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The Global Rain Forest Mapping project—a review

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Abstract. The Global Rain Forest Mapping (GRFM) project is an international endeavour led by the National Space Development Agency of Japan (NASDA), with the aim of producing spatially and temporally contiguous Synthetic Aperture Radar (SAR) data sets over the tropical belt on the Earth by use of the JERS-1 L-band SAR, through the generation of semi-continental, 100 m resolution, image mosaics. The GRFM project relies on extensive collaboration with the National Aeronautics and Space Administration (NASA), the Joint Research Centre of the European Commission (JRC) and the Japanese Ministry of International Trade and Industry (MITI) for data acquisition, processing, validation and product generation. A science programme is underway in parallel with product generation. This involves the agencies mentioned above, as well as a large number of international organizations, universities and individuals to perform field activities and data analysis at different levels.

The GRFM project was initiated in 1995 and, through a dedicated data acquisition policy by NASDA, data acquisitions could be completed within a 1.5-year period, resulting in a spatially and temporally homogeneous coverage to encompass the entire Amazon Basin from the Atlantic to the Pacific; Central America up to the Yucatan Peninsular in Mexico; equatorial Africa from Madagascar and Kenya in the east to Sierra Leone in the west; and south-east Asia, including Papua New Guinea and northern Australia. Over the Amazon and Congo river basins, the project aimed to provide complete cover at two different seasons, featuring the basins at high and low water. In total, the GRFM acquisitions comprise some 13 000 SAR scenes, which are currently in the course of being processed and compiled into image mosaics.

In March 1999, SAR mosaics over the Amazon Basin (one out of two seasonal coverages) and equatorial Africa (both seasonal coverages) were completed; the data are available on CD-ROM and, at a coarser resolution, via the Internet. Coverage of the second-season Amazon and Central America will be completed during 1999, with the south-east Asian data sets following thereafter. All data are being provided free of charge to the international science community for research and educational purposes.

1. Introduction

1.1. *Background*

It is well known that forest ecosystems exert a strong influence on us and our environment at all levels, from local to regional, continental and global. The tropical

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forests are of particular interest as they are ecosystems with extensive biodiversity that still cover substantial areas of the Earth. Although it is well known that global forests in certain areas are cleared rapidly, it is difficult to assess the exact extent and impact of such activities for several reasons. For environmental conservation, global change modelling, etc., we need to be able to assess the current status of the forests accurately, but as changes occur very quickly, the need for up-to-date information is often difficult to satisfy, in particular on a regional or global scale. The only viable means to accomplish this task is indeed by using space-borne remote sensing techniques. In the tropical region Synthetic Aperture Radar (SAR) data are particularly appropriate, as microwave signals penetrate the persistent cloud cover.

1.2. *The JERS-1 satellite*

The Japanese Earth Resources Satellite 1 (JERS-1) was launched by NASDA and MITI in February 1992; it stayed in operation for 6.5 years, until contact was lost in October 1998. The satellite operated an L-band SAR (23.5 cm/1275 MHz) with horizontal (HH) co-polarization, 35° look angle and a recurrence cycle of 44 days. It also carried optical sensors (which were not utilized within the GRFM project), as well as an on-board data recorder which enabled global data coverage and rapid access to acquired data.

Several features made JERS-1 particularly suitable for forest monitoring, most notably the low L-band frequency SAR, which is more sensitive to above-ground biomass than other (C-band) SAR instruments in orbit. L-band signals are also sensitive to standing water below the forest canopy—a unique characteristic among all contemporary Earth observation satellites (both optical and microwave). The orbital configuration also made JERS-1 particularly suitable for large-area mapping, as data were acquired with adjacent passes on consecutive days (i.e. a specific pass was acquired one day after the pass immediately east of it). This acquisition manner yielded temporally homogeneous data even over large areas, albeit with a discrete temporal gradient running in east-to-west direction.

1.3. *The Global Rain Forest Mapping project*

The concept of large-area seasonal mapping by L-band SAR originated from the Jet Propulsion Laboratory (JPL) which, in 1994, proposed a dual-season mapping venture over the Amazon basin by JERS-1. This coincided with the end of the JERS-1 System Verification Program at NASDA and the subsequent, very timely, increased operational availability of the satellite that followed. The Amazon mapping concept evolved at NASDA to cover the entire equatorial belt, and hence the establishment of the Global Rain Forest Mapping (GRFM) project (Rosenqvist 1996). The large amounts of data generated by such a global endeavour, however, incited NASDA and JPL to extend collaboration to include the Joint Research Centre of the European Commission (JRC), experienced in tropical forest monitoring through the TREES and the ERS-1 Central Africa Mosaicking Projects (e.g. Malingreau and Duchossois 1995, Malingreau *et al.* 1995), and to MITI, via the Earth Remote Sensing Data Analysis Center (ERSDAC).

