (Wang ***et al***. 1994, 1995). Longer wavelength energy at L band (~24 cm) and P band (~65 cm) have been shown to interact with the larger components of the canopy, the trunks and soil boundary layers (e.g., Wang ***et al***. 1994, 1995). A number of studies (e.g. Beaudoin ***et al***. 1994; Harrell ***et al***. 1997) have indicated that microwave data at different wavelengths and polarisations data may be used to estimate the component biomass of vegetation.

However, in establishing relationships between component biomass and SAR backscatter at different wavebands and polarisations (and also optical data), time and site-specific measurements of biomass are critical in the calibration phases. In particular, due to large variations in vegetation phenology across Australia, variations in leaf biomass will occur and unless the field and remotely sensed observations are acquired simultaneously, the ability to understand and interpret the remotely sensed data will be reduced. Site-specific estimates of biomass are also required as the application of allometric equations generated at some distance from the observation site will not provide a realistic estimate of biomass due to the likely differences in component biomass and growth form that result from environmental differences. Techniques such as RBS, importance sampling, airborne photography and laser altimetry therefore provide an opportunity to obtain the required site and time-specific estimates of biomass at minimal cost.

3.2.5 Forest productivity models

An alternative or complementary approach to estimating biomass and biomass increment is to use forest productivity models that predict biomass accumulation and allocation within different tree components (above and below ground) from basic climate and soils data. Specht (1981), for example, developed the Community Simulation model (COMSIM) to estimate community biomass and biomass accumulation for forests to any user-defined age. The Physiological Principles of Predicting Growth (3PG) model (Landsberg and Waring, 1997) also uses basic climate and soils data to estimate, on a monthly time-step, the accumulation and allocation of above and below ground biomass by forest stands. 3PGS (Coops ***et al***., 1998) is a modified version of 3PG driven partly by estimates of the fraction of light intercepted by vegetation canopies, as derived from near infrared and red reflectance from satellite sensors such as the NOAA AVHRR and Landsat TM. Initial studies in Australia and New Zealand for 8 contrasting forested sites have demonstrated a strong relationship (r^2 = 0.82) between Net Primary Productivity (NPP) predicted by 3PGS and measured above ground biomass increment.

The power of these models can be increased substantially when modified to run spatially. For Queensland, COMSIM is currently written to estimate biomass and biomass increment on a 0.05^o grid. The 3PG and 3PG-S models have recently been programmed into a fully integrated GIS framework known as 3PG-SPATIAL by the Bureau of Rural Sciences and CSIRO (Tickle ***et al*** 1999). The 3PG-SPATIAL model has recently been applied at 25m resolution over an area of 50,000 hectares in southeast NSW using climate surfaces (e.g., radiation, temperature) generated with the ESOCLIM software and adjusted for slope, aspect and horizon effects using both SRAD (Moore, 1992) and a range of satellite data. Comprehensive soil attributes are also being modeled using site data and the DEM. Results of this recent work has shown that the 3PG-SPATIAL model can actually outperform traditional forestry growth models at operational to regional scales, both spatially and temporally (Tickle ***et al*** 1999).

Process-based models offer a number of unique opportunities, in addition to the prediction of NPP from climatic and remotely sensed data, such as that described by Running ***et al*** (1999). These additional opportunities include:

- Better defining environmental gradients for the purpose of allometric development
- Their use for designing efficient field surveys
- The ability to integrate forest management level information into regional, national and global remote sensing studies.
- A capacity to project forest growth into the future based upon management and policy decisions.

A crucial aspect effecting the future adoption of process-based models is the ability to generalize them to the point where spatial data is readily available within a GIS and remote sensing environment; and the capacity to calibrate them using minimal forest mensuration data.

3.2.6 Permanent Plots

Permanent plots, within which consistent tree measurements are recorded at regular intervals, have been established by some organizations in Australia as these provide scope for monitoring long-term changes in ecosystem productivity. In Queensland, for example, a network of over 100 permanent plots has been established in representative stands of woodlands communities with monitoring undertaken using the TRAPS (Transect Recording and Processing System) system. These plots have been useful in quantifying changes in the biomass, structure and woody plant composition, particularly in areas subject to vegetation thickening (Back ***et al***., 1997). Many forestry organizations in Australia also maintain a system of permanent plots, although these are largely confined to commercial forests. The maintenance and continued establishment of permanent plots is recommended for long-term biomass monitoring particular in a climate where enhanced growth is being observed in response to enhanced levels of atmospheric CO_2. The establishment of permanent plots in non-commercial forests is also advocated.

Of crucial importance, is the re-designing of permanent plot networks to ensure that data collection is optimised for the purposes of calibrating and validating remotely sensed data. Techniques such as RBS and importance sampling provide an opportunity to obtain the required site and time-specific estimates of biomass at minimal cost. They also offer the advantage of not having to undertake complete destructive harvesting within a plot, rendering it useless for future monitoring.

The use of airborne laser altimetry and large-scale photography provide the opportunity for more cost-effective and timely ground data collection within permanent plot networks at scales more suited to calibrating satellite remote sensing. With the aid of Differential GPS, such airborne systems also offer a capacity of revisit and re-measure permanent sites in a precise manner.

4. A Proposed Inventory and Monitoring Framework

There is no doubt that Kyoto compliance is going to create an enormous challenge to the forest inventory and remote sensing fraternity. In the context of Australia, we are faced with the task of not only reporting on sinks and sources of greenhouse gas relating to LUCF at the national level, but also carbon credit and trading schemes, that will operate at the local and regional level. We will therefore need to ensure that “bottom up” and “top down” inventory methods produce similar results with known levels of accuracy and precision. In order to achieve this, we will require a combination of wall-to-wall mapping from multiple resolutions of satellite data and a variety of airborne and ground-based sampling schemes that may vary in type and intensity from region to region.

Probably the greatest challenge of initiatives such as Kyoto and the Montreal Process, is the need to report at the national level, on a 5 yearly interval for all indicators and annually for others. The best way to achieve this in a rigorous manner, and to known levels of precision, is to establish a systematic national grid of multi-stage and multi-phase sampling based around a combination of large and medium scale photography, airborne laser altimetry and airborne radar, and ground-based sampling. The above sampling would then be used in combination with wall-to-wall mapping undertaken using Enhanced Thematic Mapper Plus (ETM+), MODIS at 250m and 1km resolutions, and SAR data.

The detail of such an inventory and monitoring framework needs to be subject of a separate paper. However, a broad overview of the proposed framework is given in Table 2 below.

Table 2.

Baseline Carbon Stocks	**Description of Required Activities**
Wall-to-Wall Carbon Stocks	· Wall-to-wall landcover and forest cover density mapping using ETM+, along with wall-to-wall SAR in areas of low relief and low biomass to establish baseline carbon stocks. · Medium scale (1:20,000 scale) Aerial Photo Interpreted (API) mapping is nearly complete for the coastal forests. A range of existing vegetation maps and site specific data sets will also be utilized. · These will also require the establishment of the systematic sampling strategy described below, along with some regionally specific sampling and mapping programs to fill gaps in inventory. · The Vegetation Canopy Lidar (VCL) mission will also play a crucial role in establishing Australia’s baseline stocks. The VCL will require airborne laser altimeter to be collected across a range of vegetation and landcover types for calibration purposes.
Monitoring Framework	
Level 1	· MODIS 1km estimates of NPP, and 250m mapping of landcover change on a national and annual basis
Level 2	· ETM+ mapping of landcover change and NPP for 20km by 20km sample areas coincident with a national 100km grid on an annual basis, along with coincident SAR mapping of biomass stocks. · Used to calibrate the level 1 annual inventory. · Level 2 would be completed wall-to-wall every 5 years, with the aid of level 1 to identify areas of greatest change.
Level 3	· Medium-scale (1:10,000-1:40,000) colour or black and white photography on a 20km grid covering 1-2km^2. · These data would be used for visual interpretation mapping of landuse and landcover types as well as mapping of structural vegetation types. · This level may also include airborne SAR. · The purpose of this level is to calibrate and validate the level 1 and 2 inventory using polygon data.
Level 4	· Large-scale photography and small footprint laser altimetry strip or cluster sampling within Level 3 sample areas. · Photography would be flown at 1:1,000-5,000 scale depending on

	vegetation types. Stereo photo clusters will have coincident laser altimetry scanner data at sampling intervals of less than <1m. · Photo/Laser-Plots will need effective swath widths 100-200m wide and allow effective measurement of individual trees over a plot area of 1-5 hectares
Level 5	· Level 5 is the ground survey component of the inventory. · Will consist of the range sampling designs at the individual tree (biomass sampling) and plot level. · Level 5 will be used as a double sample for calibrating level 4, as well as provide the basis for detailed process studies.

5. Conclusions

The paper has demonstrated that, although estimates of biomass and biomass increment are obtainable using existing vegetation maps and through established relationships between biomass surrogates and remotely sensed optical data, the resulting products often poorly represent the magnitude and spatial variation in biomass and biomass increment.

A number of techniques have been proposed that may be used to refine estimates of biomass and biomass increment and are considered to be inexpensive and efficient relative to many methods currently being used. Although further applied research is required in a number of areas, studies are increasingly demonstrating that reliable and accurate estimates of biomass and biomass increment may be obtained from existing technology.

These techniques include:

- The use of alternative procedures for sampling component biomass, including double regression sampling, importance sampling and randomized branch sampling.
- The formulation of generic allometric equations
- Harvesting of a few widespread generic species across environmental gradients to establish a suite of generalized allometric equations.
- Establishment of nested sampling approaches that integrate field measurements, large-scale aerial photography and laser altimetry data.
- The establishment and re-designing of a national network of permanent plots.
- Estimation of component biomass (and hence total biomass) for selected sites using airborne Synthetic Aperture Radar (SAR).
- The use of productivity models (e.g., 3PG) for spatially estimating (potential and actual) forest and woodland biomass and biomass increment from soils, climate and remotely sensed data. Such models also enable the spatial definition of environmental gradients for improving ground sampling, and the ability to project forest growth into the future.

Finally, the paper has proposed an inventory and monitoring framework for scaling-up from the site to the national level that involves a systematic national grid of multi-stage and multi-phase sampling based around a range of airborne observations, ground-based sampling and data recorded by different satellite sensors.

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Workshop Paper 3

The Integrated Global Observation Strategy

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1. Introduction

The Integrated Global Observation Strategy (IGOS) seeks to involve the major satellite and ground based systems for global environmental observation in a framework that delivers maximum benefit and effectiveness in their final use. IGOS may become one of the primary mechanisms for ensuring international cooperation in the provision of observations including those associated with carbon and the Kyoto Protocol.

2. Principles of an IGOS

The fundamental principles of IGOS are that it should provide a framework to create a coherent integrated set of user requirements so that providers can better respond to them; assist efforts to reduce unnecessary duplication of observations and identify key deficiencies in global observations (Williams and Townshend 1998).

To achieve these goals it must assist decision-makers with responsibility for observations in the following ways by providing an overarching strategy for global observations allowing those involved in their collection to improve their contributions allowing those contributing make better decisions in the allocation of their own resources to meet their own priorities by taking advantage of improved international collaboration and coordination and provide a framework for decisions that have the goal of providing long term continuity and spatial comprehensiveness for key observations in an operational rather than an experimental mode.

IGOS is intended to take account of existing international co-ordination of observations; it should therefore build upon the strategies of existing international global observation programs and focus the need for additional efforts in areas where satisfactory international arrangements and structures do not currently exist for implementation; build on existing international structures that successfully contribute to current global observations rather than create a centralised decision-making organisation.

To be successful an IGOS must contribute to a broader understanding of the need for reliable observations by providing improved understanding for Governments of the need for global observations through the presentation of an overarching view of the capabilities and limitations of the current systems; providing opportunities for capacity building and assisting countries in obtaining maximum benefit from the total set of observations.

Since observations by themselves are rarely of value, IGOS must also be directly involved with issues of data and information systems and services, by facilitating the creation of improved higher level products through the integration of multiple data sets from different agencies and national and international organizations identifying situations where existing international arrangements for the management and distribution of key global observations and products could be improved.

The main emphasis of IGOS has been on the provision of observations to support long term operational requirements rather than on the support of process research, where the priorities are directly established by members of the scientific community, for example through the World Climate Research Programme. However it is anticipated that IGOS will have a role in relation to research activities by providing a framework for decisions supporting scientific research for a better understanding of Earth processes result especially that which is dependent on improved long term observations and assisting in the transitioning of systems from research to operational status through improved international co-operation.

3. Stages in the implementation of an IGOS

Attempts have been made to outline the main elements that must be in place to under-pin a successful implementation of an IGOS (e.g. Williams and Townshend 1998).

Assess Requirements. This means establishing a consensus on what are the requirements for observations meeting specific information needs. Products have to be defined which will respond to these needs and only then can the observations can be specified that will allow these products to be generated.

Evaluate the current capabilities of observational systems. This first involves a consideration of product capabilities and then a comparison of the capabilities of current observational systems compared with requirements.

Decide on the changes in observational capabilities. This involves an analysis of the requirements and the capabilities in order to isolate deficiencies in observational systems. Implicitly or explicitly there needs to be a process of prioritisation amongst the many deficiencies that such an analysis will reveal. The net result is a set of priorities for enhancements to the existing capabilities.

Obtaining commitments for changes. Having determined what are the priorities for change it is necessary then to establish the commitments to obtain such changes. These commitments will be made independently by the relevant national or international organisations.

Change the observational systems either by deploying new observational assets or enhancing the product processing chain. The former involves individual agencies agreeing to develop, deploy and maintain new assets, either in terms of satellite based or *in situ* systems. With regard to the latter we should note that many improvements can be made through better exploitation of existing assets. This may involve changing the acquisition strategy or making other changes in the product processing chain. There may also be changes in the key areas of calibration and validation, data access and networking, the assembly of data sets, improving data archiving and product generation.

Implementation and use. This involves the integration of the data and products to produce information that responds to the user requirements and ultimately to the scientific, social and political drivers. This is the key element because it forms the basis for assessment of the value of having an IGOS.

Monitoring and Analysis of Products and Information services. To determine whether or not the resultant observational systems are operating satisfactorily and meeting their objectives a continuous monitoring and analysis procedure is needed, which feeds back into the evaluation of current capabilities.

4. Early stages in the implementation of an IGOS.

Early conceptual development.

Discussions in the mid-1990s especially within the Committee for Earth Observing Satellites developed an initial framework for an IGOS. At this stage the space component of an IGOS has received the most attention though there was a meeting held under the aegis of the Global Climate, Ocean and Terrestrial Observation Systems (GCOS, GOOS and GTOS) to examine the *in situ* components in 1996. Currently the most accessible source of these earlier materials can be found in Dahl (1999). It became apparent that the task of comprehensively implementing the principles and processes described above was a truly daunting task even for the space component alone. As a consequence a Strategic Implementation Team was set up by CEOS to begin the task of implementation by looking at certain specific projects.

The Strategic Implementation Team and the initial six pilot projects.

Membership of the a Strategic Implementation Team (SIT) included most of the key heads of environmental space programs from throughout the world who potentially could contribute to an IGOS. In collaboration with representatives of the global observing systems six pilot projects were selected which were anticipated to be prototypical of an IGOS. Although initiated by a meeting led by CEOS there was a strong motivation to include projects involving *in situ* as well as space observations.

The projects as originally formulated are listed below. A number of these, especially the first two, had a well developed program of activities before being accepted by SIT as IGOS prototype projects. It should be stressed that these were all regarded as being projects close to going operational and hence were prototypical of an IGOS rather than being prototype projects in themselves.

i) *Global Ocean Date Assimilation Experiment (GODAE)* focussed on the comprehensive observation and modeling of the physical state of the surface ocean layers

ii) *Upper Air Measurements* and specifically the impact on weather forecasting of the loss of wind observations from radiosonde observations and the extent to which they could be replaced by satellite observations.

iii) *The Continuity of Ozone Observations* especially in relation to the roles of different national agencies providing space observations.

iv) *Global Observations of Forest Cover*, to ensure the systematic monitoring of the state of the world's forests including the impact of human disturbance and the impact on climate change.

v) *Long-term Ocean Color Measurements* primarily using satellite sources including an assessment of the extent to which redundant observations may be collected in the next few years.

vi) *Disaster Management*, primarily to explore how satellite remote sensing and their attendant data delivery systems could be used to assist disaster management.

Each of the projects has analyzed the current deficiencies in the required observations and has reported these back to the SIT. This is forming the basis for the space agencies enhancing their observational capabilities to meet these requirements.

The IGOS Partnership

To fully develop an international structure supportive of an IGOS it was clear that one had to be developed external to CEOS, notwithstanding the leadership role taken by this organization. Such a structure had to involve both representatives of users at an international level as well as those with international responsibility for *in situ* observations. It was on this basis that the IGOS Partnership (IGOS-P) was set up which includes CEOS, the three observing systems (GCOS, GOOS and GTOS), the international sponsors of the latter, specifically the Food and Agricultural Organization (FAO), the International Oceanographic Commission (IOC) of the United Nations Educational Scientific and Cultural Organization (UNESCO), the United Nations Environmental Programme (UNEP), the World Meteorological Organization (WMO), the International Council for Science (ICSU) along with its two major scientific programmes, the World Climate Research Programme (WCRP)and the International Geosphere Biosphere Programme (IGBP) and also the major funders of environmental research in the form of the International Group of Funding Agencies for Global Change Research (IGFA).

The Concept of Themes

In developing the IGOS Partnership experience was drawn from the work of the six pilot projects of SIT. Although recognized as being an important stepping stone in the development of an IGOS, it has become obvious that comprehensively in order to cover all the various requirements for observations a quite numerous set of projects would be needed. This substantial number would militate against the agencies responsible for observations being able readily to take a strategic oversight. Hence the concept of using broader *themes* was proposed, with the expectation that somewhere between eight and fifteen in total could comprehensively incorporate all the main needs for observations. One initial proposed list of themes includes a) Oceans; b) Terrestrial- (initially Estimation of Global Net Primary Production); c) Atmospheric Chemistry & Climate; d) Weather Prediction (this is assumed to be covered by ongoing WMO activities); e) Coastal Areas; f) Disaster Management; g) Carbon Cycle- (initially Carbon sinks) h) Climate Variability & Change; i) Climate Impacts; j) Water Cycle. The first theme currently being developed is the Ocean theme.

The Proposed Terrestrial Carbon Theme

In a recent draft of the Carbon Theme prepared by Josef Cihlar of CCRS the folllowing points were made:

Realization of the Terrestrial Carbon theme at the global level requires several components to work together:

Frequent and sustained satellite observations with various sensors

Ongoing ground-based measurements at locations selected across the range of biomes and climatic conditions

Reliable procedures for translating the remotely sensed and ground-based measurements into environmental variables

Quantitative models of the processes of carbon exchanges within ecosystems, within the atmosphere, and between ecosystems and the atmosphere

Systems and organisations engaged in the acquisition, processing, output generation and quality control through which the resulting products will be generated, made compatible, and made available.

Properties for which observation requirements are well established include land cover and land cover change, leaf area, biomass burning, solar radiation, atmospheric composition (especially CO2) and surface fluxes. Other key characteristics are less well established in terms of observational needs, namely biomass and its changes, canopy structure, atmospheric CO2 concentration, plant biogeochemistry and fine resolution meteorological observations.

5. Conclusions

IGOS remains in its early stages and its comprehensive implementation will take several years. Nevertheless it is likely to be an important international organizing structure, within which those concerned with terrestrial observations related to carbon should be involved.

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Workshop Paper 4

CEOS GOFC Project requirements for forest biomass and structure measurements: a role for low-frequency SAR?

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The CEOS pilot project “Global Observation of Forest Cover” (GOFC) represents the first coordinated international effort to develop institutional arrangements and systems to produce current, reliable, validated information about the Earth’s forests using space-borne and local data. The Framework Convention on Climate Change, and its Kyoto Protocol, represent one of several client groups for GOFC.

We will briefly review the information requirements which were identified during the strategic design process. We will then provide more detailed requirements for forest biomass and structure as needed for forest inventory, the Kyoto Protocol, full carbon accounting as called for by the Framework Convention on Climate Change, and ecosystem classification, needed for biodiversity studies.

Existing and proposed sensors can provide complementary information. We will review the information expected from:

- near-vertical passive multispectral optical with ~ 25 m resolution
- Moderate resolution passive multispectral (MODIS, MERIS)
- Low frequency SAR
- VCL
- Multi-angle passive optical (POLDER, MISR)

with the realization that these capabilities are subject to refinement during the workshop and later with more experience with the data.

The information expected from existing and new technology will be compared with the information requirements identified previously. This will allow us to make recommendations regarding the processing and distribution of information from existing and planned sensors, as well as recommendations about proposed new sensors. At this time of writing, before the workshop, GOFC priorities, in priority order, are identified as:

- successful Terra, ENVISAT, ADEOS-2, ALOS missions
- massive processing of data into derived products for
  - fine resolution optical sensors
  - fire sensors (AVHRR, MODIS, VEGETATION, DMSP/OLS,geostationary)
  - MODIS
- successful VCL
- operational VCL follow-on
- low frequency SAR R&D mission
- operational low frequency SAR if warranted by results of prototype mission.

1 Introduction

In 1997 the Committee on Earth Observation Satellites, responding to a realization that more effort was needed to coordinate earth observing programs to address problems and information requirements of global concern, initiated its Integrated Global Observing Strategy. This strategy was designed to improve use of E-O data to address major problems of global concern, to improve coordination of national earth observation programs, to improve co-operation between providers and users of E-O data for global applications.

Recognizing that forest problems have become global in magnitude and concern, and that spaceborne earth observations (when combined with local observations) is the only technology capable of providing consistent information about CEOS initiated "Global Observation of Forest Cover" (GOFC) as one of six pilot projects to advance the IGOS concept.

As currently implemented, GOFC is intended to be a means to facilitate sharing of data, data products, knowledge, and expertise. This is to be achieved by creating mechanisms to stimulate progress toward strategic objectives, primarily by facilitating co-operation between existing agencies and programs. GOFC is also expected to provide feedback to CEOS, allowing members to modify their programs for maximum efficiency.

2 Clients

During 1998, a strategic design was developed for GOFC. Six of categories of clients were identified, and their forest information requirements were assessed, in many cases through active participation on GOFC design teams. The categories of clients are:

- International organizations, especially FAO and UNEP.
- Global Observing Systems: GTOS, GCOS, through their joint panel, the Terrestrial Observation Panel on Climate (TOPC)
- The global change research community, primarily through IGBP
- International Protocols and Treaties, particularly the Framework Convention on Climate Change (including the Kyoto Protocol), and the International Convention on Biological Diversity.
- National forest management agencies
- Non-Governmental organizations

3 GOFC Strategic design: meeting information needs of clients

It is obviously impossible to meet all of the information needs of all the clients. In the GOFC design process we tried to identify common information requirements which could be met using data from current satellites, satellites soon to be launched, and in-situ data which are normally acquired. An evaluation of these information requirements in comparison with the information currently available enabled us to produce a strategic design to bridge the gap between what is needed and what is currently available.

3.1 Three basic components and the information they are intended to provide

The GOFC strategic design calls for three individual, but inter-connected components. Each component has its unique characteristics in terms of data types, data processing requirements, data and product access issues, and validation requirements. Progress on all three components can take place in parallel. Since the technical and institutional challenges are quite different from one component to another, progress will be more rapid from one to another.

It is important to recognize that the strategic design illuminates the way forward, but does not provide a detailed blueprint in an engineering sense. Its implementation depends on voluntary contributions of participating agencies, so a firm schedule toward completion is not a realistic expectation.

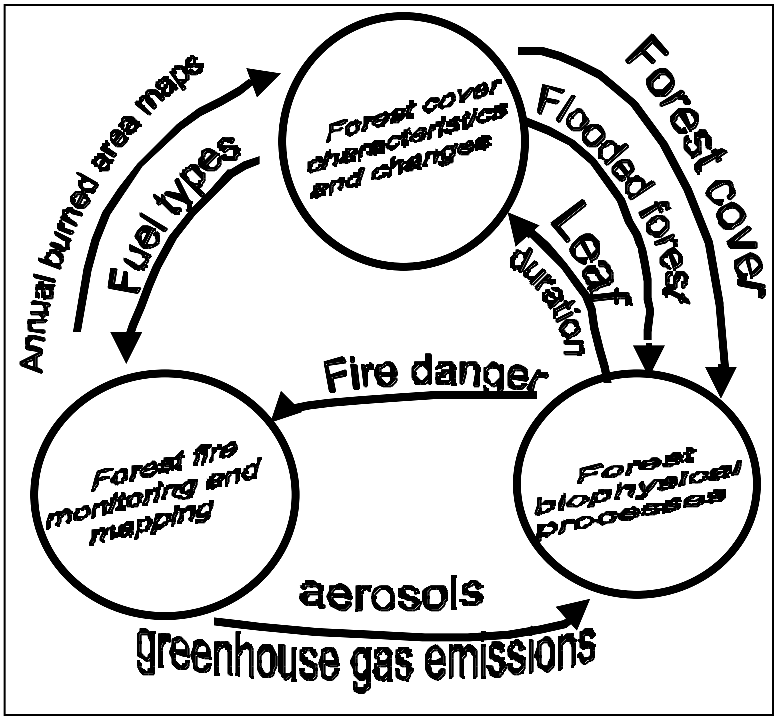
In the interest of brevity, the three components, and the information they are intended to provide, are summarized here in point form:

- Forest fire monitoring and mapping
  - Near-real-time monitoring of fires;
  - Post-season mapping of large burned areas;
  - With additional modeling, can provide information on carbon emissions.

- Forest cover characteristics and changes
  - Combines global coverage at coarse resolution with targeted coverage at fine resolution;
  - Wall-to-wall coverage of forests every 5 years (with coarse and fine data);
  - Sophisticated data acquisition strategy using coarse resolution optical (250 m - 1 km), fixed and pointable fine resolution optical (20-30 m), and microwave sensors;
  - Forest cover characteristics: leaf type, leaf longevity, per-cent canopy cover, canopy height;
  - Forest cover change: forest to non-forest, non-forest to forest, and no change.

- Forest biophysical functioning
  - Global coverage with coarse sensors;
  - Desired products: LAI, PAR, FPAR, NPP, forest biomass;
  - Additional research is needed;
  - GOFC can facilitate international liaison;
  - New sensor(s) are necessary for forest biomass:
    - Vegetation Canopy Lidar
    - P-band SAR

Each component represents a worthwhile endeavor on its own. In the GOFC strategic design, however, we identify important synergistic linkages between the components. The implementation of the whole is considerably more valuable than the implementation of any single component alone, as shown in Figure 1.



The interest of the various user groups varies from one component to another. This is summarized in Table 1.

3.2 Detailed requirements for forest biomass and structure

3.2.1 Kyoto Protocol

The Kyoto Protocol requires signatory nations to provide verifiable reporting of changes in carbon stocks from reforestation, afforestation, and deforestation which take place between 1990 and the first reporting period, which is an average of the 2008 to 2012 timeframe. Some details remain to be clarified through negotiation, but it is apparent that fine resolution earth observation data will be an essential component of any reporting scheme for two reasons:

1. Earth observation data provide the only objective historical archive for the 1990 time period;
2. Most of the forest changes brought about by reforestation, afforestation, and deforestation take place in small parcels which can only be detected with fine resolution imagery.

It is also apparent that spaceborne earth observation technology can only provide information concerning changes in area. The actual stocks involved must be ascertained through other means, although spaceborne earth observations may be used to extrapolate point measurements over larger areas.

3.2.2 Framework Convention on Climate Change

The Framework Convention on Climate Change recognizes that achievement of the ultimate objective of stabilizing the concentration of greenhouse gases will be greatly facilitated using some form of total carbon accounting, involving all forested ecosystems beyond RAD This is a very challenging scientific goal, and will not be easily(?) achieved in the near future.

Again, however, earth observation technology will play an important role. Many of the sensors and experiments planned for upcoming missions, particularly NASA's Terra, ESA's ENVISAT, and Japan's ADEOS and ALOS, are designed to address various aspects of this problem.

3.2.3 Forest inventory

The potential for spaceborne earth observation technology to satisfy some, but not all, forest inventory requirements has been recognized for some time. Earth observation technology on the horizon will increase this capability. One important challenge will be to find a way to make optimum use of earth observation technology, combined with more traditional inventory methods, to provide more current and cost-effective forest inventory information.

3.2.4 ecosystem characteristics for biodiversity

The International Convention on Biological Diversity recognizes that habitat is a key element of biodiversity and that loss of habitat is a key threat to biodiversity. Spaceborne observation of forests and forest changes can provide critical information about habitat. Both major changes in cover types and subtle changes in composition and patterns to be detected by E.O. are of interest to biodiversity assessment. The U.S. GAP analysis program has made very extensive use of Landsat Thematic Mapper data for this purpose.

3.2.5 Summary

For the purposes of this workshop, the information requirements for these four applications areas are summarized in Table 2. The figures presented in Table 2 are based on the authors' best estimates of the requirements; they should not be construed as representing a "community concensus".

Application	Spatial Resolution (m)	Temporal Resolution (years)	Biomass Accuracy (%)	Canopy Closure or LAI Accuracy (%)	Vertical Structure (No. layers)	Vertical Resolution (m)	Leaf Clumping Index
Inventory	10	1-5	10	10	2	2	N/A
Kyoto	10	1	10	N/A	N/A	N/A	N/A
Carbon bud.	10 – 1000	1	20	20	N/A	5	10%
ecosystem	10	5	50	20	2-4	1	possibly useful

4 Expected capabilities

In this section we review the capabilities on existing and soon-to-be launched sensors.

4.1 Near-vertical passive multispectral optical with ~ 25 m resolution

The most commonly-used sensors of this type include the Landsat Thematic Mapper, the SPOT HRV, and the IRS-1 LISS. There is a great deal of experience with sensors of this type; therefore there is a good understanding of their capabilities and limitations. The data from these sensors have been extensively used to map broad forest types. There is good capability to accurately map boundaries of pronounced changes such as clearcutting, conversion to agriculture, and forest fires. This capability, combined with the historical archive for 1990 which exists for Landsat and SPOT, will make data from these sensors useful for documenting changes to the forest which have taken place between 1990 and the first reporting period under the Kyoto protocol.

Under favourable circumstances, data from these sensors can be used to estimate canopy closure and to infer LAI.

4.2 Moderate resolution passive multispectral optical sensors

These sensors include MODIS on the U.S. Terra mission, MERIS on the ESA ENVISAT mission, and GLI on the Japanese ADEOS spacecraft. The resolution of these sensors is too low to be useful for monitoring changes in small parcels of land. However, they are expected to provide essential data on leaf type, leaf amount (LAI), leaf duration, and the absorbed photosynthetically active radiation by forests and other vegetation communities. This will be essential for the development of full carbon accounting.

