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Review

A review of remote sensing technology in support of the Kyoto Protocol

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Abstract

This paper presents an overview of the role of remote sensing technology in the context of the United Nations Framework Convention on Climate Change (UNFCCC) Kyoto Protocol and is based largely on discussions held at an international workshop in MI, USA, and the report that followed [A. Rosenqvist, M. Imhoff, T. Milne, C. Dobson (Eds.), Remote Sensing and the Kyoto Protocol: A Review of Available and Future Technology for Monitoring Treaty Compliance, Workshop Report, Ann Arbor, MI, USA, 20–22 October 1999, 2000a, 159 pp. Available at http://www.eecs.umich.edu/kyoto]. The implications of significant decisions pertaining to the definition of the key terms *forest* and afforestation, reforestation and deforestation (ARD) activities taken at the conference of parties (COP 6:2 and COP 7) meetings in Bonn and Marrakesh, respectively in 2001 are also discussed. Past, current and near-future remote sensing instruments with applications appropriate to Kyoto requirements are short listed; research topics that need to be advanced to support use of these are outlined, and future actions recommended.

Keywords: Kyoto Protocol; Remote sensing; Verification; Compliance; ARD

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1. Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) contains quantified and legally binding commitments to limit or reduce greenhouse gas emissions to 1990 levels. The protocol allows sinks associated with vegetation growth and expansion to be included to offset carbon emissions, which in turn raises debate about the adequacy of existing methods for establishing reliable estimates of 1990 carbon stocks/sinks levels and for measuring and monitoring current and future carbon stock/sinks. The role of remote sensing is therefore under scrutiny given its potential capacity for systematic observations at scales ranging from local to global and for the provision of data archives extending back over several decades. These issues also underscore a need for the exchange of information between remote sensing scientists and organisations (e.g. national and international policy makers, government agencies and both legal and scientific bodies) involved in the development and implementation of the protocol.

In October, 1999, two working groups of the International Society for Photogrammetry and Remote Sensing (ISPRS) joined with the University of Michigan (MI, USA) to convene discussions on how remote sensing technology could contribute to the information needs required for the implementation of the Kyoto Protocol and compliance with its terms. The workshop, which was attended by representatives from national government agencies, international organisations and academic institutions, set out to review the Kyoto Protocol and to identify areas where remote sensing technology could provide support; to review current and near future remote sensing technologies that could support the information requirements identified; and to highlight shortcomings and areas where additional research would be necessary. In addition, legal aspects of trans-national remote sensing in the context of the Kyoto Protocol were investigated.

2. Remote sensing relevance to the Kyoto Protocol

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

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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% below 1990 levels in the five-year commitment period 2008 to 2012”. Emissions of six greenhouse gases (measured in terms of carbon dioxide (CO_2) equivalents as a function of the gases global warming potential) are covered by the Kyoto Protocol; CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Of these gases, remote sensing is (at present) best equipped to quantify changes in CO_2 and, to a certain extent, CH_4, particularly in relation to land use, land use change and forestry (LULUCF) activities.

A major benefit of using remote sensing data to support calculations of emissions is that systematic observation systems are provided and historical archives of data exist, which can be augmented through current and future data acquisitions. As such, remote sensing can (to some extent) meet the requirements of Article 10, which highlights the importance of developing such systems and archives for monitoring and assessing status and trends in the global terrestrial carbon budget.

Remote sensing can also play a role in the establishment of national carbon stock baseline datasets and assessment of change in stocks. Such datasets are implicit requirements under Article 3, which introduces the need to quantify afforestation, reforestation and deforestation (ARD; Article 3.3), revegetation and land use management (under specified categories; Article 3.4) and to establish a baseline of carbon stocks for 1990 (Article 3.1; where 1990 is regarded as the starting point for accounting) against which to assess change. A role for remote sensing was also identified in relation to Articles 4 and 12, which outline the rules for emission trading between Annex-I Parties (by way of joint implementation) and between Annex-I and non-Annex-I Parties (by way of the clean development mechanism (CDM)).

References to CH_4 in the protocol are few and the role of significant anthropogenic CH_4 sources (e.g. through rice irrigation, aquaculture and hydroelectric reservoirs) is not explicitly mentioned. Directives for accounting for such CH_4 sources may, however, be included in the future and the role of remote sensing is therefore considered.

3. Implications of the Bonn Agreements and Marrakesh Accords

Although remote sensing data can be used to support the Kyoto Protocol, the utility of these data is dictated largely by protocol definitions and requirements, which are clarified in the following sections.

3.1. Definitions of land use

A point of uncertainty impeding the assessment of emissions was the lack of specific definitions relating to some of the key terms referred to in the original version of the protocol. For this reason, the characterisation of “forest”, ARD terms (under Article 3.3) and other points of uncertainty were clarified at the conference of parties (COP) meetings in Bonn and Marrakesh in 2001.

Significantly, the Bonn Agreements (UNFCCC, 2001a) state that forest and ARD activities shall be defined on the basis of change in *land use* (Annex, VII/2) rather than *land cover*, as observed through remote sensing. This implies that remote sensing data may not be used directly to distinguish land belonging to either “forest” or the inverse “non-forest” category and, in turn, recognition of A, R or D as changes between these categories. As an example, a clear-felled area that is “expected to revert to forest” will (according to this terminology) remain within the forest class and the action will not be accounted for as deforestation in the Kyoto sense. The distinction of “Kyoto ARD” events from other changes in forest cover will not therefore be possible using remote sensing data alone, and additional land-based in situ information will be required. Likewise, as only *direct human-induced* ARD events are to be accounted for, remote sensing data will have to be used synergistically with other sources of information.

3.2. Forest and ARD

Forest has been defined in the Marrakesh Accords (UNFCCC, 2001b) as a minimum area of land of 0.05–1.0 ha with tree crown cover, or equivalent stocking level, of more than 10–30% and containing trees with the potential to reach a minimum height of 2–5 m at maturity. Young natural stands, all plantations and harvested areas “temporarily” below the thresholds applied but which are *expected* to grow or revert to forest, are to be included under the forest category (UNFCCC, 2001b). The definition to be adopted by any one country is optional within the intervals given for minimum area and crown cover, implying that the (remote sensing) observation requirements will vary between countries. The minimum area specified (0.05–1.0 ha) implies observation at a minimum effective ground resolution requirement of magnitude 20–25 to 100 m.