The major objectives of the GRFM project were to create spatially and temporally consistent JERS-1 L-band SAR image mosaics at 100 m resolution (derived from full-resolution data) covering the entire equatorial belt, and to provide these as 'ready-to-use' data sets freely and openly to the international science community and educational institutions as tools to help improve our understanding of the tropical ecosystems. It was explicitly noted that the data should be used for scientific and educational purposes only.

The GRFM project was officially initiated by NASDA in 1995, and collaboration agreements were established with NASA and the JRC, through which the tasks in the data flow, from satellite acquisitions to mosaic generation and CD-ROM production, were allotted. The NASA tasks are being performed through the JPL and the Alaska SAR Facility (ASF), while on the side of the JRC, they are performed by the Space Applications Institute.

The work distribution is to a large extent a result of the availability of personnel, equipment and know-how, as well as of other ongoing projects and regional interests of the organizations involved. Although the overall project goal was to generate uniform products (i.e. mosaics) for all areas, deviations in terms of radiometry and geometry inevitably do occur as a result of differences in the SAR processors, mosaicking software, etc. Since all GRFM activities have been covered by each participating organization internally—no exchange of funds has been required—it has not been possible, nor desired, to impose wide-ranging production standards. Nevertheless, the radiometric and geometric characteristics of each mosaic are documented and provided together with the data when delivered. The contributions from each organization are summarized in table 1.

2. Product generation and data flow

2.1. *Down-link and raw data processing*

Data acquisition scheduling was performed by NASDA and all acquired data (some 13 000 scenes) were recorded onto the satellite Mission Data Recorder and subsequently down-linked either at the NASDA Earth Observation Center (EOC) in Hatoyama, north of Tokyo, or at the ASF in Fairbanks, Alaska.

Raw data processing is performed at NASDA and at the ASF for each of their respective areas (see table 1). All data are processed to full resolution (18 m ground resolution at three looks) ground range amplitude products, corresponding to the 16-bit 'Level 2.1' product from NASDA (Shimada 1996) and the 8-bit ASF high-resolution standard product from the ASF (Bicknell 1992). The choice to perform

Table 1. GRFM project work distribution. AM—Amazon and Central America; AFR—equatorial Africa; SEA—South-East Asia and north Australia; NG—New Guinea island.

	NASDA	ERSDAC	ASF	JPL	JRC
Project management	AM, AFR, SEA and NG				
Data down-link	AM, AFR, SEA and NG		AM, AFR, SEA and NG		
Raw data processing	AFR, SEA and NG		AM		
Validation and post-calibration	SEA	NG		AM	AFR
100 m product generation	SEA	NG		AM	AFR
Mosaic generation	AM (one season) and SEA	NG		AM (both seasons)	AFR
CD-ROM production	AM, AFR, SEA and NG			AM, AFR, SEA and NG	

full-resolution processing (and subsequent filtering to lower resolution), rather than significantly faster low-resolution quick-look processing, was motivated by the scientific need for the highest achievable radiometric quality of the final mosaics.

This goal, however, has its cost and the raw data processing step has consequently proven to be the most time consuming part of the GRFM project. As of March 1999, ASF has all but finalized the processing of their share, where some 10% of the second Amazon coverage remains. NASDA EOC, in turn, who commenced processing in November 1996, following an up-grade of their processor, have finalized the processing of Africa, New Guinea and north Australia, while the major parts of South-East Asia still remain in the pipeline. Limited processor throughput at NASDA EOC, where on average some 75 scenes per week are processed, has however prompted NASDA to develop a new SAR processor dedicated to the JERS-1 science activities at NASDA Earth Observation Research Center (EORC). The new EORC processor was put into operation in early 1999, significantly speeding up the processing of the remaining data. In order to assure regional homogeneity for all the south-east Asian mosaics, NASDA also plans to re-process New Guinea island and northern Australia with the new processor.

