

REMOTE SENSING AND THE KYOTO PROTOCOL - A WORKSHOP SUMMARY -

Åke ROSENQVIST¹, Marc IMHOFF², Anthony MILNE³ and Craig DOBSON⁴

¹Joint Research Centre of the European Commission

ake.rosenqvist@jrc.it

²NASA Goddard Space Flight Center, USA

mimhoff@ltpmail.gsfc.nasa.gov

³University of New South Wales, Australia

T.Milne@unsw.edu.au

⁴University of Michigan

dobson@umich.edu

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1 INTRODUCTION

1.1. Background

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

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

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

1.2. Remote Sensing and the Kyoto Protocol

While global inventory of all six greenhouse gases covered by the Kyoto Protocol is an overarching goal and a daunting task, it was recognized that, at present, the remote sensing community is best equipped to address CO₂ and CH₄. Within the context of the Kyoto Protocol, Article 10 was recognized as the main driver, in which contributions can be made to provide systematic observations and data archives in order to reduce uncertainties in the global terrestrial carbon budget. Specific contributions can be made to supporting national and international networks and observation programs, especially those that focus on the measurement of above-ground biomass, the mapping of land use and land cover and changes in land use and land cover. The importance of Article 3 and Article 12 (the Clean Development Mechanism) of the Kyoto Protocol were recognized, and that Earth Observation can help support national accounting of Afforestation, Reforestation and Deforestation (ARD) under those articles.

2 OVERVIEW OF REMOTE SENSING TECHNOLOGY CAPABILITIES

2.1 Applying Remote Sensing to the Kyoto Protocol

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

- Provision of systematic observations of relevant land cover (Art. 5, Art. 10);
- Support of the establishment of a 1990 carbon stock baseline (Art. 3);
- Detection and quantification of change in forest area (Art. 3, Art. 12);
- Quantification of above-ground vegetation biomass stocks and associated changes therein (Art. 3, Art. 12);
- Mapping and monitoring of sources of anthropogenic CH₄ (Art. 3, Art. 5, Art. 10);

2.1.1 Provision of systematic observations of relevant land cover

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

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

It is recognized that a federated approach having common goals and thematic definitions will be required to effectively support the Kyoto Protocol. Such an effort is currently underway within the framework of the Global Observations of Forest Cover (GOFC) Pilot Project (Ahern *et al.* 1998), under the auspices of CEOS.

[Passive] Optical (Multi-spectral and Panchromatic) Systems

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

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

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

Active Microwave Systems (SAR).

The thematic mapping of vegetation using satellite based radar imaging systems has been less successful than optical systems. This is primarily due to the fact that the current suite of orbiting SAR systems all operate with a single-band and a single polarization. Classification accuracy with SAR, however, increases notably with the inclusion of additional bands

and polarizations, and very good results can be achieved when optical and microwave data are combined. While multi-band/polarimetric and interferometric radar systems are not yet available in a space-borne mode, they are available on aircraft platforms and could be used for local to regional scale applications.

A major limitation of radar systems, with respect to vegetation mapping, is their sensitivity to surface topography which limits their application to flat or gently undulating terrain. Radar data are also subject to speckle, which on one hand enables techniques such as radar interferometry, but reduces the effective ground resolution. The advantage of radar systems is their all-weather capability, which assures image acquisitions independent of cloud cover and daylight, thereby enabling timely and reliable acquisitions at local, regional and global scales.

Active Optical Systems (LIDAR)

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

2.1.2 Support to the establishment of a 1990 carbon stock baseline

According to Art. 3:4 of the Kyoto Protocol, each Annex I country shall "provide data to establish its level of carbon stocks in 1990 and to enable an estimate to be made of its changes in carbon stocks in subsequent years". However, Art. 3:5 of the Protocol also states that Annex I countries "undergoing the process of transition to a market economy" may, under certain circumstances, "use a historical base year or period other than 1990 for the implementation of its commitments" under Art. 3. Hence, baselines formulated after 1990 may, for certain countries, be considered. Nevertheless, as it can be expected that the year 1990 will be the by far predominant base year, the selection of potential sensors to be used to support the establishment of this base line will to the largest extent be limited to those in operation during this specific year.

