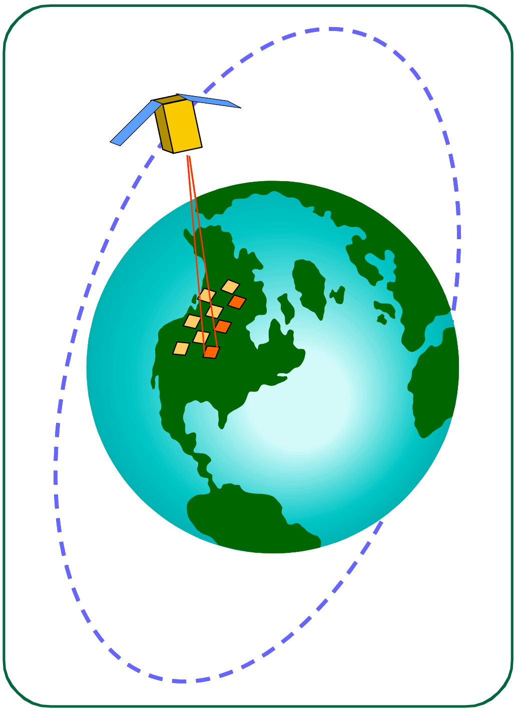
ESPOO 2006 VTT PUBLICATIONS 599



Tuomas Häme, Osmo Aulamo, Javier Gallego,
Martti Hallikainen, Pekka Kauppi, Panu Lahtinen,
Norman Miller, Jouni Pulliainen, Heikki Saari,
Tony Sephton, Jari Stenberg & Carl Warren

Kioto+ mission

Global and accurate monitoring of forest, land cover and carbon

VTT PUBLICATIONS 599

Kioto+ mission

Global and accurate monitoring of forest, land cover and carbon

Tuomas Häme
VTT

Osmo Aulamo
Finnish Meteorological Institute

Javier Gallego
Joint Research Centre

Martti Hallikainen
TKK Helsinki University of Technology

Pekka Kauppi
University of Helsinki

Panu Lahtinen
TKK Helsinki University of Technology

Norman Miller
Berkeley National Laboratory, University of California

Jouni Pulliainen
TKK Helsinki University of Technology

Heikki Saari
VTT

Tony Sephton
EADS Astrium Ltd.

Jari Stenberg
Patria Systems Oy

Carl Warren
EADS Astrium Ltd.

ISBN 951–38–6832–X (soft back ed.)
ISSN 1235–0621 (soft back ed.)

ISBN 951–38–6833–8 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1455–0849 (URL: http://www.vtt.fi/publications/index.jsp)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 3, PL 1000, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 4374

VTT, Bergsmansvägen 3, PB 1000, 02044 VTT
tel. växel 020 722 111, fax 020 722 4374

VTT Technical Research Centre of Finland, Vuorimiehentie 3, P.O.Box 1000, FI-02044 VTT, Finland
phone internat. +358 20 722 111, fax + 358 20 722 4374

Technical editing Anni Kääriäinen

Otamedia Oy, Espoo 2006

Häme, Tuomas, Aulamo, Osmo, Gallego, Javier, Hallikainen, Martti, Kauppi, Pekka, Lahtinen, Panu, Miller, Norman, Pulliainen, Jouni, Saari, Heikki, Sephton, Tony, Stenberg, Jari & Warren, Carl. Kioto+ mission. Global and accurate monitoring of forest, land cover and carbon. Espoo 2006. VTT Publications 599. 42 p.

Keywords Kioto+, forests, vegetation, monitoring, super-high resolution satellites, satellite technology, remote sensing, earth observation, terrestrial carbon sinks, carbon cycles, carbon storage

Abstract

This publication presents the results of a feasibility study on a proposed super-high resolution satellite mission Kioto+. The study was conducted by an international consortium in response to the 2005 call for ideas for Earth Explorer missions of the European Space Agency (ESA).