2.2. *Generation of low-resolution data and calibration/validation*

The next step in the GRFM processing chain entails downsampling of the full-resolution scenes from 12.5 m pixel spacing to low-resolution framelets of 100 m pixel size. In order to maintain highest possible radiometric resolution, downsampling is performed by either wavelet decomposition (Africa) or by block averaging in power domains within an 8 pixel $\times$ 8 pixel window. The radar texture, calculated as the coefficient of variation within the same window, is computed in the same step. This results in one amplitude image and one texture image, both co-registered and with a geometry corresponding to the original full-resolution scenes.

Validation of the image radiometry (and geometry) and additional calibration are performed on the 100 m resolution framelets. Although the data processed by the ASF have proven to have comparably stable radiometry, a standardized antenna patterns correction, derived from analysis of a large number of scenes over uniform rain forest regions, is employed by JPL. Additional calibration of deviating framelets is only occasionally required. The data processed by NASDA EOC on the other hand, display significant antenna pattern variations and random gain deviations that, for the African data, encouraged the JRC to implement a supervised calibration procedure where corrections are applied to all scenes (Rauste *et al.* 1999a). The radiometric quality of the new NASDA EORC processor, which will be used for all South-East Asian data, remains to be verified.

2.3. *Generation of 100 m regional mosaics*

The image mosaicking procedures developed and utilized at NASDA, JPL and the JRC vary on several points, but the basic concepts can be illustrated by the JRC procedure (Rauste 1999, Rauste *et al.* 1999b) now described.

Using the 100 m framelets together with their orbital header information as input, image mosaicking is performed by means of block adjustment. Relative scene displacements, calculated by image correlation in the overlapping areas between scenes (both in azimuth and range directions), are used as observations in the adjustment procedure. Ground control points for absolute geolocation, derived from e.g. existing maps (with varying quality) and the World Vector Shoreline data set, are added as additional observations with higher weight. As a first step, only the transformation parameters are calculated, and the result is scanned for gross errors or other outliers which need to be corrected before the actual mosaic is assembled. The steps of parameter calculation and geometric verification are repeated until acceptable geometric accuracy has been achieved. In order to assure relative co-registration between mosaics acquired at different seasons (both the Amazon basin and the Congo basin were acquired at two seasons), block adjustment is performed for all scenes covering the region simultaneously. For the case of Africa (excluding Madagascar which is treated separately), this involves some 3600 scenes, resulting in a normal equation matrix larger than 10 000 lines by 10 000 columns. Still, the calculation can be performed within a few hours. Once the transformation parameters have been calculated, the geometry is fixed and the actual mosaic generation can either be completed in one single step, or it can be performed in sub-regions and assembled at a later stage. From a computational point of view the latter is more feasible, as simultaneous mosaicking of 3600 scenes currently requires some 20 hours of computation time. The characteristics of the JRC output are 100 m nominal ground resolution, amplitude and texture mosaics in Mercator projection with 240 m root mean square error (RMSE) absolute geolocation accuracy and 56 m (RMSE) relative internal accuracy.

The procedure employed at JPL for the Amazon and Central America corresponds largely to the JRC flow described above. The major difference is that least-squares block adjustment is applied to data from one season only and the second coverage is rectified scene-by-scene to the first 'master' mosaic. The characteristics of the JPL output are 100 m nominal ground resolution, amplitude and texture mosaics on a latitude/longitude grid. The final versions of the South American mosaics have not yet been generated and appraisal of the geometric accuracy hence remains.

The mosaicking algorithm currently applied by NASDA differs from the JRC and JPL procedures in that orbital information is used to compute the approximate position for the scene in the mosaic, followed by image correlation in the overlapping areas of neighbouring scenes for fine adjustment. An improved version of the algorithm is foreseen for South-East Asian mosaic generation.

2.4. *CD-ROM generation*

All mosaics generated within the GRFM project will be featured on CD-ROM at 100 m and 500 m ground resolution (Chapman *et al.* 1998). Due to the large sizes of the 100 m data files (typically 400–600 Mbytes), it was considered necessary to divide the 100 m canvases into smaller regional mosaics, or tiles, (typically corresponding to $5° \times 5°$, 30–40 Mbytes or 80–100 scenes) in order to ensure that users with relatively limited computer capacity can display and work with the data. Adjacent tiles can be re-assembled to form larger units if so desired. An educational CD-ROM aimed at high schools and universities with restricted computer resources and limited knowledge of SAR, is also foreseen, featuring educational documentation and selected mosaics at 100 and 500 m resolution. As of early 1999, two CD-ROM sets have been released.