Multi-spectral Sensors.

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

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

Active Microwave Systems.

No orbital active microwave systems were in operation in 1990 and the use of SAR data to support a 1990 baseline is thus not feasible. For non-1990 baseline countries in the tropical and boreal zones of the Earth, continental scale (100 m resolution) JERS-1 L-band SAR mosaics from 1995-96, generated within the GRFM/GBFM projects (Rosenqvist *et al.* 2000), can be used to support the establishment of a mid-1990's carbon baseline.

LIDAR.

Not feasible. No data available.

2.1.3 Detection and quantification of change in forest area

This application concerns the detection and spatial quantification of afforestation, reforestation and deforestation (ARD) activities, and changes resulting from fire events. Article 3:3 of the treaty states that "The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article...". Article 12 furthermore defines a "clean development mechanism", which in principle stipulates the conditions for "carbon trading" between countries. This, in turn, requires verifiable measurements of ARD.

While the articles above concern measurements of carbon stocks and changes therein, a first important step is the identification and quantification of the areas subject to ARD. In combination with up-to-date *in situ* data and relevant allometric models, changes in biomass (carbon) stocks may be estimated. In order to detect ARD activities, image acquisitions at a repetitive basis will be required, preferably annually and performed during a specific season, in order to

minimize the effects of seasonal artefacts in the data. A spatial resolution better than the minimum area of interest - still to be defined - will be required for this task.

Passive Optical (Multi-spectral and Panchromatic) Systems

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

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

Active Microwave Sensors.

Microwave sensors are particularly sensitive to detecting changes between images acquired at different times, even in areas of topographic terrain, provided that the viewing geometry is kept the same. Instruments operating with long wavelengths (L-band or longer) are more suitable for forest related monitoring than short wavelength sensors (C-band or shorter) as the L-band signals interact with the forest at branch and trunk level, while the main interaction at C-band occurs with the canopy. Rough soil and herbaceous vegetation may in the latter case be confused with forest.

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

Polarimetric SAR systems can be expected to improve the capabilities for ARD monitoring and at least three such systems are currently planned for the near future ALOS (L-band), Envisat (C-band) and Radarsat-2 (C-band). The LightSAR (L-band) mission has been halted, but NASA are currently studying alternative mission concepts.

Active Optical Systems (LIDAR)

As long as no imaging LIDAR system is available, detection of ARD activities and burn scars will be limited to those areas sampled by the VCL. As such, the feasibility of using LIDAR to address ARD events is, as of yet, unproven. However, LIDAR should have the ability to repeatedly characterize structural attributes at specific locations or collect sample sets in known ARD areas which could prove useful.

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

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

Multi-spectral Systems.

Direct measurements of total above ground forest biomass stocks or changes in such is not feasible with (passive) optical systems. However, indirect estimations of biomass change is possible to a limited extent using photosynthetic indices based on photosynthetically active radiation (PAR). PAR measurements have been routinely made using multi-spectral sensors and may be combined with environmental data and forest growth models to predict NPP (net primary production) which is presented in terms of units of carbon.

Active Microwave sensors.

The application of radar systems to measure and detect changes in above-ground biomass stocks is an active area of research and development. There was general agreement among the workshop participants, that currently available radar satellite systems (ERS-2 and Radarsat-1), which operate with single channel C-band, are not well suited for biomass

estimation, since the signals saturate at low biomass levels. Although C-band sensitivity to biomass up to almost 100 t/ha in certain circumstances may be achieved by dual-pass interferometric technique (Askne *et al.* 1997, Santoro *et al.* 1999), the accuracy is largely dependent on factors such as the baseline distance and surface conditions, and more R&D is required before the technique may become operational with single band data.

