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

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

Workshop Report

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I. INTRODUCTION

1.1 Background

The Kyoto Protocol to the United Nations Framework Convention on Climate Change contains quantified, legally binding commitments to limit or reduce greenhouse gas emissions to 1990 levels and allows carbon emissions to be balanced by carbon sinks represented by vegetation. The issue of using vegetation cover as an emission offset raises a debate about the adequacy of measurement and monitoring methodologies, and of current and planned remote sensing systems and data archives to both assess carbon stocks/sinks at 1990 levels, and monitor the current and future global status of those stocks. These concerns and the potential ratification of the Protocol among participating countries is stimulating policy debates and underscoring a need for the exchange of information between the international legal community and the remote sensing community. On October 20-22 1999, two working groups of the International Society for Photogrammetry and Remote Sensing (ISPRS) joined with the University of Michigan (Michigan, USA) to convene discussions on how remote sensing technology could contribute to the information requirements raised by implementation of and compliance with the terms of the Kyoto Protocol. The meeting originated as a joint effort between the Global Monitoring Working Group and the Radar Applications Working Group in Commission VII of the ISPRS, co-sponsored by the University of Michigan. The meeting was attended by representatives from national government agencies and international organizations and academic institutions. Some of the key themes addressed were: ·

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

1.2 Remote Sensing and the Kyoto Protocol

While global inventory of all six greenhouse gases covered by the Kyoto Protocol is an overarching requirement and a daunting task, it was recognized by the workshop participants that, at present, the remote sensing community is best equipped to address CO_2 and CH_4. Within the context of the Kyoto Protocol (see Annex III), Article 10 was recognized as a key driver, in which contributions can be made to provide systematic observations and data archives in order to reduce uncertainties in the global terrestrial carbon budget. Specific contributions can be made to supporting national and international networks and observation programs, especially for above-ground biomass, and for assessing trends and shifts in land cover. The importance of Article 3 and Article 12 (the Clean Development Mechanism) of the Kyoto Protocol were recognized, and that Earth Observation can help support national accounting of Afforestation, Reforestation and Deforestation (ARD) under these articles. Also relevant is that countries shall, by the first commitment period (2008-2012), report in a transparent and verifiable matter their CO_2 equivalent emissions of greenhouse gases. Another milestone is 2005, by which
countries shall have made "demonstrable progress" towards achieving their assigned emission limitation and reduction commitments under the Protocol (Article 3). The group reviewed a large number of remote sensing instruments and categorised them according to how they might

be best applied to support the Kyoto Protocol. The primary emphasis was on satellite based technologies - although some aircraft platform based sensors were also discussed.

II. SOME LEGAL CONSIDERATIONS ABOUT REMOTE SENSING

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

A few points of relevance were acknowledged:

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

However the UN Principles Relating to Remote Sensing of the Earth from Outer Space, which is not a binding Treaty, but a Statement from the United Nations to which many countries agree, provides, that:

- Remote sensing activities should be carried out for the benefit and in the interests of all countries, taking into particular consideration the needs of the developing countries (Principle II);
- Remote sensing activities should include international co-operation and technical assistance (Principles V and VIII);
- When one country acquires data over another country, the sensed country should have access to the data on a non-discriminatory basis and at reasonable cost terms (Principle XII).

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

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

III. OVERVIEW OF REMOTE SENSING TECHNOLOGY CAPABILITIES

3.1. Applying Remote Sensing to the Kyoto Protocol

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

In this context, five areas were identified where remote sensing technology may be applied, partly or fully, toward facilitating the treaty:

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

3.1.1. Provision of systematic observations of relevant land cover

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

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

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

Passive Optical (Multi-spectral and Panchromatic) Systems

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

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

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

Active Microwave Systems (SAR)

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

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

Active Optical Systems (LIDAR)

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

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

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

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

Passive Optical (Multi-spectral and Panchromatic) Systems

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

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

Active Microwave Systems (SAR)

No orbital active microwave systems were in operation in 1990 and the use of SAR data to support a 1990 baseline would thus in general not be feasible. SAR data could however possibly be useful for quantification of component biomass (leaves, branches, stems) of the extensive areas of woodlands that occur throughout Australia, Africa and South America, for which the establishment of a 1990 baseline could be supported. For non-1990 baseline countries in the tropical and boreal zones of the Earth, continental scale (100 m resolution) JERS-1 L-band SAR mosaics from 1995-96, generated within the GRFM/GBFM projects (Rosenqvist *et al.* 2000), can be used to support the establishment of a mid-1990's carbon baseline.