2.5. *Internet access*

All 500 m resolution mosaics are subsequently being made available on the Internet for on-line browsing and, for non-commercial purposes, for downloading.

CD-ROM sets containing 100 m resolution data are available on request. The following websites are currently available:

- NASDA/Japan (http://www.eorc.nasda.go.jp/Sciences/Forest/);
- JPL/USA (http://southport.jpl.nasa.gov/GRFM/);
- JRC/EC (http://www.gvm.sai.jrc.it/);
- Satellus/Sweden (http://www.satellus.se/projects/GRFM).

3. Coverages and acquisition schedules

3.1. *Data acquisition scheduling*

The data acquisitions were scheduled with the particular intention of obtaining, as far as possible, temporally homogeneous data coverages over extensive areas. Radiometric differences between adjacent swaths could be minimized by taking advantage of the fact that two adjacent JERS-1 swaths were acquired with only 1-day time difference, and special attention was thus paid to avoid temporal gaps in the acquisitions. Inevitably, gaps nevertheless did occasionally occur due to satellite manoeuvres, acquisition conflicts, etc., and missing passes were in such cases either re-scheduled or replaced by scenes from the existing archive, as far as possible taking the seasonality of the missing pass into consideration. A side effect of the sequential acquisition scheme, which should be borne in mind when analysing data over extensive areas, is a distinct temporal gradient (1 day/60 km) which runs in an east-to-west direction.

3.2. *South and Central America*

The GRFM coverage over South and Central America (figure 1(*a*)) extends over the area latitude 14° S to 12° N and longitude 50° W to 80° W. The first coverage, extending over the whole Amazon river basin (figure 2), was acquired over a 62-day period in 1995, starting in Belém in September and ending in Equador in November (hence the temporal gradient). The acquisitions coincide with the annual low-water mark of the Amazon river, as measured in Manaus. A second acquisition, featuring the corresponding high-water peak, was performed during the period May to August 1996. This second coverage also includes the Pantanal wetlands, the north-western part of the South American continent and Central America (figure 1(*a*)). The two coverages together amount to some 5000 scenes.

Figures 2 and 3 illustrate the multi-scale characteristics of the GRFM mosaics. The former figure portrays the Amazon river basin at a low resolution, showing semi-continental scale features such as drainage patterns and geomorphologic features. Regional differences within the mosaic are also apparent at this scale: while low water prevails in the central and eastern part of the basin, flooded forest areas (appearing bright in L-band SAR imagery) can be seen in Peru, in the westernmost part of the basin. Figure 3 is an extract from the same mosaic, but displayed with 100 m pixel spacing, exhibiting local-scale features such as shifting cultivation and deforestation patterns (Rondônia).

3.3. *Equatorial Africa*

The African GRFM acquisitions (figure 1(*b*)), comprising some 3950 scenes, feature east, central and west Africa (9.5° S–9.5° N/40° E–14° W), which were acquired in one sweep in early 1996. Acquisitions commenced in Kenya in January and ended by the Atlantic coast two months later, in March 1996. Central Africa was re-visited in October–November the same year, in order to—in analogy with the Amazon