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

While the biomass levels approachable by L-band SAR are still way below those of mature forests, which vary between 100 - 600 t/ha, longer wavelengths, together with polarimetric and/or interferometric techniques, can be used to push the biomass saturation levels forward and to improve accuracy (Dobson *et al.* 1992, Imhoff 1995). Aircraft based radar sensors having full multi-band, polarimetric, and interferometric capabilities currently exist and have proven capable of detecting biomass in a wide range of forests up to 200 tons/ha dry above ground biomass (Ranson *et al.* 1997), primarily due to the long wavelength P-band channel.

No space-borne P-band SAR system has been launched up-to-date, mainly due to unresolved ionospheric effects associated with low frequency radars. These effects, which are functions of the total electron content (TEC) in the ionosphere, result in deformation and polarimetric rotation of the signal (Ishimaru *et al.* 1999). It has however recently been shown that polarimetric (Faraday) rotation may be corrected for by using a fully polarimetric system (Freeman *et al.* 1998), while other ionospheric artefacts may be reduced to acceptable levels by accurate timing of the data acquisition (early dawn) when TEC is at minimum. Physical constraints in instrument design, relating to minimum antenna dimensions, can be by-passed by using a lower (50-100 m) ground resolution (Freeman *et al.* 1999).

Lower frequency SAR systems (VHF and UHF bands) may also prove very useful for biomass mapping. Recent studies have shown that these frequencies are capable of accurately measuring biomass above 100 tons/ha (dry above ground biomass). Results from the aircraft based CARABAS (20-90 MHz; Luanda *et al.* 1998), deployed in temperate and boreal forests in Europe, and the bios system (80-120 MHz, Imhoff *et al.* 2000), deployed in the neo-tropics, have shown that biomass measures can be accurately derived (within $\pm 10\%$ of field measures) for forests between 100 and 500 tons/ha (actual saturation levels for the bios and CARABAS systems have yet to be determined). These systems show great promise for local to regional applications using aircraft. However, the deployment of space-based VHF/UHF sensors may not be technically feasible due to ionospheric interference with the signal and has yet to be explored.

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

Active Optical Systems (LIDAR)

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

2.1.5 Mapping and monitoring of certain sources of anthropogenic CH₄

Article 3:1 of the Kyoto Protocol states that " The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts..." , "with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012". Hence, the Kyoto Protocol relates to all six greenhouse gases listed in Annex A, including CH₄, which is the second of the two greenhouse gases, apart from CO₂, considered relevant in the context of this report.

Although it may well be included in the paragraphs above, mapping and monitoring of certain sources of anthropogenic CH₄ is here listed separately, as it is not generally related to forestry or to forest change. Apart from livestock management - which is not considered feasible to monitor by remote sensing - CH₄ is also emitted as a result of anaerobic conditions in open water bodies following extended inundation. Typical anthropogenic sources of CH₄ include irrigated rice paddies, aquaculture (e.g. fish- and shrimp cultivation) and hydroelectric reservoirs.

Multi-spectral Sensors.

Detection and spatial quantification of open water bodies such as aquaculture and hydroelectric reservoirs can be performed by single date high resolution optical sensors. Rice paddies may also be identified in a single date, although repetitive measurements during the growth season are recommended in order to be able to separate it from other agricultural crops and to monitor the water regime - the key factor triggering the CH₄ emissions. Cloud cover will however in the latter case constitute an obstacle to obtaining the relevant multi-temporal data.

Active Microwave Systems.

SAR data can be used to map the three CH₄ sources referred to above. SAR data is particularly suitable for multi-temporal monitoring of irrigated rice, as regular acquisitions can be performed irrespective of the cloud conditions. Both C-band (Le Toan et al 1997) and L-band (Rosenqvist 1999) SAR have been used to map rice growth, and it is now deemed possible to perform this in an operational way, using current sensors (ERS-2 and Radarsat-1) as well as sensors planned in the near future (ALOS PALSAR, ENVISAT ASAR, Radarsat-2).