Afforestation is the direct human-induced conversion of land that has not been forested for a period of at least 50 years, while *reforestation* implies conversion of land that once was forested, but that had been converted to non-forested land. For the first commitment period, reforestation activities are limited to reforestation occurring on those lands that did not contain forest on 31 December 1989. *Deforestation* is simply defined as the direct human-induced conversion of “forest” to “non-forest” (UNFCCC, 2001b).

3.3. Revegetation and land management

As an option, revegetation, forest management, cropland management and grazing land management may, according to the Bonn Agreements, also be accounted for under Article 3.4 and during the first commitment period (UNFCCC, 2001a).

Revegetation is an activity which does not meet the definition of either afforestation or reforestation, but which aims to increase carbon stocks (on sites larger than 0.05 ha) through the establishment of vegetation (UNFCCC, 2001b). While the carbon stock levels presumably remain within the "non-forest" category, the detection and monitoring of such areas may be undertaken by remote sensing.

Forest management is defined as a system of practices for stewardship and use of forested lands aimed at fulfilling relevant ecological, economic and social functions of the forest in a sustainable manner. *Cropland management* is the system of practices on agricultural land and on land that is set aside or temporarily not being used for crop production; *grazing land management* is the system of practices on land used for livestock production aimed at manipulating the amount and type of vegetation and livestock produced (UNFCCC, 2001b). While the three management categories and the "systems of practices" referred to do not rule out the potential use of remote sensing, the definitions are presently too general to establish clear strategies.

3.4. The clean development mechanism

The CDM is intended to encourage, through transfer of technology and capacity building, sustainable development of Annex-I countries and to enable these countries to meet part of the Kyoto commitments through abatement projects in non-Annex-I countries. At COP 6:2 in Bonn, it was determined that afforestation and reforestation projects may optionally be accounted for under the CDM (Article 12). The decision concerns the first commitment period only and the regulations for CDM in subsequent commitment periods are to be decided as a part of future negotiations between the parties (UNFCCC, 2001a).

The inclusion of LULUCF projects under CDM is, from the remote sensing perspective, a significant decision which, amongst others, implies an extension of eligible lands in the Kyoto context, from Annex-I territory only, to encompass areas in all ratifying countries. A key and notable issue is that eligible LULUCF activities comprise afforestation and reforestation projects whilst deforestation activities are excluded. This omission raises the possibility that forest accumulation through the CDM may result in deforestation elsewhere, or that deforestation may precede a CDM project. There is thus a need for a surveillance system to document the past and future land use history—a task in which remote sensing can be expected to play a significant role. As information about CDM projects, including start-dates, areal coverage and geographic locations are not publicly available—at least not at present—repetitive observations with extensive global coverage will be required.

4. The contribution of remote sensing

Over the past half century, a range of airborne and space-borne sensors has acquired remote sensing data, with the number of sensors and their diversity of capability increasing over time. Today a large number of satellite sensors observe the Earth at wavelengths ranging from visible to microwave, at spatial resolutions ranging from sub-metre to kilometres and temporal frequencies ranging from 30 min to weeks or months. In addition, archives of remotely sensed data are increasing and provide a unique, but not complete, chronology of the Earth during this time period. New sensors are continually being launched and existing sensors are often replaced to ensure continuity in the data record. Given this enormous resource, there seems potential for remote sensing to assist countries meet their obligations under the Kyoto Protocol.

Five major areas have been identified where remote sensing technology could be applied to support implementation of the treaty:

- provision of systematic observations of relevant land cover (Articles 5 and 10);
- support to the establishment of a 1990 carbon stock baseline (Article 3);
- detection and spatial quantification of change in land cover (Articles 3 and 12);
- quantification of above-ground vegetation biomass stocks and associated changes therein (Articles 3 and 12);
- mapping and monitoring of certain sources of anthropogenic CH_4 (Articles 3, 5 and 10);
- the application of remote sensing to each of these areas is outlined in the following sections.

4.1. Provision of systematic, repetitive and consistent observations

Remote sensing instruments are capable of providing systematic observations of land cover, repeatedly and consistently, as implied under Articles 5 and 10. Optical sensors providing systematic observations at the regional/global level and at coarse ($\geq$1 km) spatial resolution include the NOAA advanced very high resolution radiometer (AVHRR) and SPOT VEGETATION. At finer (10–30 m) spatial resolution, Landsat sensor (currently the Enhanced Thematic Mapper Plus or ETM+) and SPOT sensor (currently the high resolution visible infrared or HRVIR) data can be combined to provide regional and even continental level observations. The Terra-1 Moderate Resolution Imaging Spectroradiometer (MODIS) and ADEOS II Global Land Imager (GLI) represent a new generation of medium (250–500 m) spatial resolution sensors and an important bridge between those observing at fine and coarse spatial resolutions.

The frequency of observation by optical sensors ranges from several times daily (e.g. NOAA AVHRR) to every 16–18 days (e.g. Landsat ETM+) although cloud cover, haze and smoke often limit the number of usable scenes. These limitations can be overcome using fine (10–20 m) space-borne synthetic aperture radar (SAR) sensors that observe under all weather conditions and also during day and night. Key sensors include the European Resources Satellite (ERS-1/2), RADARSAT-1/2, the Japanese Earth Resources Satellite (JERS-1) SAR and the ENVISAT Advanced SAR (ASAR). These sensors have the capacity to provide more consistent coverage at continental scales and over short timeframes—if systematic acquisition strategies are implemented–and their use for regional-scale vegetation mapping has been demonstrated both for the tropics and the boreal zone (Rosenqvist et al., 2000b; Schmullius et al., 2001).