4.3 Low frequency SAR

There is a considerable body of literature relating to the capabilities of low frequency SAR for forestland applications. These show some promising capabilities to estimate biomass, with a larger dynamic range than higher frequencies. The saturation level is estimated between 100 and 200 T/ha at P-band. The best results have been obtained for monoculture plantations; the capability to make useful biomass estimates has not been widely confirmed for a variety of natural forests. Based partly on results obtained at higher frequency, it is expected that low frequency SAR will be susceptible to extraneous effects, particularly meteorological conditions such as freezing or thawing, recent rainfall, and soil moisture. These effects can complicate the extraction of information so greatly that the technology becomes unusable. To minimize these effects, dual or multiple frequency sensors on the same platform may be useful.

4.4 VCL

The Vegetation Canopy LIDAR mission is a NASA proof-of-concept scheduled for launch in 2000. It proposes to sample canopy height with a vertical resolution of 1 – 2 m, and a horizontal sample interval of 30 m (along-track) by 2000 m (cross-track). In many cases it will be possible to infer canopy closure and biomass from these measurements. Only experience will demonstrate the accuracy and limitations associated with this technology.

4.5 Multi-angle passive optical (POLDER, MISR)

Multi-angle passive optical sensors include POLDER on ADEOS, and MISR on Terra. These sensors offer to provide additional information on forest type. Multi-angle measurements are not only sensitive to canopy closure but also to the canopy architecture. Data can be used to derive a leaf clumping index, which improves LAI estimation and quantifies the effect of 3-D canopy architecture on radiation absorption and photosynthesis. Data from these sensors are not expected to provide additional information about canopy height and closure unless constrained using additional information.

5 GOFC priorities

Based on the above analysis, we summarize our conclusions in the form of priorities for GOFC. In order of importance, we list them as follows:

1. A successful Landsat-7 mission. Data from Landsat-7 provides a central underpinning for all three components of GOFC. The Landsat-7 data acquisition strategy provides a mechanism to assure the collection of global data sets at the optimum phenological periods. We are very encouraged by the success of Landsat-7 to date.
2. Successful Terra, ENVISAT, ADEOS-2, ALOS missions. The first three missions will provide data needed for the forest biophysical functioning component of GOFC. The ALOS mission carries the only L-band SAR follow-on to the JERS-1 mission. This SAR will provide data on deforestation, and on forest flooding, both of which are valuable for GOFC.
3. Massive processing of data into derived products. This is a critical area where inadequate emphasis has been placed in the past. At present, tremendous amounts of data, particularly from fine-resolution optical sensors, have been acquired, only to languish in archives. Clients need information about forests, not massive amounts of data.

- MODIS, MERIS, GLI. NASA has ambitious plans to process massive quantities of MODIS data into higher-level products. This initiative is to be commended. The plans for MERIS and GLI are much less comprehensive at present, and its contribution to the knowledge of forest functioning is not yet clear.

- fire sensors (AVHRR, MODIS, VEGETATION, DMSP/OLS, geostationary). Processing of data from these sensors is becoming more routine. The GOFC workshop on Forest Fire Monitoring and Mapping is expected to lead to plans for increased automation and integration, further leading to a global system for forest fire monitoring and mapping.
- fine resolution optical sensors. This is the area with the greatest need, which represents the greatest challenge. The data from these sensors is particularly valuable for mapping land cover and monitoring land cover change. To data, such mapping and monitoring has required a large amount of labour, on a scene-by-scene basis. Techniques must be developed and implemented to process data from these sensors into land cover and land cover change products for large areas, in a highly-automated fashion to achieve the client needs identified in the GOFC strategic design.

4. Successful VCL. VCL represents a high opportunity to produce quantitative estimates of vertical and horizontal forest stand structure information which is for many GOFC clients. It is very desirable to carry VCL to a successful technical and scientific conclusion, with rigorous validation of its capabilities for the full spectrum of forest ecosystems.
5. Operational VCL follow-on. If VCL can be successfully demonstrated, it should be followed as quickly as possible with an operational mission, in which forest canopy structure products would be produced in a routine, on-going basis and made available to the research and forest management communities.
6. Low frequency SAR R&D mission. Low frequency SAR could provide a unique capability to make direct estimates of forest biomass. These are useful for assessing forest carbon stocks, and possibly changes in stocks. They are also valuable for estimating the autotrophic respiration requirements of forests and other vegetated ecosystems, for input into NPP models. Finally, forest biomass can be related to timber volume, which is of great interest to forest managers everywhere. The R&D mission must validate the ability of low frequency SAR to provide reliable estimates of forest biomass for a wide range of forest conditions. It must also demonstrate a reliable capability to overcome the adverse effects of changing meteorological conditions on information extraction.
7. Operational low frequency SAR. As in the case of VCL, if low frequency SAR can be successfully demonstrated, it should be followed as quickly as possible with an operational mission, in which forest biomass products would be produced in a routine, on-going basis and made available to the research and forest management communities.

Workshop Paper 5

Optical Remote Sensing For Monitoring Forest And Biomass Change In The Context Of The Kyoto Protocol

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INTRODUCTION

Global estimates of the net flux of carbon due to land cover change have been made for over ten years, yet still the research community has been unable to balance the carbon budget or produce estimates reliable enough to implement international policy such as the Kyoto Protocol. There are three critical uncertainties in estimating the biogenic emission of greenhouse gases: 1) the rate and geographical distribution of land cover change due to deforestation and biomass burning, primarily in the tropical forests, but also in various under-studied temperate and boreal forests, 2) the fate of land converted from natural land cover, and the rate of abandonment or regrowth of deforested or burned land, and 3) the standing stocks and response characteristics of carbon in vegetation and soils following disturbance.

The most tractable problems are the first two. The past use of tabular data from national census documents alone has been insufficient for quantifying rates, distributions, and dynamics of land cover conversion. The research and policy communities require increased spatial resolution to support national emission inventories or compliance with the terms and spirit of the Framework Convention on Climate Change. Moreover, such aggregate analysis is not sufficient for addressing many emerging, important questions such as the role and dynamic pattern of secondary growth. Thus, new efforts using remotely sensed data will be necessary to improve our understanding beyond the general level of detail the community now has (see Skole et al. 1997).

To develop a comprehensive analysis of greenhouse gas emissions, land cover change monitoring will necessarily have to be coupled to efforts to obtain better ancillary data on carbon in vegetation and soil. As the uncertainty in carbon emission estimates is reduced through better information on land cover conversion rates and the fate of converted land, the third area of uncertainty will be increasingly significant. Thus, while an emphasis on land cover change monitoring is necessary, a prudent and long-term strategy should include efforts to better quantify biomass, soil organic matter, and their response characteristics that can potentially be remotely estimated.

THE KYOTO PROTOCOL AND FULL CARBON ACCOUNTING

The Kyoto Protocol is a mechanism established by diplomatic agreement for measuring and reporting greenhouse gas sources and sinks on a nation-by-nation basis(Grubb et al. 1999). The Kyoto Protocol specifies a method for national carbon emission inventories related to land cover changes only with respect to Afforestation, Reforestation, and Deforestation, or ARD as it is often called. Thus, the focal point for measurement and monitoring is on forests, and in particular forests which are directly affected in these three specific ways by direct human action. Because the amount of carbon held in the vegetation and soils of terrestrial ecosystems varies spatially and temporally as a result of *both* human activities *and* natural processes, it is important to differentiate the conditions set by the Protocol and those needed for full carbon accounting, a calculation which accounts for carbon fluxes from all possible sources and sinks (Houghton and Ramakrishna 1999, Steffen et al. 1997). The issue addressed in this paper is whether remote sensing methods of measuring stocks and losses and accumulations of carbon are compatible with requirements of the Kyoto Protocol, and in particular whether the precision and costs of such methods will enable changes in carbon stocks to be determined over the Protocol's commitment period, 2008-2012. There are several important implications.

First, it is necessary to be able to define a forest, and from a monitoring and remote sensing perspective, this means being able to discriminate vegetation types according to an *a priori* definition of forest. The first issue here is to discriminate forests from other forms of vegetation, such as grasslands. Although forest coverage can conceivably be reported by each nation according to its own forest definition, without a common definition it would be difficult to estimate forest coverage across national boundaries (ie for large regions), particularly when using remote sensing as means to document ARD on a continuous basis for all nations. The second issue here is to discriminate those areas which are classified as forests into sub-classes based on fractional, or percent, cover. For instance, the FAO definition of a forest includes areas which the fraction of forest cover is greater than 10%. Other definitions are more restrictive. Thus, while deforestation measurement aims to account for forests which get converted to non-forest, simple classification schemes based on forest/non-forest would need to be replaced with, or at least supplemented with, characterization based on fractional cover or density, in order to establish precisely what changes would be considered deforestation. Current satellite systems, especially the high resolution TM and ETM+ on the Landsat series, have been used to quantify the extent of deforestation (Skole and Tucker, 1993; Houghton et al., 1999). Although many studies have reported that accuracy of classification can reach up to 95% (e.g. Senoo et al., 1990, and Peddle and Franklin 1991), unaccounted sources of uncertainty exist and are often not reported (Hammond and Verbyla, 1996). These classifications are primarily based on the aggregate spectral and spatial patterns to identify the deforested areas. But, requirements of Kyoto are for systems and methods capable of mapping continuous fields of forest cover and its density.

Second, it is necessary to discriminate areas which have been altered by *direct human action*, rather than other forms of disturbance, such as windthrow or wildfire. This is a difficult task in that it simultaneously requires: (1) separation of various forms of forest disturbances simultaneously within a single monitoring system or program and (2) that the observations reveal intention. For instance, in the former situation, remote sensing of fires alone is insufficient and would need to indicate which fires are of human origin and which are not. In the second instance, monitoring would need to consider the influence of forestry management practice which directly results in an increase or decrease biomass, or other direct actions of policy which lead to ARD. This requires, in essence, tracing the monitored event back to its root cause. Moreover, because Kyoto only applies to ARD, forestry management practices which increase or decrease growth rates of intact forests are not considered. Optical remote sensing is capable of monitoring, with some uncertainties, but interpretation and inference of the possible causes of such change is extremely difficult. Clearly an remote sensing monitoring system will need to be coupled to ground level assessments.

Third, the Protocol leaves ample room for the occurrence of *perverse* effects. For example, consider using a definition of forest using 40% cover as the criterion. Selective logging which removes considerable biomass but not more than 60% would not be considered to be a component of ARD within the terms of the Protocol, but would be a significant reduction (ergo, source) of carbon on land. Monitoring carbon for instance through measurement of changes in stand biomass is not by itself applicable to the conditions for measurement set forth within the Protocol (Houghton and Ramakrishna 1999). Thus, there can be an immediate decoupling of the requirements for monitoring changes in biomass for full carbon accounting and measuring changes in carbon stocks for emission inventories under Kyoto Protocol.

Finally, the terms of the Protocol call for measurements to be made only during a specific *commitment period*, which is then referenced against a baseline in 1990. An effect of this measurement and accounting nuisance is the separation of those forests in a region which have been lost or created during a commitment period from all other forests (compared to a 1990 baseline). These special forests are often referred to as *Kyoto Forests*. Thus, the *total* net flux for a country or area may be more or less than that solely associated with their Kyoto Forests. The implications for remote sensing measurements transcend issues of technical capability into the overall operational approach which is implemented, including the acquisition and availability of a baseline data set for 1990 and the acquisition and availability of data specifically during the commitment period. Serious consideration needs to be given to both technical and operational capabilities for obtaining all necessary bits of information are precisely the right time and location. While progress has been made in terms of technical issues, there has been considerably less progress in operationalizing them (Skole et al. 1997).

These implications suggest that accurate budgeting of global carbon or national level emission inventories will be difficult unless we account for all possible sources and sinks with improved estimation accuracy through a well-specified operational program.

OPTICAL REMOTE SENSING FOR MEASURING AFFORESTATION, REFORESTATION AND DEFORESTATION

Estimating sources and sinks of carbon from ARD activities requires: (1) repeated measurements (annually) of deforestation over large areas and (2) fine spatial and temporal scale analyses of the dynamics of land-cover change in order to separate and quantify regrowth (afforestation or reforestation). Optical remote sensing has been used extensively to map forest extent, and the temporal and spatial dynamics of deforestation, regrowth, and fire (Mayaux and Lambin, 1995; DeFries et al., 1995, Li and Cihlar, 1997, and Ahern et al., 1998 and 1999). The requirements for both coarse and fine spatial resolution satellite imagery for monitoring forest cover and its change in general has been identified in a recent series of reports from the Global Observations of Forest Cover project, an international program for forest cover monitoring being developed by the international space agencies in support of the International Global Observing Strategy (Ahern et al., 1999). The GOFC efforts are broadly defined to provide a comprehensive program of observations, including space borne and ground based measurements. In this section we review the potentials and limitations of optical remote sensing specifically in the context of Kyoto Protocol and particularly within the context of ARD.

Accurate measurement of ARD requires satellite observations with high temporal frequency. Because changes in ARD occur with considerable interannual variability, it is necessary to measure deforestation and forest change annually, or nearly annually. Annual measurements overcome the limitations of using average rates over long time periods, which can lead to loss of information (ie short term events may go undetected) or mis-specification of information (ie. aliasing of data trends). An annual measurement protocol also permits temporal co-registration and sequencing of deforestation and regrowth events.

Accurate measurement of ARD also requires data of high spatial resolution (Ahern et al., 1999). Townshend and Justice (1988) demonstrated the value of data with spatial resolution less than 250m. Therefore, a system is required which uses annual data from Landsat, SPOT, JERS-OPS, or any of the other high resolution sensors. With the launch of EO-1 satellite and commercial satellites such as IKONOS, it is expected that the spatial capability will increase significantly. It must also be noted that inclusion of hyperspectral bands on EO-1 offers great promise for improving the classification of ARD activities, but remains a research issue at the present time.

High resolution data from the Landsat and Spot class of earth observation satellites can be employed to make regular measurements of deforestation, afforestation, and reforestation. Large amounts of these data exist in national and foreign archives, dating back approximately 20 years. Thus, a continuous and consistent source of data is available upon which a fine- scale (1:250,000) mapping systems could be developed.

There is also a body of considerable technical and practical experience. Many countries are routinely performing regular assessments of deforestation, in particular Brazil, Thailand, Canada, and Indonesia as examples. An international program being developed under the auspices of the International Global Observing Strategy (IGOS), the Global Observations of Forest Cover (GOFC) program (Ahern et al. 1999), provides a design and strategy for national-level and global observations for application to forest management and global change research. Table 3 is a summary of needed products based on Ahern et al., (1999) but extended to include emerging needs for ARD activities in the context of balancing carbon budget. Skole et al. (1997) provide a national-level and global observation strategy, which would be generally applicable for global carbon cycle research. This strategy, compatible with the missions of GOFC, calls for effort based on existing worldwide programs those of the space agencies and international organizations, such as FAO Forest Resource Assessment in the Tropics.,

The TREES Project (TRopical Ecosystem Environment observations by Satellite) is developing techniques for global tropical forest inventory and for monitoring deforestation using satellite imagery at coarse resolution. This work has focused on defining a base line assessment of humid tropical forest extent using 1 km resolution remote sensing satellite data, predominantly from AVHRR. Vegetation maps have been produced (Mayaux et al., 1999, Eva et al., 1999) and tropical forest area statistics have been derived from these maps (Mayaux et al., 1998). The project is also developing a prototype method for global forest change assessment in the humid tropics based on a statistical sampling of sites with a higher sampling rate for fast changing areas. A pre-stratification was performed using two parameters: the forest cover area (from the 1 km resolution maps) and areas where changes are expected to be higher based on individual expertise: the ‘Hot Spot Report’ (Achard et al., 1997). Forest cover change during the period 1992-1997 will be estimated from the ninety-five sampled sites using fine spatial resolution satellite imagery (Richards et al., 2000).

The sampling work of the TREES group is demonstrating ways in which improved sample-based observations can be developed in tandem with large area inventories, or “wall-to-wall” assessments. Recent research by Sanhez et al (1997) show that stratified sampling can be used on an annual basis in inter-census years in conjunction with complete inventories every 3-5 years. This work suggests accuracy levels within 10 percent can be obtained with a 30% sample, if the spatial distribution of ARD is well known from complete inventories. Such approaches will reduce the demand for data. A study published as part of the Global Observation of Forest Cover program (Skole et al. 1999) concluded that a global, multi-sensor campaign would require several thousand scenes.

VALIDATION AND ACCURACY OF CURRENT OPTICAL APPROACHES.

The basic measurements of ARD can be made with very high accuracy. The specifications of Kyoto do not require classification of forests into multiple classes. The most difficult consideration is separation of areas of forest from non forest. Once a method for defining which areas are included as forest is defined, then statistical classifiers usually do very well for simple forest-non forest classification. Research in tropical forest classifications suggest very high accuracy. Woodcock et al (pers.comm) have looked at classification accuracy for temperate forest and reach similar conclusions. Table 1 below shows the results of field based accuracy of a forest/non-forest classification for tropical forest areas in the eastern Brazilian Amazon. Overall accuracy is 97% with producer and consumer errors never in excess of 20%. When reforested areas are taken into account, the accuracy decreases due to confusion of the secondary growth class with other classes.

Table 1. Summary of results of optical analysis accuracy assessment in the eastern Amazon region.

Class Data	Forest	Deforested	Secondary Forest	Water	Cerrado	Row Total	Percent Correct	Comission
Forest	22	0	0	0	0	22	100%	0.0%
Deforested	0	92	1	0	0	93	98.9%	1.08%
Secondary Forest	0	3	14	0	0	17	82.35%	17.65%
Water	0	0	0	7	0	7	100%	0.0%
Cerrado	0	0	0	0	4	4	100%	0.0%
Column Total	22	95	15	7	4	143	97%	
Omission	0.0%	3.16%	6.67%	0.0%	0.0%			

Table 2 below shows similar analyses for the western Amazon, with generally the same results for the forest/non-forest classification accuracy, but with more confusion with secondary growth areas, which often get confused with forest.

Table 2. Summary of results of optical analysis accuracy assessment in the western Amazon region.

Class Data	Forest	Deforested	Secondary Forest	Water	Cerrado	Row Total	Percent Correct	Comission
Forest	14	0	2	0	0	16	88%	12%
Deforested	0	60	2	0	0	62	97%	3%
Secondary Forest	1	12	12	0	0	25	48%	52%
Water	0	1	0	3	0	4	75%	25%
Cerrado	0	0	0	0	7	7	100%	0.0%
Column Total	15	73	16	3	7	114	85%	
Omission	6.7%	17.8%	25%	0%	0%			

Kimes et al (1998) reviewed the error associated with multi-temporal classification of secondary growth and concluded that 92% of pixels were correct with respect to age and 85% are correctly classified as secondary forest. However, due to temporal gaps, 8-32% of scene pixels may be mis-classified if complete time series are not available, and that these errors translate into a errors in estimating biomass regeneration by 8-23%.

OPTICAL REMOTE SENSING FOR DIRECTLY MEASURING BIOMASS AND ITS CHANGE

Although optical remote sensing has been demonstrated to have potential to estimate forest biomass directly, there are several limitations. Optical remote sensing can only "penetrate" to a limited depth through the forest canopy. In other words, the spectral signature observed with optical remote sensors provides information for only the upper layers of forest canopies. As often the case, when canopy density increases, for instance leaf area index increases to 3 or 4, commonly used spectral indices such as NDVI become “saturated” or insensitive to further change of forest biomass. This results from the insensitive nature of forest reflectances in the red and near infrared spectral bands. Other spectral bands, such as the shortwave infrared region (ETM+ band 5) have shown to have potential to increase the sensitivity. This band is primarily sensitive to the water content of vegetation, therefore, having potential to estimate not only green component of vegetation canopies but also senescent components. The saturation of current vegetation indices at high forest density present a major challenge to science community to estimate forest biomass.

Current high spatial resolution optical sensors are limited to the Landsat class of polar orbiting sensors, which are of limited use for monitoring seasonal dynamics of forest vegetation. Moreover, the presence of clouds makes it impossible to difficult to acquire data throughout the phenological period, or growing season. Increased temporal frequency of Landsat type sensors cannot be achieved unless more satellites of its type are launched, however the current mission profile for Landsat 7 set to maximize acqusitition for a seasonal refresh four times each year. On the other hand coarse resolution sensors of the AVHRR type can be acquired at daily frequency, but its spatial resolution (1km) is too coarse to map forest changes at the accuracy that Kyoto Protocol will require.

Although biomass estimation from optical remote sensing is feasible, there is a lack of acceptable algorithms for forest canopies. This is due to two major reasons. The first one is the limitations stated above. The second reason is the practical difficulties for pilot projects in forest areas. Particular challenges include ground truth biomass sampling and field accessibility for radiometric measurements of ground-based sensing systems. In order to correlate remote sensing observations, more ground truth biomass and other biophysical variables need to be collected across forest types.

Limited angular sampling from current sensors such as Landsat ETM+ also reduces the ability of optical remote sensing to infer forest biophysical variables such as biomass. Landsat type sensors, having fine spatial resolution, often measure the reflectance factors at a nadir viewing angle. A single nadir measurement often does not represent the entire picture of the forest biophysical attributes. Research results have increasingly shown that multiangular sampling critically important in order to characterize the annual dynamics of forest, especially for regowth and selectively degraded forest (Asner et al., 1998). The ASTER sensor on Terra satellite holds promise for multi-angle viewing such, but its anticipated lifetime and duty cycle may be too short to be useful during the Kyoto commitment period.

A limited number of spectral bands and associated spectral resolution is another factor. Special features of forest canopies are often smoothed over by wide-bandwidth sensors and therefore result in the loss of spectral information for detailed characterization. The Hyperion on EO-1 sensor will be the first space borne hyperspectral sensor and the imagery to be acquired should ease holds promise, but the EO-1 mission has a limited duty cycle as research sensor.

NEW DIRECTIONS AND REQUIREMENTS FOR OPTICAL REMOTE SENSING

Most of the current remote sensing work has focused on classification approaches. These have been useful for mapping the extent of forest changes over very large regions and for the initial characterization of rates of forest loss for carbon cycle studies. These types of studies will continue to play an important role. Meanwhile it will be necessary to develop new techniques and methods which specifically relate to the needs for the Kyoto Protocol and full carbon accounting. The main emphasis for future work must be focused on products which provide continuous fields of forest attributes (e.g. fractional forest cover) and direct paramertization of forest attributes. One of the key requirements for forest monitoring will be to move the observational approaches beyond classification of the more dramatic changes, such as deforestation, toward parameterization of the full gradient of human induced degradation of forest environments. In this section we provide an overview of five essential observational products which are being developed to suit this need. These products will both improve our understanding the carbon dynamics of global forest and reduce the uncertainties in the carbon flux budget. These products are identified in the second half of Table 3.

Table 3. List of needed products derived from optical remote sensing systems

Product	Description	Frequency
Geometrically Rectified Data product (GRD)	Landsat, SPOT, EO-1, image products which are referenced to earth coordinates (+ 60m) by scene	30m/5yrs & 1km/1yr
Geometrically and Atmospherically Corrected Data Products (GACD)	Atmospherically corrected GRD products.	Same as GRD product
Mosaicked GACD	Mosaicked GACD image products (Note: precision in the GACD products would amount to mosaicking without actually scene merging	Same as GRD product
Co-registered Image Pairs for change detection analysis (FCCD)	Image to image registered pairs (±30m) at multiple dates for change detection analysis. A “wall-to-wall” data product initially at t_o and t_{+3}, then every five years.	Same as GRD product
Forest Cover Product (FC)	Large area (i. e. "wall-to-wall”) classification of global forest.	30m/5yrs & 1km/1yr
Forest Cover Change Product (FCC)	Large area (i. e. "wall-to-wall”) forest/non forest classification change products derived from change detection analysis of multi-dates	30m/5yrs & 1km/1yr

Forest Cover Change Sample Product (FCC-s) Over the focus areas	Stratified sample change detection based on scene pairs at 30% sampling or less on an annual basis using the FCCD products	30m/1yr & 1km/mon.
Forest Density (FD) or Forest Fractional Cover (ffc)	*Computed forest fractional cover from mosaicked GACD products*	*30m/5yrs & 1km/1yr*
Forest Fire Scar (FFS)	*Maps of forest fire scar derived from GACD products at coarse resolution*	*Same as above*
Forest Biophysical Attributes (FBA)	*Biophysical property maps, including total green leaf area index, fPAR, total above ground biomass for carbon flux computation*	*30m/5yrs & 1km/1mon*
Above Ground Biomass	*Total above ground biomass to account for carbon storage*	*30m/5yrs & 1km/3yr*
Selective Logging Indicator (SLI)	*Quantitative indicator of selectively logged areas derived from GACD products.*	*Same as above*

Note: The products in italics need further research effort.

Mapping Forest Fractional Cover

Forest fractional cover mapping from satellite remote sensing provides a mechanism for mapping continuous fields of forest density rather than discrete classes of cover types. Unlike traditional discrete forest classification, which classifies a pixel either as forest or non-forest, these variables are continuous indicators of amount of forest. Forest clearing, such as deforestation, results in an immediate conversion from forest to non-forest, a form of forest cover change which can be readily monitored using satellite remote sensing (Skole and Tucker 1993). However, other forms of forest conversion, such as thinning forest by selective logging, small to moderate forest fires (those that damage only understory vegetation), and degradation due to climate pattern changes, are slower processes of forest conversion, and often can not be mapped by spectral and statistical classification techniques. Although slow, these processes can result in substantial reduction of carbon stocks. In terms of the Kyoto Protocol, such reduction of carbon stocks is not considered when forest cover remains above the threshold of forest cover which defines “forest.” Instead of using binary classification (forest vs. non-forest) a continuous variable such as fractional cover of forest should be used to define forest.

The fractional cover of forest can be estimated from remotely sensed imagery using a linear mixture model (Zeng et al., 1999, Qi et al., 1999a, and DeFries et al., 1999). An example of fractional cover map is demonstrated in Figures 1 and 2, which were derived from the SPOT VEGETATION and the Landsat 7 ETM+ imagery over tropical Amazonia. This map indicates that even at 1km resolution, the derived fractional cover shows large-scale variation in forest cover from regions of savanna to regions of dense forest, providing a means to delineate zones of forest based on a continuous variable (Figure 1). Indications of forest fragmentation are also revealed. With higher resolution

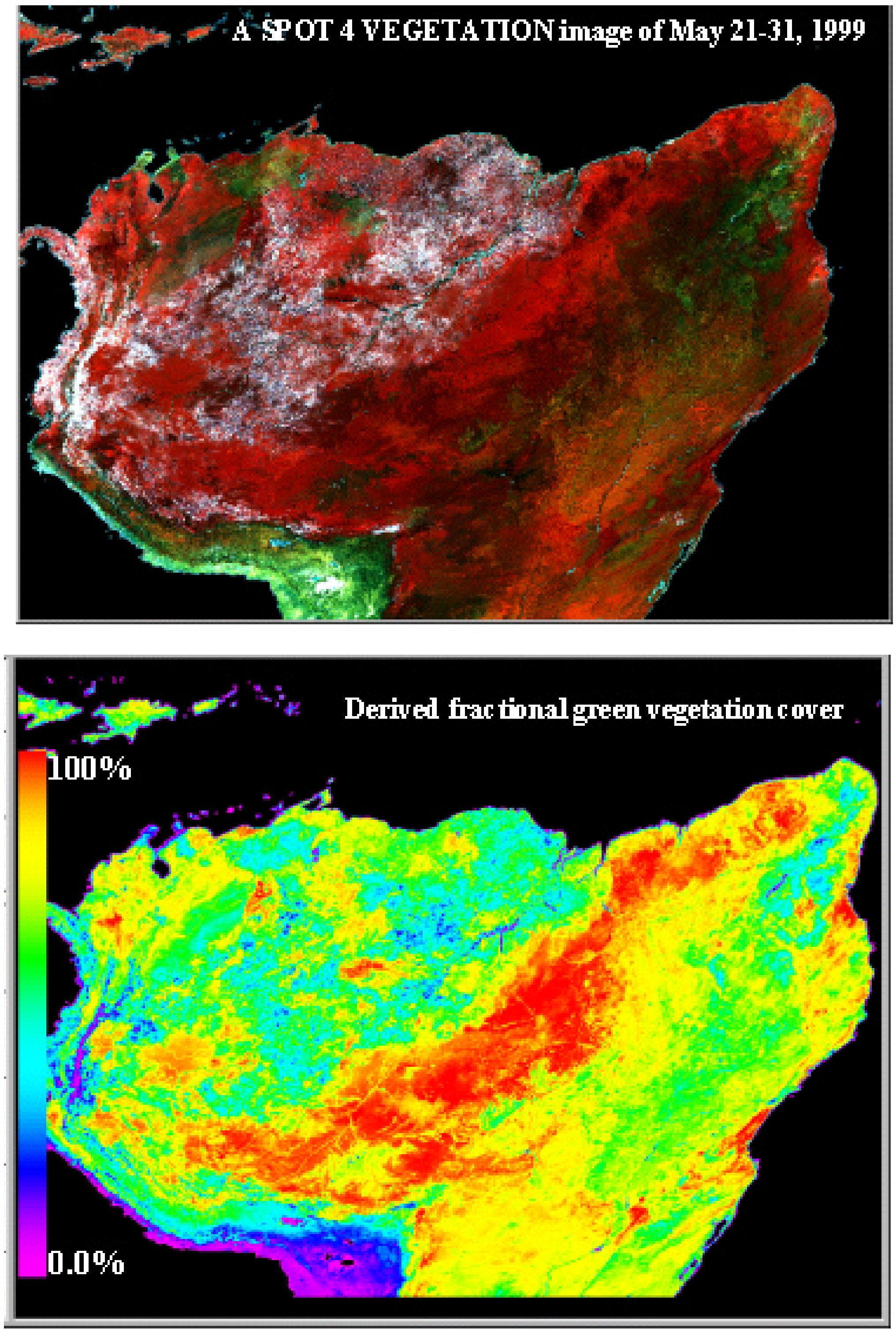

Figure 1. Vegetation image and derived fractional cover of the Amazon region

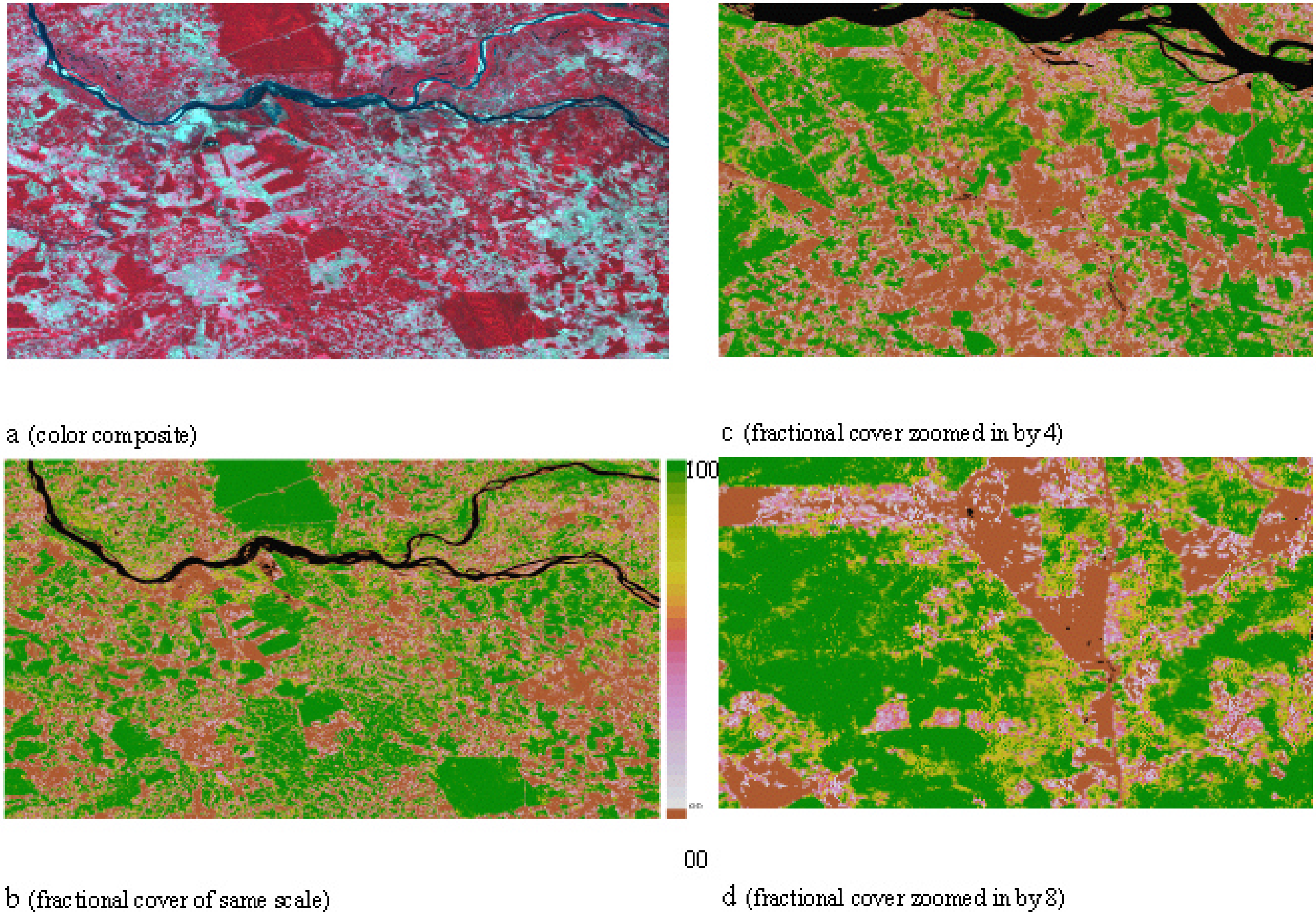

Figure 2. Forest fractional cover derived from a Landsat 7 ETM+ image on 13 July, 1999 (path/row 223/64)

ETM+ data, the fractional cover map reveals detailed patterns of degradation as well as deforestation (Figure 2). When enlarged individual areas of deforestation, selective logging, and regrowth can be differentiated.