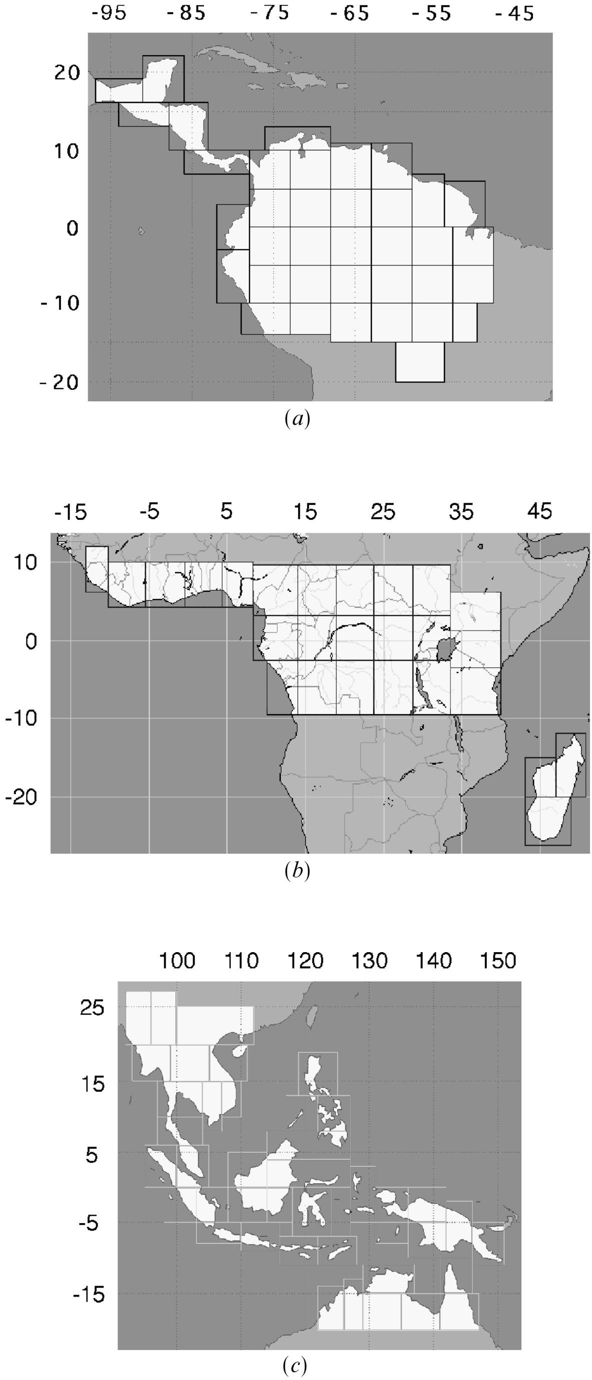

Figure 1. GRFM coverage over (*a*) South and Central America, (*b*) equatorial Africa and (*c*) South-East Asia and northern Australia.

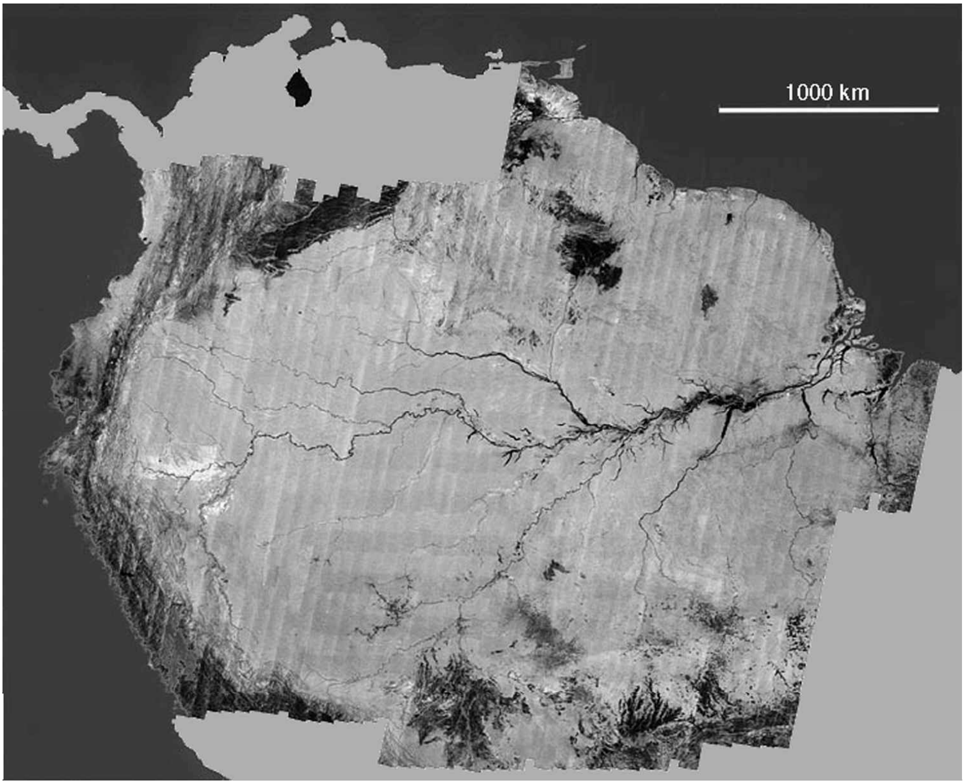

Figure 2. JERS-1 SAR mosaic covering the Amazon Basin at low water (October–December 1995). Original mosaic pixel size 100 m. JERS-1 GRFM © NASDA/MITI/JPL/JRC.