LIDAR.

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

2.2 In-Situ Data

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

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.

3 RECOMMENDED FUTURE ACTIONS

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

The following areas of research were identified by the workshop participants:

Optical and SAR data fusion

While both optical and microwave technologies have their specific advantages and disadvantages, fusion of the two technologies holds a great potential for enhanced thematic mapping and biomass estimation. Both technologies have co-existed for almost a decade but surprisingly little work has attempted to take advantage of the potential of fusion.

VCL and synergy with other sensors

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

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

Interferometric, polarimetric and/or multi-frequency SAR applications

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

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

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

Spaceborne P-band applications

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

Low frequency SAR

Low-frequency (VHF and UHF band) radar holds a great potential for biomass determination on a local to regional scale. While low-frequency radar data have been demonstrated to be free of saturation characteristics up to as much as 400 t/ha (Imhoff 2000, Ulander *et al.* 1998), there are several research questions still to be addressed. The first concerns the lack of applications data. Further tests of low frequency radar systems should be made to fully explore their capabilities for biomass retrieval and for potential for soil penetration. Experiments need to be carried out where the number of test sites are expanded to include forests that are fully representative of the world's forests. The possibility of combining VHF and UHF band data with LIDAR and/or optical data should also be explored.

Field measurements and networking

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

4 CONCLUSIONS

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

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

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

5 REFERENCES

- Ahern, F. J., A. Belward, P. Churchill, R. Davis, A. Janetos, C. Justice, T. Loveland, J.-P. Malingreau, M. Maiden, D. Skole, V. Taylor, Y. Yausuoka, and Z. Zhu, 1998. A Strategy for Global Observation of Forest Cover: Executive Summary, published by the Canada Centre for Remote Sensing, Ottawa, Ontario, Canada. GOF C TP-3.
- Askne J., Dammert P., Ulander L. and Smith G. "C-Band Repeat-Pass Interferometric SAR Observations of the Forests", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 35 (1), pp. 25-35, 1997.
- Barbosa P.M., J-M. Grégoire, and J.M.C. Pereira, 1999. An Algorithm for Extracting Burned Areas from Time Series of AVHRR GAC Data Applied at a Continental Scale. *Remote Sensing of the Environment*, 69(3), 253-263.
- Barbosa P.M., J.M.C. Pereira, and J-M. Grégoire, Compositing criteria for burned area assessment using multitemporal low resolution satellite data. *Remote Sensing of the Environment*, 65:38-49 (1998).
- Belward, A.S., Estes, J.E. and Kline, K.D., 1999, The IGBP-DIS global 1 km land cover data set DISCover: A Project Overview, *Photo. Eng. Rem. Sens*, **65**, 1013 - 1020.
- Dobson M. C. *et al.* "Dependence Of Radar Backscatter On Coniferous Forest Biomass", *IEEE Transactions on Geoscience and Remote Sensing*, 30: (2), pp. 412-415 March 1992.
- Dubayah R., Blair B., Bufton J., Clark D., Jálá J., Knox R., Luthcke S., Prince S. and Weishampl J. "The Vegetation Canopy Lidar Mission". Symp. for Land Satellite Information in the Next Decade II, *ASPRS, Washington D.C., 1997*.