From the perspective of the Kyoto Protocol it is a necessary measurement to delineate areas which are and are not consider forest, and to capture changes in forest cover in the processes of deforestation or afforestation and reforestation. From the perspective of full carbon accounting it is a necessary measurement for quantifying changes within forest covers due to degradation.

Biomass Burning Detection and Fire Scar Mapping

Biomass burning is frequently an important step in the process of land cover change. Forest fires in the tropics have increased drastically in the last two decades. This is primarily due to increases in cultivated areas associated with the expansion of population in South America, Asia, and Africa (Seiler and Crutzen 1980) where fire is used as a land management tool. Because development in the tropics is often widely-scattered and unconsolidated, satellite remote sensing of forest fire hot spots and scars offers a practical solution for large-area assessment of tropical forest conversions (Matson and Holben 1987). Biomass burning represents areas of a major flux of stored carbon, and areas where a large amount of trace gases and particulates were released to the atmosphere during the burning process.

In the tropics there are two distinct types of anthropogenic biomass burning. The first occurs when natural ecosystems are initially cleared, often in forests, but also in savannas and grasslands (it is important to note that conversion of these systems is not important with respect to Kyoto even while they are important for full carbon accounting). The second is repeated burning of existing savannas or pastures on a short rotation as a form of land management to maintain forage productivity. In temperate and boreal ecosystems, improved information on fire is required to address two issues. The first is a better quantitative understanding of anthropogenic fires, or fire suppression, as a form of land cover change in undisturbed ecosystems. The second is understanding how the temporal frequency of natural fires may change over time in response to climatic change, and in turn influence the global budget calculations during the time period of observations (fire mapping is also important for several management and risk assessment objectives, but these applications are not directly relevant to Kyoto).

A few studies have attempted to define regional and temporal (daily) distribution of biomass burning. The GVM unit of JRC/SAI has performed the mapping of active fires, daily, for a 21 months period, worldwide, from AVHRR data (Dweyer et al. 1998, Dwyer et al. In press, Gregoire et al. 1998, Stroppiana et al., in press). The GVM unit has also performed a continental scale mapping of burnt areas for the African continent, for an 8-year period (Barbosa et al. 1998, 1999, 1999b). Justice et al. (1993, 1995, in press) have demonstrated the use of fire detection and monitoring for Agfrican savannas.However, there is as yet no global operational mechanism in place for monitoring fires, which requires daily observations (Justice et al., 1993). The Global Observations of Forest Cover project is attempting to establish the protocol for operational monitoring of fires.

Quantitative Indicator of Biophysical Attributes

Although fractional cover is a quantitative descriptor of forest density, it only characterizes the horizontal distribution of trees. Since carbon stocks are directly related to the total amount of biomass of the forest, a vertical characteristic of forest density is needed. Leaf area index is such forest parameter and can be estimated with optical remote sensing. Together with fractional cover parameter, leaf area index can be used to estimate biomass.

Traditional approach to estimating LAI using remotely sensed data has been associated with computation of vegetation indices such as normalized difference vegetation index (NDVI). Although NDVI has been used extensively in relating to LAI (Asrar et al., 1985, Price, 1993, Baret 1995, Chen et al., 1996, Qi et al., 1999b), the nature of NDVI is only sensitive to green component of LAI, often referred as GLAI, and more importantly, it becomes saturated when LAI is greater than 4 (Baret 1995; Chen et al., 1996; Steininger 1996). According to the data acquired in the boreal forest (Chen et al., 1996), and other studies, it can be concluded that the NDVI is incapable of characterizing boreal forest. In the tropical regions, forest density is believed to be denser, use of NDVI as direct method for LAI estimation appears impossible.

Use of multiple angular measurements to be provided by sensors such as AVHRR, VEGETATION, POLDER, and future MODIS, MISR, and ASTER, will open a new era for quantitative estimates of LAI, fPAR, and other biophysical attributes of forest (Running and Nemani, 1988, Myneni et al., 1997, Knyazikhin et al., 1998a and 1998b, Tian et al., 1999). Currently, it has been proposed to use bi-directional reflectance distribution function (BRDF) models and multidirectional measurements for global estimation of LAI and fPAR, as one of the products of MODIS and MISR science teams (Running et al., 1996, Myneni et al., 1997, Knyazikhin et al., 1998a and 1998b, Tian et al., 1999). This approach has been used in various studies and proved to be quite successful (Goel 1988; Jacquemond, 1993;Qi et al., 1995 and 1999b;). The basic physics of this approach employs radiative transfer models from which a look up table is created for different types of land surfaces. By comparing the observed bidirectional reflectance values with the model simulation, the closest match of corresponding LAI is located in the LUT and used as the most probable LAI value. This approach requires the global terrestrial land be classified into six biomes, where forest is classified either as needle leaf or broad leave forest. This approach will produce LAI maps but the spatial resolution will be 1km. The modeling approach is appealing partly because it can map forest density at a higher LAI value, less affected by the saturation problem. It would be even more promising if the LAI algorithm is used with fused data from MODIS/MISR/ASTER and high spatial resolution Landsat and its follow-on satellite EO-1 data.

With the launch of new sensors at high resolution such as those from EO-1 satellite, innovative use of newer spectral bands from EO-1 Hyperion sensor can improve the accuracy of biophysical attributes estimations.

Above Ground Biomass

To model the carbon cycle, a critical physical property of forest is the total biomass. Although limited results have been obtained with optical remote sensing, some preliminary work suggests that the total biomass can be estimated remotely (Runninng et al., 1994 and 1999). The data to be provided by the vegetation canopy lidar (VCL) will be very useful in relating the profile to the DBH which is highly correlated to the total above ground biomass.

Forest Selective Logging Indicator (FSLI)

As stated earlier, the Kyoto Protocol specifies the ARD as the only related activities affecting carbon budget, but does not account for full carbon sources/sinks. An example is the selectively logged areas. Although there is evidence from the tropics of extensive reduction of biomass from selective logging (Nepsted et al 1999), it often does not result in a land cover change. However, selective logging can indeed remove substantial carbon stocks. Furthermore, it also increases the fire potentials as well (Cochrane et al. 1999). In order to account for full carbon fluxes, there is a need to develop indicators of selective logging, which would require a measure with a continuous field such as forest density or fractional cover. Optical remote sensing has been used to monitor regrowth and the technique can be applied to investigate the selective logging. Spectral vegetation indices may be optimized for such specific purpose (Pinty and Verstraete, 1996). The ratio of the reflectance of selectively logged areas to that of a mature forest can be quantitative indicators of selective logging. These approaches have been used for succession regrowth (Nelson et al., 1999 and Boyd et al. 1996) and revealed they were more correlated with regeneration stage. Ratioing of different spectral bands and spectral indices should be investigated for this purpose.

CONCLUSION

Some important research is needed to develop optical remote sensing for full carbon accounting. Limitations exist for current optical remote sensing in the number and placement of spectral bands, and lack of high spatial resolution data on a frequent basis. However, optical remote sensing has been quite successful for monitoring ARD activities, in particular for mapping deforested areas. Yet, more work needs to be done before there are universal, or objective, forest classifiers which can be used across of wide number of scenes. Ways to derived biophysical attributes of forest cover, in particular fractional forest cover described in this paper, need to be developed and procedures for their operational implementation also need to be developed.

Both global and country-level estimates of land cover change and greenhouse gases fluxes are poorly known. This presents major difficulties for developing international policies and mitigation strategies. For most developing countries the major source of greenhouse emissions is biogenic, rather than from fossil fuel combustion. For most developed countries the major sinks are biogenic. A major new effort must be mounted to develop country-level estimates of land cover change in support of the IPCC and FCCC initiatives (Houghton et al., 1995) as well as the Protocol itself. To do this at a country level uniformly worldwide, it will be necessary to develop consensus methods for measuring land cover change, development of assessments, compliance.

Yet, despite this need for precise estimates of land cover change, an operational program of measurement, monitoring and mapping has yet to be developed. For example, comprehensive and systematic information on the extent of forest and forest loss is not available on a global basis. Global Observation of Forest Cover (GOFC) is a new initiative of the Committee on Earth Observation Satellites (CEOS) to improve the quality and availability of satellite observations of forests and the information derived from these data. This objective will be accomplished by: (a) providing a forum for users of earth-observations to discuss their needs and for producers to respond through improvements to their programs; (b)Providing regional and global datasets containing information on location of different types of forests, major changes in forests resulting from logging, agricultural conversion, fire, and environmental stresses such as insect outbreaks and pollution; biological functioning of forests (such as the length of the growing season) which may lead to reliable estimates of the biological productivity of forests over large areas. This will help quantify the contribution forests make as absorbers and emitters of greenhouse gases. (c) Promoting globally consistent data processing and interpretation methods; (d) Promoting international networks for data access, data sharing, and international collaboration; and (e) Stimulating the production of improved products.

This program is made possible by the deplyment of new optical sensors such as ETM+ on Landsat 7 and MODIS and ASTER on the Terra platform, will provide new opportunities for global operational forest montoring. The Landsat 7 science mission calls for global acquisition of data 4 times each year, or once each season. The Long Term Acquisition Plan will permit large area acquisition of ETM+ data in a strategic fashion to support the needs of the global carbon research community and the Kyoto Protocol.The MODIS products (such as LAI and NPP) may provide improved accuracy in estimates of forest biophysical attributes. MODIS features spectral channels that approximate the spectral locations of the visible, near-IR and mid-IR TM channels with a spatial resolution of 250 m or 500 m at nadir. Additionally, MODIS will provide a spectral channel (1.23 μm – 1.25 μm; 500 m spatial res.) that is not available from the ETM+ sensor. This channel, which was designed to be sensitive to leaf and canopy properties (Running et al. 1994), may provide increased information content for the definition of spectral angle signatures using the MODIS sensor.

Therefore, it is possible that the vegetation structural and biophsyical products described in this paper may be derived from MODIS data in the near future, while ETM+ data will provide a more accurate area estimation of changes in forest cover. At the same time, recent studies show that a single sensor approach to monitoring is less efficient than one based on multisensor strategies, which could combine Landsat 7 and MODIS with SPOT-VEGETATION AND ERS-ATSR. Such a multi-sensor approach will require a large degree of international cooperation across the various national space agencies own missions.

There are also positive ancillary benefits from implementing an operational forest cover monitoring program, other that support for Kyoto and related carbon initiatives. For instance, at a national level, numerous reports identify the need for accurate forest monitoring to support national forest management programs and biodiversity studies, particularly in developing countries where tropical hardwoods are an increasingly important source of foreign exchange. An accurate and up-to-date assessment of forest area and rates of depletion is fundamental to the development of improved national forest management strategies. Moreover, issues such as soil fertility and erosion, water yield, water pollution, and land use planning are directly linked to forest resource development and its management, which could benefit from such an assessment.

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Workshop Paper 6

THE VEGETATION CANOPY LIDAR MISSION

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Contents:

Abstract

The Vegetation Canopy Lidar (VCL) is the first selected mission of NASA's new Earth System Science Pathfinder program. The principle goal of VCL is the characterization of the three-dimensional structure of the earth: in particular, canopy vertical and horizontal structure and land surface topography. Its primary science objectives are: landcover characterization for terrestrial ecosystem modeling, monitoring and prediction; landcover characterization for climate modeling and prediction; and, production of a global reference data set of topographic spot heights and transects. VCL will provide unique data sets for understanding important environmental issues including climatic change and variability, biotic erosion and sustainable landuse, and will dramtically improve our estimation of global biomass and carbon stocks, fractional forest cover, forest extent and condition, and provide canopy data critical for biodiversity studies. as well as for natural hazard and climate studies. Scheduled for launch in early 2000, VCL is an active lidar remote ensing system consisting of a five-beam instrument with 25 m contiguous along track resolution. The five beams are in a circular configuration 8 km across and each beam traces a separate ground track spaced 2 km apart, eventually producing 2 km coverage between 65° N and S, VCL's core measurement objectives are: (1) canopy top heights; (2) vertical distribution of intercepted surfaces (e.g. leaves and branches); (3) ground surface topographic elevations. These measurements are used to derive a variety science data products including canopy heights, canopy vertical distribution, and ground elevations gridded monthly at 1 resolution and and every 6 months at 2 km resolution, as well as a 2 km fractional forest cover product.

INTRODUCTION

The National Aeronautics and Space Administration has established the Earth System Science Pathfinder (ESSP) Program within the Office of Mission to Planet Earth (MTPE) to provide a means by which small, scientific space missions can be proposed and developed by individual investigators and their teams in response to research priorities not adequately addressed by current space missions such as those in EOS. The ESSP philosophy is to identify low-cost (less than $90M), quick-turnaround missions of limited duration that will provide data required to answer focused questions of importance to earth system science. As such, the ESSP program has been described as another tool among those in the existing NASA observational tool kit for improved understanding and comprehension of the components and interactions of the Earth system. The ESSP program is on-going and anticipates yearly mission launches.

In response to this opportunity, the Vegetation Canopy Lidar (VCL) mission was proposed by the University of Maryland, College Park, NASA Goddard Space Flight Center, and other university and industrial collaborators, to collect canopy and topography landcover data critical for terrestrial ecology and climate studies. In spring of 1997, VCL was selected as the first ESSP mission at a total cost of $59.8 M to NASA, along with the second mission, the Gravity Recovery and Climate Experiment (GRACE).

Mission Overview

The priniciple goal of the Vegetation Canopy Lidar is the characterization of the three-dimensional structure of the earth: in particular, canopy vertical and horizontal structure and land surface topography. The VCL mission has two main science objectives:

I. Landcover characterization for:
(a) terrestrial ecosystem modeling and prediction; and,
(b) climate modeling and prediction.
II. Global reference data set of topographic spot heights and transects.

The datasets derived from the laser altimetry instrument will make a unique and catalytic contribution to pressing environmental issues -- climatic change and variability, biotic erosion and sustainable landuse, and should dramtically improve our estimation of global biomass and carbon stocks, fractional forest cover, forest extent and condition, and provide canopy data critical for biodiversity studies. In addition, through its characterization of land surface canopy and topographic structure, VCL provides new knowledge of biophyscial parameters critical for climate, hydrologic, and other global modeling activities, activities that are essential for our ability to plan and predict for global change in the next century. Lastly, VCL provides a dense, global network of accurate topographic heights, including sub-canopy topography, data which are invaluable for future topographic missions, as well as for natural hazard and climate studies.

VCL is an active remote sensing system built around the Multi-Beam Laser Altimeter (MBLA), a five-beam instrument with 25 m contiguous along track resolution. The five beams are in a circular configuration 8 km across and each beam traces a separate ground track spaced 2 km apart, eventually producing 2 km coverage between 65° N and S, with orbit crossovers producing a denser grid away from the equator.

VCL's core measurement objectives are:
(1) canopy top heights;
(2) vertical distribution of intercepted surfaces (e.g. leaves and branches);
(3) ground surface topographic elevations.

VCL measurements are used to derive a variety science data products including canopy heights, canopy vertical distribution, and ground elevations gridded monthly at 1° resolution and and every 6 months at 2 km resolution, as well as a 2 km fractional forest cover product. These products are created at the VCL Data Center at the University of Maryland and archived and distributed through a collaboration with the EROS Data Center.

Motivation

The primary focus of the VCL mission is to provide quantitative description of landcover and global productivity, one of five science priorities of MTPE (Harris et al., 1996). Landcover change or dynamics is directly linked to several important environmental issues, including climatic change and variability, biotic erosion (loss of biodiversity), and sustainable landuse. Landcover is a first order component of general circulation models. Its status and dynamics have a direct feedbacck on the climate system by determining the boundary conditions of the exchange of momentum, energy and mass between the atmosphere and the land. Landcover also exerts an indirect or trace gas feedback because it represents a significant and dynamic pool in the carbon cycle. Similarly, landcover dynamics are the principal driver of biotic erosion. It is changes in landcover structure and composition that in turn, determines changes in habitat suitability. Any predictive understanding of biotic erosion, a necessary prerequisite for slowing and reversing that loss, will be underpinned by a quantitative comprehension and representation of current landcover status and the regime of disturbance by landuse.

For understanding and managing these environmental issues, there is a prerequisite for describing landcover status and dynamics to initialize, parameterize and validate modeling efforts. This description is required in many forms. To represent landcover in models of the climate system, it must be first be parameterized with respect to albedo, aerodynamic roughness, and surface resistance to evaporation, among others; these parameters being functions of vegetation structure, e.g. height, canopy closure, and leaf-area index (LAI), and composition (annual/ perennial, etc.). Similarly, for biogeochemical modeling, biotic erosion, and land degradation, the vegetation component of landcover must be represented in structural terms (biomass) and by composition (annual/perennial, woody/non-woody, and their age structures).

These arguments are not new. Indeed, they have justified the significant efforts by the global remote sensing community to better characterize the global land surface. The principal data source thus far for these efforts has been that from the AVHRR instrument of the NOAA spacecraft series, e.g. the NASA AVHRR Pathfinder Program. The ISLSCP Initiative (Sellers et al. 1995) is one example of the intensive use of existing data to parameterize landcover for modeling purposes. While these AVHRR-derived datasets represent a significant contribution, there remains considerable uncertainty associated with the estimated parameters. For example, important parameters such as height, LAI, woody biomass, aerodynamic roughness, and surface resistance are poorly estimated by existing methods using AVHRR data alone. Nor will any of the EOS-suite of instruments provide the requisite observations of these variables. However, given an independent and systematic sampling of vegetation based on laser returns, global data sets can be developed that will provide much improved estimates of critical variables such as canopy height, aerodnamic roughness and biomass. Furthermore, the recovery of explicit vegetation structure should provide new insight into traditional measures of surface reflectance and structure, obtained from passive remote sensing instruments, such as NDVI, LAI, BRDF, thereby extending the usefulness of the existing and planned remote sensing archive.

VCL also provides a near-global dense reference network of height transects including sub-canopy topography. The importance of accurate topographic data for global change and earth system science is increasingly being recognized, as evidenced by efforts to assimilate global topographic data, declassify defense digital elevation data, and the creation of new technologies for accurate mapping (such as GPS and interferometric SAR). This data set should prove invaluable for calibration and registration of data from future topographic missions, such as the Shuttle Radar Topography Mapper (SRTM), as well as providing detailed information on topographic roughness and scaling.

SCIENTIFIC RATIONALE

Forests comprise 29% of the world's terrestrial sruface and, as indication by the seasonal changes in atmospheric CO2 (Denning et al. 1995), these systems represent key dynamic components in the global carbon cycle. Besides harboring the bulk of the Earth's biodiversity (Erwin 1995), forest canopies are the primary interfce between terrestrial ecosystems and the atmosphere, accounting for greater than 50% of the annual CO2 flux (Potter et al 1993). Knowledge of canopy structure is required for modeling processes such as photosynthesis, energy transfer, and evapotranspiration at local to global scales.

Heretofore, the lack of broad scale data on vegetation morphology has limited the implementation of canopy-related processes into earth system models (Asrar and Dozier 1994), and is a priority for earth system science. Our crude knowledge about fundamental landcover characteristics, especially their vertical and horizontal structure and gradients, is remarkable given the level of sophistication and complexity of many global modeling activities that rely on this data. DeFries et al. (1995) have outlined the weaknesses of current landcover schemes in their discreet mapping of the land surface characteristics required to calculate land surface parameters such as absorbed radiation, albedo, canopy conductance, roughness, photsynthesis, transpiration, net primary production, carbon and nutrient dynamics. Although further development and refinement of the passive remote sensing techniques generally used for such characterization may provide some improvement, truly dramatic gains may be realized only with the advent of active remote sensing systems, such as laser altimetry, which directly measure surface structure

Landcover characterization for terrestrial ecosystem modeling and prediction

• Vegetation height:

With a VCL signal, the first return above a threshold represents the top of the canopy, and the midpoint of the last return represents the ground return (Figure 1).

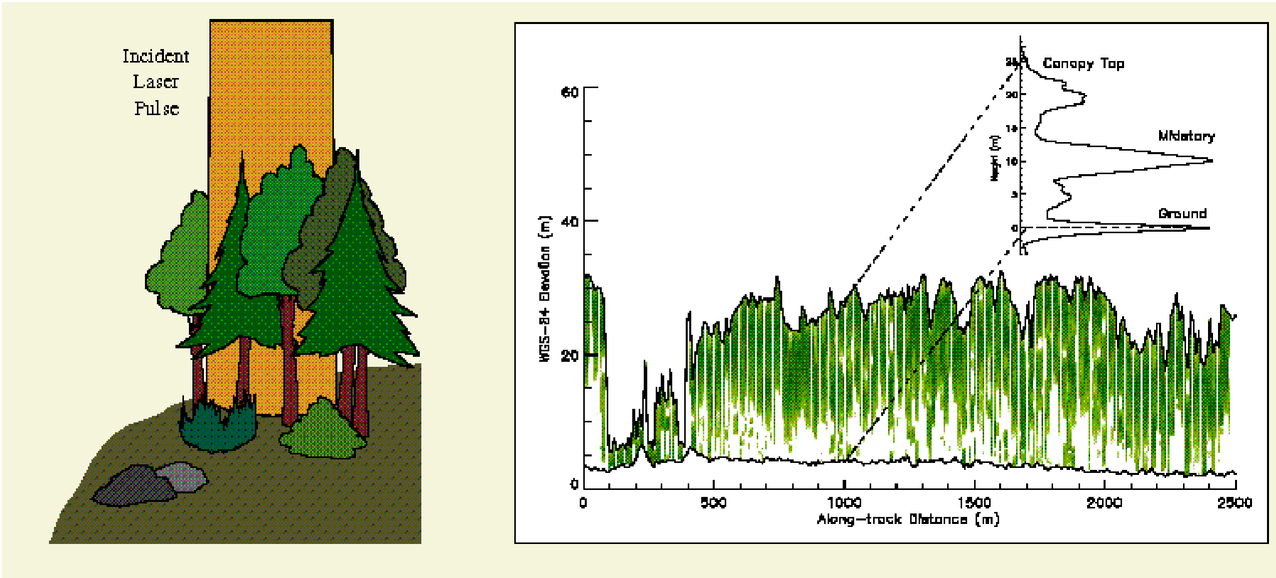

Figure 1 *. Return waveform for a laser pulse. An incident gaussian laser pulse's interaction with surface structural components leads to the distorted (relative to a gaussian) return waveform or echo. Measuring the return travel time of pulse gives distance from the sensor. By knowing where the last return is from the ground, shown as the strong pulse, this distance can be translated into height above the ground. The magnitude at any height (time) of the waveform is directly related to the number of intercepting surfaces and their reflectance. Thus where the amplitude of the waveform is larger implies more canopy materials, for example.*

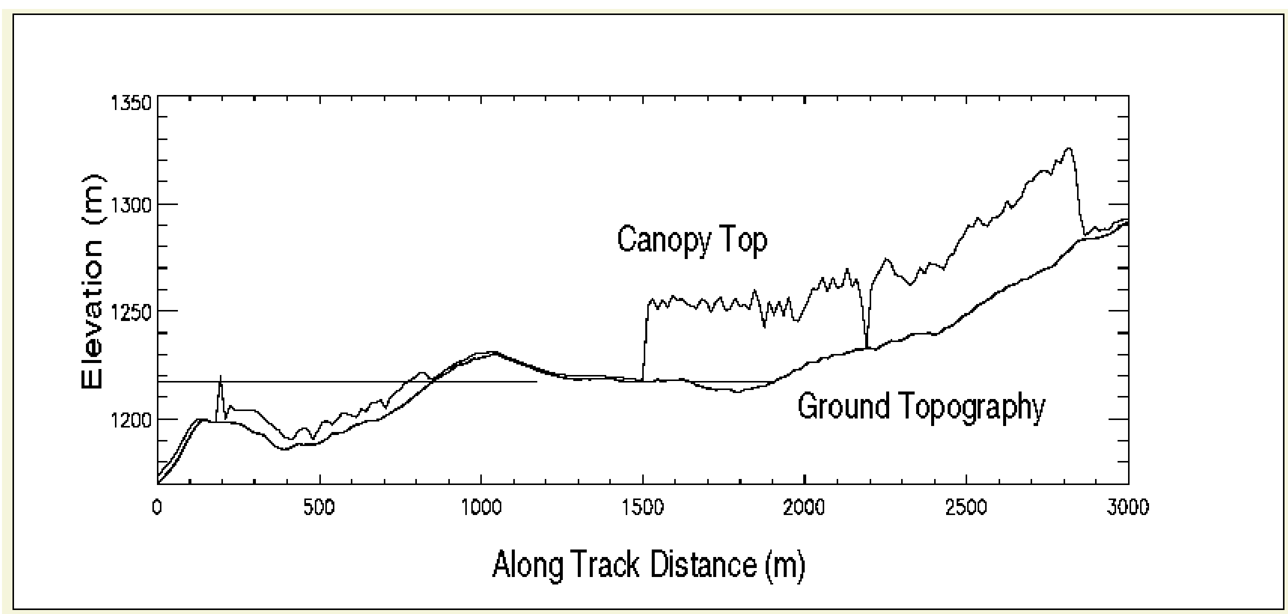

Figure 2 . *Profile of canopy height, canopy density and subcanopy topography from an airborne laser altimeter (SLICER) over a forest near Salisbury Maryland. The individual waveform contains multiple distinct returns, The the independence of canopy top and ground topography, as well as the ability to detect the ground below the canopy.*

Figure 2 shows typical laser returns over a vegetation canopy. Canopy height is calculated by subtracting the elevations of the first and last returns. Vegetation height is is a function of species composition, climate and site quality, and can be used for land cover classification alone or in conjunction with vegetation indices (e.g., NDVI). Along track measurements, i.e., footprint-to-footprint, of VCL-derived height variation provides additional information such as fractal (Palmer 1988) or autocorrelative (Cohen et al. 1990) properties of the canopy that further may be used to differentiate among natural and anthropogenically-disturbed land cover patterns (Krummel et al. 1987). When coupled with species composition and site quality information (e.g., edaphic and climatic variables), height serves as an estimate of stand age or successional state which can be correlated to carbon flux rates (Ustin et al. 1993).

In addition to providing a unique metric, i.e., the vertical dimension, to classify vegetative cover at global scales, height is highly correlated with aboveground biomass (Oliver and Larson 1990, Avery and Burkhart 1994, Nilsson 1996). Biomass in forests represents the major reservoir of carbon in terrestrial ecosystems that can be quickly mobilized by disturbance or land use change (e.g., Houghton et al. 1987, Dixon et al. 1994).