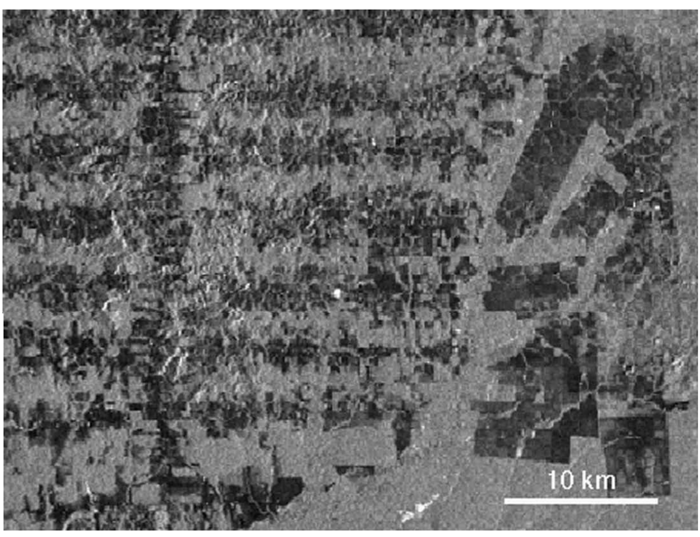

Figure 3. Rondônia, Brazil. Full-resolution extract from the GRFM Amazon mosaic (figure 2). Shifting cultivation can be seen on the left-hand side of the image and cattle ranges on the right. JERS-1 GRFM © NASDA/MITI/JPL/JRC.

acquisitions—feature seasonal variations in the Congo river basin (figure 4). Madagascar was covered in February 1997.

An extract from a temporal composite mosaic, using data acquired in February (red) and November (green) 1996, together with a radar texture mosaic image (blue) is shown in figure 5. The area featured is the confluence of the Congo and Ubangi rivers. Forest areas which were inundated during both acquisitions appear bright white in the image, while areas that were inundated at only one occasion appear

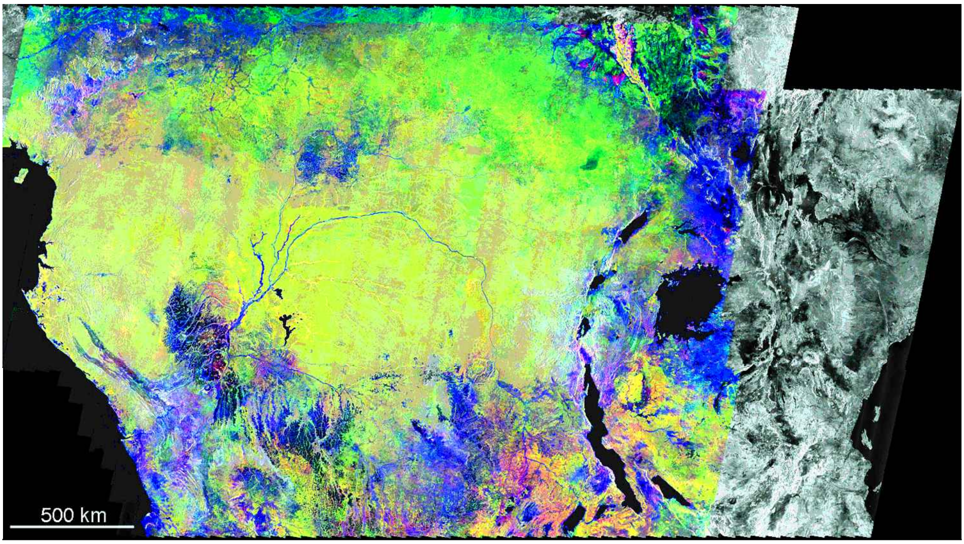

Figure 4. GRFM mosaics over equatorial Africa (west Africa and Madagascar not shown). The colour composite area shows the extent of the dual-seasonal coverage. (R—radar amplitude February 1996; G—radar amplitude November 1996; B—aradar texture February 1996). JERS-1 GRFM © NASDA/MITI/JRC/JPL.