Data from both optical and SAR sensors are available to support the requirements of the Kyoto Protocol on a long-term basis. As time progresses, archives of these data are augmented allowing long-term continuity of observation and chronicling of land cover change. As examples, data from the NOAA, Landsat and SPOT sensors are available from the 1960s, early 1970s and mid 1980s, respectively and continuation of these archives is anticipated given the planned launch of Landsat-8 and NOAA AVHRR successors. New sensors are often designed such that data are inter-comparable (in terms of their spectral, temporal and spatial resolutions) with their predecessors, and successful deployment and provision of data by several (e.g. Terra-1 ASTER and MODIS) is likely to render these as key complementary or supplementary land observing systems in future years.

Although space-borne sensors can provide ample data, the systematic acquisition of data is essential to optimise support for the Kyoto Protocol and climate change research (as addressed by the UNFCCC). For fine spatial resolution optical and SAR sensors, which operate at local to regional rather than continental scales, observations at similar times (i.e. seasons) within and between years is critical and "random" observations should be discouraged. Although most satellite operators have performed dedicated acquisition campaigns for certain regions, repetitive regional-scale monitoring over longer time periods is essential (Rosenqvist et al., 2003). However, to achieve this, a federated multi-national approach with common goals and thematic definitions is required, and schemes such as those undertaken within the framework of the global observations of forest cover (GOFC) pilot project (now under the auspices of FAO GTOS; Ahern et al., 1998) should be encouraged.

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

Article 3:4 of the Kyoto Protocol states that 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, Article 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". Hence, baselines formulated after 1990 may (for certain countries) be considered. Nevertheless, as 1990 is expected to be the dominant base year, the selection of sensors used to support the establishment of this base line dataset will be limited to those in operation during or in proximity to that year.

Among the fine spatial resolution optical sensors providing local to regional observations, only Landsat TM and SPOT High Resolution Visible were in operation in 1990. The use of these data for compiling a regional 1990 land cover map to support the establishment of the carbon stock baseline is realistic, particular at a national level and for smaller countries or regions. Furthermore, the cost of historical data from these sensors has generally been lowered in recent years. An assessment of land (vegetation) cover in 1990 can be made using these data, although carbon stocks are less easily quantified for several reasons. First, relationships established between vegetation biomass (carbon stocks) and data from optical sensors are generally weak. Second, in many countries, biomass data are often sparse and inaccurate and generally insufficient to quantify the carbon stocks of the diverse range of vegetation types/covers mapped using such remote sensing data, particularly where a wide range of regeneration and degradation stages exist.

An alternative approach is to use coarser resolution remote sensing data acquired during or in proximity to 1990 to generate the baseline datasets. As an example, a Global Land Cover map (for 1992) was generated from 1 km NOAA AVHRR data within IGBP DIS. Archives of NOAA AVHRR data are also available to assist establishment of a 1990 baseline (Belward et al., 1999; Townshend, 1994). However, to be useful, land cover classes need to be re-defined and adapted to classes relevant to the Kyoto Protocol. An more involved approach would be to integrate data from both fine and coarse spatial resolution systems to provide greater detail in areas of change and less in areas of no-change.

No orbital active microwave systems were in operation in 1990 and the use of SAR data to support a 1990 baseline is generally not feasible. Even so, established relationships between JERS-1 SAR data and above ground biomass (Luckman et al., 1998; Lucas et al., 2000) could be used to generate baseline datasets of regenerating forest biomass for any period between 1992 and 1998 (i.e. the active operation period) which could subsequently be backdated to 1990 using knowledge of vegetation biomass accumulation rates (obtained either through field observations or productivity models) and information on land use change over the intervening period. For non-1990 baseline countries in the tropical and boreal zones of the Earth, continental scale (100 m resolution) JERS-1 SAR mosaics from 1995–1996, generated within the Global Forest Mapping projects (Rosenqvist et al., 2000b), could support the establishment of a mid-1990s carbon baseline.

A major limitation of SAR systems with respect to vegetation mapping is their sensitivity to surface topography, which limits their general 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 on the other reduces the effective ground resolution—typically by a factor of 3 to 4. As a result, effective resolutions in the order of 50–100 m are generally the best that past, current and near future space-borne SAR systems can provide.

4.3. Detection and spatial quantification of change in land cover

Articles 3.3, 3.4 and 12 are indirectly concerned with the identification and spatial quantification of areas affected by ARD, including changes resulting from fire and revegetation. The issue of biomass quantification is discussed in Section 4.4. While the accounting of land cover change is limited to direct human-induced changes, all disturbances and changes initially need to be identified before the human-induced ones can be distinguished. As mentioned previously, distinction between natural and human-induced changes cannot be performed using remote sensing data alone and contemporary in situ information may often be required for this task. Nevertheless, the identification of land cover changes (both natural and human-induced), and hence potential ARD, is still considered a valid and major contribution that remote sensing can make in the context of the protocol.

To detect land cover change effectively, image acquisitions on a repetitive basis are required and data from Landsat and SPOT sensors are well suited for this purpose. Observations should preferably occur on an annual basis and at a similar time of year to minimise the effects of seasonality in the data. In regions where rates of vegetation change are low or less easily detected (e.g. through low rates of regeneration), observations over 5-year periods may be sufficient. Spatial resolutions less than ∼20–25 m are generally required to detect changes in the smallest Kyoto land parcels at 0.05 ha, although integration within coarser spatial resolution data may be useful for detecting large disturbances or changes in land cover.

Techniques for detecting and spatially quantifying types of deforestation (D) activities that lead to removal of the entire forest canopy and stock (e.g. clear felling or severe fires) are reasonably well established. However, gradual degradation/decrease of vegetation through thinning or selective logging (D) or gradual vegetation increase through growth (A, R or revegetation) is generally more difficult to discern, and longer time series (i.e. several years or even decades) of satellite sensor data are often needed. Furthermore, as A, R and revegetation often occur in relative small patches within non-forest areas, extensive monitoring of these non-forest areas is an implied requirement.