- Vertical distribution of aboveground surfaces:

By recording the complete time-varying amplitude of the return signal of the laser pulse between the first and last returns (representing the canopy top and the ground), VCL captures a waveform that is related to canopy architecture, specifically the nadir-projected vertical distribution of the surface area of canopy components (foliage, trunk, twigs, and branches). Like the simple height estimate, the vertical distribution of laser return provides a new means to classify vegetation and functions as a predictor of the successional state of a forest. Trees in younger stands tend to exhibit a more leptokurtic vertical distribution of phytomass concentrated near the ground. As a stand ages and grows, the vertical distribution of canopy components becomes more platykurtic. Bimodal distributions are associated with the presence of an understory which may occur in more mature stands. Older stands characterized by canopy gaps and trees of multiple ages and sizes exhibit a more even distribution of canopy components (e.g., Aber 1979, Brown and Parker 1994).

When combined with greeness measures from other sensors, such as TM, MODIS or AVHRR, VCL observations may be used to determine whether the greeness signal is the result solely of low-lying vegetation (via the height distribution). Many areas of the world have ground covers with greeness indices comparable to those of forests, making landcover discrimination based on greeness measures alone difficult. Measures of the vertical organization of canopy components are also critical for modeling factors that relate to biophysical and micrometerological processes at the atmospheric-vegetation boundary layer such as radiative transfer, evapotranspiration, and trace gas flux (Gro 1993, Fournier et al. 1995).

Landcover characterization for climate modeling

Direct measurements of canopy height, canopy vertical and spatial structure, and ground topography would allow determination of landcover properties critical to GCMs, SVATs and mesoscale models, whether used for climate modeling or numerical weather forecasting. There have been efforts to include complex land surface parameterization schemes both on-line and off-line in these models, as well as to understand the effects of various schemes on model outputs (e.g. see the Project for Intercomparison of Landsurface Parameterization Schemes - PILPS - activities). The determination of bulk aerodynamic parameters that control the transfer of energy, mass and momentum between the atmosphere and the surface, roughness length, zero-plane displacement, and canopy and ground resistances, is generally regarded as a major source of uncertainty. For example, in SiB2 (Sellers et al. 1996) 1 @times@ 1 maps of the bulk aerodynamic parameters are found by first using a global landcover classification. Mean values of eight canopy and ground morphological and physical parameters (canopy top height, canopy base height, ground roughness length, leaf-area density inflection height, leaf width and length, leaf-angle distribution factor and leaf area index) are assigned from the literature based on landcover type. These variables are then used with estimates of LAI from satellite data to derive the bulk parameters at 1 @times@ 1 spatial resolution. This procedure can only be seen as inadequate given the sparsity of literature values for canopy variables and their gross spatial and categorical generalization.

In contrast VCL would provide direct measurements of canopy top height, canopy base height, sub-canopy ground roughness length, and vertical density of interceptors (woody and non-woody). Maps of these variables would then be available globally, and gridded to a resolution as fine as 2 km @times@ 2 km. These can then be used to derive the bulk aerodynamic parameters at accuracies and spatial extents never before possible, with a resultant improvement in our ability to model momentum, water vapor and sensible heat fluxes. In addition, a global data base of canopy structure, especially when combined with other remote sensing data, such as greeness indices from MODIS, should enhance our ability to model the interaction of energy with the surface via better estimates of LAI and FPAR (fractional absorbed photosynthetically active radiation), as well as the interaction of precipitation with the surface through interception and retention, with resulting improvements in model photosynthesis, net primary production, trace gas and hydrologic fluxes.

Globally distributed topographic control points

The strong scientifc need for accurate, global topographic data bases has led to recent progress in limited release of portions of the Defense Mapping Agency Digital Terrain Elevation Data (DTED) Level 1 data that has 90 spatial (horizontal) pixel resolution and 16 m vertical accuracy. Despite this progress the scientific benefit for global MTPE studies is not nearly realized. The existing DTED Level 1 data will not be released for the entire Earth and space-based imaging sensors now in orbit and planned in the EOS-AM1 era (1998-2003) require global topography at DTED Level 2 (30 m spatial, 16 m vertical) for full realization of their science potential in land cover/global productivity, short-term climate modeling, and natural hazard studies. The Shuttle Radar Topography Mission (SRTM) has been announced to address these needs. Since IFSAR data, or the conventional photogrammetric data sets, are only relative in their measurement of surface elevation, direct measurements are needed to "control" the vertical dimension of the topographic image. Estimates of TCPs needed for a global DTED Level 2 are well in excess of 100,000,000. Only a limited number of these TCPs can be provided by ground-based radar targets and GPS receivers, the remainder will have to be estimated from existing maps and digital elevation models that do not routinely achieve the 1 meter level of vertical accuracy and do not have a common reference frame. The VCL surface elevation measurements will have a common, global reference frame and are "direct" rather than inferred. Furthermore, only VCL will address the vegetation cover issues that limit all present mapping techniques to tens-of-meters rms in forested areas. The VCL Mission, by virtue of its primary vegetation canopy measurements, will provide billions of sub-canopy surface elevation points.

MISSION DESCRIPTION

VCL is scheduled for launch in early 2000 on board a Pegasus XL launch vehicle. The VCL mission will be conducted by means of a small satellite carrying the MBLA instrument in a 400 km orbit of 65° inclination with a two-year nominal lifetime. This will provide sufficient coverage of the Earth to characterize the vegetation canopy structure on a global basis during two complete growing seasons and produce a global reference grid of land topography. Because of increased atmospheric drag caused by the solar maximum during the mission, monthly reboosts are required to maintain nominal orbital altitude. Command and control of the spacecraft during operation, as well as data processing will take place at the University of Maryland. Distribution and archiving of VCL data products will be performed by the EROS Data Center. Table 1 lists VCL data characteristics and quality.

VCL visits, on average, the same 1 cell at the equator every two weeks, with more frequent revisits away from the equator. The exact ground track through any cell is essentially random, being a function of orbital drag and the monthly reboost required to keep the satellite at altitude. The number of visits to a 2 km cell, globally averaged over all cells, is approximately 10 during the two-year mission (with more frequent visits away from the equator, and less frequent visits at the equator).

Measurement Objectives and Requirements

To address its major science goals, the VCL mission has 3 direct measurement objectives listed above, all at sub-meter vertical accuracies: (1) canopy top height; (2) the vertical distribution of nadir intercepted surfaces; and, (3) surface topography elevation, including sub-canopy topography.

VCL science goals place further constraints on the measurements, achieved through sensor design, orbit configuration and mission lifetime. Among these constraints are: laser footprint of 25 m to adequately resolve vegetation height and structure; continuous along track returns to adequately characterize horizontal spatial variability and vertical height distributions; 5 beams separated by 2 km across-track spacing to achieve sufficient global sampling and exact positioning and pointing; precessing, inclined orbital configuration such that the sensor passes within the same 1 @times@ 1 block along the equator every two weeks, allowing for (a) seasonal refresh of canopy structure and, (b) global 2 km coverage every 6 months, minimizing the effects of clouds.

Canopy measurements are achieved through analysis of laser pulse returns (waveforms) and require that return signals include the canopy top, adjacent structural elements and, eventually, the underlying ground. Waveform analyses based on extensive airborne and spaceborne laser altimetry have revealed the need for footprint sizes on the order of 1 to 2 canopy diameters. This guarantees a resulting reflection from the very top of each canopy within the sampled area as well as sufficient intra- and inter-tree gaps required to image the underlying ground. Dynamic range in the receiver as well as sufficient laser output energy are required to detect small (< 1%) weighted returns from the canopy top and, in dense canopies, the underlying ground. So, potentially, even the most dense canopies still reveal their heights and sub-canopy topography. Smaller footprints under-represent the canopy structure especially with respect to true height. This results from the reduced probability of sampling the top of the canopy: smaller footprints most often hit the shoulders of the canopy. Conversely, with larger footprints (beyond a few tens of meters), similar to those proposed for space-borne missions of the future, such as the Geoscience Laser Altimeter Sensor (GLAS) and Shuttle Laser Altimeter (SLA) series, the precent of the total return that is contributed by the canopy top is greatly reduced making height measurement inaccurate.

The footprint size selected for VCL will be especially suitable for high biomass tropical forests where canopy diameters can reach 10 to 25 m. The medium size footprint of VCL also reduces any surface slope spreading of the ground return, most notably in the case where the surface slope, canopy height, and canopy thickness combine to convolve the canopy return with the ground return.

A 65° orbital inclination was selected to provide near-complete coverage of vegetation areas of interest. Such an inclination samples 98% of closed canopy forest, and gives at least 92% coverage for all the major types of close-canopy forest, and at least 89% for all but one type of open woodland.

The orbit and 2 km beam spacing allows VCL to cover the entire earth between 65 N and S in less than 6 months, so that over an 18 month mission VCL will visit the same general 2 km @times@ 2 km area 3-4 times near the equator (with higher repeats at higher latitudes). Cloud probability studies have shown that this leads to a 85-90% chance of obtaining at least one clear pass through the area.

VCL acquires data 10 times over an average 2 km @times@ 2 km cell during a 2 year mission, accumulating 19.1 km lf laser ground tracks. This samples 9.4% of an average cell's area, or after adjusting for cloud cover, 4.7% of the land area between 65° N and S. VCL's mission duration is driven by requirements for coverage in the tropics, where there are the greatest uncertainties in present land cover data. The more frequent coverage where orbital paths converge at higher latitudes yields measurements of canopy heights and median intercepts during the summer growing season, even where deciduous trees are in leaf for but a few months a year.

Baseline Instrumentation

The MBLA is comprised of five laser transmitters in a single altimeter instrument. Each laser beam operates at the 1064 nm fundamental wavelength of the neodymium-doped yttrium aluminum garnet (Nd:YAG) solid-state laser, are arranged in a pentagon inside a 20 mrad telescope circular field-of-view that is centered on nadir as illustrated in Figure 3.

The optical telescope is 0.9 m in diameter composed of beryllium. For the VCL orbital altitude of 400 km the across-track separation between adjacent tracks is 2 km. VCL makes simultaneous measurements of range to the surface by synchronous triggering of the 5 laser pulse transmitters and detection with a single telescope that is staring at nadir and is equipped with multiple silicon avalanche photo diode detectors in its focal plane. Individual laser footprints are 25 m in diameter and are contiguous along-track, commensurate with the best DTED Level 2 topography mapping resolution and LANDSAT Thematic Mapper pixel resolution. Surface echoes from the 5 beams are digitized in the MBLA electronics at 250 Megasamples per sec to achieve the required sub-meter vertical resolution in the vegetation canopy and permit pulse centroid correction of the range measurement.

The MBLA pulsed laser transmitter modules are based on high power Nd:YAG and employ the Q-switching technique to concentrate laser energy in a short pulse. Each of these laser modules produces a laser pulse of 5 nsec duration at the rate of 290 pps. Laser pulse energy of 10 mJ per pulse will be sufficient to establish a link performance for the MBLA instrument that results in 95% probability of detection of the Earth's surface under clear atmospheric conditions and permits surface lidar investigations.

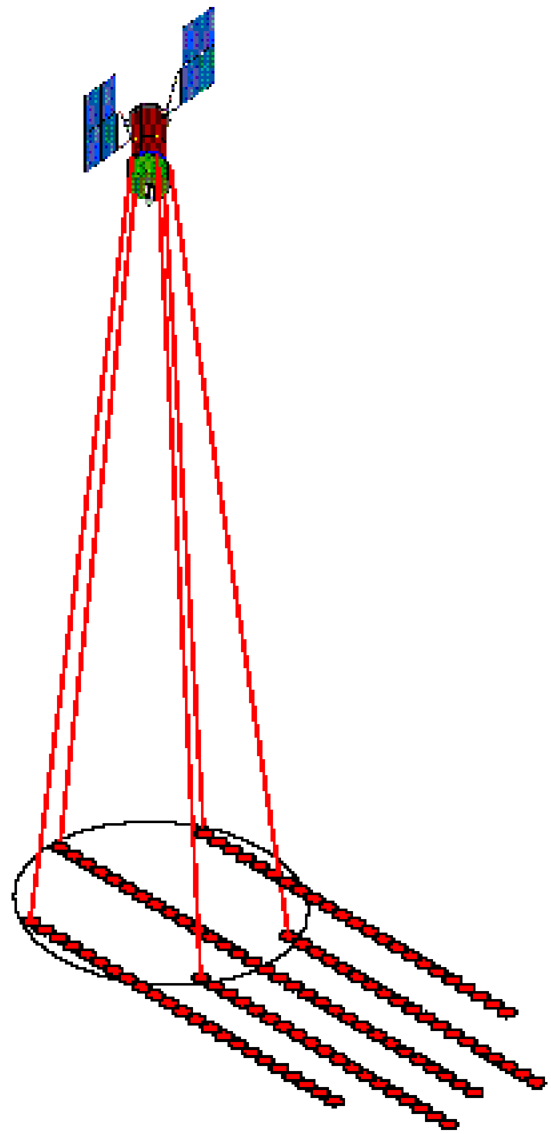

Figure 3 . VCL mission concept.

DATA PROCESSING AND DISTRIBUTION

The ultimate goal of the VCL project is to produce quality data products that the science community may use to answer the scientific questions posed earlier. The VCL data processing and distribution plan assures the quality of final data products and their timely release. There are several pre-launch elements of this plan including: calibration and validation activities to assist in algorithm development and data quality evaluation; precision orbit determination strategy for VCL; laser waveform processing algorithm development; in partnership with EROS data center, development of web sites, interfaces, distribution, archiving, data and metadata structures and other protocols. Post-launch, all data processing is done at the VCL Data Processing Center (VDC) and the University of Maryland. During the first 6 months after on-orbit check-out, calibration and validation activities confirm data quality, after which the frist Level 1B through Level 3 data products will be available on-line from VDC and transferred to EDC for archiving and distribution.

Table 1. VCL Data Characteristics and Quality	
Swath width	8 km
Number of beam tracks	5
Footprint (at 400 km)	25 m (60 @ mu @rad)
Footprint spacing	contiguous over land (approx)
Track spacing	2 km
Pulses per second	290 over land (approx.)
Wavelength	1064 nanometer
Coverage	between 65 eg N and S
Elevation accuracy	< 1 m in low slope terrain
Waveform digitization	250 Megasamples/sec
Samples per waveform	10-200, average=50
Sample precision	10 bits
Pulse detection dynamic range	100:1

Table 2. VCL Data Set Levels and Descriptions

Level	Description	Estimated Data Volume
0	Uncompressed instrument data	5.0 Gb/day
1A	Orbital, calibration and time parameters inserted	5.0 Gb/day
1B	Calibrated waveforms and ranges	6.0 Gb/day
2	Geolocated canopy top heights	0.5 Gb/day
	Geolocated vertical distribution of intercepted surfaces	6.0 Gb/day
	Geolocated ground heights (including sub-canopy)	0.5 Gb/day
3	Gridded mean canopy top height and variances (1 deg by 1 deg)	0.4 MB/month
	Gridded median height of intercepted surfaces (1 deg by 1 deg)	0.2 MB/month
	Gridded mean ground height and variances (1 deg by 1 deg)	0.4 MB/month
	Gridded mean canopy top height and variances (2 km)	130 MB/6 months
	Gridded median height of intercepted surfaces (2 km)	65 MB/6 months
	Gridded mean ground height and variances (2 km)	130 MB/6 months
	Gridded fractional forest cover (2 km)	32 MB/6 months

VCL Data Products

There are two basic types of data products delivered by VCL: gridded and ungridded (Table 2). The ungridded data products are the along-track, contiguous footprint observations. The ungridded data products consist of calibrated waveforms and ranges, should users wish to derive their own parameters from the lidar measurements (Level 1B), and data products derived from these (Level 2), but using VCL developed algorithms. These Level 2 products consist of geolocated measurements of canopy top heights, ground height, and the vertical distribution of intercepted surfaces.

VCL will provide products gridded at two different spatial and temporal resolutions: 1 , monthly products and 2 km, 6 monthly products, these time periods a function of the revisit times to any particular cell for the given spatial resolution. During a one month period, VCL will visit a 1 grid cell at the equator twice (with more frequent visits away from the equator). Every month the derived Level 2 parameters accumulated for a cell will be gridded and released as Level 3 products (see Table 1). Similarly, every 6 months the accumulated Level 2 data for a particular 2 km grid cell will be gridded and released as a Level 3 product, the longer time period being needed to accumulate enough returns for the smaller area. An additional Level 3 data set, 2 km fractional forest cover. will also be derived from these observations. Every 6 months these 2 km grids will be updated with the accumulated returns.

Calbration and Validation Activities

The VCL science team (see below) has primary responsibility for calibration of algorithms for extracting geophysical fields, for validation of the results, and for assuring the accuracy and quality of the science data products.

Calibration.

Calibration of ground height measurements requires on-orbit bias and drift retrievals. These are obtained through comparisons with results from the TOPEX/POSEIDON altimeter at ocean orbital crossover points between VCL and TOPEX/POSEIDON, as well as comparisons of VCL ocean altimetry with high resolution mean sea surface elevation maps.

Calibrating canopy top heights.

Before launch, the science team will develop and unambiguous calibration relating an extreme percentile fo the canopy return (e.g. the first 2%) and the most widely encountered definition of stand height (the average of top heights for plants forming the canopy, i.e. the dominant and codominant tress in forests). We will test whether the same percentile and calibration coefficient can be used for canopies with markedly different crown forms. To help with this assessment ee will acquire aircraft data with the Laser Vegetation Imaging Sensor (LVIS) instrument (Blair et al. 1996), configured as a VCL simulator over a variety of forest types including moist tropical forests, deciduous and mixed conifer, and open woodland, among others.

Validation.

Validation has three components: comparing results from aircraft data with localized ground data, comparing VCL data products with aricraft data for the same areas, and comparing gridded products with data from global site networks. The combination allows us to scale from small field plot data to landscape-level estimates, an then to gridded products from VCL. Alogrithms for Level 2 products are validated by compariso with groudn data. Level 1 and Level 3 products are validated by comparing them with aircraft data and landscape estimates from aircraft data, respectively. Global Level 3 products are cehced against several distributed data sources.

VCL Institutional Partners and Science Team Membership

VCL was conceived and executed as a collaboration among various university, federal agency, and private industrial partners. Such a collaboration is neccesitated through the "Principal Investigator" mode required by the ESSP program, where the PI and mission team are solely responsible for all aspects of the mission from engineering design, construction, launch, and ground systems, to processing, archiving and release of final data products. The VCL partners and their roles are given in Table 3. The great advantage of PI-mode is that allows a mission team great flexibility to design and implement a mission in efficient and novel ways with limited NASA direction, and thus represents a radically "new way of doing business" for the space agency. NASA provides oversight of the project through the valuable efforts of the ESSP project office.

Table 3. VCL institutional partners.	
Institution	Role
University of Maryland , College Park	PI institution and prime contractor, Science Team, data processing
Laboratory for Terrestrial Physics, NASA Goddard Space Flight Center	Instrument, alogorithms, orbits, Science Team
CTA Space Systems	Spacecraft bus
Omitron, Inc	Project management, ground systems
Fibretek, Inc	Instrument lasers
University of Central Florida	Science Team
University of Missouri - St. Louis	Science Team

As required by the ESSP program, a VCL Science team was formed prior to mission selection. The VCL Science Team is responsible for developing science requirements for the instrument, developing and implementing calibration and validation plans, developing science algorithms, implementing and monitoring science outreach, evaluating data products and ensuring their timely release. Table 4 lists science team members and their roles in the mission.

It is important to note that the VCL Science Team does not directly attempt to meet any of the science objectives of the mission, nor do they receive any funding to do so; rather, each member's participation is focused solely on some aspect of the production of VCL data sets. Through its Science Development and Analysis Program (SDAP), NASA plans to competitively fund research projects proposed by members of the scientific community that make use of data from ESSP missions to answer the questions posed by particular project(s). The use of VCL observations for estimating global biomass and carbon reserves would be one example of an investigation properly funded by the SDAP program.

Table 4. Science team membership and responsibilities.		
Member	Institution	Role
Ralph Dubayah	University of Maryland	Principal Investigator, Cal/val
J. Bryan Blair	NASA GSFC	Alogrithm development, LVIS, cal/val
Jack L. Bufton	NASA GSFC	MBLA instrument
David B. Clark	University of Missouri - St. Louis	Cal/val
Robert G. Knox	NASA GSFC	Cal/val coordinator
Scott Luthke	NASA GSFC	Precision orbit determination
Stephen Prince	University of Maryland	Cal/val
John Weishampel	University of Central Florida	Cal/val

SUMMARY

The Vegetation Canopy Lidar will be a key instrument in the EOS-era of earth observation. Its 5-beam, active remote sensing system will provide unprecedented information on the structure of the Earth's forests and land surfaces, directly observing vegetation canopy height, forest vertical and spatial distriubtion, and ground topography at high resolution. In its two year mission VCL will acquire billions of cloud-free observations that will prove invaluable for estimating the current status and dynamics of the earth's landcover and topography in structural terms never before possible, and the implications of these for biophysical and climatological processes. When fully integrated with observations expected from other EOS-era sensors, these data should revolutionize our perspective and understanding on the role of the land surface as part of the earth system, and the effects of human activites therein.

Workshop Paper 7

MONITORING BIOMASS USING POLARIMETRIC MULTI-FREQUENCY SAR

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Introduction

Australian eucalypt species are not well characterised in terms of biometric models which allow the relative components of green foliage and woody biomass to be determined or to be predicted reliably. In forest and woodland analysis there is a strong reliance on developing better field based measurements. Also, as a result of the Kyoto Protocol and Australia's commitment to meet carbon emission levels under the UN Framework Convention on Climatic change, there is an increasing need to develop spatial extrapolation procedures that will provide accurate estimates at both the local and regional level of changes in vegetation cover.

The potential of SAR to map the distribution of forests and woodlands and to monitor long term developments in these ecosystems, as well as to contribute to an understanding of global change, depends on the ability to unravel the relationships that exist between microwave backscatter of the return signal and the physical characteristics of trees and forests.

In order to use the radar parameters of wavelength, polarisation, phase difference and incidence angle to maximum effect to discern differences within forest environments, backscatter and linking models need to be developed that allow the biophysical properties of trees to be determined. In respect to temporal studies, such models must not only take into account structural components such as tree height, trunk diameter, branching pattern and canopy characteristics, but also incorporate the impact of changing environmental conditions such as prolonged wet and dry periods and the impact of stress caused by factors such as disease, fire and human interference, and the underlying slope of the land surface.

The first established empirically based relationships between radar backscatter and field measurements of selected tree parameters in tropical Australian forests that demonstrated multi-polarimetric SAR responds to differences in vegetation structure (eg. total biomass, leaf-area index, branch surface/volume ratio etc.) in predictable ways were presented by Imhoff (1997). These results show radar sensitivity to floristically induced structural changes, indicating that given appropriate algorithms, the physiognomic classifications of trees and community typology might be possible with radar. Also, in associated research at the same site the vegetation structural changes identified in the radar analysis were shown to be significantly related to avian habitat quality thereby demonstrating the potential of SAR for studying biodiversity and habitat change.

More recent work reported in this paper shows a direct relationship between total above ground biomass and SAR backscatter for two sites in Queensland. At Injune in Central Queensland, a significant non-linear correlation between trunk biomass and JERS-1 single band SAR data was obtained with an r^2 statistic of 0.72. Strong relationships between multi-band SAR data and component biomass (ie branch, trunk, leaf and total biomass) were recorded for eucalypt woodland sites at Talwood in Southern Queensland. Here r^2 values of 0.91 were obtained for P-band SAR and total biomass.

The ability to derive estimates of tree stand parameters directly from SAR depends on the development of inversion models that facilitate prediction based on radar scattering characteristics alone and which include a means of extrapolating tree characteristics to areal measurements. The correlative relationships described above between biomass and floristic induced structural changes and radar backscatter have been modelled using wavelet transform techniques to suppress speckle noise in the imagery and a segmentation routine based on a Gaussian Markov Random Field Model has been developed to classify and spatially extrapolate the distribution of different stand densities and land cover types. These techniques are described later in this paper and an example of their application is presented in relation to the Injune and Talwood study sites.

SAR and Biomass Estimation

A number of studies have suggested that, due to the penetrative capacity of microwaves, the total biomass of vegetation may be estimated using single polarized data, although C, L and P band data have been shown to saturate at a biomass of approximately 20-40 Mg ha^{-1}, 60-100 Mg ha^{-1} and 150 Mg ha^{-1} respectively. However, by employing multi-band polarimetric data, the range of biomass detected by SAR may be extended. For example, by relating different SAR frequencies and polarisations to different components of the biomass, Dobson *et al.* (1995) and Kasischke *et al*. (1995) were able to estimate biomass up to 250 Mg ha^{-1} (± 16 Mg ha^{-1}) and 400 Mg ha^{-1} (± 80 Mg ha^{-1}) respectively. Other studies (e.g., Beaudoin *et al*., 1994; Harrell *et al*., 1997) have also indicated that polarimetric data may be used to estimate the component biomass of vegetation.

Use of SAR in Australia

The majority of studies investigating the use of SAR data for biomass estimation have focused largely on coniferous forests in the northern hemisphere, particularly in North America and Eurasia (e.g., Sader, 1997, Wang *et al*., 1994; 1995, Harrell *et al*., 1997; Baker *et al*. ,1994, and Green, 1998). A few studies have also concentrated on mixed forests in boreal (Fransson and Israelsson, 1999), temperate (e.g, Bergen *et al*., 1998; Ranson *et al*., 1997) and tropical regions (Luckman *et al*., 1997; Foody *et al*., 1998).

In Australia, the use of both spaceborne and airborne Synthetic Aperture Radar (SAR) for quantifying forest biomass has not been rigorously investigated. This is despite the availability, since 1991, of SAR data from a range of airborne and spaceborne sensors. These include the European Earth Resources Satellites (ERS-1 and ERS-2), the Canadian RADARSAT, the Japanese Earth Resources Satellite (JERS-1) Synthetic Aperature Radar (SAR), the Space Shuttle Imaging Radars (SIR-B and C) and the NASA JPL AIRSAR. This lack of research and development is surprising given the increasing demonstration internationally of the potential of SAR for biomass estimation.

The use of SAR data for estimating the biomass of Australia's vegetation should be advocated for several reasons.

- The majority (124 million ha) of Australia's 155 million ha of forested area is represented by woodlands, the biomass of which rarely exceeds 100 Mg ha^{-1} and is especially low in areas of regeneration. Therefore, the biomass of most woodland areas should be quantifiable using, as a minimum, single polarised L band data as most of the biomass is below the threshold of saturation.
- A large proportion of the Australian continent receives little rainfall compared to many regions of the world and the moisture content of vegetation and soil, particularly in the dryer areas supporting woodland, is unlikely to vary substantially.
- Much of the landscape is relatively flat and the influence of the terrain on the SAR backscatter is likely to be minimal.

Kakadu World Heritage Region

The analysis of P-, L-, and C- band SAR data collected during the first NASA/JPL AIRSAR Campaign in Australia in 1993 over a section of the South Alligator River in Kakadu demonstrated the usefulness of SAR in identifying changes in woodland vegetation types occasioned by both structural and floristic differences. Statistically significant changes were evident where (1) a *Melaleuca cajuputi* woodland changed in structure from a tall, closed canopy to a more densely stocked formation of smaller trees of the same species, and (2) where the Melaleuca were replaced by a mixed eucalypt woodland that characterises the drier uplands of Kakadu National Park. The best correlations between bole biomass and Surface Area/Volume ratios were achieved between C-HV, L-VV, P-VV, C-VV, L-VV AND P-VV respectively (Imhoff et al 1997).

Queensland study sites

The following sections outline two more recent case studies that provide a further demonstration of the potential of SAR for estimating the biomass of Australian woodland vegetation. The first considers the use of JERS-1 SAR L band HH (horizontally transmitted, horizontally received) for quantifying the biomass of woodlands near Injune, central Queensland. The second examines the use of NASA JPL AIRSAR polarimetric data for quantifying the component biomass (i.e., leaves, branches, trunks) of woodlands near Talwood, southern Queensland.

Natural vegetation and land use
Both sites are located in the Southern Brigalow Belt (SBB), a biogeographic region of southeast and central Queensland (Figure 1). More than 50 % of clearing in Queensland has occurred in the SBB, with over 40 % occurring on freehold rather than leasehold land (Carter *et al*., 1998). Wholesale clearance of vegetation in the region has been extensive, due largely to the establishment of cattle pasture, the expansion of the wheat farming and, more recently, the formation of cotton fields. Partial clearance of vegetation has also been commonplace in the pastoral areas, whereby most of the woody vegetation has been removed or poisoned whilst the herbaceous plants have been retained. Due to the complex nature of land use and management practices, the landscape consists of a mosaic of cleared fields and forest and woodland communities in various stages of degradation and/or regeneration.

Most of the SBB receives an annual average rainfall of between 500-750 mm, with between 60 % and 70 % occurring in the summer months from October to March. A detailed description of climate regimes, soil types and plant community composition for both sub-regions is provided by Neldner (1984). Within the Injune and Talwood regions, the gently undulating country supports white cypress pine (*Callitris glaucophylla*) stands on the sandy hills. The more alluvial clays in the valleys are dominated by *Eucalyptus* and *Acacia* woodlands, comprising mainly Poplar Box (*E. populnea*), Silver-leaved Ironbark (*E. melanaphloia*) and Brigalow (*A. harpophylla*). Common understorey species include Wilga (*Geijera parviflora*) and Sandalwood Box (*Eremophila mitchelli*). At Talwood, *C. glaucophylla* is at the southern end of its range although Belah (*Casuarina cristata*) is common.

Case Study I: Injune

Field data collection and estimation of stand biomass
In July, 1997, field data were collected from 70 plots located in a range of disturbance and regeneration classes within the major woodland types. The selection of sample sites was based largely on existing vegetation mapping and descriptions (Neldner, 1984). Landsat TM and aerial photographs were also used to delineate broad forest types and growth stages and to assess structural homogeneity within the delineated stands.

At each of the 70 sample sites, data on individual species and diameter at 1.3 m were recorded using the prism sweep method (Beers and Miller, 1965; Dilworth and Bell, 1971). The method uses a critical angle from a central location to determine the inclusion or exclusion of individual trees within the sample. The critical angle is determined using wedge prisms of variable size. The GPS coordinates of the centre of each sweep (up to five per site) were also obtained with an accuracy of ± 10 metres.

For each plot, and using the allometric equations outlined above, the above ground and component (leaf, branch and trunk) was estimated. The subsequent scaling up of the measurements to a per hectare basis was based on the assumption that each tree selected within each plot had the same basal area and component biomass per unit area (Dilworth and Bell, 1971).