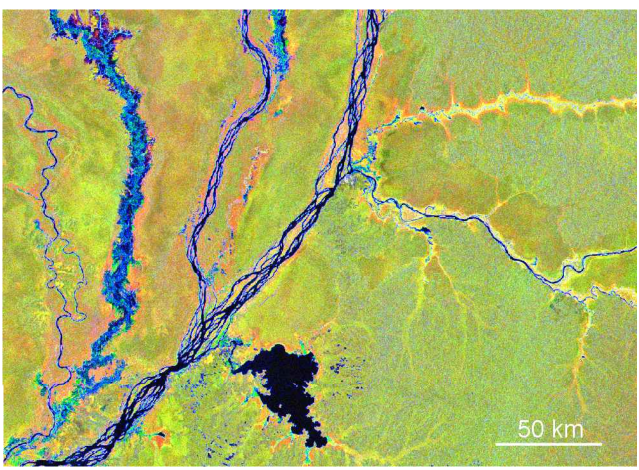

Figure 5. Confluence of the Congo and Ubangi rivers in Central Africa. Dual-season composite GRFM mosaic. (R—radar amplitude February 1996; G—radar amplitude November 1996; B—radar texture February 1996). JERS-1 GRFM © NASDA/MITI/JRC/JPL.

bright yellow or orange. Rough surfaces, due to the higher texture, appear with a blueish tone. The floodplain forest, with its homogeneous structure, lacks the blue tone and is easily distinguishable from the more textured dryland forest, as can be seen along the tributary (Kwa river) which stretches eastwards from the centre right-hand part of the image.

3.4. *South-East Asia (including Papua New Guinea) and north Australia*

Acquisition planning over South-East Asia was complicated by several factors, primarily by the fact that the region consists of a large number of islands distributed over extensive sea areas. The uniform blanket acquisition approach, as was practised for the other two continents, was consequently not considered feasible. The region was therefore instead divided into a number of sub-areas (basically represented by the main islands (figure 1(*c*))) over which data were acquired over a larger time span. Temporal uniformity was nevertheless maintained within each sub-region. The acquisitions, which were limited to one single coverage per sub-region, resulted in some 4300 scenes and were performed according to the following schedule.

- Papua New Guinea/Irian Jaya: March–April 1996 (figure 6).
- Malay Peninsular and Sumatra: August–September1996.
- Borneo/Kalimantan, Java and Sulawesi: September–October 1996.
- N. Australia (above S20°): October–November 1996.
- The Philippines: December1996.
- Burma, Thailand, Cambodia, Laos and Vietnam: January–February 1997.

4. GRFM science projects

A scientific programme is underway within the context of the GRFM project with the aim of exploiting the use of JERS-1 SAR data and the GRFM products in the tropical region. These so-called GRFM Science Projects are independently managed by researchers and scientists from a large number of organizations and universities worldwide. The activities include mapping of the spatial and temporal distribution of annual flooding in the Amazon and Congo river basins (Freeman *et al.* 1996, Costa *et al.* 1997, Miranda *et al.* 1997, Rosenqvist and Birkett 1999), studies of secondary growth and deforestation patterns (Hashimoto and Tsuchiya 1995), investigations of microphyte vegetation in water reservoirs, geomorphologic studies

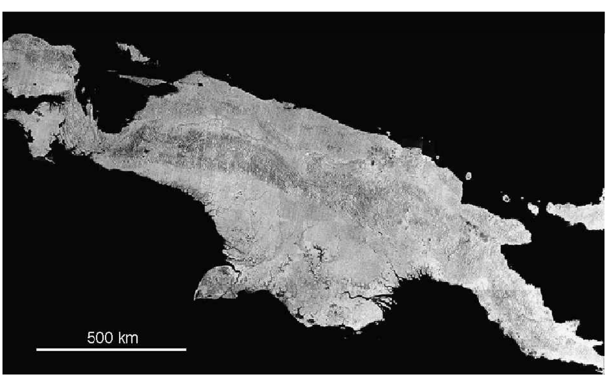

Figure 6. Papua New Guinea/Irian Jaya. GRFM mosaic (March–April 1996). JERS-1 GRFM © NASDA/MITI/ERSDAC.

(Forsberg *et al.* 1998), estimations of regional emissions of trace gases from the floodplain environments (Rosenqvist *et al.* 1998), forest classifications in the Amazon and Central Africa (Siqueira *et al.* 1997, De Grandi *et al.* 1998), regional-scale vegetation studies (Hess *et al.* 1998, Leysen *et al.* 1998), and others. Figure 7 shows a land cover classification over the Gamba Complex in Gabon, derived from the dual-season Africa GRFM mosaic.