Establishing a consistent remote sensing approach for identifying when an area passes the crown closure threshold of 10–30% (and thereby changes from "forest" to "non-forest" or vice versa) is critical to the Kyoto Protocol. The approaches adopted are, however, likely to vary depending upon the country and biota considered and also the characteristics of the observing sensor(s). In many cases, it is anticipated that accuracy in the determination of the threshold will be insufficient for Kyoto requirements and field verification will be necessary.

For estimating canopy closure, optical systems are more likely to be useful as data acquired in visible, near infrared and short wave infrared wavelength regions are more sensitive to the structure and closure (including the absorbed photosynthetically active radiation (APAR)) of the vegetation canopy. Indices such as foliage projected cover (FPC), canopy projected cover (CPC) and leaf area index (LAI) can be quantified using optical data (Kuhnell et al., 1998) and changes in these indices may reflect the nature of ARD activities and the impacts of, for example, fire damage.

In many cases, repetitive (annual and/or seasonal) measurements will generally be required to detect forest change activities, particularly in rapidly changing environments. However, regional to global observation using fine spatial resolution data is demanding of time and resources and a more efficient approach would be to utilise coarser spatial resolution sensors with shorter revisit cycles and larger swaths for identifying "hot spots" of change. Once identified, the extent of the changes in these areas could be investigated further using finer spatial resolution data (Achard et al., 1997). Sensors (e.g. AVHRR, ATSR) observing in the mid infrared (∼3.55 μm wavelength) are particularly useful for detecting hotspots of changes as, at these wavelengths, fires are easily detected and often signal a change in land cover at regional (Barbosa et al., 1998, 1999) and/or global (Dwyer et al., 1998; Grégoire et al., 1998; Stroppiana et al., 2000; Pinnock and Grégoire, 2000) scales.

Space-borne SAR data may also prove useful for detecting land cover change and quantifying canopy closure. For example, shorter wavelength (∼5.5 cm) C-band and longer wavelength (∼23.5 cm) L-band and SAR backscatter data are sensitive to the amount of foliage/small branches and woody (branch/trunk) components respectively and time-series of these data could be used for quantifying changes in vegetation through ARD activities. Even so, confusion with rough surfaces and herbaceous grasslands may occur at C-band. If limited to one band, the detection and quantification of ARD areas is best addressed using longer wavelength L-band SAR systems, which are more sensitive to the range of vegetation structures associated with different growth stages of forests. The integration of longer and shorter wavelength SAR data also improves the capacity for vegetation distinction as demonstrated through studies using the 1994 multi-band, polarimetric space Shuttle Imaging Radar (SIR-C SAR) data (Ranson and Sun, 1994; Way et al., 1994). Although no space-borne multi-band missions are yet planned, polarimetric and dual-band data will be available in the near future by the synergistic use of the Advanced Land Observing Satellite (ALOS) Phased Array L-band SAR (PALSAR), and the C-band ENVISAT Advanced SAR (ASAR) and RADARSAT-2/3 SAR. A prerequisite for successful utilisation of data from different sensors however, is that the data are acquired during the same time periods, thus calling for joint observation campaigns and close collaboration between satellite operators, which currently is not the case.

To the extent that short-repeat observations of C-band data can be obtained, a technique based on interferometric coherence can be applied to significantly improve C-band sensitivity to biomass and thus changes in canopy cover and land cover (Treuhaft et al., 1996; Wegmüller and Werner, 1997). Coherence measurements require that SAR observations occur over a short (1 day) repeat period and such interferometric (tandem) datasets have been provided by the ERS-1 and ERS-2 SAR sensors. RADARSAT-2/3 SAR provide the next potential opportunity for tandem operations (Lee and James, 2001).

An advantage of SAR data for detecting land cover change is that data takes can be timed accurately due to their all-weather capability, thereby optimising conditions for detecting changes in land cover. Even so, ground conditions (e.g. moisture in the soil and on vegetation following rainfall) can impact on the SAR response and repetitive data acquisitions therefore need to be planned (e.g. for a specific month or season) such that seasonal bias in the time series is avoided (Rosenqvist et al., 2003). 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.

As long as imaging laser infrared detection and ranging (LIDAR) systems from space are unavailable, detection of ARD activities and burn scars will be limited using this technology. As such, the feasibility of using LIDAR to address ARD events for extensive areas is (as yet) unproven. However, LIDAR should provide the capacity to repeatedly characterise structural attributes at specific locations or collect sample sets in known ARD areas (Blair et al., 1999).

4.4. *Quantifying above-ground vegetation biomass stocks and changes in stocks*

In the context of ARD (Article 3.3) and the CDM (Article 12), direct estimation of changes in biomass stocks using remote sensing data is of prime interest. A wide range of approaches have been proposed for quantifying biomass using optical, SAR and LIDAR systems, although no studies have yet presented a technique that is consistent, reproducible and applicable at regional or continental scales.

Using optical data, direct measurement of total above ground biomass stocks, or changes in such, have not been achieved. Indirect estimates have nevertheless been generated; with most relying on (either singly or in combination) empirical relationships established with vegetation indices (e.g. the normalised difference vegetation index (NDVI)), canopy cover measurements (e.g. FPC) and reflectance data in the red, NIR and/or SWIR regions. Photosynthetically active radiation (PAR) has also been estimated routinely from multi-spectral sensors and has, in some studies (e.g. Asrar et al., 1984; Tucker and Sellers, 1986; Prince and Goward, 1995), been combined with environmental data and/or forest growth models to predict net primary productivity (NPP). More recently, the use of multi-angular measurements (e.g. from the Terra-MISR instrument) has shown promise for indirectly quantifying biomass (Martonchik et al., 1998).