Acquisition and processing of remotely sensed data

For the study area, a 1995 Landsat TM channel 3 (red), 4 (near infrared) and 5 (mid infrared) image, acquired through the SLATS (Statewide Land Cover and Trees) project, was georeferenced to AMG coordinates using control points located with differential Global Positioning Systems (Collett *et al*., 1998; Kuhnell *et al*., 1998). Two overlapping JERS-1 SAR L channel HH scenes were acquired for August and September, 1994 and were each registered to the Landsat TM data using ground control points (GCPs) located in both images. The root mean square (r.m.s) errors for all transformations were within ± 1 pixel and the resampled pixel size for the JERS-1 SAR data was 25 m. The JERS-1 SAR data were calibrated to the backscatter coefficient (σ^o, m^2 m^{-2}), defined as the average radar cross section per unit area of the individual scattering elements. For display purposes, σ^o was expressed in decibels (dB). Speckle suppression within the JERS-1 SAR data was based on consecutive applications of a 3 x 3 Lee Sigma, a 5 x 5 Lee Sigma and a 5 x 5 Local Region Filter.

For each of the 70 sites and using the GPS coordinates for each of the sweep centres, a polygon was produced by connecting the centre coordinates and buffering the joining lines by 50 metres. The actual distance from the sweep centre of trees that are included for measurement depended upon the size of the prism used and the diameter of the individual stems. A distance of 50 metres ensured that the majority of trees fell within the polygon. As most sites were located well within particular woodland classes, there was a minimal chance of overlap between the created polygon and adjacent woodland classes. For each of the 70 polygons generated, the average (and standard deviation) JERS-1 SAR σ^o data values were extracted and related to the estimates of total and component biomass.

Results

The estimates of total above ground biomass ranged from 34 Mg ha^{-1} to 156 Mg ha^{-1}, with a mean biomass of 71.5 ± 29.9 Mg ha^{-1}. The larger estimates of biomass were associated with woodlands dominated by *C. glaucophylla*. As younger regrowth was not measured, the range of biomass from 0 to 34 Mg ha^{-1} was not represented, although a number of locations representing pasture were identified.

L HH values for woodland areas ranged from –7 to –15 dB. Where pasture sites were excluded, relationships between L HH and both leaf and branch biomass were barely significant with r^2 values of 0.09 in both cases (Table 1; Figure 1). By including pasture sites, the r^2 values defining the relationship between LHH and leaf and branch biomass increased to 0.26 and 0.53 respectively. The strongest relationship was observed between L HH and trunk biomass with r^2 values of 0.49 without pasture sites and 0.67 with pasture sites. Relationships between L HH and both stem (trunk and branch) and above ground (trunk, branch and leaf) were low. A strong relationship between L HH and above ground biomass was, however, observed (r^2 = 0.62) when pasture sites were included although saturation occurred at an above ground biomass of approximately 80 Mg ha^{-1}.

Table 1: Relationship between C, L and P band σ^o and component biomass, expressed as the correlation coefficient (r^2).

	SAR backscatter coefficient (dB)					
	PHH	PVV	PHV	PTP	LVV	CHH
Log Branch	0.85	0.80	0.83	0.84	0.83	0.64
Log Trunk	0.81	0.75	0.80	0.80	0.78	0.55
Log Leaf	0.36	0.33	0.35	0.36	0.41	0.46
Log Total	0.91	0.83	0.91	0.89	0.88	0.69

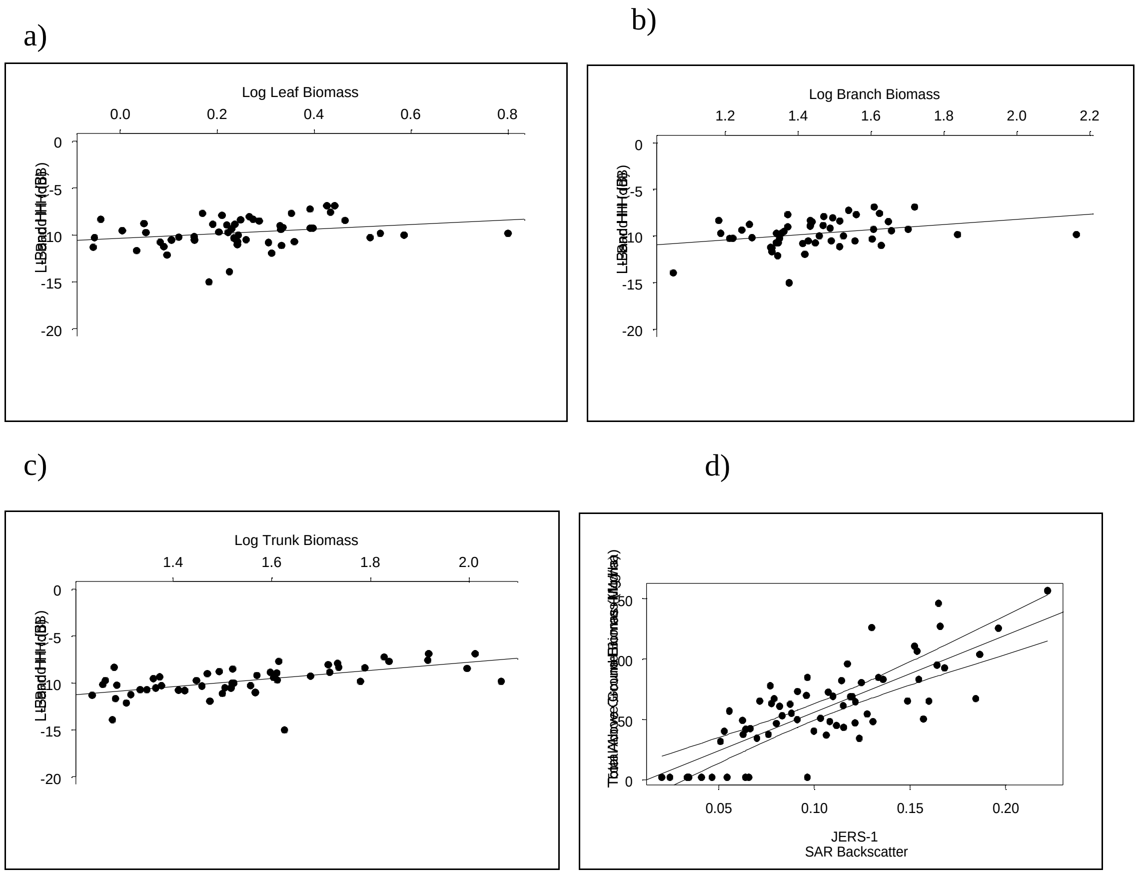

Figure 1: Relationships between JERS-1 SAR L band HH (σ^o dB) and (a) leaf biomass, (b) branch biomass, and (c) trunk biomass (without pasture sites). The relationship between L HH σ^o (m^2 m^{-2}) with total above ground biomass (including pasture sites) is shown in (d).

Case Study II: Talwood

Field data collection

In October, 1998, field data were collected from 29 fixed and variable area plots sited in woodlands at varying states of degradation and/or regeneration. The GPS coordinates of the centre of each sweep (up to five per site) were obtained with an accuracy of ± 10 metres. Fixed area plots were preferentially established in areas of younger regeneration. All trees < 3 cm in diameter were identified to species, counted and the height estimated.

Variable area plots, sampled using the prism wedge method, were established in the older regenerating woodlands and in intact, albeit degraded, woodlands where fixed area plots were considered to be overly time-consuming. Within these plots, all included trees were identified to species and the diameters at both 30 cm and 130 cm were recorded. For the understorey species *E. mitchelli* and *G. parviflora*, relationships were established between tree height and diameter (at 30 cm), as both parameters could be used as input to the equations of Harrington (1979). For all trees, the component biomass was estimated using the allometric equations outlined above and scaled up to a per hectare basis using standard procedures (Dilworth and Bell, 1971).

Acquisition and pre-processing of remotely sensed data

On the 12th November, 1996, AIRSAR data were acquired over a 10 x 60 km strip of the study area. In this overflight, AIRSAR topographic and interferometric SAR (TOPSAR) data were acquired for the generation of digital elevation models (DEMs). TOPSAR data are effectively polarimetric SAR with the horizontal components used to generate DEMs, leaving only single polarised C VV and L VV and polarimetric P band (HH, VV and HV) available for analysis.

Landsat TM data of the sub-region had been acquired previously for July, 1995, through the Statewide Landcover And Trees Study (SLATS; Queensland Department of Natural Resources, 1997) and were georeferenced to AMG coordinates. The AIRSAR image was then registered to the Landsat TM data using GCPs located in both images and resampled, using a nearest neighbour algorithm, to a pixel resolution of 12.5 metres. The AIRSAR C, L and P band intensity data were calibrated to the backscatter coefficient (σ^o, $m^2\ m^{-2}$). Speckle was removed from all SAR data by applying a 3 x 3 Lee Sigma, 5 x 5 Lee Sigma and a 5 x 5 Local Region Filter.

Results

For the Talwood site, the above ground biomass ranged from 22 Mg ha^{-1} (young regenerating woodlands) to 138 Mg ha^{-1} (mature *C. cristata* woodlands) with a mean biomass of 57 Mg ha^{-1}. Pasture sites were assumed to support no woody biomass and a leaf biomass of 1 Mg ha^{-1}.

Relationships between σ^o and component biomass were established by first extracting C VV, L VV and multipolarimetric P band data from a 3 x 3 pixel window centred on each plot location and second, establishing a linear regression between the log of σ^o (dB) and the log of component biomass. The r^2 values for the regression are shown in Table 2 whilst selected relationships between C VV σ^o and leaf biomass, L VV σ^o and branch biomass, and P band σ^o and both branch and trunk biomass are illustrated in Figure 2. The relationships established included data for low biomass pastures.

Table 2: Relationships (r^2) between L HH (dB) and the log of component biomass, without and with pasture sites ($p < 0.001$)

Biomass component	Without pasture (r^2)	With pasture (r^2)
leaf	0.09	0.26
branch	0.09	0.53
trunk	0.49	0.67
stem	0.35	0.61
ground biomass	0.34	0.62

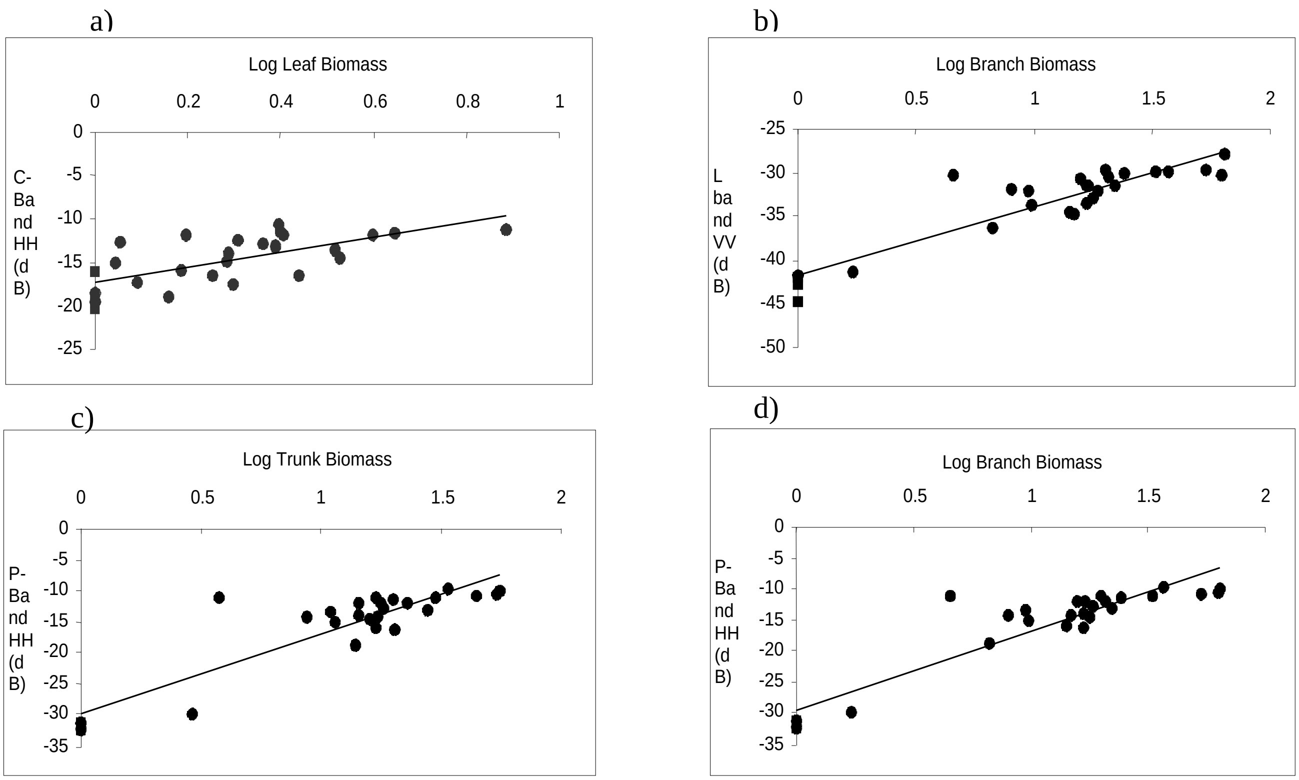

Figure 2: Relationships between a) C band HH and leaf biomass, b) L band VV and branch biomass, c) P band HH and trunk biomass and d) P band HH and branch biomass, Talwood study region. (Pasture sites ■ woodland plots ●)

The strongest relationship with leaf biomass was obtained using C HH data, with backscatter ranging from –12 to –20 dB. The relationship was similar, although slightly weaker, with L VV data (range –15 to –23 dB) and was least with P band data (all polarisations).

The relationship with branch biomass was relatively weak using C HH data but was of similar magnitude for both L VV and P band (all polarisations), with r^2 ranging from 0.80 to 0.85. C HH was least related to the trunk biomass whilst a strong relationship ($r^2 > 0.75$) was observed using both L VV and P band data.

Significant relationships at the 95 % confidence level between above ground biomass and σ^o (dB) at all wavebands and polarisations was observed, although the strongest relationship ($r^2 = 0.91$) was observed using P HV and HH data. However, the range of values for P HV was 27.4 (–18.5 to - 45.9 dB) which was far greater than the range for P HH and VV which was 22.57 (-9.56 to –32.1 dB) and –18.8 (-12.0 to –30.8) respectively. Saturation of the C, L and P band data occurred at approximately 20-30 Mg ha^{-1}, 60 Mg ha^{-1} and 80-100 Mg ha^{-1}.

Areal Estimates of Biomass

The classification of SAR data is often based on the information contained within individual pixels. Such classifications are unlikely to provide satisfactory results due to the large amount of image speckle that results from coherent processing. A more reliable classification can generally be obtained using statistics of clusters rather than individual pixels. Simple averaging with an *n x n* pixel window centered on pixels of known interests is an example of this approach.

The image segmentation algorithm developed by Dong *et al.* (1997) is a similar procedure and uses an Gaussian Markov Random Field (GMRF) model to separate the SAR image into disjointed regions (or segments) that correspond to objects, or parts of objects, which differ from their surroundings. The GMRF model is based on a normal or Gaussian distribution of the probability density function (pdf). SAR data are generally processed using multi-look averaging techniques to reduce the level of speckle and it has been shown that the pdf corresponds more to a K, or Gamma, distribution. However, according to the Central Limit Theorem in statistics, such distributions can be approximated to a Gaussian distribution with acceptable limits of error thereby allowing the application of the GMRF model. An advantage of the assumption of a Gaussian distribution is that mathematical descriptions for such distributions are more complete and the difference between segmentation results based on the Gaussian and Gamma distribution is small. Objects are segmented on the basis of the regional distribution of data values and their spatial relationships are described using first and second order statistics.

The GMRF model considers two regions to be separate if one or more of the following conditions is true:

- The first order statistics (i.e., the means for a single frequency image or the mean vectors for a multi-frequency image) differ.

- The second order statistics (ie., the variances for a single frequency images or the covariance matrices for a multi-frequency image) differ.

- The spatial textures differ.

Recent studies have shown that regions whose mean differences are as small as 0.5 dB (10%), and the ratios of the standard deviation to the mean are as high as 0.35, can be separated to an accuracy exceeding 95%. Subsequent classification of the segmented image is then based on a user-defined categorisation of information distributed across all segments. The segmentation procedure can be applied to single frequency, single polarisation or multi-frequency, multi-polarisation SAR images. Examples of these techniques are presented in Dong, *et al*, 1999.

Other Data

Under the Global Rainforest Mapping experiment (GRFM) being conducted as part of the JERS-1 Verification Program, large scale mosaics of Amazonia, Central Africa and South-East Asia using L-band imagery have been prepared under the auspices of the National Space Development Agency of Japan. A preliminary version of the North Australian portion of the South-East Asia mosaic has recently become available. The mosaic is made up of 50 satellite passes collected over Australia during 1996/97. Resampling and compression of the image data has resulted in 100 metre pixels with matching positional accuracy. Analysis of the radiometric variation between neighbouring swaths and thematic interpretation of the data have yet to be concluded. Very preliminary investigation of this data shows discernible patterns within the distribution of forests and woodlands of Northern Australia suggesting a potential for identifying regional land cover changes and for assessing environmental gradients within the vegetation biomes of Northern Australia.

Conclusions and future work

The case studies reported in this paper are unique in that, for the first time in Australia, the potential use of both single band and multi-band polarimetric SAR for quantifying the above ground and component biomass of woodlands has been demonstrated. Using JERS-1 SAR and AIRSAR data for woodland sites in south and central Queensland, the study has demonstrated that:

- JERS-1 L HH backscatter was related to the trunk biomass, but provided limited information on branch and leaf biomass.
- A strong relationship between L HH and above ground biomass was obtained when low biomass pasture sites were included.
- AIRSAR L VV and P band backscatter (all polarisations) from woodlands were related to both trunk and branch biomass, due largely to the similarity in the size distribution and orientation of these components.
- AIRSAR C band backscatter may be related to leaf biomass, although time and site specific measurements of leaf biomass, that were coincident with a SAR overpass, would be required to confirm this relationship.
- Saturation of C, L and P band data occurred at approximately 20-30 Mg ha^{-1}, 60 Mg ha^{-1} and 80-100 Mg ha^{-1}.

The biomass of woodlands in Australia may exceed 150 Mg ha^{-1} and the establishment of relationships between different components of the biomass and C, L and P band data may be necessary to estimate biomass with confidence. However, as much of the vegetation cleared is of low biomass (Burrows, 1990), the use of L band data alone may be sufficient, although other polarisations other than L HH (i.e., L HV) may be required.

Further research should be aimed at obtaining a better understanding the interaction of microwaves of different length and polarisation with components of vegetation canopies, determining the influence of the ground layer and assessing the consistency of relationships between and within sites and using different airborne and spaceborne sensors. The synergistic use of optical data for estimating leaf biomass should also be investigated.

In mid-2000, AIRSAR POLSAR and TOPSAR data will again be acquired at sites across Australia and, under an Australian Research Council (ARC) grant, site and time specific estimates of vegetation biomass will be obtained for Injune. This study will therefore allow the use of polarimetric C, L and P band data and also SAR interferometry for quantifying both the biomass and structure of the biomass of Australia's woodlands to be further investigated From the early 2000s, also, the satellite borne ENVISAT ASAR, LightSAR and JERS-2 SAR are scheduled for launch and will be acquiring polarimetric data at C and L band. The ARC study will therefore provide some insight into the most suitable sensors for spatially estimating biomass on a regional basis.

In closing, it is hoped that the study encourages State and Federal agencies to re-examine the potential of SAR data for rangeland assessment and management and for better understanding the carbon dynamics of Australia's woodlands.

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Workshop Paper 8

The Vertical Structure of Vegetated Surfaces from Interferometric and Polarimetric Radar Data

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Abstract

This paper casts microwave remote sensing of the vertical structure of vegetated land surfaces as the quantitative estimation of vegetation parameters using physical models. These parameters can be used to calculate biomass density and leaf area density. In layered vegetation, integrating biomass density leads to biomass, which can be used to quantify the amount of carbon currently stored in vegetation. Leaf area sets the upper limits to gross carbon uptake by vegetation from the atmosphere, and therefore it is a key variable in ecosystem process models that are being applied from landscapes to the globe. Biomass and leaf area density can be used to monitor changes in land-use and land cover, and to improve ecosystem- process modeling of spatial and temporal variation in net carbon uptake by terrestrial ecosystems. These parameters are therefore important to quantifying sources and sinks of atmospheric CO_2, consistent with the Kyoto Protocol. Making correspondences between radar-derived scatterer number density and biomass and leaf area density leads to a method for obtaining biomass and leaf area density. This method also relies on hyperspectral reflectance to obtain leaf area index and thereby convert relative number densities into leaf area densities. The parameter-estimation approach used to estimate vertical structure information from interferometry and polarimetry is equivalent to physical-model based data fusion. A calculation based on physical-model, parameter-estimation considerations suggests that radar power, interferometry, and polarimetry may all contribute to biomass determination. Vegetation canopy LIDAR should also be combined with microwave and hyperspectral techniques in a unified, physical-model approach. Quantitative physical models, expressing each data-type in terms of vegetation structural parameters, will lead to error budgets for each technique, separately and in concert with combinations of others. These physical models and error analyses are a prerequisite for their effective combination to best meet the Kyoto-Protocol monitoring goals.

I. Biomass and Biomass Density from Interferometry and Polarimetry

Vegetated surfaces can be described by parameters, such as tree height, vegetation density, and ground reflection coefficient (which depends on surface roughness and moisture). Schematically, parameter estimation can be represented as

$$\vec{P} = M^{-1}\vec{O} \qquad (1)$$

where $\vec{P}$ is a vector of parameters to be estimated from a vector of observations $\vec{O}$. The physical model M expresses the observations in terms of the parameters. For radar interferometry and polarimetry, there are at best a few tens of observations constituting $\vec{O}$, which motivates considering simple models M, which depend on a very few parameters. In order to solve (1), the derivatives of the elements of $\vec{O}$ with respect to the parameters in $\vec{P}$ must be sufficiently large and diverse, and the dimension of $\vec{O}$ $\geq$ the dimension of $\vec{P}$ Biomass and biomass density, which can be used to quantify the amount of carbon currently stored in vegetation, are functions of scatterer-number-density parameters that can be derived from interferometry and polarimetry as follows:

$$Biomass = \int dz \, \text{Biomass density}(z) = \int dz \, \rho_0(z) m(z) \qquad (2)$$

where $\rho_0(z)$, the scatterer number density at z, is proportional to the extinction coefficient which is estimated from radar interferometry and polarimetry. In (2), $m(z)$ is the average biomass per scatterer at altitude z in the vegetation, and must be obtained from regression to field-measured biomass or allometrics. In a stepwise layer model, ρ_0 is also related to layer dimensions and backscattering power ratios, all of which can be estimated from interferometry and polarimetry. An example of a 2-layer profile model parameter estimation scenario from which biomass could be derived is [Treuhaft et al., 1996; Treuhaft and Siqueira, in press]

$$\begin{pmatrix} \text{Forest height} \\ \text{Canopy extinction} \\ \text{Subcanopy height} \\ \text{Subcanopy extinction} \\ \text{Canopy / subcanopy backscat} \\ \text{Canopy / subcanopy backscat} \\ \text{Real ground dielectric} \\ \text{Underlying topgraphy} \end{pmatrix} = \mathrm{M}^{-1} \begin{pmatrix} \text{Int.Ampl.} - \text{8km} \\ \text{Int.Phase} - \text{8km} \\ \text{Int.Ampl.} - \text{8km} - \text{ping} \\ \text{Int.Phase} - \text{8km} - \text{ping} \\ \text{Int.Ampl.} - \text{4km} \\ \text{Int.Phase} - \text{4km} \\ \text{Int.Ampl.} - \text{4km} - \text{ping} \\ \text{Int.Ampl.} - \text{4km} - \text{ping} \\ \text{Int.Ampl.} - \text{2km} \\ \text{Int.Phase} - \text{2km} \\ \text{Int.Ampl.} - \text{2km} - \text{ping} \\ \text{Int.Phase} - \text{2km} - \text{ping} \\ \text{HHHH/ VVVVRatio} \end{pmatrix} \qquad (3)$$

Biomass density can potentially be derived from the first five parameters above, which determine the two-layer number density and dimensions (through "forest height" and "subcanopy height"). In currently-envisioned approaches, the Canopy/subcanopy backscat parameter gives the ratio of number densities between the canopy and subcanopy layer. If $m(z) = m$ is taken to be constant, and derived from regression relations or allometrics, the two-layer biomass density can be obtained from the number density ratio. The observations on the right side of (3) are interferometric amplitudes and phases at 8-, 4-, and 2-km aircraft altitudes, in single-transmit and pingpong modes. The advent of polarimetric interferometry may obviate the need for many altitudes (or baselines). The inverse model M^{-1} contains a physical model relating the parameters to the observations and also the inverse of the observation error covariance matrix [Hamilton, 1964].

In order to estimate the parameters on the left side of (3) from the observations on the right, those observations must be sensitive to the parameters. The changes induced in interferometry and polarimetry by changes in, for example, forest height or extinction coefficient, are detailed in Treuhaft and Siqueira, in press. In general, radar interferometry is sensitive to the location and distribution of scatterers, while polarimetry is sensitive to their shape and orientation. If oriented objects occupy characteristic locations in a vegetation canopy (e.g. the oriented ground is at the bottom of the canopy) then polarimetry also contains structure information.

II. Leaf Area Density from Interferometry, Polarimetry, and Hyperspectral Reflectance

Leaf area index (LAI) and leaf area density (LAD) are needed to improve ecosystem-process modeling of spatial and temporal variation in net carbon uptake by terrestrial ecosystems. Analogous to the biomass expression in terms of the scatterer number density (2), LAD and LAI can be related to the number density from interferometry and polarimetry as

$$LAI = \int dz\, \mathrm{LAD}(z) = \int dz\, \rho_0(z)\, l(z) \tag{4}$$

where $l(z)$ is a profile converting microwave scatterer number density to LAD and is defined by (4), and, again, $\rho_0(z)$ comes from the microwave measurements via the extinction coefficient and power ratio parameters. If $l(z) = l$ is taken to be constant, and hyperspectral data are used to establish LAI [Asner et al., 1998], then both LAI and LAD can be determined. A 2-layer model as in (3) will determine a 2-layer LAD. This method is now being demonstrated with AIRSAR polarimetric interferometry and AVIRIS hyperspectral data over Central Oregon.

III. Derivative Magnitude and Diversity

Equation (3) suggests that parameter estimation is an expression of quantitative data fusion. The criteria for whether a collection of data types provides adequate parameter estimates are schematically illustrated in Figure 1 below:

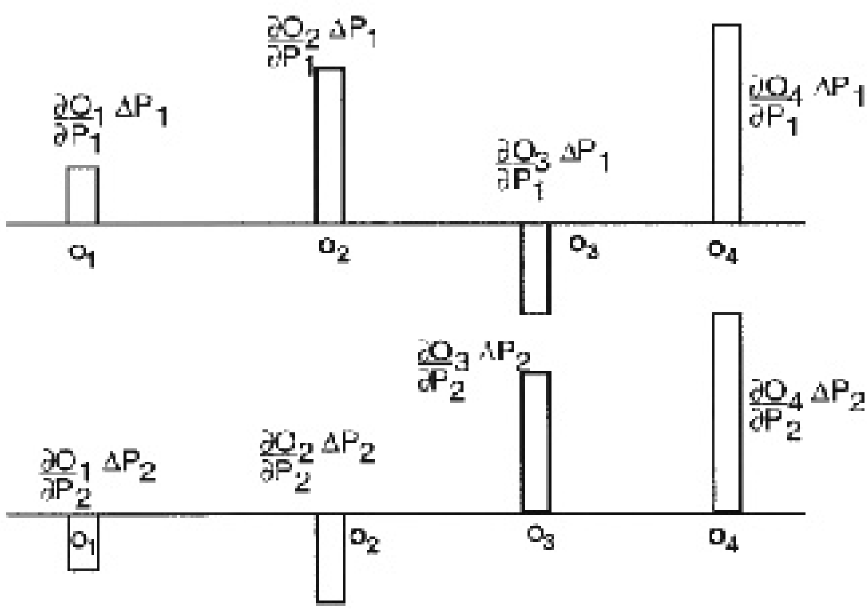

Figure 1: Schematic representation of the response of four observations, $O_{1\rightarrow 4}$ to shifts in two parameters $P_{1\rightarrow 2}$

Parameters in Figure 1 could be, for example, forest height, or the ratio of the scatterer number density of one layer to that of another, or leaf area index. Observations could be interferometric phase or amplitude, or the power in a hyperspectral channel. For a shift in a given parameter, say P_1, to be adequately estimated, it must have a "big enough" effect on some of the observations. Quantitatively, the shift in observation 1 due to a shift ΔP_1 in parameter 1, for example, must be bigger than the observation noise in O_1:

$$\Delta P_1 \frac{\partial O_1}{\partial P_1} > \text{ Observation Error in } O_1 \tag{5}$$

The first criterion for accurate parameter estimation, represented by (5), is "derivative magnitude." For a parameter estimation scenario to produce useful results, (5) must be true for a sufficient number of combinations of parameters and observations. From the Figure, the pattern of observation shifts induced by P_1 in the top line of the Figure must be different from that induced by P_2 in the bottom line, or their effects will be indistinguishable and ΔP_1 and ΔP_2 will not be simultaneously well-determined. The second criterion is therefore "derivative diversity:" The derivatives of observations with respect to parameters must be sufficiently diverse to separate the effects of each parameter uniquely. In least squares formulations, the degree to which these two criteria have been met is reflected in the parameter estimate error bars.

IV. Parameter Estimation as Data Fusion: Biomass from Power' Interferometry, and Polarimetry

As an example of how parameter-estimation considerations determine the optimal combination of techniques, Figure 2 illustrates biomass determination from radar power, interferometry, and polarimetry. The calculated shift in the total power, interferometric amplitude, and HHHH/VVVV ratio, in units of the observation error, is shown versus extinction coefficient, which is proportional to scatterer number density ρ_0 and therefore to biomass[1] .