Kioto+ offers reliable and global data to near *in-situ* measurement accuracy on land cover and forest cover. It also gives information about their development over time. A super-high resolution optical instrument is proposed to achieve statistically representative and precise measurements. The information will greatly improve our understanding of the global carbon and water cycles, and the credibility of estimates of terrestrial carbon storage. The imagery will also give globally accurate training and validation data for wall-to-wall imaging instruments. The mission is named Kioto+ because the projected timescale of the mission (post-2011) means that it will primarily have relevance to successor treaties of the Kyoto Protocol to the FCCC of the United Nations.

Preface

This publication reports the results of a feasibility study on a proposed super-high resolution optical satellite mission Kioto+. The study was conducted in response to the call for ideas for the Earth Explorer core missions of the European Space Agency ESA (European Space Agency 2005). The publication is an elaborated and defined version of the original proposal that was prepared by an international consortium and submitted in August 2005. The Kioto+ mission was not included in the list of the candidate missions that were proposed for the pre-phase A studies by the ESA.

The main contributors to the feasibility study and the proposal are the actual authors of this publication. They are listed in alphabetical order after the principal author. In addition, the following individuals (listed in alphabetical order) have made a significant contribution to the study as the science team members: Heikki Ahola, VTT; Heikki Astola, VTT; Klaus Briess, Technical University of Berlin; Sandra Brown, Winrock International, US; Nektarios Chrysoulakis, Foundation for Research and Technology, Hellas; Jean-Baptiste Henry, VTT; Sami Kemppainen, TKK Helsinki University of Technology; Markku Kivioja, Finnish Meteorological Institute; Matthieu Molinier, VTT; Ranga Myneni, Boston University; Tiit Nilson, Tartu Observatory; Yrjö Rauste, VTT; Jesus San Miguel-Ayanz, Joint Research Centre; Pauline Stenberg, University of Helsinki; Riku Tajakka, Finnish Meteorological Institute; Simo Tauriainen, TKK; Erkki Tomppo, Finnish Forest Research Institute.

The study project was supported by Tekes, the Finnish Funding Agency for Technology and Innovation. The project steering group members were Prof. Väinö Kelhä as chairman, and Mr. Heikki Hannula, Dr. Esko Kyrö, Prof. Seppo Linnainmaa, Mr. Kimmo Myllyoja and Dr. Jouko Ritakari as members. Steering group individuals gave a significant contribution to the proposal itself. Dr. Jussi Tuovinen gave valuable comments to the manuscript.

Contents

List of acronyms and abbreviations

ARD	Afforestation, Reforestation, Deforestation
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
B	Blue
CCD	Charge Coupled Device
CORINE	Coordination of Information on the Environment
EFICS	European Forest Information and Communication System
EM	Engineering Model
EO	Earth Observation
ERS	Earth Resources Satellite
ESA	European Space Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FCCC	Framework Convention on Climate Change
FM	Flight Model
FRA	Forest Resources Assessment
G	Green

GMES	Global Monitoring of Environment and Security
GSE-FM	GMES Service Element Forest Monitoring
IEOS	Integrated Earth Observation System
IGBP	International Geosphere-Biosphere Programme
LEO	Low Earth Orbit
NIR	Near Infra-Red
NOAA	National Oceanic and Atmospheric Administration
PAN	Panchromatic
R	Red
SAR	Synthetic Aperture Radar
SNR	Signal-to-Noise Ratio
SWIR	Short-Wave Infra-Red
TBFRA	Temperate and Boreal Forest Resources Assessment
TDI	Time Delayed Integration
TKK	TKK Helsinki University of Technology
TTC	Telemetry, Tracking and Command
VTT	VTT Technical research Centre of Finland
WCRP	World Climate Research Programme

1. Mission justification and objectives

1.1 The need

1.1.1 Ecology and economics of forests and land use

The world's forests cover 3 952 million hectares according to the FAO Global Forest Resources Assessment 2005 (FRA 2005). This is approximately 30% of the global land area. The carbon stock of forest biomass is estimated to be about 300 Gt (Gt = 10^9 tons) of carbon, which is the majority of carbon of all vegetation (FRA 2000, Kauppi 2003, FRA 2005). Within the forests, the carbon stock of trees in the tropical forests (164 Gt) is the largest. The vegetation of croplands is estimated to include only 0.6% carbon of all vegetation, and even including the soil the carbon of croplands is only about 5% of the carbon of vegetation and soil of all land cover classes.