For some time, the potential of SAR data for quantifying the above ground biomass of vegetation has been demonstrated and Kasischke et al. (1997) provide a comprehensive review of the use of imaging SAR for biomass estimation and other ecological applications. The SAR response from vegetation varies with wavelength and polarisation and is dependent largely upon the size, dielectric constant (which relates to moisture content) and the geometry of leaves, branches and trunks and the roughness and moisture content of the underlying surface. At C-band, microwaves interact largely with the leaves and smaller branches and are generally not well suited to biomass estimation, particularly as saturation of the signal occurs at approximately 20–30 $\mathrm{Mg\,ha^{-1}}$. At L-band microwaves penetrate the leaves and smaller branches and interact with larger woody components, particularly branches. Depending upon attenuation in the crown layer and the openness of the vegetation, interaction with trunks may occur. Saturation of the L-band return tends to occur at approximately 60–100 $\mathrm{Mg\,ha^{-1}}$, depending upon the species type and biota (Dobson et al., 1992; Imhoff, 1995; Luckman et al., 1998).

Space-borne SAR typically operate at C- and L-band. The saturation of C- and L-band data at relatively low levels of biomass limits the use of these data for routinely quantifying biomass, particularly as the majority of forests and woodlands globally support an above ground biomass of $>100\,\mathrm{Mg\,ha^{-1}}$. Even so, these data may be useful for quantifying the biomass of vegetation $<100\,\mathrm{Mg\,ha^{-1}}$, particularly those associated with A, R and revegetation activities after 1990. While the “biomass equivalent” forest/non-forest threshold will vary within and between regions and biota, the threshold nevertheless is generally set low and for a majority of areas can be expected to lie within the sensitivity range of L-band SAR. The combination of C- and L-band and also optical data may also be useful for discriminating regenerating forests with high leaf/canopy cover and low woody biomass (Lucas et al., 2003a). Improved C-band sensitivity to biomass has also been achieved using interferometric techniques (Askne et al., 1997; Santoro et al., 1999), although the accuracy is largely dependent on factors such as the orbit and surface conditions, and more research is required before the technique might become operational.

Time-series of SAR data, in particular at L-band, is suitable for detecting areas of change and establishing relative estimates of incremental biomass change. The integration of spatial information on land use change (derived from time-series comparison of remote sensing data), species/community composition (derived from classification of reflectance data) and biomass (derived from SAR data) can also be used to better understand, quantify and predict rates of biomass accumulation and turnover (Lucas et al., 2003b).

The ability to retrieve biomass is enhanced when fully polarimetric SAR data are acquired. Such data are provided largely using sensors onboard airborne platforms (e.g. NASA Jet Propulsion Laboratory's (JPL) AIRSAR or the ESA's E-SAR). Several of these sensors also observe at longer P-band (∼68 cm) wavelengths, which are able to penetrate further into the canopy and interact largely with trunks and larger branches, and saturation occurs at higher levels of biomass up to ∼150–200 Mg ha^{-1} (Ranson et al., 1997). These polarimetric systems provide cross-polarised (HV) data, which generally have a large dynamic range and exhibit greater sensitivity to canopy structures. Several studies (e.g. Dobson et al., 1995) have tried to extend the range of biomass that can be estimated by relating SAR backscatter at different wavelengths and polarisation's to the biomass of components (i.e. leaves, branches and trunks).

Though using polarimetric data, alternative approaches to biomass estimation have been advocated. Saatchi and Moghaddam (2000), for example, presented a semi-empirical approach to the estimation of biomass through evaluating the contribution, through different scattering mechanisms, of different components of the vegetation (stem and canopy) to the SAR return. More recently, Moghaddam and Lucas (2003) have demonstrated the potential of SAR inversion modelling for quantifying vegetation biomass from polarimetric SAR data.

The use of polarimetric C- and L-band SAR data is anticipated to increase with the dual polarimetric ENVISAT ASAR and the forthcoming dual polarimetric/fully polarimetric ALOS PALSAR (L-band) and RADARSAT-2/3 (C-band). The potential for mapping ARD activities and quantifying vegetation biomass, either through empirical or semi-empirical (inversion) approaches, may be enhanced considerably by the introduction of such data.

Although space-borne P-band SAR systems have been proposed, questions over the ionospheric effects on these and other low frequency radars have not been resolved. These effects relate to understanding the impact of total electron content (TEC) in the ionosphere, which results in deformation and polarimetric rotation of the transmitted signal (Kim and van Zyl, 1999; Ishimaru et al., 1999). Such polarimetric rotation may be corrected using a fully polarimetric system (Siqueira et al., 2000), while other ionospheric artefacts may be reduced to acceptable levels by accurate timing of the data acquisition (dawn/dusk) when TEC is at minimum (Snoej et al., 2001).

Airborne SAR systems operating in VHF-band, with even longer wavelengths than P-band are potentially the most useful for directly measuring and quantifying biomass as tree trunks act as the dominant scatterers and linear relationships between the SAR return and trunk volume has been observed. Results from the airborne CARABAS (wavelength 3.3–15 m; Ulander, 1998), deployed in temperate and boreal forests in Europe, and the BioSAR system (2.5–3.75 m; 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 up to 500 Mg ha^{-1}. Saturation of the two systems has not yet been encountered and remains to be determined. The sensitivity to surface topography is less than for shorter wavelength SAR and topographic effects can, to a large extent, be corrected (Smith and Ulander, 2000). These systems show great promise for local to sub-regional applications using aircraft. However, the deployment of space-based VHF sensors is not technically feasible due to ionospheric interference with the signal and its potential 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 could have an endurance of 6 months to 5 years using combinations of solar and fuel cell technologies.

LIDAR technology has only recently been explored for vegetation characterisation and mapping. The LIDAR transmits a vertical near infrared (NIR) laser pulse towards the land surface which then reflects from objects and returns to the sensor. The delay in time between the transmission and receipt of the pulse is related directly to distance and hence the height of objects (e.g. tree crowns) and the ground surface can be retrieved. LIDAR footprint sizes may vary from 0.25 to 5 m with accuracies of <25 cm in elevation achievable. Using small footprint laser, strong relationships with variables such as tree height, stem volume, biomass and canopy closure have been obtained (Tickle et al., 2003). Large footprint LIDAR are able to provide a complete waveform of reflected light allowing attributes such as stem diameter, basal area, stem volume and above ground biomass to be retrieved (Means et al., 1999; Weishampel et al., 2000). Such sensors are currently available on airborne platforms (Blair et al., 1999). A space-borne instrument, the vegetation canopy lidar (VCL), has been planned (Dubayah et al., 1997), although the launch has been postponed indefinitely. The VCL is not an imaging instrument but has been designed to collect a series of point samples along the flight path. Thematic products could only be foreseen if these data are used in combination with other spatially extensive data (e.g. optical or SAR).