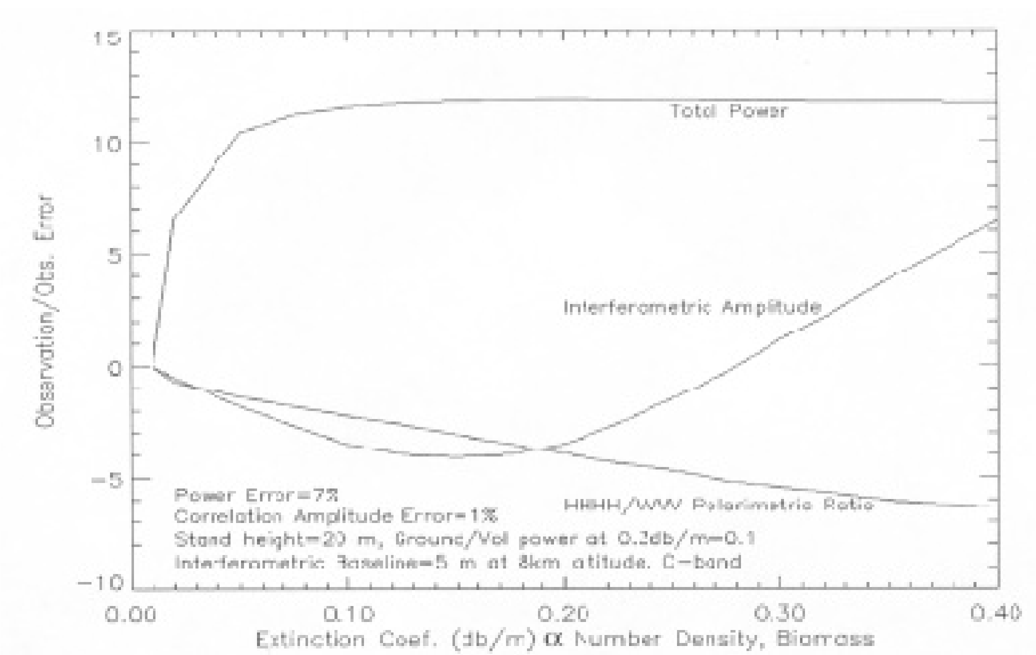

Figure 2: Calculation of observation shift in units of observation error, as a function of extinction coefficient, which is proportional to scatterer number density and biomass.

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[1] Figure 2 assumes that the power, interferometry, and polarimetry measurements are made at the same frequency. If they are not, then the correspondence of biomass with extinction coefficient will be different for each frequency. The general conclusion about the applicability of interferometry to biomass determination still holds.

Note that for low biomass, the derivative of power with respect to biomass $(\partial O/ \partial P)$ divided by the observation error is much larger than either interferometry or polarimetry. The calculation is for a randomly oriented volume over a specularly reflecting surface. The errors are based on Gaussian-distributed electric fields' with about 200 looks. When the biomass increases, the frequently-observed [e.g. Waring et al., 1995] "saturation" of power occurs. For higher biomass, the change of power induced by a change in biomass of, say 25%, is not greater than the typical observational error. Conversely, the interferometric amplitude derivative per observational error is small for small biomass values, but increases for higher biomass values. The HHHH/VVVV polarimetric is somewhere between the power and interferometric amplitude. This calculation suggests that in a parameter-estimation scenario in which all three observation types were used, the power would determine the biomass parameter at low values and the interferometric amplitude would determine at high biomass values, with some contribution from the polarimetric ratio throughout.

V. Data Fusion: Power, Interferometry, Polarimetry, Hyperspectral, and Vegetation Canopy LIDAR

Ultimately, all of the above data types could be useful in a combined parameter estimation

$$\begin{pmatrix} \text{Biomass Density} \\ \text{LAD} \end{pmatrix} = M^{-1} \begin{pmatrix} \text{Power} \\ \text{Interferometry} \\ \text{Polarimetry} \\ \text{Polarimetric Int} \\ \text{Hyperspectral Optical} \\ \text{Vegetation Can LIDAR} \end{pmatrix} \tag{6}$$

Each has an appreciable observation derivative with respect to parameters such as vegetation height and density, which can be used to determine biomass density and LAD. They also have considerable derivative diversity. For example, interferometry responds to changes in the distribution of scatterer microwave characteristics, while vegetation canopy LIDAR (VCL} responds to the distribution of scatterer optical, geometric characteristics. While interferometry may be unable to estimate the properties of as many vegetation layers as VCL, VCL has errors which depend on geometric tree properties [Dubayah, 1999] which do not affect radar in the same way. Hyperspectral reflectance responds to structure and total scatterer content changes because they affect the strength of absorption features at different wavelengths. A quantitative parameter-estimation procedure, incorporating physical models describing all of these observation types, would take full advantage of the strengths of each of these techniques.

Summary

Biomass density and leaf area density are related to the layer-relative number density and canopy-dimension (e.g. height) parameters, which are estimated from interferometry and polarimetry. Parameter estimation scenarios might call for multilatitude interferometry and polarimetry, and/or polarimetric interferometry. Adding hyperspectral optical data allows for leaf area density estimation. Combining multilatitude interferometry and polarimetry with parameter estimation is data fusion. An example calculation further combining power, interferometry, and polarimetry to determine biomass shows that interferometry may be useful at high biomass values where power is no longer sensitive. Physical-model-based parameter estimation combining interferometry, polarimetry, hyperspectral optical, and LIDAR data will produce the most accurate data fusion for biomass and other profile

parameters needed for monitoring according to the Kyoto Protocol Quantitative models and error analyses are required for each technique in order to combine with parameter estimation.

Acknowledgment

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Workshop Paper 9

Biomass Retrieval in Very Dense Forest using low VHF-band SAR

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ABSTRACT

This paper discusses biomass retrieval in forest stands which are inaccessible using microwave SAR. The work is based on data collected by the airborne CARABAS-II SAR which operates in the 20-90 MHz band. Analysis of CARABAS-II data show a radar response which increases linearly with biomass without saturation even for the highest biomass of 375 tons/ha. Recently, work has also been performed on scattering modelling as well as stem volume estimation in coniferous boreal forest. The results are quite good with an accuracy of the same order as better subjective field inventory, i.e. 10-20%. We propose that a low VHF-band SAR system can be designed to enable large-scale biomass monitoring without the microwave saturation problem. This system cannot be satellite-based due to the deleterious effect of the ionosphere on low VHF-band signals. Instead, our proposal is based on a stratospheric platform, i.e. either a manned/unmanned aircraft or an airship. The latter is the platform of preference for several reasons. A major advantage is the large volume available for the antenna system as well as the lack of a metal structure causing electromagnetic coupling with the antenna. The airship is based on "green" technology, i.e. propelled purely by solar energy and does not, unlike satellites, cause atmospheric pollution during launch. Recent feasibility studies shows that such a stratospheric airship can be available by year 2004.

INTRODUCTION

In recent years a new class of ultra-wideband synthetic-aperture radar (SAR) systems operating in the low-end of the VHF-band has been developed by the Defence Research Establishment (FOA) in Sweden. The most recent is the airborne CARABAS-II SAR [1] which operates in the frequency band 20-90 MHz and has an azimuth beamwidth of about 90^{o}. The system provides radar imagery with a spatial resolution of 2.5 x 2.5 m^2, i.e. about half a wavelength at the centre frequency, which is close to the absolute wavelength limit [2,3]. The development of these systems have mainly been motivated by the need to penetrate dense foliage. The measured two-way attenuation through the canopy is in fact only a few dB even for a very dense forest, i.e. it acts essentially as a "window" for the propagating waves. One important application of the technology is parameter-retrieval in dense forests, in particular measuring forest stem volume (m^3/ha) [4,5] which is closely related to above-ground dry biomass. The basic idea is that the radar scattering amplitude is proportional to the trunk volume of a single tree, and therefore the stem volume is linearly related to the averaged scattering amplitude in a given area. The underlying assumption is that the trunk acts like a Rayleigh scatterer, which requires that the trunk radius is much smaller than the wavelength. This indicates that the wavelength needs to be greater than about 3 m for a trunk radius of 0.3 m, i.e. the frequency needs to be lower than 100 MHz.

The paper reviews experimental and theoretical work which show that low VHF-band SAR is a proven technology for biomass retrieval in dense forests. It also outlines a possible large-scale monitoring system based on a stratospheric airship as payload carrier.

CARABAS-II LOW-VHF-BAND SAR

CARABAS-II [1] is an airborne SAR which is designed to operate over an altitude range from 3 to 10 km. It transmits a stepped-frequency chirp waveform covering 20-90 MHz. The instantaneous bandwidth is only 2 MHz which facilitates an ultra-linear receiver design with a spurious-free dynamic range of 88 dB. This is important to accommodate very strong signals due to the nadir echo as well as radio-frequency interference (RFI). The latter frequently occurs in the band due to short-wave communication, low-VHF TV, FM-radio, and numerous mobile communication channels.

The antenna system consists of two push-booms, each containing a biconical wideband antenna of 5-m length. These provide an essentially omni-directional gain pattern and a wide azimuth beamwidth close to 90^{o}. During transmission, a single beam is steered to either side of the aircraft by time-delaying, whereas the received signal from each antenna is digitized in separate receiver channels. Data are stored on tape and image formation is performed off line. The signal processing requires accurate information of the flight track which is measured using phase-differential GPS. The latter results in a positional accuracy of about 0.5 m with an update rate of 1 Hz.

The basic signal processing steps [6] are illustrated in Figure 2. A block of radar data is read from tape and decoded to a burst of pulse echoes. Interpolation in "slow time" is used to match the pulse echoes to a common time base for all frequency sub-bands. Each sub-band pulse echo is then compressed by matched filtering using a reference function measured during system calibration. In practise, this step is implemented as a multiplication in the frequency domain after a range FFT. The full bandwidth spectrum corresponding to a particular slow time is reconstructed by frequency shifting the individual pulse spectra in accordance with their centre frequencies and summed together. The range-compressed data includes a significant amount of RFI which is suppressed before azimuth compression.

An inverse FFT brings data back to "fast time" domain and azimuth compression is performed using backprojection inversion [3]. The main advantage of the latter is that a well-focused image can be achieved irrespective of the flight track geometry as long as accurate antenna positioning data and a digital elevation model of the ground is available. The main disadvantage is the heavy computational cost, but fast backprojection algorithms are also used which approach FFT-performance.

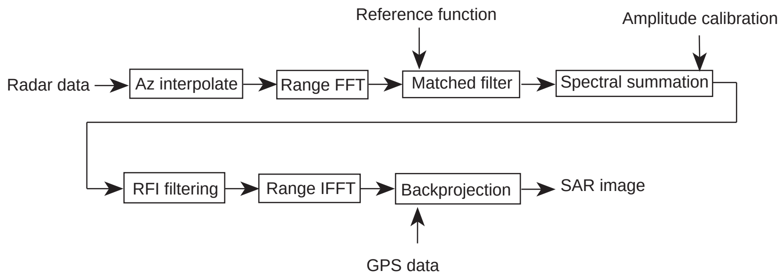

Figure 1. SAR processing steps for CARABAS-II

FOREST PHENOMENOLOGY AT P- VS. LOW VHF-BAND

A number of investigations have been conducted on biomass retrieval using P-band SAR [7, 8, 9]. The conclusion from these experiments is that the radar reponse is sensitive to biomass and generally increases up to a point of saturation. It is agreed that the latter is in the range 100-200 tons/ha. The same principle behaviour is found for different forest types, i.e. coniferous forests as well as tropical rain forest. It is not surprising that a saturation level is reached for different forest types since it is related to strong attenuation and scattering from the basic structural elements. A summary of published results is shown in Figure 2 for HH- and HV-polarisation. VV is not shown in the figure but is similar in behaviour to HH. We see that the responses curve indeed become near-horisontal at about 100-200 tons/ha. The more optimistic saturation levels assume more averaging (coarser spatial resolution) and *a priori* information.

By moving downwards to the low VHF-band where the CARABAS-II operates, the wavelength is increases by about a factor 10 (5-20). We expect that the response curve scales with frequency, i.e. the saturation limit should be close to 1000 tons/ha. Measurements using CARABAS have been performed for mainly coniferous forest in Sweden, Finland, and France. Results at HH-polarisation also show a linear response and no signs of saturation even for the highest biomass of 350 tons/ha. No results are available for either VV- or HV-polarisation due to their unavailability on CARABAS-II. A summary of the response curve for low VHF-band is also included in Figure 2. The included data points correspond to results recently published [5], which are considered to have the best available ground truth (about 10% accuracy).

It has been noted that the biomass response at both P- and low VHF-band is sensitive to moisture conditions as well as ground slope. The effect of the latter is more significant and results in ambiguous biomass retrieval. The reason for this effect is that the principle backscatter mechanism, particularly at HH-polarisation, is often the dihedral reflection between ground and trunk. The dihedral geometry is "broken" by a sloping ground surface since the trunk most often grows vertically. We expect this effect to be more serious at P-band than at low VHF-band because the resulting linear phase error for a given ground slope condition is proportional to frequency. Note also that the phase error grows with larger trees for the same reason. Observation of this effects is not well documented but the effect seems to be serious already for a 1^o slope at P-band and a 4^o slope for low VHF-band [5]. The ground slope effects also depends on aspect angle and the largest backscatter reduction is observed when the plane of incidence includes the ground normal vector.

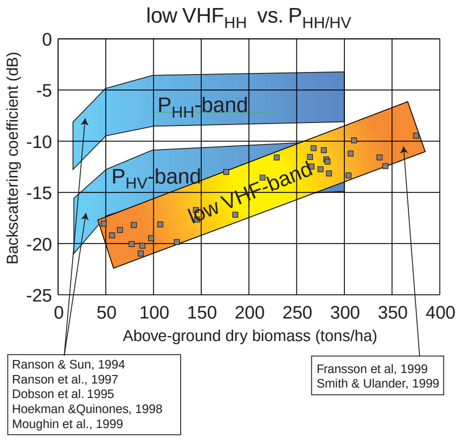

Figure 2. Comparison between biomass response at P- and low VHF-band.

BACKSCATTER MODEL AND STEM VOLUME RETRIEVAL IN CONIFEROUS FOREST

In the low VHF-band only the largest structures in the forest contribute significantly to the scattering. In this section, we describe a scattering model useful for coniferous boreal forest dominated by scattering from the trunk on horizontal ground [4]. The contributing components are the direct trunk backscatter, the trunk-ground and ground-trunk dihedral scattering, and the ground-trunk-ground scattering. As shown in [10], a reasonable model for combining the scattering from these mechanisms at low frequencies is to ignore near-field interactions and simply add them in amplitude with corresponding phase terms. It is also shown in [4] that the trunk-ground and ground-trunk mechanisms normally dominate except for short trees. With this assumption and the Rayleigh-Gans approximation [11], we can determine the scattering amplitude for a thin cylinder on horisontal ground according to

$$S_{HH} \approx -R_F \cdot \frac{k^2(\varepsilon_r - 1)}{\pi(\varepsilon_r + 1)} V \tag{1}$$

The following conditions must be fulfilled for the Rayleigh-Gans approximation to be valid

$$ka << 1 \quad \text{and} \quad l/a > 20\sqrt{\varepsilon_r} \tag{2}$$

where *a* and *l* is the cylinder radius and length, respectively, and ε_r is the relative permittivity of the trunk [12]. For a forest stand two additional factors enter the model, i.e. the attenuation *L* and interference caused by the neighbouring trees. The importance of the interference depends on the number of trees within a given resolution cell of the SAR. In managed boreal forests the trees are planted very close together, but thinning practices generally result in the spacing increasing as the forests mature. In [5] measurements of spruce forests in southern Sweden indicated that the spacing between trees is larger than the resolution of CARABAS for stem volumes above about 200 m^3/ha. In this situation the effect of interference between trees within one resolution cell is negligible, so that an incoherent summation of the scattering from the N trees in a given area, A, is appropriate, giving the normalised scattering amplitude of the forest

$$s^o \approx \frac{2|R_F(\theta)|k^2}{\sqrt{\pi}L}\left|\frac{(\varepsilon_r - 1)}{(\varepsilon_r + 1)}\right|\frac{1}{A}\sum_{i=1}^{N} V_i = \frac{2|R_F(\theta)|k^2}{\sqrt{\pi}L}\left|\frac{(\varepsilon_r - 1)}{(\varepsilon_r + 1)}\right| v \tag{3}$$

i.e. a linear relationship between s^o and the forest stem volume v.

Based on the linear relationship (3) it is possible to retrieve stem volume from low VHF-band SAR images. The main test site used to statistically evaluate this method is Tönnersjöheden forestry park, which is situated in southwest Sweden [5]. The prevailing tree species is Norway spruce which covers 75% of the park. The field inventory used for comparison is based on objective measurements with an acccuracy of 10% for stem volume. Thirty stands were selected which satisfied the following criteria: more than 70% Norway spruce, relatively flat terrain (< 4^o ground slope), and stand area > 2 ha. The forest stand map and the SAR images were geocoded and a regression analysis was performed based on the linear model (3). The resulting RMS error was 66 m^3/ha for the full data set which covered stem volumes in the range 0-625 m^3/ha. The resulting stem volume map is shown in Figure 4, and the field inventory in Figure 3 [13].

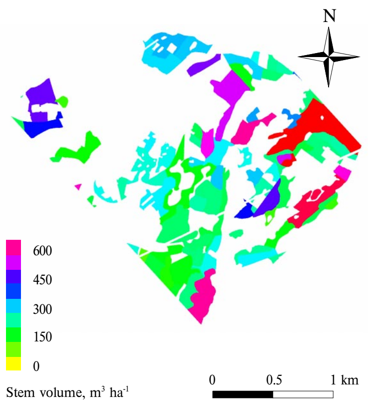

Figure 3 Stand-wise field inventory [13]

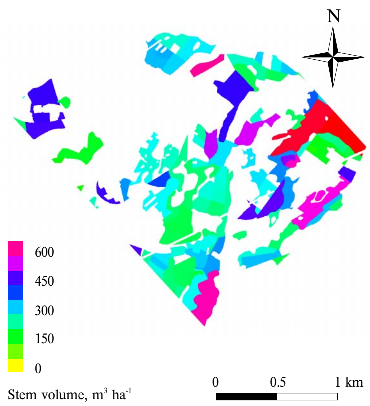

Figure 4 Stem volume retrieved from CARABAS-II [13]

LARGE-SCALE FOREST MONTORING SYSTEM

We conclude that frequencies below 100 MHz are quite necessary for biomass retrieval in dense forests. It is therefore of interest to discuss a system which would enable large-scale biomass mapping on a routine basis. We will in this section discuss a few design trade-offs for such a system, including platform selection, frequency allocation and data rate requirements.

First it should be noted that it is not possible to operate a low VHF-band SAR for Earth Observation from space. The reason is the deleterious effect of ionospheric distortions at these frequencies. Secondly it should be noted that there is presently no frequency allocation for SAR below 1 GHz. All experiments with CARABAS-II and other low-frequency systems have therefore been conducted on the basis of experimental day-to-day transmission licences. It is desirable to obtain at least a narrow-band frequency allocation for SAR mapping although ultra-wideband SAR may still be used under experimental licence. For the latter to be feasible, special waveform designs with frequency notching has proven useful in CARABAS-II. A tentative frequency selection seems to be 4 MHz bandwidth within the 30-47 MHz band for the large-scale mapping mode, whereas the ultra-wideband mode should operate in the 30-80 MHz band. The reason for staying below 47 MHz is the importance for frequency allocation of staying outside the 47-68 MHz TV-band, whereas frequencies below 30 MHz are partially affected by short-wave communication.

The present CARABAS-II platform is a small business jet (Rockwell Sabreliner). It is not suitable for large-scale mapping mainly due to its limited endurance of 2.5 hours. Based on a swath width of 25 km and a flight speed of 120 m/s, it is possible to cover up to about 0.01 million km^2 in one mission, including take-off and landing. This corresponds to a 100 x 100 km^2 large area but is only about 0.1% of a country like Canada or Brazil. For large-scale mapping it is therefore necessary to integrate the radar in a platform with significantly larger areal coverage, i.e. larger swath and endurance. The preferred choice is a platform which operates at an altitude of 15-25 km which would enable swath widths of the order of 45-75 km. Options for such a platform includes both manned and unmanned aircraft, as well as air ships.

One new and interesting option for a large-scale monitoring system is to capitalise on recent advances in airship design. Proposed already in the 1960's by the US Navy, new developments in solar and fuel cell technology has made "green" stratospheric airships feasible. These are designed to operate in the wind minimum at 21 km altitude and only use solar energy as power source. A recent feasibility design funded by ESA has shown that such an air ship can be available by 2004 [14]. During day time, solar cells on top of the flexible balloon provide excess energy which are stored as oxygen and hydrogen for later use during night-time in fuel cells. The airship is propelled using a 25 kW DC-motor with a nominal ground speed of 40 m/s. For station-keeping this means it can withstand 80 knot winds. The proposed air ship has a length of 200 m, a diameter of 50 m, and can carry a payload up to 1 ton.

The main advantage of the airship platform for low VHF-band SAR is that it operates at stratospheric altitudes, i.e. maximum altitude below the ionosphere. A second advantage is the large volume available for the antenna structure, which is important for several reasons. The present CARABAS-II antenna system has a rather poor isolation between right- and left-hand sides of the flight track which affects image quality in a negative sense. A large antenna enables improved backlobe suppression and therefore also right/left isolation. Another possibility that opens up is the design of a fully polarimetric antenna, e.g. using crossed dipoles. Additional benefits of a large antenna is increased gain and thus less transmit power requirement and narrower beam for interference suppression. Finally, an important advantage of an airship is that it lacks a metal structure which otherwise causes electromagnetic coupling to the antenna.

The SAR system itself can be designed using similar principles as CARABAS-II. Since the airship speed is lower than the typical aircraft this relaxes data rate requirements, both in terms of the communication link as well as processing requirements. A tentative design is shown in Table 1 based on a large-scale monitoring mode with 50-m resolution, as well as a high-resolution mode with 3-m resolution. The data rate estimates are based on a single antenna channel, a nominal ground speed of 40 m/s, and 12 bit data. The latter can probably be relaxed by using block-adaptive quantisation techniques. For a 50 km swath, the data rate of the large-scale monitoring mode is only about 1 Mbit/s which enables use of low-cost communication technology using geo-stationary satellites.

The proposed system is illustrated in Figures 5 and 6. It generates three 8-look image strips corresponding to three squinted beams (fore/middle/aft) of about 30^o within a 90^o sector. This provides speckle-reduced imagery which are used for biomass retrieval, including topographic corrections based on the different squint angles. The coherent integration angle is about 4^o which gives a cross-range resolution of about 50 m. Motion measurement is based on wide-area DGPS technology which is available today. The high-resolution imaging mode provide a single imaged swath with a 90^o integration angle. This mode is similar to the standard CARABAS-II imaging mode and gives a data rate of 20 Mbit/s. The high-resolution mode is particularly interesting for detailed change detection studies. Change detection is considered a very promising technique for this system and has already a proven capability for detecting man-made objects under foliage. Single large tree or small tree cluster should be possible to detect with this technique.

Table 1. Radar parameters for low VHF-band HALE-SAR

Mode	Large-scale mapping	High-resolution imaging
Frequency band	42-46 MHz	30-80 MHz
Resolution	50 m x 50 m	3 m x 3 m
Swath	50 km	50 km
Processed beams	Three 30^o "beams" (fore/center/aft)	One 90^o "beam"
Number of looks	Eight look images	One look image
Data rate	1 Mbit/s	20 Mbit/s

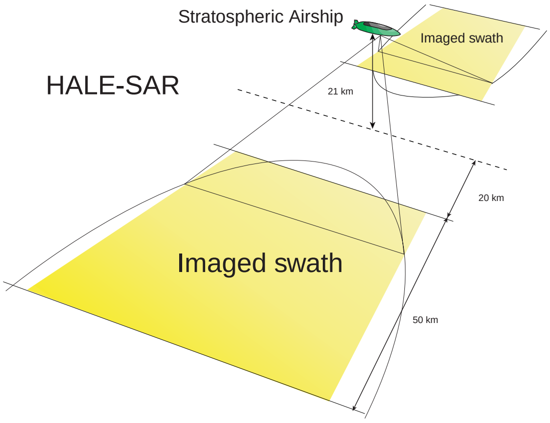

Figure 5 HALE-SAR imaging geometry

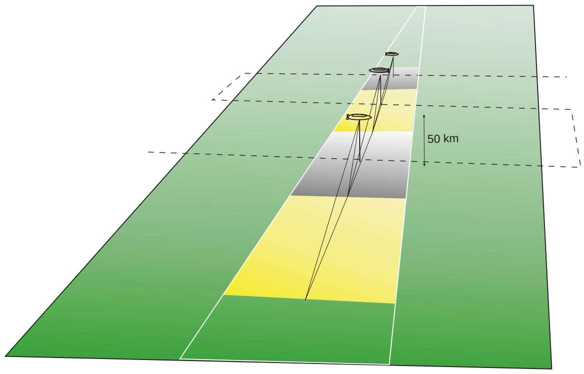

Figure 6 HALE-SAR concept of operations

CONCLUSIONS

This paper has discussed biomass retrieval in forest stands which are inaccessible using traditional microwave radar (see also [15, 16]). The work is based on data collected by the airborne CARABAS-II SAR which operates in the 20-90 MHz band. Analysis of CARABAS-II data show a radar response which increases linearly with biomass without saturation even for the highest biomass of 375 tons/ha. Evaluation of stem volume estimation in coniferous boreal forest also show good results with an accuracy of 10-20%.

We propose that a low VHF-band SAR system can be designed to enable large-scale biomass monitoring without the saturation problem. This system is based on a stratospheric platform, i.e. either a manned/unmanned aircraft or an airship. The latter is the platform of preference for several reasons. A major advantage is the large volume available for the antenna system as well as the lack of a metal structure causing electromagnetic coupling with the antenna. The airship is also based on "green" technology, i.e. propelled purely by solar energy and does not, unlike satellites, cause atmospheric pollution during launch. During day time, solar cells on top of the flexible balloon provide excess energy which are stored as oxygen and hydrogen for later use during night-time in fuel cells. The airship is propelled using electrical motors which give a nominal ground speed of 40 m/s. It has a length of 200 m, a diameter of 50 m, and can carry a payload up to 1 ton. Recent feasibility studies shows that such a stratospheric airship can be available by year 2004.

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Workshop Paper 10

Challenges Associated with Spaceborne Low-Frequency For Achieving The Goals Of The Kyoto Protocol

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The following paper describes the technological challenges faced for putting a low-frequency SAR in space whose mission will be to detect the presence of forest cover and to estimate the quantity of above ground biomass. After discussing the issues involved, this paper will present a minimum mission design (absolute bare bones essentials for putting a P-band SAR into space) and a baseline design (a basic P-band SAR with additional instrumentation and modes of operation) for achieving these goals.

Microwave observations, and more specifically synthetic aperture radar (SAR) have a strong potential for making global observations of forests because of the technology's sensitivity to above ground landcover and its ability to make repeated and reliable images of the earth's surface regardless of solar illumination and cloud cover. Missions such as the Canadian Radarsat, Japanese JERS-1, ERS-1 and -2 from Europe, and the SIR-C mission from the United States have all demonstrated the utility of using Radar data for delimiting regions of forest cover and estimating to some extent the amount of above ground biomass. Most of these techniques require ancillary information, either from ground measurements, or complemented by optical observations using techniques generally referred to as data fusion.

This short paper will first discuss the advantages and disadvantages of using a spaceborne SAR for measuring biomass as well as provide the basic concept behind the relationship of backscattered power to forest biomass. One of the conclusions of this discussion will be that sensitivity to biomass improves as the wavelength of the observing platform increases, thus explaining the need for low frequency systems. There are basically three fundamental challenges that are often associated with space-borne low frequency systems. These are i) ionospheric effects which manifest themselves in phenomena such as ray bending, azimuth defocusing (due to turbulence) and Faraday rotation, which affects polarization, ii) antenna dimension and ambiguity suppression, and finally iii) frequency allocation issues. Modeling of the incident field with the forest structural components are an important issue as well because ultimately this will govern the interpretation of the observation into a biomass estimate and will also guide the configuration and final design of a satellite platform.

One caveat that should be kept in mind while reading this document is to understand that no one system will be able to accomplish the complete task of estimating above ground biomass on a global scale. Other instruments such as vegetation canopy lidar, Landsat, MODIS, and SPOT are all examples of non-microwave systems that are likely to make a considerable contributions to this goal. Advantages that are unique to SAR such as its all weather capability, high-resolution large area coverage coverage and calibratable system performance are reasons why this technology will be necessary to satisfy the fundamental needs in a variety of global-scale remote sensing strategies. This paper assumes that the tradeoffs between this instrument and the other instrumentation will occur at stages further along in the planning process. The purpose of this document is to provide information specific to SAR and to put forth a design that will go a long way to satisfying the needs of the Kyoto protocol.

Role of spaceborne SAR for estimating above ground biomass

Radar fulfills a unique roll in the field of earth science observing platforms for three basic reasons: i) all weather capability, ii) calibratable product iii) its sensitivity to a unique set of biophysical parameters. The first of these is that radar typically works at microwave frequencies (wavelength between 1 centimeter and 1 meter), a region where meteorological disturbances and even some types of ground cover are transparent. This characteristic makes radar coverage for most of the earth's surface both reliable and repeatable under almost every conceivable weather condition. In comparison, optical imagery, because of its considerably shorter wavelength (on the order of 100's of nanometers), is often obscured by atmospheric disturbances. Figure 1 below illustrates the cloud index statistics for one year's images taken over South America. Images with cloud indices over 1 (or 10% cloud cover) are generally considered to be unusable for most remote sensing applications.

The second strength of radar is that it comes with its own signal source (i.e. an active sensor as opposed to passive). This allows for quantitative measurement of terrain backscatter characteristics and the ability of the instrument to operate without the presence of external illumination sources such as the sun. By carrying its own signal source, radar can make amplitude and timing (i.e. phase) measurements, and thereby take advantage of techniques such as aperture synthesis and interferometry.