In collaboration with, among others, the Brazilian National Institute for Space Research (INPE), the Brazilian National Institute for Amazonian Research (INPA) and the University of California Santa Barbara (UCSB), field measurements were performed simultaneously with the GRFM acquisitions in several parts of the Amazon during both satellite overpasses. The activities included both videography and photography from a small aeroplane along a number of pre-determined flight lines as well as ground-based measurements in areas or transects of specific interest. Field measurements were also performed in connection with the GRFM acquisitions over northern Australia, which coincided with an airborne SAR campaign (AIRSAR Pacific Rim deployment). The AIRSAR campaign included flights over several transects and subsequent ground measurements.

5. Future perspectives

With all the GRFM acquisitions completed and the JERS-1 satellite still functional, in 1996 NASDA decided to proceed with a new global forest mapping venture with a focus on the boreal forest belt in Siberia, Canada, Alaska and northern Europe, thus establishing the Global Boreal Forest Mapping (GBFM) project. The objectives of the GBFM project are similar to those of the GRFM, i.e.

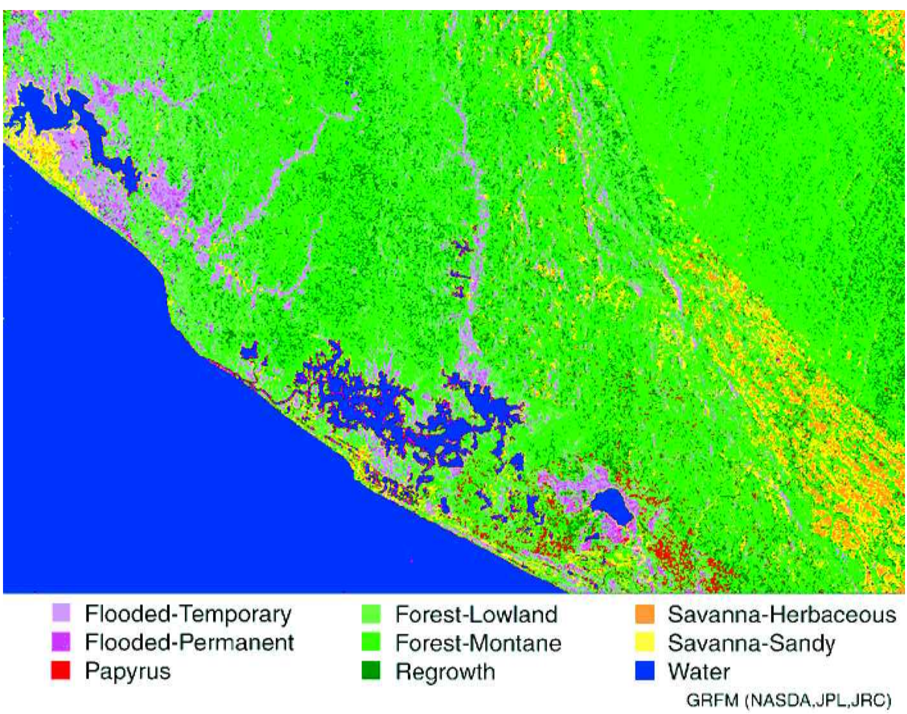

Figure 7. Land cover classification of the Gamba Complex, Gabon (Saatchi *et al.* 1998).

continental-scale mosaic generation and an active science programme. In addition to the collaboration partners involved in the GRFM, the National Swedish Space Board, via the Swedish Space Corporation Subsidiary Satellus, is also involved as a Science Node for research activities in the northern European boreal zone. Contacts were also established with the German Aerospace Research Establishment (DLR) and the European Space Agency (ESA), for coordination of data acquisitions and scientific activities in the Siberian region.

Boreal data acquisitions started in late 1996 and the major parts of the targeted areas were completed successfully before the on-board data recorder was taken out of operation in August 1997. Through direct down-links by ASF, the Tromsø Satellite Station in Norway and the mobile DLR ground station located in Ulaanbaatar in Mongolia, data acquisitions continued over certain areas until contact with the JERS-1 was finally lost in October 1998. Through the collaboration with DLR and the SIBERIA project (Schmullius *et al.* 1999), simultaneous JERS-1 and ERS-1/ERS-2 acquisitions were performed over central Siberia in 1996 and 1997.

It is anticipated that both GRFM and GBFM acquisitions will be repeated in a 10-year time frame within the framework of the NASDA Global Forest Mapping Program, by use of the polarimetric L-band SAR instrument on-board the Advanced Land Observation Satellite (Wakabayashi *et al.* 1998), scheduled for launch by NASDA in 2002.

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