Combined with allometric models, which approximate component or total biomass from measurable parameters such as tree height, diameter and canopy closure, point data collected by LIDAR systems relating to height and canopy dimensions can also facilitate measurements of above ground biomass to acceptable levels of accuracy. Interpolation of LIDAR-derived estimates of biomass may then be undertaken in conjunction with SAR and optical data

(Lucas et al., 2003a). A recognised limitation of LIDAR, however, is that tree species/genera cannot be discriminated from the signal return and as wood density (and hence biomass) varies between tree species of similar height and age, biomass estimates may be less accurate from LIDAR alone. Even so, integration of LIDAR with hyperspectral data (e.g. from the compact airborne spectrographic imager (CASI) instrument), from which tree species can be discriminated, may allow this information to be incorporated.

4.5. Mapping and monitoring of certain sources of anthropogenic CH_4

The mapping and monitoring of certain sources of anthropogenic CH_4 is 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 emitted as a result of anaerobic decomposition in open water bodies following extended periods of inundation. Typical anthropogenic sources of CH_4 include irrigated rice paddies, aquaculture (e.g. fish and shrimp cultivation) and hydroelectric reservoirs. CH_4 is also emitted through burning of vegetation.

Detection and spatial quantification of open water bodies, such as those used for aquaculture and hydroelectric reservoirs, can be undertaken using single date fine spatial resolution optical sensors (e.g. SPOT HRVIR). Rice paddies may also be identified in a single date image although repetitive measurements during the growth season are recommended for allowing discrimination from other agricultural crops and to monitor changes in the water regime, a key factor triggering the CH_4 emissions. However, cloud cover may, in the latter case, constitute an obstacle to obtaining relevant multi-temporal data. SAR data are also well suited for multi-temporal monitoring of irrigated rice, as regular acquisitions can be performed irrespective of weather conditions. Both C- 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 SAR, ENVISAT ASAR and RADARSAT-1 SAR) as well as those planned in the near future (ALOS PALSAR and RADARSAT-2 SAR). Estimates of CH_4 emissions from fire may also be refined using datasets on burning patterns and burnt area, as derived from optical and/or SAR data. The use of LIDAR for estimating CH_4 emissions has not, as yet, been considered.

5. The requirement for in situ data

For all applications discussed, up-to-date, quantifiable, in situ data are needed for development of algorithms for quantifying land cover, land cover change, biomass and sources of anthropogenic CH_4 and validating derived products. 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 is generally a painstaking, time consuming and expensive endeavour, the relevance of in situ data cannot be over-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 that estimate, for example, biomass from tree size (e.g. height) measurements. A key concept is that allometric equations may be similar for a number of genera at any one site 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 and global application and could be used to further the interpretation of remote sensing data and validation of data products. Cost effective and efficient methods of quantifying component biomass in the field also need to be developed further.

6. Accessibility and affordability

Over the last two decades there has been a revolution in the way information about the environment is acquired, processed and stored, which has centred on the use of computer technology for data collection and manipulation, including the ability to spatially integrate, interrogate and analyse the nature of the relationships that exist with co-located data. Remote sensing, together with the use of geographic information systems (GIS) and global positioning systems (GPS), has played a key role in this development and has had a significant impact on the way local, regional and global data about the environment are acquired and analysed.

The major characteristics of 'geographic information' are that the feature or object in question can be located accurately, its dimensionality can be captured and it can be measured and described. Given that attributes about objects are obtained through remote sensing, it is important that the processed 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 modelling real world vegetation (including forest) scenarios. GIS provides such a facility. The connectivity afforded by these systems is important because applications require not only an interdisciplinary approach, but also the integration of information derived from a variety of sources which span the physical and human sciences.

The development of such decision-support systems for vegetation assessment and analysis activities is jeopardised by difficulties arising out of *operational* constraints, namely accessibility, affordability and timeliness and from *infrastructure* problems related to poor management, inadequate staffing and lack of training opportunities within country agencies. Appropriate government policies and institutional frameworks therefore need to be introduced to address these limitations and to facilitate further applications research, training and education.

Accessibility and affordability of remote sensing and related technologies 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 having access to both optical and SAR remote sensing for vegetation, biomass and vegetation change analysis.

Strengthening the institutional infrastructure capabilities of countries and organisations involved in implementing the protocol, needs collaborative technology transfer programs in which the ideas, skills and operational procedures necessary to utilise remote sensing and spatial information technologies are shared. 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 remote sensing 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 vegetation analysis and biomass estimation exists, need to be become involved in sharing the necessary data, skills and operational procedures with those wishing to upgrade their national capability for using this technology.

As always, the cost incurred in acquiring remotely sensed data constitutes a major problem for many developing countries. This is likely to become a major constraint in the future as more and more governments opt out of the role of data provider, preferring instead to hand this over to private sector groups. Equity of access to remotely sensed data continues to be an issue that has not been adequately addressed by the international community.

7. Research topics

While remote sensing technology stands alone in being able to provide regional-global scale data acquisition schemes and comparable datasets, it can not yet be considered operational in more than a handful of applications relevant to the Kyoto Protocol. Furthermore, it is important to acknowledge that research should not be limited to fulfilling the requirements of the Kyoto Protocol but 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 partial requirement. Key areas of research are identified below.

7.1. Optical and SAR data fusion

While the advantages and disadvantages of using optical and microwave technologies have been outlined, fusion of the two technologies is expected to hold 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 and data mining.