The relationship of radar backscatter to biomass exists due to the volume scattering interaction of the incident field with the tree canopy and the forward scattering of the signal by the dihedral formed by the trunk-ground interface. The depth of penetration of a signal into a forest canopy is governed by the degree of interaction that the field has with the canopy. C- and X-band microwave frequencies (5 and 3 cm wavelengths) interact most strongly with the leaves and branches of the upper canopy while P- and L-band signals (68 and 24 cm wavelength) penetrate through the upper canopy of the forest

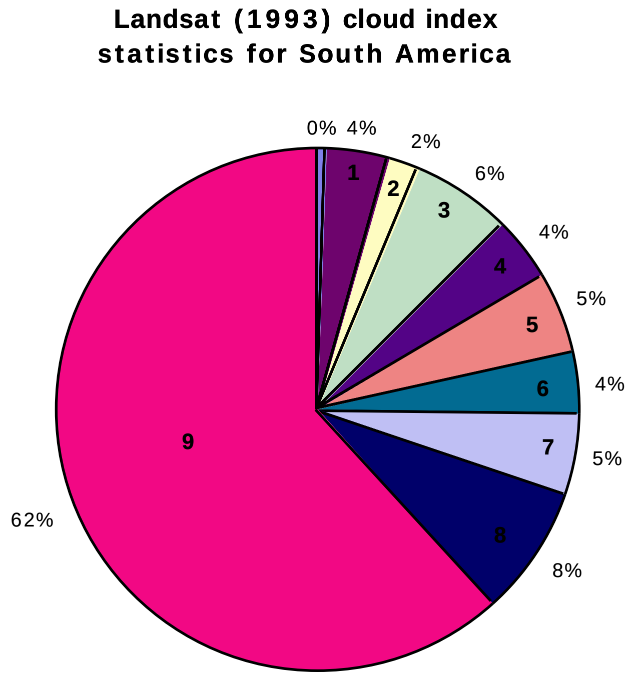

Figure 1.. *Landsat cloud index statistics for the Amazon region of South America. The cloud index is a measure of the percentage cloud cover within the image. One index point is equivalent to ten percentage points. Scenes with cloud indices greater than or equal to one (ten percent cloud cover) are generally considered to be unusable.*

and interact most strongly with the trunk and ground. For relating biomass to backscatter values, low frequency SAR is the most appealing because of the comparatively more simplistic scattering mechanisms and the fact that the low frequency radars have been demonstrated to be more sensitive to a wider range of forest biomass than their higher frequency counterparts [Dobson et al, 1992].

Of the existing spaceborne systems, L-band is the lowest frequency to have been extensively tested in a public, openly scientific domain, first during the NASA's Seasat and SIR (shuttle imaging radar) experiments, and then operationally by the Japanese (NASDA) JERS-1 satellite. Of particular interest is the demonstrated ability (through global forest mapping projects initiated by NASDA) for L-band SAR to be used for radar images to be made on continental scales from data collected over short periods of time (2-3 months).

Experimentally, L-band SAR has been shown to be sensitive to biomass up to a level of 100 tons per hectare, after which the backscatter signal tends to saturate [Dobson et al., 1992] This saturation is due to the fact that the backscatter power relationship to biomass is a non-linear relationship. The region where the signal falls out of the linear region is often taken to indicate that the sensor is no longer sensitive to changes in biomass of the target. For the sake of this development we will assume that 40 tons per hectare is the limit of the instrument sensitivity.

As wavelengths get longer, the ability of the signal to penetrate deeper into the canopy increases. P-band (UHF) systems have been shown a linear relationship between biomass and backscatter power for biomass levels up to 200 tons per hectare. [Dobson et al., 1992] Even lower frequency systems (below 100 MHz VHF bands) have been hypothesized to be sensitive to biomass levels exceeding 1000 tons per hectare [discussion during Kyoto meeting; see also Israelsson et al., 1997].

As mentioned previously, backscatter power and amplitude are not the only radar measurement that can be related to forest biomass. Interferometry is one such technique that uses observations separated in space (and potentially time) for inferring canopy height and density. This height and density could in turn be converted to biomass via a vertical integration of these two quantities. A spaceborne version of this technique may work best at L-band, a research area whose development is ongoing.[Treuhaft et al, 1996; Treuhaft and Siqueira, 2000].

Historically, backscatter measurements, perhaps using multiple polarizations, have been the most studied resource for relating biomass to radar measurements [addressed by many authors; see for instance Le Toan et al., 1992 and Dobson et al., 1992]. Hence, the remainder of this treatment will focus on the more immediate challenges of putting a low frequency P-band SAR in space. The three most important components that need to be investigated are i) the effect that the ionosphere has on the signal, ii) the requirements that a P-band SAR would put on a spaceborne antenna (the largest and heaviest component of the instrument), and iii) frequency allocation issues, which is a political/regulation problem that has proved to be very problematic for terrestrial radars operating in this frequency domain. We begin with a discussion of each of these topics in depth, which is then followed by a sample mission design.

Ionosphere

The ionosphere is a plasma of ions created through the interaction of solar radiation with the earth's atmosphere. Depending on the density of electrons, the plasma can act as a very good conductor at low frequencies, hence shielding the earth's surface from large wavelength fields. Because the principal source of ions in the atmosphere is the sun, their density is dependent on the time of day and level of sunspot activity. Electron density in the ionosphere typically varies between 3×10^{12} electrons/m^3 curing dusk and 3×10^{11} electrons/m^3 at dawn. The plasma frequency is the frequency at which the ionosphere naturally begins to resonate and hence causes a strong, reflective interaction with incident fields. Signals within a factor of ten of the plasma frequency are effected by the ionosphere as well, by both attenuation and phase shifts, much like optical light is bent and distorted as it passes through a column of water.

For a first order analysis, it is the vertical integration of the electron density (or the total electron content, TEC, where 1 TEC unit = 1×10^{16} electrons/m^2) which affects the signal as it passes through the ionosphere (Figure 2). Typical values for TEC vary between 5 TEC units at dawn and 50 TEC units at dusk ([Evans and Hagfors, 1968]).

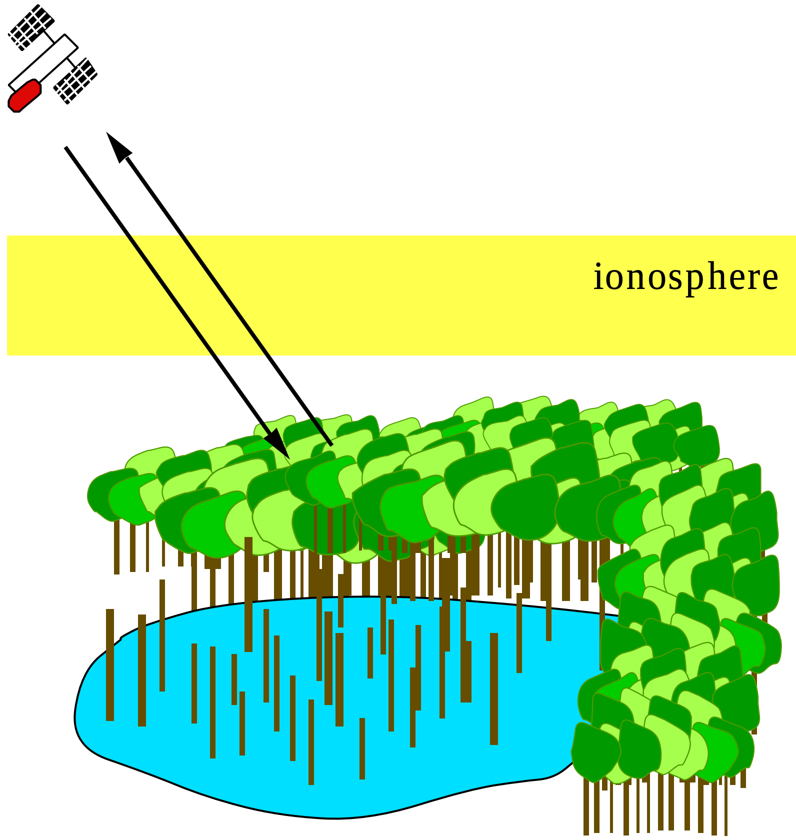

Figure 2. *Model of the ionosphere with respect to a satellite system. Not illustrated are i) a gentle bending of the field as it passes through the ionosphere, ii) density variations in the ionosphere, and iii) rotation of the incident field polarization.*

For P-band SAR, the ionosphere manifests itself in three ways: i) the signal is bent such that it does not follow a direct line of sight (i.e. the signal is refracted by the ionosphere), ii) the distance and length of time that the ‘target’ can be observed may be limited by turbulence in the ionosphere, an effect which ultimately limits the azimuthal resolution of a SAR, and iii) the polarization of the signal is rotated (i.e. Faraday rotation) as it passes through the atmosphere, thus distorting the polarization of the incident and return signals.

The effect of signal bending is perhaps the least problematic because it serves only to shift an image away from the presumed line of sight. Small shifts may be corrected in post processing. The order of magnitude of these shifts has been calculated by Ishimaru et al [1998] and is shown in Figure 3, where it can be seen that the worst case shift is expected to be less than 50 meters for a 50 degree look angle at 500 MHz. Larger shifts, while possible in a number of different scenarios (i.e. frequency and look angle decreases) are correctable due to the low sensitivity of the shift to these parameters.

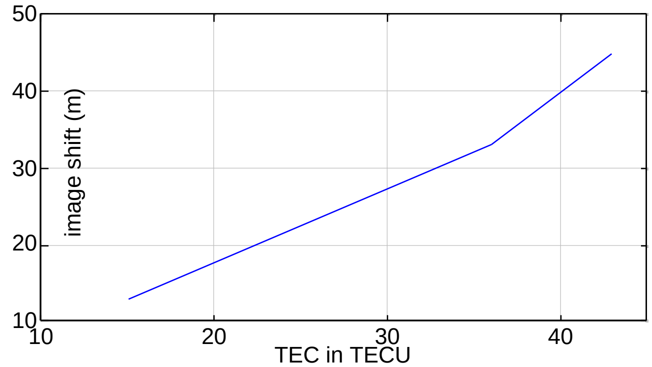

Figure 3. *Image (range) shift as a function of total electron content.*

Turbulence in the ionosphere has the effect of adding an unknown phase (path length) term into each observation. This is problematic for a low frequency SAR system because the length of the synthesized aperture is proportionally larger by the wavelength than its high frequency counterparts for a given resolution. If the signal path does not remain consistent for the duration of the observation, the image will be degraded in much the same way that raindrops on a pair of eyeglasses will distort the user's view. By assuming a moderate amount of variation in the electron density of the ionosphere (10%), Ishimaru et al [1998] calculated the maximum achievable synthetic aperture, and hence, the highest possible azimuth resolution. These results are summarized in Figure 4.

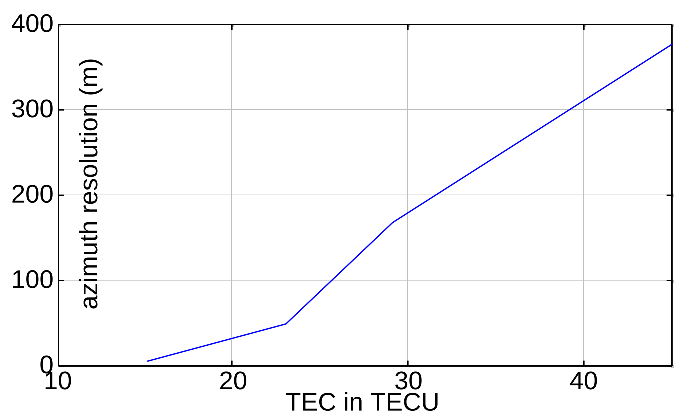

Figure 4. *Azimuth resolution as a function of total electron content and a 10% inhomogeneity in the electron density.*

Because of the random nature of the occurrence, loss of azimuth resolution is potentially the most problematic issue introduced by the ionosphere. The best possible solution is to put a satellite into a sun-synchronous orbit, where one of the passes (either ascending or descending) collects data during the local dawn hours (i.e. the time of ionospheric minimum). Thus, resolution of the instrument can be kept within reasonable limits. It should be noted too that a high resolution instrument may not be required for estimating above ground biomass. That is, a low-resolution (on the order of 100 m) product may be sufficient, and perhaps desired, to reduce the natural variability in vegetation density.

The last effect that the ionosphere may have on a signal is that of Faraday rotation. Faraday rotation describes the rotation effect that a plasma (the ionosphere) in a constant magnetic field (the earth's) has on a signal passing through it. This type of rotation is non-reciprocal, in the sense that a signal passing in one direction through the ionosphere does not revert back to the polarization sense of the original signal on its way back. The net rotation of the signal has been calculated by Freeman and Saatchi [in preparation, 2000] and Ishimaru et al [1998]. The degree of rotation as a function of the total electron content is significant for TEC values above 10, as shown in Figure 5.

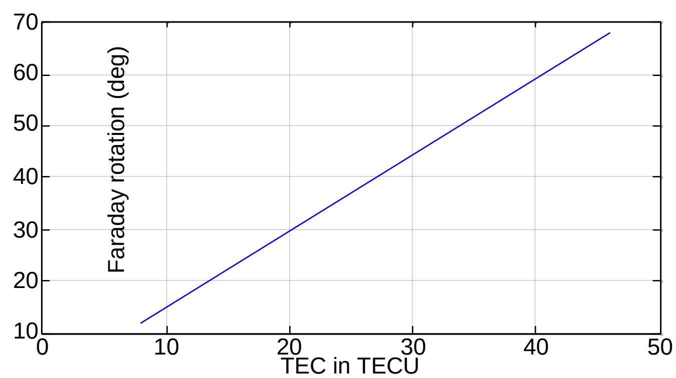

Figure 5. *Faraday rotation as a function of TEC.*

Using a fully polarimetric radar however, does offer a solution. When a field's polarization is rotated and measured using a polarimetric radar, it may be reconstructed using a simple geometric transformation. When a particular polarization is transmitted, it is expected that the majority of the energy returning will be of like polarization (i.e. co-polarized). If the principal scattering object is aligned in a plane away from the incident polarization, that object will depolarize the signal to some degree. When measured by the radar however, the degree of depolarization for the opposite sense transmit polarization for the majority of natural targets, is the same. Hence the degree of depolarization for both measurements should be equal, and if they are not, it is due to an intervening non-reciprocal medium, such as the ionosphere. Forcing the two cross-polarized measurements to be equal then can be used firstly correct the imagery and secondly to estimate the TEC of the ionosphere.

Antenna Dimension

For SAR, high resolution in the along track dimension is obtained by coherently forming an equivalent array as the satellite travels through space. This is achieved by sending out radar pulses and recording their round trip delay time. The delay is converted to an electronic phase, which, by making the assumption that the scene has not changed during the short time of observation, can be summed together as if a much larger fixed array where present.

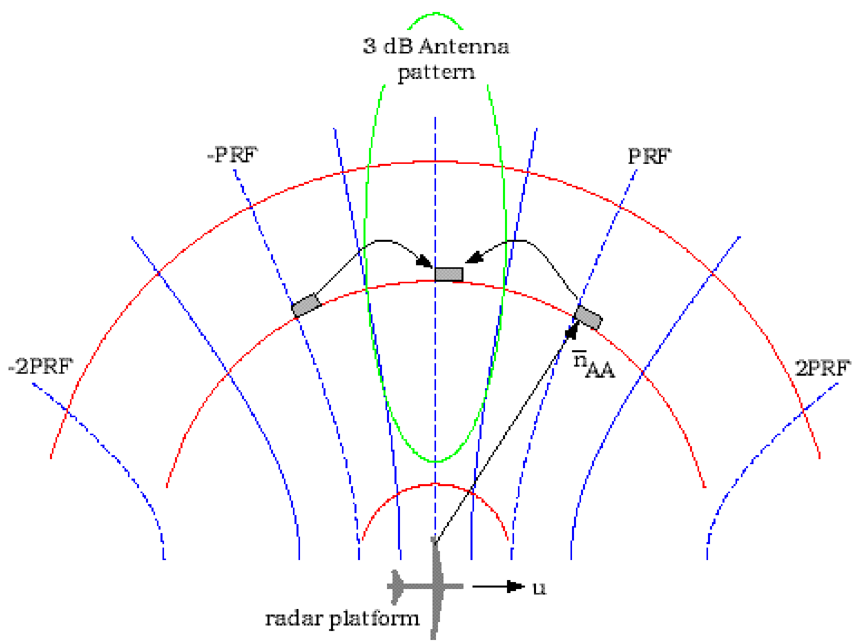

Figure 6. *Illustration of azimuth ambiguities. Illustration is shown for an aircraft, but the effect for a spaceborne system would be the same.*

The field of view for any particular pulse is limited by the dimension of the physical antenna onboard the satellite. The along-track dimension of the antenna limits the contribution of returns to a narrow field in the azimuth direction. Since Doppler increases as a function of along-track distance from the instrument's broadside, the shape of the azimuth beam is used to eliminate the high -frequency Doppler contributions to the observed signal. This low-pass filtering of the Doppler is necessary because the Doppler is sampled by the radar pulses, i.e. the pulse repetition frequency (PRF). To unambiguously sample the Doppler, the PRF must sample the Doppler returns at the Nyquist frequency (i.e. two times the largest expected Doppler). Figure 6 above illustrates the source of Doppler ambiguities in the instrument swath, and Figure 7 shows how aliasing returns will affect the received signal.

With reference to Figure 7, the location and pattern of the frequency aliasing due to a poorly sampled Doppler signal is set by the antenna pattern and the PRF. The processing bandwidth, B_{proc}, , and hence the resolution is something ultimately set by the processing system, and it is this parameter which in combination with the others that sets the degree of aliasing due to ambiguous Doppler returns. Hence for a fixed antenna dimension and PRF, if we are willing to reduce resolution, the effect of azimuth ambiguities can be reduced by narrowing the processing bandwidth. It is therefore possible to design a SAR with a reduced azimuth antenna dimension at the expense of reduced resolution.

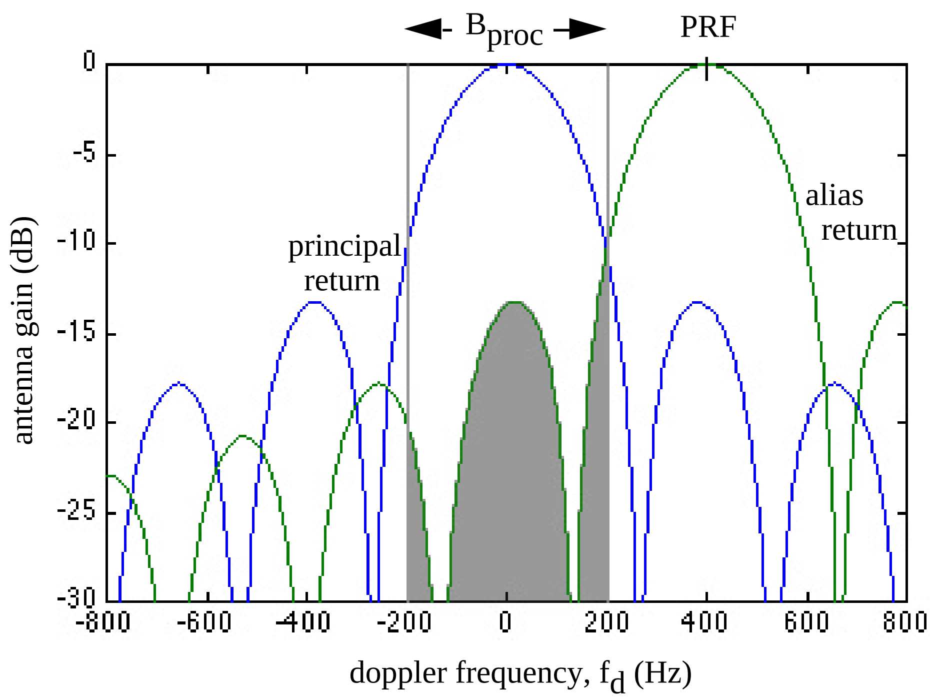

Figure 7. *Effect of changing the processing bandwidth on azimuth ambiguities. Show is the azimuth antenna pattern mapped to Doppler frequency for both the principal and aliased returns.*

Due to historical reasons, this has not been considered in the system design and has led to incorrect assumptions about limits put on overall SAR antenna dimensions (see Freeman et al, 1999). These results are particularly meaningful for a low-frequency mission, because of the impact of a long wavelength on antenna dimensions and its effect on the overall mass and dimension of the satellite.

Frequency Allocation

To make global observations using a P-band SAR will require permissions by the individual countries to transmit in the UHF bands. Because of the low frequency and relative simplicity of design, UHF has been utilized by society since nearly the invention of radio, and hence is a commonly used band for communication. This, compounded with the fact that low frequency signal travel farther (i.e. signal loss as a function of range is proportional to wavelength) makes obtaining the permission required to transmit a P-band signal a potentially difficult task. There are however a number of aspects particular to SAR that make it a good candidate for receiving the necessary permission.

The first of these is that a broad-band system could easily be designed so that the frequencies where power is actually transmitted may be adjusted according to the limitations set by individual nations. Broad band antennas and hardware capable of spanning decades of MHz are well established and tested. The actual bandwidth required for any particular observation is set by the desired range resolution, and will be on the order of 10 - 20 MHz. Additionally, the technology to remove specific frequencies from a radar chirp also exists and may be used in a P-band friendly system. Hence, transmission slots as well as chirp masks can be assigned depending on local frequency restrictions.

The second advantage that SAR has in terms of maintaining a minimum disturbance level at UHF frequencies is that it is not a fixed-base system, and any disturbances that do occur, will be limited only for the time of the satellite overpass and within the limits of the antenna beam and transmit pulse length. The amount of power which exists at any single frequency is actually quite small since power is spread throughout the bandwidth. Persistent disturbances could be eliminated by altering the frequencies in the transmit chirp.

System Design

With the ability to overcome the three challenges described in this treatise, we believe a longer wavelength, earth-orbiting SAR becomes feasible. Our calculations show that a P-Band SAR, in a 600 km altitude polar orbit, with a simple linearly polarized reflector antenna and a low RF-power (100 Watts peak, 10 Watts average) solid-state amplifier with two receive channels, could generate fully polarimetric SAR strip map measurements at an incidence angle of ~35 degrees over a swath width of 50 km at 50 to 100m spatial resolution (on the ground). Such a low-power instrument could easily operate continuously, providing a monitoring capability currently unavailable to earth scientists studying biomass and land cover changes, etc. With the proper choice of a dusk/dawn sun-synchronous orbit, earth scientists studying these phenomena could remove uncertainties due to diurnal effects from their observations, and study seasonal effects with a guaranteed revisit period of approximately one month.

SUMMARY

In this treatise we have discussed the challenges associated with implementing a spaceborne SAR. As a result of our studies, we have identified five challenges that need to be met, three having to do with the ionosphere, and the others relating to antenna dimension and frequency allocation issues. In summary, our investigations have shown that:

1. image shift due to the ionosphere is not significant
2. azimuth resolution will likely be limited by the ionosphere, but this can be reduced by a judicious choice of satellite orbit and observing time, and
3. the effect of Faraday rotation can be removed by making fully polarimetric measurements.
4. the minimum antenna area constraint which impacts launch costs can be overcome by reducing azimuth resolution, and
5. frequency restrictions can be dealt with by designing a wide-bandwidth system for which bandpass slots and frequency notching are used to comply with local restrictions.

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Appendix III

The Kyoto Protocol

KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE

The Parties to this Protocol,

Being Parties to the United Nations Framework Convention on Climate Change, hereinafter referred to as “the Convention”,

In pursuit of the ultimate objective of the Convention as stated in its Article 2,

Recalling the provisions of the Convention,

Being guided by Article 3 of the Convention,

Pursuant to the Berlin Mandate adopted by decision 1/CP.1 of the Conference of the Parties to the Convention at its first session,

Have agreed as follows:

Article 1

For the purposes of this Protocol, the definitions contained in Article 1 of the Convention shall apply. In addition:

1. “Conference of the Parties” means the Conference of the Parties to the Convention.

2. “Convention” means the United Nations Framework Convention on Climate Change, adopted in New York on 9 May 1992.

3. “Intergovernmental Panel on Climate Change” means the Intergovernmental Panel on Climate Change established in 1988 jointly by the World Meteorological Organization and the United Nations Environment Programme.

4. “Montreal Protocol” means the Montreal Protocol on Substances that Deplete the Ozone Layer, adopted in Montreal on 16 September 1987 and as subsequently adjusted and amended.

5. “Parties present and voting” means Parties present and casting an affirmative or negative vote.

6. “Party” means, unless the context otherwise indicates, a Party to this Protocol.

7. “Party included in Annex I” means a Party included in Annex I to the Convention, as may be amended, or a Party which has made a notification under Article 4, paragraph 2(g), of the Convention.

Article 2

1. Each Party included in Annex I, in achieving its quantified emission limitation and reduction commitments under Article 3, in order to promote sustainable development, shall:

(a) Implement and/or further elaborate policies and measures in accordance with its national circumstances, such as:

(i) Enhancement of energy efficiency in relevant sectors of the national economy;

(ii) Protection and enhancement of sinks and reservoirs of greenhouse gases not controlled by the Montreal Protocol, taking into account its commitments under relevant international environmental agreements; promotion of sustainable forest management practices, afforestation and reforestation;

(iii) Promotion of sustainable forms of agriculture in light of climate change considerations;

(iv) Research on, and promotion, development and increased use of, new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies;

(v) Progressive reduction or phasing out of market imperfections, fiscal incentives, tax and duty exemptions and subsidies in all greenhouse gas emitting sectors that run counter to the objective of the Convention and application of market instruments;

(vi) Encouragement of appropriate reforms in relevant sectors aimed at promoting policies and measures which limit or reduce emissions of greenhouse gases not controlled by the Montreal Protocol;

(vii) Measures to limit and/or reduce emissions of greenhouse gases not controlled by the Montreal Protocol in the transport sector;

(viii) Limitation and/or reduction of methane emissions through recovery and use in waste management, as well as in the production, transport and distribution of energy;

(b) Cooperate with other such Parties to enhance the individual and combined effectiveness of their policies and measures adopted under this Article, pursuant to Article 4, paragraph 2(e)(i), of the Convention. To this end, these Parties shall take steps to share their experience and exchange information on such policies and measures, including developing ways of improving their comparability, transparency and effectiveness. The Conference of

Parties serving as the meeting of the Parties to this Protocol shall, at its first session or as soon as practicable thereafter, consider ways to facilitate such cooperation, taking into account all relevant information.

2. The Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively.

3. The Parties included in Annex I shall strive to implement policies and measures under this Article in such a way as to minimize adverse effects, including the adverse effects of climate change, effects on international trade, and social, environmental and economic impacts on other Parties, especially developing country Parties and in particular those identified in Article 4, paragraphs 8 and 9, of the Convention, taking into account Article 3 of the Convention. The Conference of the Parties serving as the meeting of the Parties to this Protocol may take further action, as appropriate, to promote the implementation of the provisions of this paragraph.

4. The Conference of the Parties serving as the meeting of the Parties to this Protocol, if it decides that it would be beneficial to coordinate any of the policies and measures in paragraph 1(a) above, taking into account different national circumstances and potential effects, shall consider ways and means to elaborate the coordination of such policies and measures.

Article 3

1. The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts, calculated pursuant to their quantified emission limitation and reduction commitments inscribed in Annex B and in accordance with the provisions of this Article, with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012.

2. Each Party included in Annex I shall, by 2005, have made demonstrable progress in achieving its commitments under this Protocol.

3. The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article of each Party included in Annex I. The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner and reviewed in accordance with Articles 7 and 8.

4. Prior to the first session of the Conference of the Parties serving as the meeting of the Parties to this Protocol, each Party included in Annex I shall provide, for consideration by the Subsidiary Body for Scientific and Technological Advice, data to establish its level of carbon

stocks in 1990 and to enable an estimate to be made of its changes in carbon stocks in subsequent years. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall, at its first session or as soon as practicable thereafter, decide upon modalities, rules and guidelines as to how, and which, additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories shall be added to, or subtracted from, the assigned amounts for Parties included in Annex I, taking into account uncertainties, transparency in reporting, verifiability, the methodological work of the Intergovernmental Panel on Climate Change, the advice provided by the Subsidiary Body for Scientific and Technological Advice in accordance with Article 5 and the decisions of the Conference of the Parties. Such a decision shall apply in the second and subsequent commitment periods. A Party may choose to apply such a decision on these additional human-induced activities for its first commitment period, provided that these activities have taken place since 1990.

5. The Parties included in Annex I undergoing the process of transition to a market economy whose base year or period was established pursuant to decision 9/CP.2 of the Conference of the Parties at its second session shall use that base year or period for the implementation of their commitments under this Article. Any other Party included in Annex I undergoing the process of transition to a market economy which has not yet submitted its first national communication under Article 12 of the Convention may also notify the Conference of the Parties serving as the meeting of the Parties to this Protocol that it intends to use an historical base year or period other than 1990 for the implementation of its commitments under this Article. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall decide on the acceptance of such notification.

6. Taking into account Article 4, paragraph 6, of the Convention, in the implementation of their commitments under this Protocol other than those under this Article, a certain degree of flexibility shall be allowed by the Conference of the Parties serving as the meeting of the Parties to this Protocol to the Parties included in Annex I undergoing the process of transition to a market economy.

7. In the first quantified emission limitation and reduction commitment period, from 2008 to 2012, the assigned amount for each Party included in Annex I shall be equal to the percentage inscribed for it in Annex B of its aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A in 1990, or the base year or period determined in accordance with paragraph 5 above, multiplied by five. Those Parties included in Annex I for whom land-use change and forestry constituted a net source of greenhouse gas emissions in 1990 shall include in their 1990 emissions base year or period the aggregate anthropogenic carbon dioxide equivalent emissions by sources minus removals by sinks in 1990 from land-use change for the purposes of calculating their assigned amount.

8. Any Party included in Annex I may use 1995 as its base year for hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride, for the purposes of the calculation referred to in paragraph 7 above.

9. Commitments for subsequent periods for Parties included in Annex I shall be established in amendments to Annex B to this Protocol, which shall be adopted in accordance

with the provisions of Article 21, paragraph 7. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall initiate the consideration of such commitments at least seven years before the end of the first commitment period referred to in paragraph 1 above.

10. Any emission reduction units, or any part of an assigned amount, which a Party acquires from another Party in accordance with the provisions of Article 6 or of Article 17 shall be added to the assigned amount for the acquiring Party.

11. Any emission reduction units, or any part of an assigned amount, which a Party transfers to another Party in accordance with the provisions of Article 6 or of Article 17 shall be subtracted from the assigned amount for the transferring Party.

12. Any certified emission reductions which a Party acquires from another Party in accordance with the provisions of Article 12 shall be added to the assigned amount for the acquiring Party.

13. If the emissions of a Party included in Annex I in a commitment period are less than its assigned amount under this Article, this difference shall, on request of that Party, be added to the assigned amount for that Party for subsequent commitment periods.

14. Each Party included in Annex I shall strive to implement the commitments mentioned in paragraph 1 above in such a way as to minimize adverse social, environmental and economic impacts on developing country Parties, particularly those identified in Article 4, paragraphs 8 and 9, of the Convention. In line with relevant decisions of the Conference of the Parties on the implementation of those paragraphs, the Conference of the Parties serving as the meeting of the Parties to this Protocol shall, at its first session, consider what actions are necessary to minimize the adverse effects of climate change and/or the impacts of response measures on Parties referred to in those paragraphs. Among the issues to be considered shall be the establishment of funding, insurance and transfer of technology.