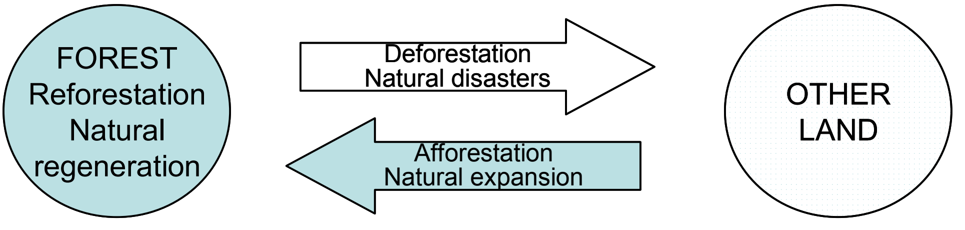


Figure 1. Basic change processes between forest and other land: increase of forest area through man-made afforestation or natural expansion; decrease through deforestation or natural disasters (FRA 2005).

The atmosphere contains about 900 Gt of carbon. The carbon stock of the atmosphere is increasing at an annual rate of 2–3 Gt/year, driven mainly by the combustion of oil, coal, and gas reserves as well as deforestation. Non-tropical forests, in which the soil carbon storage is also high, are estimated to be significant carbon sinks (Myneni et al. 2001, Liski et al. 2003).

If the land cover type changes from forest to cropland (or desert) the carbon storage reduces drastically at this location. Thus, it is easy to understand that forest area and forest area change estimation are baseline parameters when the role of forest in the carbon cycle is evaluated (Figure 1).

Forests are a major source of raw material for mankind. The annual production of round wood is more than 3000 million m^3 (without bark), of which approximately half is used for fuel wood and charcoal and the other half as industrial round wood. The annual round wood production has grown from 2000 million m^3 to its present level within the last 40 years. The growth has been fastest in Asia, but also in North America and Africa the production has increased significantly (FAO State of the World's Forests 2005, Finnish Statistical Yearbook of Forestry 2003).

The cycling of water through the atmosphere, land surface, and deep ground is intrinsically coupled to the cycling of carbon. Through the microscopic stomata pores on their leaves, forests take in carbon, and emit oxygen and water to the atmosphere. This balance is critical for the maintenance of healthy sustainable forests. Understanding the details of these processes and how they are modulated with climate, atmospheric carbon dioxide changes, and other factors is critical to the management of high latitude forests, a region most sensitive to climate change. (Bonan and van Cleve 1992, Bonan et al. 1992, Miller et al. 2005.)

1.1.2 International policy driven information needs

At least 10 policy processes are relevant to the collection of the data from global forests. The most important process is the Kyoto Protocol to the United Nations Framework Convention on Climate Change. Other important policies include the United Nations Convention on Biological Diversity, the United Nations Convention to Combat Desertification, and the United Nations Forum on Forests. At European level, important International agreements are the Criteria and Indicator Processes of the Ministerial Conference on the Protection of Forests in Europe, The Council of Europe Landscape Convention, the European Union (EU) Regulation Forest Focus, the EU regulation on a European Forest Information and Communication System (EFICS), and the EU Forest Strategy.

In addition to the international forestry policies, national forest policies require collection of information about forests.

The policies have been analyzed from the point of view of forest information needs in the Teseo Carbon project for ESA (Häme et al. 2003), and more thoroughly again in the GSE Forest Monitoring project for ESA (GSE-FM 2006). The analysis showed that the most important variables to be monitored are:

- area of forest and its condition (fragmentation);
- area of afforestation, reforestation and deforestation (ARD);
- above-ground vegetation biomass and changes therein;
- land use and land use change within and between different land use classes.

Three of the four variables are associated with the area variables, *i.e.* forest area, land cover (land use) and their changes. The Kyoto Protocol does not explicitly require very specific stratification within the forest class, but other international agreements like the Ministerial Conference on the Protection of Forests in Europe has a requirement for the sub-division to forest types.

The definition of forest in the Kyoto Protocol leads to demanding requirements on the spatial resolution of the data collected from forests. Although other policies do not require such a high resolution, it is important in all cases that the information on forests and land cover does not include any systematic errors. A small error range can be achieved when an adequate amount of detailed observations are available. The implementation of the policies does not require wall-to-wall mapping, but does require adequate and reliable statistical data.