- Dwyer E., J-M. Grégoire, and J.P. Malingreau, A global analysis of vegetation fires: Spatial and temporal dynamics. *AMBIO*, 27(3), pp. 175-181, May 1998.
- Freeman A., Johnson W.T.K, Huneycutt B., Jordan R. Hensley S., Siqueira P. and Curlander J. "The 'Myth' of the Minimum SAR Antenna Area Constraint". IGARSS'99. Hamburg, Germany, 1999. Proceedings. IEEE Catalog No. 99CH36293C.
- Freeman A., Saatchi S., Kuga Y. and Ishimura A. "Detection, Estimation and Correction of Faraday Rotation in Linearly Polarized SAR Backscatter Signatures". Submitted to Radio Science, January 1998.
- Imhoff M., Carson S. and Johnson P., "A low frequency radar sensor for vegetation biomass measurement", *IEEE Transactions on Geoscience and Remote Sensing*, In Press 2000.
- Imhoff M., "Radar backscatter and biomass saturation: ramifications for global biomass inventory," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 33, no. 2, pp. 510-518, 1995.
- Ishimaru, A., Y. Kuga, J. Liu, Y. Kim, and T. Freeman, "Ionospheric effects on synthetic aperture radar imaging at 100 MHz to 2 GHz," *Radio Science*, 34(1), 1999.
- Justice C.O., Kendall J.D., Dowty P.R., Scholes R.J. "Satellite remote sensing of fires during the SAFARI campaign using NOAA advanced very high resolution radiometer", *Journal Geoph. Res. Atmos.*, 101: (D19) 23851-23863 Oct 30 1996.
- Le Toan T., Ribbes F., Floury N., Wang L.F., Ding K.H., Kong J.A., Fujita M., Kurosu T., 1997. "Rice Crop Mapping and Monitoring Using ERS-1 Data Based on Experiment and Modeling Results" *IEEE Tr. Geo. RS* Vol.35, No.1, pp. 41-56.
- Mayaux P., Achard F. and J.P. Malingreau, 1998, Global tropical forest area measurements derived from coarse resolution maps at a global level: a comparison with other approaches, *Environmental Conservation*, 25(1):37-52.
- Pinnock S. and Gregoire J-M, 2000. "The World Fire Web network - A satellite based system for globally mapping fires in vegetation", Joint Research Centre Space Applications Institute. European Community publication S.PI.00.11.
- Ranson K.J., Sun, G., Weishample, J. F., and Knox, R. G., "Forest biomass from combined ecosystem and radar backscatter," *Remote Sensing of Environment*, Vol 59, pp. 118-133, 1997.
- Richards T.S., Gallego J. and Achard F., 2000, Sampling for forest cover change assessment at the pan-tropical scale, *International Journal of Remote Sensing*, in press.
- Rosenqvist Å., Shimada M., Chapman B., Freeman A., De Grandi G., Saatchi S. and Rauste Y., 2000. "The Global Rain Forest Mapping Project - A Review". *International Journal of Remote Sensing*, In press.
- Rosenqvist Å., "Temporal and Spatial Characteristics of Irrigated Rice in JERS-1 SAR Data". *International Journal of Remote Sensing*, 1999, Vol. 20, No. 8, pp. 1567-1587.
- Santoro, M., Askne J, Dammert P., Fransson J and Smith G., 1999, Retrieval of biomass in boreal forest from multitemporal ERS-1/2 interferometry. Fringe 99: 2nd Int'l WS on ERS SAR Interferometry, Liege, Belgium, 1999.
- Stroppiana D., S. Pinnock , and J-M. Grégoire, The Global Fire Product: daily fire occurrence, from April 1992 to December 1993, derived from NOAA-AVHRR data. *Int. J. of Remote Sensing*, in press 1999.
- Townsend J.R.G. *et al.* "The 1km Resolution Global Data Set - Needs Of The International Geosphere Biosphere Program" *ISPRS 15: (17)* pp. 3417-3441 Nov 20, 1994.
- Ulander L., *et al.* "EUROFA data collection with the CARABAS-II VHF-band SAR," *Progress In Electromagnetics Research Symposium 1998*, Nantes, France, Vol. 1, pp. 536, 1998.
- Wegmüller U and CL Werner C.L. "Retrieval of vegetation parameters with SAR interferometry", *IEEE Trans. Geosc. Remote Sensing*, 35,1, 18-24, 1997.