Article 4

1. Any Parties included in Annex I that have reached an agreement to fulfil their commitments under Article 3 jointly, shall be deemed to have met those commitments provided that their total combined aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts calculated pursuant to their quantified emission limitation and reduction commitments inscribed in Annex B and in accordance with the provisions of Article 3. The respective emission level allocated to each of the Parties to the agreement shall be set out in that agreement.

2. The Parties to any such agreement shall notify the secretariat of the terms of the agreement on the date of deposit of their instruments of ratification, acceptance or approval of this Protocol, or accession thereto. The secretariat shall in turn inform the Parties and signatories to the Convention of the terms of the agreement.

3. Any such agreement shall remain in operation for the duration of the commitment period specified in Article 3, paragraph 7.

4. If Parties acting jointly do so in the framework of, and together with, a regional economic integration organization, any alteration in the composition of the organization after adoption of this Protocol shall not affect existing commitments under this Protocol. Any alteration in the composition of the organization shall only apply for the purposes of those commitments under Article 3 that are adopted subsequent to that alteration.

5. In the event of failure by the Parties to such an agreement to achieve their total combined level of emission reductions, each Party to that agreement shall be responsible for its own level of emissions set out in the agreement.

6. If Parties acting jointly do so in the framework of, and together with, a regional economic integration organization which is itself a Party to this Protocol, each member State of that regional economic integration organization individually, and together with the regional economic integration organization acting in accordance with Article 24, shall, in the event of failure to achieve the total combined level of emission reductions, be responsible for its level of emissions as notified in accordance with this Article.

Article 5

1. Each Party included in Annex I shall have in place, no later than one year prior to the start of the first commitment period, a national system for the estimation of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol. Guidelines for such national systems, which shall incorporate the methodologies specified in paragraph 2 below, shall be decided upon by the Conference of the Parties serving as the meeting of the Parties to this Protocol at its first session.

2. Methodologies for estimating anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol shall be those accepted by the Intergovernmental Panel on Climate Change and agreed upon by the Conference of the Parties at its third session. Where such methodologies are not used, appropriate adjustments shall be applied according to methodologies agreed upon by the Conference of the Parties serving as the meeting of the Parties to this Protocol at its first session. Based on the work of, *inter alia*, the Intergovernmental Panel on Climate Change and advice provided by the Subsidiary Body for Scientific and Technological Advice, the Conference of the Parties serving as the meeting of the Parties to this Protocol shall regularly review and, as appropriate, revise such methodologies and adjustments, taking fully into account any relevant decisions by the Conference of the Parties. Any revision to methodologies or adjustments shall be used only for the purposes of ascertaining compliance with commitments under Article 3 in respect of any commitment period adopted subsequent to that revision.

3. The global warming potentials used to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases listed in Annex A shall be those accepted by the Intergovernmental Panel on Climate Change and agreed upon by the Conference of the Parties at its third session. Based on the work of, *inter*

alia, the Intergovernmental Panel on Climate Change and advice provided by the Subsidiary Body for Scientific and Technological Advice, the Conference of the Parties serving as the meeting of the Parties to this Protocol shall regularly review and, as appropriate, revise the global warming potential of each such greenhouse gas, taking fully into account any relevant decisions by the Conference of the Parties. Any revision to a global warming potential shall apply only to commitments under Article 3 in respect of any commitment period adopted subsequent to that revision.

Article 6

1. For the purpose of meeting its commitments under Article 3, any Party included in Annex I may transfer to, or acquire from, any other such Party emission reduction units resulting from projects aimed at reducing anthropogenic emissions by sources or enhancing anthropogenic removals by sinks of greenhouse gases in any sector of the economy, provided that:

(a) Any such project has the approval of the Parties involved;

(b) Any such project provides a reduction in emissions by sources, or an enhancement of removals by sinks, that is additional to any that would otherwise occur;

(c) It does not acquire any emission reduction units if it is not in compliance with its obligations under Articles 5 and 7; and

(d) The acquisition of emission reduction units shall be supplemental to domestic actions for the purposes of meeting commitments under Article 3.

2. The Conference of the Parties serving as the meeting of the Parties to this Protocol may, at its first session or as soon as practicable thereafter, further elaborate guidelines for the implementation of this Article, including for verification and reporting.

3. A Party included in Annex I may authorize legal entities to participate, under its responsibility, in actions leading to the generation, transfer or acquisition under this Article of emission reduction units.

4. If a question of implementation by a Party included in Annex I of the requirements referred to in this Article is identified in accordance with the relevant provisions of Article 8, transfers and acquisitions of emission reduction units may continue to be made after the question has been identified, provided that any such units may not be used by a Party to meet its commitments under Article 3 until any issue of compliance is resolved.

Article 7

1. Each Party included in Annex I shall incorporate in its annual inventory of anthropogenic emissions by sources and removals by sinks of greenhouse gases not controlled by the Montreal Protocol, submitted in accordance with the relevant decisions of the Conference of the Parties, the necessary supplementary information for the purposes of

ensuring compliance with Article 3, to be determined in accordance with paragraph 4 below.

2. Each Party included in Annex I shall incorporate in its national communication, submitted under Article 12 of the Convention, the supplementary information necessary to demonstrate compliance with its commitments under this Protocol, to be determined in accordance with paragraph 4 below.

3. Each Party included in Annex I shall submit the information required under paragraph 1 above annually, beginning with the first inventory due under the Convention for the first year of the commitment period after this Protocol has entered into force for that Party. Each such Party shall submit the information required under paragraph 2 above as part of the first national communication due under the Convention after this Protocol has entered into force for it and after the adoption of guidelines as provided for in paragraph 4 below. The frequency of subsequent submission of information required under this Article shall be determined by the Conference of the Parties serving as the meeting of the Parties to this Protocol, taking into account any timetable for the submission of national communications decided upon by the Conference of the Parties.

4. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall adopt at its first session, and review periodically thereafter, guidelines for the preparation of the information required under this Article, taking into account guidelines for the preparation of national communications by Parties included in Annex I adopted by the Conference of the Parties. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall also, prior to the first commitment period, decide upon modalities for the accounting of assigned amounts.

Article 8

1. The information submitted under Article 7 by each Party included in Annex I shall be reviewed by expert review teams pursuant to the relevant decisions of the Conference of the Parties and in accordance with guidelines adopted for this purpose by the Conference of the Parties serving as the meeting of the Parties to this Protocol under paragraph 4 below. The information submitted under Article 7, paragraph 1, by each Party included in Annex I shall be reviewed as part of the annual compilation and accounting of emissions inventories and assigned amounts. Additionally, the information submitted under Article 7, paragraph 2, by each Party included in Annex I shall be reviewed as part of the review of communications.

2. Expert review teams shall be coordinated by the secretariat and shall be composed of experts selected from those nominated by Parties to the Convention and, as appropriate, by intergovernmental organizations, in accordance with guidance provided for this purpose by the Conference of the Parties.

3. The review process shall provide a thorough and comprehensive technical assessment of all aspects of the implementation by a Party of this Protocol. The expert review teams shall prepare a report to the Conference of the Parties serving as the meeting of the Parties to this Protocol, assessing the implementation of the commitments of the Party and identifying any potential problems in, and factors influencing, the fulfilment of commitments. Such

reports shall be circulated by the secretariat to all Parties to the Convention. The secretariat shall list those questions of implementation indicated in such reports for further consideration by the Conference of the Parties serving as the meeting of the Parties to this Protocol.

4. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall adopt at its first session, and review periodically thereafter, guidelines for the review of implementation of this Protocol by expert review teams taking into account the relevant decisions of the Conference of the Parties.

5. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall, with the assistance of the Subsidiary Body for Implementation and, as appropriate, the Subsidiary Body for Scientific and Technological Advice, consider:

(a) The information submitted by Parties under Article 7 and the reports of the expert reviews thereon conducted under this Article; and

(b) Those questions of implementation listed by the secretariat under paragraph 3 above, as well as any questions raised by Parties.

6. Pursuant to its consideration of the information referred to in paragraph 5 above, the Conference of the Parties serving as the meeting of the Parties to this Protocol shall take decisions on any matter required for the implementation of this Protocol.

Article 9

1. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall periodically review this Protocol in the light of the best available scientific information and assessments on climate change and its impacts, as well as relevant technical, social and economic information. Such reviews shall be coordinated with pertinent reviews under the Convention, in particular those required by Article 4, paragraph 2(d), and Article 7, paragraph 2(a), of the Convention. Based on these reviews, the Conference of the Parties serving as the meeting of the Parties to this Protocol shall take appropriate action.

2. The first review shall take place at the second session of the Conference of the Parties serving as the meeting of the Parties to this Protocol. Further reviews shall take place at regular intervals and in a timely manner.

Article 10

All Parties, taking into account their common but differentiated responsibilities and their specific national and regional development priorities, objectives and circumstances, without introducing any new commitments for Parties not included in Annex I, but reaffirming existing commitments under Article 4, paragraph 1, of the Convention, and continuing to advance the implementation of these commitments in order to achieve sustainable development, taking into account Article 4, paragraphs 3, 5 and 7, of the Convention, shall:

(a) Formulate, where relevant and to the extent possible, cost-effective national and, where appropriate, regional programmes to improve the quality of local emission factors, activity data and/or models which reflect the socio-economic conditions of each Party for the preparation and periodic updating of national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies to be agreed upon by the Conference of the Parties, and consistent with the guidelines for the preparation of national communications adopted by the Conference of the Parties;

(b) Formulate, implement, publish and regularly update national and, where appropriate, regional programmes containing measures to mitigate climate change and measures to facilitate adequate adaptation to climate change:

(i) Such programmes would, *inter alia*, concern the energy, transport and industry sectors as well as agriculture, forestry and waste management. Furthermore, adaptation technologies and methods for improving spatial planning would improve adaptation to climate change; and

(ii) Parties included in Annex I shall submit information on action under this Protocol, including national programmes, in accordance with Article 7; and other Parties shall seek to include in their national communications, as appropriate, information on programmes which contain measures that the Party believes contribute to addressing climate change and its adverse impacts, including the abatement of increases in greenhouse gas emissions, and enhancement of and removals by sinks, capacity building and adaptation measures;

(c) Cooperate in the promotion of effective modalities for the development, application and diffusion of, and take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies, know-how, practices and processes pertinent to climate change, in particular to developing countries, including the formulation of policies and programmes for the effective transfer of environmentally sound technologies that are publicly owned or in the public domain and the creation of an enabling environment for the private sector, to promote and enhance the transfer of, and access to, environmentally sound technologies;

(d) Cooperate in scientific and technical research and promote the maintenance and the development of systematic observation systems and development of data archives to reduce uncertainties related to the climate system, the adverse impacts of climate change and the economic and social consequences of various response strategies, and promote the development and strengthening of endogenous capacities and capabilities to participate in international and intergovernmental efforts, programmes and networks on research and systematic observation, taking into account Article 5 of the Convention;

(e) Cooperate in and promote at the international level, and, where appropriate, using existing bodies, the development and implementation of education and training programmes, including the strengthening of national capacity building, in particular human and institutional capacities and the exchange or secondment of personnel to train experts in this field, in particular for developing countries, and facilitate at the national level public awareness of, and public access to information on, climate change. Suitable modalities should be developed to implement these activities through the relevant bodies of the Convention, taking into account Article 6 of the Convention;

(f) Include in their national communications information on programmes and activities undertaken pursuant to this Article in accordance with relevant decisions of the Conference of the Parties; and

(g) Give full consideration, in implementing the commitments under this Article, to Article 4, paragraph 8, of the Convention.

Article 11

1. In the implementation of Article 10, Parties shall take into account the provisions of Article 4, paragraphs 4, 5, 7, 8 and 9, of the Convention.

2. In the context of the implementation of Article 4, paragraph 1, of the Convention, in accordance with the provisions of Article 4, paragraph 3, and Article 11 of the Convention, and through the entity or entities entrusted with the operation of the financial mechanism of the Convention, the developed country Parties and other developed Parties included in Annex II to the Convention shall:

(a) Provide new and additional financial resources to meet the agreed full costs incurred by developing country Parties in advancing the implementation of existing commitments under Article 4, paragraph 1(a), of the Convention that are covered in Article 10, subparagraph (a); and

(b) Also provide such financial resources, including for the transfer of technology, needed by the developing country Parties to meet the agreed full incremental costs of advancing the implementation of existing commitments under Article 4, paragraph 1, of the Convention that are covered by Article 10 and that are agreed between a developing country Party and the international entity or entities referred to in Article 11 of the Convention, in accordance with that Article.

The implementation of these existing commitments shall take into account the need for adequacy and predictability in the flow of funds and the importance of appropriate burden sharing among developed country Parties. The guidance to the entity or entities entrusted with the operation of the financial mechanism of the Convention in relevant decisions of the Conference of the Parties, including those agreed before the adoption of this Protocol, shall apply *mutatis mutandis* to the provisions of this paragraph.

3. The developed country Parties and other developed Parties in Annex II to the Convention may also provide, and developing country Parties avail themselves of, financial resources for the implementation of Article 10, through bilateral, regional and other multilateral channels.

Article 12

1. A clean development mechanism is hereby defined.

2. The purpose of the clean development mechanism shall be to assist Parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the Convention, and to assist Parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments under Article 3.

3. Under the clean development mechanism:

(a) Parties not included in Annex I will benefit from project activities resulting in certified emission reductions; and

(b) Parties included in Annex I may use the certified emission reductions accruing from such project activities to contribute to compliance with part of their quantified emission limitation and reduction commitments under Article 3, as determined by the Conference of the Parties serving as the meeting of the Parties to this Protocol.

4. The clean development mechanism shall be subject to the authority and guidance of the Conference of the Parties serving as the meeting of the Parties to this Protocol and be supervised by an executive board of the clean development mechanism.

5. Emission reductions resulting from each project activity shall be certified by operational entities to be designated by the Conference of the Parties serving as the meeting of the Parties to this Protocol, on the basis of:

(a) Voluntary participation approved by each Party involved;

(b) Real, measurable, and long-term benefits related to the mitigation of climate change; and

(c) Reductions in emissions that are additional to any that would occur in the absence of the certified project activity.

6. The clean development mechanism shall assist in arranging funding of certified project activities as necessary.

7. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall, at its first session, elaborate modalities and procedures with the objective of ensuring transparency, efficiency and accountability through independent auditing and verification of project activities.

8. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall ensure that a share of the proceeds from certified project activities is used to cover administrative expenses as well as to assist developing country Parties that are particularly vulnerable to the adverse effects of climate change to meet the costs of adaptation.

9. Participation under the clean development mechanism, including in activities mentioned in paragraph 3(a) above and in the acquisition of certified emission reductions, may involve private and/or public entities, and is to be subject to whatever guidance may be provided by the executive board of the clean development mechanism.

10. Certified emission reductions obtained during the period from the year 2000 up to the beginning of the first commitment period can be used to assist in achieving compliance in the first commitment period.

Article 13

1. The Conference of the Parties, the supreme body of the Convention, shall serve as the meeting of the Parties to this Protocol.

2. Parties to the Convention that are not Parties to this Protocol may participate as observers in the proceedings of any session of the Conference of the Parties serving as the meeting of the Parties to this Protocol. When the Conference of the Parties serves as the meeting of the Parties to this Protocol, decisions under this Protocol shall be taken only by those that are Parties to this Protocol.

3. When the Conference of the Parties serves as the meeting of the Parties to this Protocol, any member of the Bureau of the Conference of the Parties representing a Party to the Convention but, at that time, not a Party to this Protocol, shall be replaced by an additional member to be elected by and from amongst the Parties to this Protocol.

4. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall keep under regular review the implementation of this Protocol and shall make, within its mandate, the decisions necessary to promote its effective implementation. It shall perform the functions assigned to it by this Protocol and shall:

(a) Assess, on the basis of all information made available to it in accordance with the provisions of this Protocol, the implementation of this Protocol by the Parties, the overall effects of the measures taken pursuant to this Protocol, in particular environmental, economic and social effects as well as their cumulative impacts and the extent to which progress towards the objective of the Convention is being achieved;

(b) Periodically examine the obligations of the Parties under this Protocol, giving due consideration to any reviews required by Article 4, paragraph 2(d), and Article 7, paragraph 2, of the Convention, in the light of the objective of the Convention, the experience gained in its implementation and the evolution of scientific and technological knowledge, and in this respect consider and adopt regular reports on the implementation of this Protocol;

(c) Promote and facilitate the exchange of information on measures adopted by the Parties to address climate change and its effects, taking into account the differing circumstances, responsibilities and capabilities of the Parties and their respective commitments under this Protocol;

(d) Facilitate, at the request of two or more Parties, the coordination of measures adopted by them to address climate change and its effects, taking into account the differing circumstances, responsibilities and capabilities of the Parties and their respective commitments under this Protocol;

(e) Promote and guide, in accordance with the objective of the Convention and the provisions of this Protocol, and taking fully into account the relevant decisions by the Conference of the Parties, the development and periodic refinement of comparable methodologies for the effective implementation of this Protocol, to be agreed on by the Conference of the Parties serving as the meeting of the Parties to this Protocol;

(f) Make recommendations on any matters necessary for the implementation of this Protocol;

(g) Seek to mobilize additional financial resources in accordance with Article 11, paragraph 2;

(h) Establish such subsidiary bodies as are deemed necessary for the implementation of this Protocol;

(i) Seek and utilize, where appropriate, the services and cooperation of, and information provided by, competent international organizations and intergovernmental and non-governmental bodies; and

(j) Exercise such other functions as may be required for the implementation of this Protocol, and consider any assignment resulting from a decision by the Conference of the Parties.

5. The rules of procedure of the Conference of the Parties and financial procedures applied under the Convention shall be applied *mutatis mutandis* under this Protocol, except as may be otherwise decided by consensus by the Conference of the Parties serving as the meeting of the Parties to this Protocol.

6. The first session of the Conference of the Parties serving as the meeting of the Parties to this Protocol shall be convened by the secretariat in conjunction with the first session of the Conference of the Parties that is scheduled after the date of the entry into force of this

Protocol. Subsequent ordinary sessions of the Conference of the Parties serving as the meeting of the Parties to this Protocol shall be held every year and in conjunction with ordinary sessions of the Conference of the Parties, unless otherwise decided by the Conference of the Parties serving as the meeting of the Parties to this Protocol.

7. Extraordinary sessions of the Conference of the Parties serving as the meeting of the Parties to this Protocol shall be held at such other times as may be deemed necessary by the Conference of the Parties serving as the meeting of the Parties to this Protocol, or at the written request of any Party, provided that, within six months of the request being communicated to the Parties by the secretariat, it is supported by at least one third of the Parties.

8. The United Nations, its specialized agencies and the International Atomic Energy Agency, as well as any State member thereof or observers thereto not party to the Convention, may be represented at sessions of the Conference of the Parties serving as the meeting of the Parties to this Protocol as observers. Any body or agency, whether national or international, governmental or non-governmental, which is qualified in matters covered by this Protocol and which has informed the secretariat of its wish to be represented at a session of the Conference of the Parties serving as the meeting of the Parties to this Protocol as an observer, may be so admitted unless at least one third of the Parties present object. The admission and participation of observers shall be subject to the rules of procedure, as referred to in paragraph 5 above.

Article 14

1. The secretariat established by Article 8 of the Convention shall serve as the secretariat of this Protocol.

2. Article 8, paragraph 2, of the Convention on the functions of the secretariat, and Article 8, paragraph 3, of the Convention on arrangements made for the functioning of the secretariat, shall apply *mutatis mutandis* to this Protocol. The secretariat shall, in addition, exercise the functions assigned to it under this Protocol.

Article 15

1. The Subsidiary Body for Scientific and Technological Advice and the Subsidiary Body for Implementation established by Articles 9 and 10 of the Convention shall serve as, respectively, the Subsidiary Body for Scientific and Technological Advice and the Subsidiary Body for Implementation of this Protocol. The provisions relating to the functioning of these two bodies under the Convention shall apply *mutatis mutandis* to this Protocol. Sessions of the meetings of the Subsidiary Body for Scientific and Technological Advice and the Subsidiary Body for Implementation of this Protocol shall be held in conjunction with the meetings of, respectively, the Subsidiary Body for Scientific and Technological Advice and the Subsidiary Body for Implementation of the Convention.

2. Parties to the Convention that are not Parties to this Protocol may participate as observers in the proceedings of any session of the subsidiary bodies. When the subsidiary

bodies serve as the subsidiary bodies of this Protocol, decisions under this Protocol shall be taken only by those that are Parties to this Protocol.

3. When the subsidiary bodies established by Articles 9 and 10 of the Convention exercise their functions with regard to matters concerning this Protocol, any member of the Bureaux of those subsidiary bodies representing a Party to the Convention but, at that time, not a party to this Protocol, shall be replaced by an additional member to be elected by and from amongst the Parties to this Protocol.

Article 16

The Conference of the Parties serving as the meeting of the Parties to this Protocol shall, as soon as practicable, consider the application to this Protocol of, and modify as appropriate, the multilateral consultative process referred to in Article 13 of the Convention, in the light of any relevant decisions that may be taken by the Conference of the Parties. Any multilateral consultative process that may be applied to this Protocol shall operate without prejudice to the procedures and mechanisms established in accordance with Article 18.

Article 17

The Conference of the Parties shall define the relevant principles, modalities, rules and guidelines, in particular for verification, reporting and accountability for emissions trading. The Parties included in Annex B may participate in emissions trading for the purposes of fulfilling their commitments under Article 3. Any such trading shall be supplemental to domestic actions for the purpose of meeting quantified emission limitation and reduction commitments under that Article.

Article 18

The Conference of the Parties serving as the meeting of the Parties to this Protocol shall, at its first session, approve appropriate and effective procedures and mechanisms to determine and to address cases of non-compliance with the provisions of this Protocol, including through the development of an indicative list of consequences, taking into account the cause, type, degree and frequency of non-compliance. Any procedures and mechanisms under this Article entailing binding consequences shall be adopted by means of an amendment to this Protocol.

Article 19

The provisions of Article 14 of the Convention on settlement of disputes shall apply *mutatis mutandis* to this Protocol.

Article 20

1. Any Party may propose amendments to this Protocol.

2. Amendments to this Protocol shall be adopted at an ordinary session of the Conference of the Parties serving as the meeting of the Parties to this Protocol. The text of

any proposed amendment to this Protocol shall be communicated to the Parties by the secretariat at least six months before the meeting at which it is proposed for adoption. The secretariat shall also communicate the text of any proposed amendments to the Parties and signatories to the Convention and, for information, to the Depositary.

3. The Parties shall make every effort to reach agreement on any proposed amendment to this Protocol by consensus. If all efforts at consensus have been exhausted, and no agreement reached, the amendment shall as a last resort be adopted by a three-fourths majority vote of the Parties present and voting at the meeting. The adopted amendment shall be communicated by the secretariat to the Depositary, who shall circulate it to all Parties for their acceptance.

4. Instruments of acceptance in respect of an amendment shall be deposited with the Depositary. An amendment adopted in accordance with paragraph 3 above shall enter into force for those Parties having accepted it on the ninetieth day after the date of receipt by the Depositary of an instrument of acceptance by at least three fourths of the Parties to this Protocol.

5. The amendment shall enter into force for any other Party on the ninetieth day after the date on which that Party deposits with the Depositary its instrument of acceptance of the said amendment.

Article 21

1. Annexes to this Protocol shall form an integral part thereof and, unless otherwise expressly provided, a reference to this Protocol constitutes at the same time a reference to any annexes thereto. Any annexes adopted after the entry into force of this Protocol shall be restricted to lists, forms and any other material of a descriptive nature that is of a scientific, technical, procedural or administrative character.

2. Any Party may make proposals for an annex to this Protocol and may propose amendments to annexes to this Protocol.

3. Annexes to this Protocol and amendments to annexes to this Protocol shall be adopted at an ordinary session of the Conference of the Parties serving as the meeting of the Parties to this Protocol. The text of any proposed annex or amendment to an annex shall be communicated to the Parties by the secretariat at least six months before the meeting at which it is proposed for adoption. The secretariat shall also communicate the text of any proposed annex or amendment to an annex to the Parties and signatories to the Convention and, for information, to the Depositary.

4. The Parties shall make every effort to reach agreement on any proposed annex or amendment to an annex by consensus. If all efforts at consensus have been exhausted, and no agreement reached, the annex or amendment to an annex shall as a last resort be adopted by a three-fourths majority vote of the Parties present and voting at the meeting. The adopted annex or amendment to an annex shall be communicated by the secretariat to the Depositary, who shall circulate it to all Parties for their acceptance.

5. An annex, or amendment to an annex other than Annex A or B, that has been adopted in accordance with paragraphs 3 and 4 above shall enter into force for all Parties to this Protocol six months after the date of the communication by the Depositary to such Parties of the adoption of the annex or adoption of the amendment to the annex, except for those Parties that have notified the Depositary, in writing, within that period of their non-acceptance of the annex or amendment to the annex. The annex or amendment to an annex shall enter into force for Parties which withdraw their notification of non-acceptance on the ninetieth day after the date on which withdrawal of such notification has been received by the Depositary.

6. If the adoption of an annex or an amendment to an annex involves an amendment to this Protocol, that annex or amendment to an annex shall not enter into force until such time as the amendment to this Protocol enters into force.

7. Amendments to Annexes A and B to this Protocol shall be adopted and enter into force in accordance with the procedure set out in Article 20, provided that any amendment to Annex B shall be adopted only with the written consent of the Party concerned.

Article 22

1. Each Party shall have one vote, except as provided for in paragraph 2 below.

2. Regional economic integration organizations, in matters within their competence, shall exercise their right to vote with a number of votes equal to the number of their member States that are Parties to this Protocol. Such an organization shall not exercise its right to vote if any of its member States exercises its right, and vice versa.

Article 23

The Secretary-General of the United Nations shall be the Depositary of this Protocol.

Article 24

1. This Protocol shall be open for signature and subject to ratification, acceptance or approval by States and regional economic integration organizations which are Parties to the Convention. It shall be open for signature at United Nations Headquarters in New York from 16 March 1998 to 15 March 1999. This Protocol shall be open for accession from the day after the date on which it is closed for signature. Instruments of ratification, acceptance, approval or accession shall be deposited with the Depositary.

2. Any regional economic integration organization which becomes a Party to this Protocol without any of its member States being a Party shall be bound by all the obligations under this Protocol. In the case of such organizations, one or more of whose member States is a Party to this Protocol, the organization and its member States shall decide on their respective responsibilities for the performance of their obligations under this Protocol. In such cases, the organization and the member States shall not be entitled to exercise rights under this Protocol concurrently.

3. In their instruments of ratification, acceptance, approval or accession, regional economic integration organizations shall declare the extent of their competence with respect to the matters governed by this Protocol. These organizations shall also inform the Depositary, who shall in turn inform the Parties, of any substantial modification in the extent of their competence.

Article 25

1. This Protocol shall enter into force on the ninetieth day after the date on which not less than 55 Parties to the Convention, incorporating Parties included in Annex I which accounted in total for at least 55 per cent of the total carbon dioxide emissions for 1990 of the Parties included in Annex I, have deposited their instruments of ratification, acceptance, approval or accession.

2. For the purposes of this Article, "the total carbon dioxide emissions for 1990 of the Parties included in Annex I" means the amount communicated on or before the date of adoption of this Protocol by the Parties included in Annex I in their first national communications submitted in accordance with Article 12 of the Convention.

3. For each State or regional economic integration organization that ratifies, accepts or approves this Protocol or accedes thereto after the conditions set out in paragraph 1 above for entry into force have been fulfilled, this Protocol shall enter into force on the ninetieth day following the date of deposit of its instrument of ratification, acceptance, approval or accession.

4. For the purposes of this Article, any instrument deposited by a regional economic integration organization shall not be counted as additional to those deposited by States members of the organization.

Article 26

No reservations may be made to this Protocol.

Article 27

1. At any time after three years from the date on which this Protocol has entered into force for a Party, that Party may withdraw from this Protocol by giving written notification to the Depositary.

2. Any such withdrawal shall take effect upon expiry of one year from the date of receipt by the Depositary of the notification of withdrawal, or on such later date as may be specified in the notification of withdrawal.

3. Any Party that withdraws from the Convention shall be considered as also having withdrawn from this Protocol.

Article 28

The original of this Protocol, of which the Arabic, Chinese, English, French, Russian and Spanish texts are equally authentic, shall be deposited with the Secretary-General of the United Nations.

DONE at Kyoto this eleventh day of December one thousand nine hundred and ninety-seven.

IN WITNESS WHEREOF the undersigned, being duly authorized to that effect, have affixed their signatures to this Protocol on the dates indicated.

Annex A

<u>Greenhouse gases</u>

Carbon dioxide (CO_2)
Methane (CH_4)
Nitrous oxide (N_2O)
Hydrofluorocarbons (HFCs)
Perfluorocarbons (PFCs)
Sulphur hexafluoride (SF_6)

<u>Sectors/source categories</u>

Energy
- Fuel combustion
  - Energy industries
  - Manufacturing industries and construction
  - Transport
  - Other sectors
  - Other
- Fugitive emissions from fuels
  - Solid fuels
  - Oil and natural gas
  - Other

Industrial processes
- Mineral products
- Chemical industry
- Metal production
- Other production
- Production of halocarbons and sulphur hexafluoride
- Consumption of halocarbons and sulphur hexafluoride
- Other

Solvent and other product use

Agriculture
- Enteric fermentation
- Manure management
- Rice cultivation
- Agricultural soils
- Prescribed burning of savannas
- Field burning of agricultural residues
- Other

Waste

Solid waste disposal on land
Wastewater handling
Waste incineration
Other

Annex B

Party	Quantified emission limitation or reduction commitment (percentage of base year or period)
Australia	108
Austria	92
Belgium	92
Bulgaria*	92
Canada	94
Croatia*	95
Czech Republic*	92
Denmark	92
Estonia*	92
European Community	92
Finland	92
France	92
Germany	92
Greece	92
Hungary*	94
Iceland	110
Ireland	92
Italy	92
Japan	94
Latvia*	92
Liechtenstein	92
Lithuania*	92
Luxembourg	92
Monaco	92
Netherlands	92
New Zealand	100
Norway	101
Poland*	94
Portugal	92
Romania*	92
Russian Federation*	100
Slovakia*	92
Slovenia*	92
Spain	92
Sweden	92
Switzerland	92
Ukraine*	100
United Kingdom of Great Britain and Northern Ireland	92
United States of America	93

* Countries that are undergoing the process of transition to a market economy.

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