Active Optical Systems (LIDAR)

Not feasible. No data available.

3.1.3. Detection and spatial quantification of change in land cover

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

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

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

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

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

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

Passive Optical (Multi-spectral and Panchromatic) Systems

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

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

Active Microwave Systems (SAR)

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

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

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

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

Active Optical Systems (LIDAR)

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

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

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

Passive Optical (Multi-spectral and Panchromatic) Systems

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

Active Microwave Systems (SAR)

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

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

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

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

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

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

Active Optical Systems (LIDAR)

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

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

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

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

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

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

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

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

Active Optical Systems (LIDAR)
The feasibility of using LIDAR to address this issue is not currently known.

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

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

[Passive] Optical (Panchromatic/Multi-spectral) Systems - Coarse Resolution
Spatial resolution 250 m - 1 km.
Temporal re-visit time daily - weekly.
NOAA AVHRR, USA, 1970’s - present;
ERS ATSR, ATSR-2, Europe, 1991 - present;
SPOT VEGETATION, France/EU/Sweden/Belgium, 1998 - present;
ADEOS OCTS, Japan, 1996 - 1997.

CBERS WFI, Brazil/China, 1999 - present.
EOS-AM MODIS, USA, 1999 - present.
ADEOS-II GLI, Japan, planned launch 2000.
ENVISAT MERIS, AATSR, Europe, planned launch 2001.

Active Microwave Systems (SAR)

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

Active Optical Systems (LIDAR)

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

3.3. *In Situ* Data

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

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

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

IV. FUTURE ACTIONS

4.1. Research topics

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

Optical and SAR data fusion

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

VCL and synergy with other sensors

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

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

Interferometric, polarimetric and/or multi-frequency SAR applications

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

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

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

Spaceborne P-band applications

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

Low frequency SAR

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

Field measurements and networking

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

4.2. Access and affordability

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

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

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

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

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

V. SUMMARY AND RECOMMENDATIONS

5.1. Summary

The state-of-the-art of the remote sensing technology in the context of the information requirements raised by the implementation of, and compliance with, the Kyoto Protocol were assessed. A large number of remote sensing sensors and applications were reviewed and it could be concluded that remote sensing technology as such, with its inherent advantages and current limitations, may be used to contribute to meeting some critical and strategically important information needs of the Protocol. The greenhouse gases considered relevant in the context of remote sensing were C_{O2} and C_H4. The areas where the technology may contribute significantly to the information needs of the Protocol are listed below. Relevant articles of the Kyoto Protocol are given within parenthesises.

- Provision of systematic observations of relevant land cover (Art. 5, Art. 10);
- Support to the establishment of a 1990 carbon stock baseline (Art. 3);
- Detection and spatial quantification of change in land cover (Art. 3, Art. 12);
- Quantification of above-ground vegetation biomass stocks and associated changes therein (Art. 3 Art 12)
- Mapping and monitoring of certain sources of anthropogenic C_{H4} (Art. 3, Art. 5, Art. 10);

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

- Optical and SAR data fusion
- VCL and synergy with other sensors
- Interferometric, polarimetric and/or multi-frequency SAR applications

- Spaceborne P-band applications
- Low frequency SAR
- Field measurements and networking

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

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

The issue of accessibility and affordability of geographic information along with the need for training were also raised and it was recommended that these issues be addressed through agreed international protocols that ensure the open exchange of remotely sensed data and training to all. The legal aspects of utilising remote sensing technology in the context of the Kyoto Protocol were reviewed briefly, and it can be concluded that, while there are no obvious legal impediments to prevent global acquisitions of remote sensing data from outer space, it was deemed unlikely that the data could be used to compel a state to fulfil certain obligations unless the state itself expressly had consented to satellite monitoring. The issue of treaty verification is not addressed in the Protocol.

5.2. Recommendations

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

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

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

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

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