Major candidate instruments for the synergistic use of datasets have been described in Section 4.1. A high priority is the need to be able to seamlessly translate and integrate data acquired from newer or replacement sensors with that obtained from older sensors in order to ensure the long term continuity of data flow. The calibration of MODIS data with AVHRR data is a case in point. In this calibration it is important that indices, such as the NDVI used over the past 20 years as a major indicator of vegetation status and condition, can be continue to be derived into the future.

The ability to incorporate conventional aerial photography and imagery from airborne sensors (e.g. CASI, AIRSAR and CARABAS) enhances the prospect of data integration and the likelihood of performing scalar studies of vegetation cover and biomass. Clearly, major outcomes of data fusion will be improved delineation of vegetation and land cover types, with the facility to use very fine to fine resolution hyperspectral data to classify within genus groups.

7.2. LIDAR and synergy with other sensors

With the indefinite postponement of the launch of the VCL sensor, space-borne LIDAR systems are unlikely to be available in the near future. Nevertheless, LIDAR holds a specific potential for contributing to the Kyoto Protocol through estimation of above ground biomass, although research needs to concentrate on how the LIDAR returns can be translated to provide estimates of above ground and component biomass and define the structure of forests and woodlands. The integration of hyperspectral data for refining estimates of biomass should also be investigated further. A second research topic related to the LIDAR is synergy with data from other sensors. As LIDAR can only provide data in a sampled manner, extrapolation between LIDAR sample points should be attempted using optical or SAR data, or a combination of both.

7.3. Interferometric, polarimetric and/or multi-frequency SAR applications

SAR interferometry has recently been shown to have potential for quantifying biomass, even at C-band which, with traditional processing techniques, saturates at very low levels of biomass (Askne et al., 1997; Santoro et al., 1999). The use of interferometric C-band, as well as, L- and P-band data for biomass retrieval requires further investigation.

Airborne SAR campaigns and the Shuttle Imaging Radar (SIR-C) missions have shown the potential of polarimetric SAR applications for enhanced thematic sensitivity and vegetation structure. With the availability of ENVISAT ASAR and the forthcoming launch of RADARSAT-2 and ALOS (all with polarimetric capabilities) SAR, 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 research issues.

Multi-frequency SAR applications also constitutes an area which has been largely overlooked, despite the co-existence of ERS-1 (C-band), RADARSAT-1 (C-band) and JERS-1 (L-band) SAR for several years. This may be partly attributed to the lack of consistent data from the different sensors to allow fusion, and if synergies of using multi-band SAR are to be explored further, proper co-ordination between space agencies to align the acquisition plans will be required.

7.4. Space-borne P-band applications

Ionospheric interference with the radar signal at VHF-band will 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., 2000). Given the potential of polarimetric P-band data for retrieving biomass, it is recommended that research be dedicated to further investigate the use of data from a variety of airborne platforms for biomass estimation and characterisation of vegetation structures across a range of vegetation types. It is furthermore recommended that the necessity of a space-borne P-band platform for terrestrial carbon assessment be investigated not only in a scientific perspective, but also at political and administrative levels to overcome frequency allocation problems. Frequency allocation requirements need to be put forward to the International Telecommunications Union (ITU) and the World Radio Conference (WCR) so that some part of the spectrum can be reserved specifically for remote sensing purposes.

7.5. Low frequency SAR

Low-frequency (VHF band) radar holds a certain potential for biomass determination on a local to regional scale, particularly as saturation of the signal has not been observed (Imhoff et al., 1998, 2000; Ulander, 1998). The capabilities of low frequency radar systems for biomass retrieval therefore need to be explored further within experiments carried out across a greater range of vegetation types, particularly tropical rainforests and mixed species forests and woodlands. The integration of VHF band radar data with LIDAR and/or optical data also warrants further investigation, as well as the feasibility of developing platforms with long endurance.

7.6. 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 should be standardised and managed as a part of an international effort, such as that initiated within the IGOS-P or the CEOS GOFC projects.

8. Legal issues

From the viewpoint of governing international laws and treaties, a key consideration is the legal restrictions hat might affect the utilisation of remote sensing technology to support treaty verification. Relevant in this context are the UN Remote Sensing Principles (United Nations, 1986) and the Outer Space Treaty (United Nations, 1967), as well as the 1944 Chicago Convention governing international air law.

The UN Remote Sensing Principles—which do not constitute a binding treaty, but a set of statements from the UN to which many countries subscribe—provide that space-borne remote sensing activities can in principle be undertaken without the specific permission of the state being imaged. In contrast, airborne remote sensing activities fall within the jurisdiction of international aviation law which provide that flights into and within the airspace of a country require the explicit consent of the country in question. Neither air nor space law make any distinction between passive and active remote sensing techniques.

While the restrictions applying to space-borne remote sensing appear more liberal, the UN Remote Sensing Principles highlight the fact that remote sensing activities should (a) 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) and, (b) include international co-operation and technical assistance (Principles V and VIII). Furthermore, when one country acquires data over another, the sensed country should have access to the data on a non-discriminatory basis and at reasonable cost (Principle XII).

In short, if monitoring is performed from outer space, states can legally collect data useful for the purposes stated in the Kyoto Protocol but should be willing to make these data available to the sensed state. It is not clear however, 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 yet to be addressed.

Remote sensing technology should be viewed as a tool to support the Kyoto Protocol and its signatories and not as 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.

9. Summary and recommendations

To support the requirements of the Kyoto Protocol, remote sensing can play an important role in providing systematic observations of land cover, supporting establishment of a 1990 carbon stock baseline, detecting and quantifying rates of land cover change, quantifying above ground biomass stocks and changes in these, and mapping and monitoring certain sources of anthropogenic CH_4. The greenhouse gases considered relevant in the context of remote sensing are essentially CO_2 and CH_4.

Systematic observations of the world's forested regions are presently provided at a global level by coarse and medium resolution sensors. For detecting hotspots of change, data from such sensors are most useful due to their frequent temporal coverage, although for quantifying change at the local to regional level, data provided by finer resolution instruments, such as Landsat and SPOT sensors are required. Space-borne SAR are suitable for detection and quantification of land cover change, particularly in areas with persistent cloud cover.

For establishing a 1990 carbon stock baseline, historical Landsat and sensors as well as JERS-1 SAR are most useful. Within their range of biomass sensitivity ($<100\,\mathrm{Mg\,ha^{-1}}$), SAR have the greatest potential for quantifying biomass (carbon stocks) at regional scales (Schmullius et al., 2001). At more local levels and for a restricted range of environments, airborne LIDAR, polarimetric SAR and VHF band radar have shown significant potential for biomass estimation. For detecting anthropogenic sources of CH_4, both space-borne SAR and optical data are deemed important.

Key areas where further research activity should be directed to assist solving the specific needs of the protocol include the fusion of optical and SAR data and development of procedures for data mining, increased synergy between LIDAR and other sensors, development of applications using SAR interferometry and polarimetry and low frequency radar, and the development of options for providing space-borne P-band data. Better integration of field measurements and increased networking and communications between scientists were also considered as priorities.

To ensure the uptake of remote sensing technology in supporting the Kyoto Protocol, access to and greater affordability of geographic information (including remote sensing data) are considered essential. Internationally agreed protocols are therefore required to ensure the open exchange of remote sensing data but also the provision of appropriate training in the use of existing and new remote sensing technologies, particularly in applications relevant to the Kyoto Protocol.

While the technological capacity of remote sensing to support the Kyoto Protocol exists, there seems a lack of commitment 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 commitment may in turn partly be linked to a lack of explicit demands from policy makers in the environment arena. Nevertheless, the usefulness of remote sensing data on a regional scale will depend largely upon whether a dedicated and systematic strategy for providing regional repetitive satellite sensor data acquisition is implemented. 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 as for use in the broader global change scientific framework.

Arguments have been presented that much of the data required for the Kyoto Protocol could be centralised, thereby ensuring consistency in data acquisition, interpretation, product generation and emission estimation. Legally, no obvious impediments to the acquisition of remote sensing data over countries is evident. However, such data cannot be used to compel states to fulfil certain obligations unless the states themselves expressly consent to monitoring by remote sensing. The issue of treaty verification is not addressed in the protocol.

10. Conclusions

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 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 to remote sensing but also to the need for the availability of in situ information.

Credibility and international acceptance of any method 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 and dialogue to the Kyoto Protocol are duly recognised. 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.

It is acknowledged that harmonising international efforts is essential. Therefore, the activities recommended here could best be pursued within the context of the terrestrial carbon initiative and through IGOS Partnership and the

GOFC Project, both which are considered to be of particular importance and relevance in this context.

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Appendix A. Overview of remote sensing instruments

Optical systems (*panchromatic*/*multi-spectral*)—*fine resolution*

Spatial resolution: 1–250 m.

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.
Terra MODIS, ASTER, MISR, USA/Japan, 1999–present.
Aqua ALI and Hyperion, USA, 2000–present.
ALOS AVNIR-2 and PRISM, Japan, planned launch 2004.

Optical systems (*multi-spectral*)—*medium and coarse resolution*

Spatial resolution: 250 m–1 km.

Temporal re-visit time: daily–weekly.

NOAA AVHRR, USA, 1970s–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.
Terra ASTER, MISR and MODIS, USA, 1999–present.
ADEOS-II GLI, Japan, 2002–present.
ENVISAT MERIS, AATSR, Europe, 2002–present.
AQUA MODIS, USA, 2002–present.

Active microwave systems (*SAR*)

Spatial resolution: 3–100 m.

Temporal re-visit time: ∼14–45 days.

SEASAT (L-HH), USA, 1976.
Shuttle Imaging Radar (SIR-A, SIR-B) (L-HH) USA, 1981, 1984.
SIR-C/X-SAR (L- and C-band polarimetric, X-VV) USA/Germany/Italy, 1994.
Shuttle Topography Radar Mission (SRTM/X-SAR) (C-HH, C-VV, X-VV) USA/Germany/Italy, February 2000.
Almaz (S-HH), Russia, 1992–1993.
ERS AMI (C-VV), Europe, 1991–present.
JERS SAR (L-HH), Japan, 1992–1998.
RADARSAT-1 (C-HH), Canada, 1995–present.
ENVISAT ASAR (C-band dual polarisation), Europe, 2002–present.
RADARSAT-2 (C-band polarimetric), Canada, planned launch 2004.
ALOS PALSAR (L-band polarimetric), Japan, planned launch 2004.

Active optical systems (*LIDAR*)

Spatial resolution: [VCL] 25 m (point measurements: non-spatial extensive)

Temporal re-visit time: [VCL] 2 weeks.

Height accuracy: [VCL] <1 m.

Vegetation canopy LIDAR—VCL, USA, launch postponed indefinitely.

Appendix B. Acronyms used

APAR	absorbed photosynthetically active radiation
ARD	afforestation, reforestation and deforestation
ATSR	along track scanning radiometer
AVHRR	advanced very high resolution radiometer
CASI	compact airborne spectrographic imager
CDM	clean development mechanism
COP	conference of parties
CPC	canopy projected cover
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization of the United Nations
FPC	foliage projected cover
GEF	global environment facility
GLI	Global Land Imager

GOFC	global observations of forest cover
GTOS	global terrestrial observing system
HRVIR	high resolution visible infrared
IGBP	International Geosphere Biosphere Programme
IGBP-DIS	IGBP-data and information system
IGOS-P	integrated global observation strategy partnership
IHDP	International Human Dimensions Programme
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
ISPRS	International Society for Photogrammetry and Remote Sensing
ITU	International Telecommunications Union
IUFRO	International Union of Forest Research Organisations
LAI	leaf area index
LIDAR	laser infrared detection and ranging
LULUCF	land use, land use change and forestry
NDVI	normalised difference vegetation index
NIR	near infrared
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
PAR	photosynthetically active radiation
SAR	synthetic aperture radar
SWIR	short-wave infrared
TEC	total electron content
UAV	unmanned aerial vehicle
UNFCCC	United Nations Framework Convention on Climate Change
WCRP	World Climate Research Programme

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