1.1.3 Information acquisition at the present time – main information gaps

Long-term sequestration of carbon into land-based or marine reservoirs is capable of mitigating the carbon accumulation in the atmosphere. Land use change (afforestation in particular) is recognized as a net sink for greenhouse gases.

Global forest statistics are compiled by the FAO. For their Forest Resources Assessment 2005 (FRA 2005), the FAO had to rely largely on secondary information and/or expert estimates. In the developing countries the information was also quite old, for instance the most recent estimates were from 1974 and 1980 from Zambia and Somalia, and no confidence intervals to the estimates could be given. In all cases, the information is compiled from national statistics with the implicit knowledge that the methods and the definitions at the national level are very different, which leads to large errors in the estimates. This problem is less acute in the Temperate and Boreal region although it occurs also there.

In the earlier report FRA 2000 also a satellite-based survey on forest areas with confidence intervals of the forest area estimates was reported. The standard error for the estimated forest area of 1571 million hectares was 66 million ha in the pan-tropical region. In the country data of FRA 2000, the pan-tropical forest area differed from the satellite survey forest area by more than 300 million ha.

The global forest growing stock volume estimates are much less reliable than those of forest area, particularly in the non-industrialized countries.

As regards land cover estimation, global land cover maps are prepared under the umbrella of the International Geosphere-Biosphere Programme (IGBP 2006). The mapping has thus far been based on satellite data with a resolution coarser than 1 km^2. The Globcover project by ESA aims at a global vegetation map of 300-metre resolution (GLOBCOVER 2005). In Europe, the Corine 2000 mapping has been completed (CLC 2000). The mapping is based on Landsat data of 30-metre resolution. A statistical viewpoint has not been dominating in the global land cover surveying, but the projects have focused on wall-to-wall mapping. It should be noted that the definition of forests used in those approaches is often different. For instance, the forest definition for CORINE (30% crown cover) differs considerably from the FAO definition (10% crown cover).

To summarize, the global forestry statistics have rather big uncertainties and the estimates that have been acquired using different procedures differ significantly within the same geographic region. The reliability and time of information acquisition varies from country to country. The procedure to collect the information is heavy and time-consuming. Satellite data have proven their potential, but representative global datasets have been available only with medium to low resolution. This means uncertainty in the estimation, which is of particular concern since the existence of systematic errors cannot be ruled out. It is not feasible to consider that global inventories of forest and land cover could be based on field sampling.

Several projects, including the GSE Forest Monitoring by ESA (GSE-FM 2006), develop and apply satellite image-based methods to help implementation of the Kyoto Protocol and other policies, but their scope is relatively local and their aim is to serve individual customers.

1.1.4 Potential and limitations of present and planned satellite systems to respond to the need

Various satellite-borne instruments such as Meris and AATSR onboard Envisat, Modis onboard the Terra and Aqua satellites, and the AVHRR instruments of the NOAA series of satellites give wall-to-wall information on the Earth's surface with a high repeat frequency. Satellites of the ASTER, Landsat and Spot programs produce imagery whose resolution is of the order of tens of metres.

The present spaceborne radar instruments ERS-2 SAR, Envisat ASAR, and Radarsat provide imagery in C-band with a resolution that is roughly comparable to the resolution of Landsat (ERS 2005, ASAR 2005, Radarsat 2005, Landsat 2006). In the coming years, the resolution of SAR data will improve, but the high resolution images will be available from selected sites only.

The coarse resolution is common to all of the above remote sensing data types. If low spatial resolution satellite data are used for forest and land cover assessment, the computed estimates are uncertain, which decreases the credibility of the results. This uncertainty is difficult to express quantitatively, which makes the estimates somewhat speculative. Currently, satellite imagery are mainly used in the pre-inventory phase in order to stratify the area and to identify the forest strata. Further processing for inventory estimates is carried out with higher spatial resolution data such as aerial photography and ground-collected data. For most applications, *in-situ* data are needed to train the models and to validate the results. However, *in-situ* data are very expensive to collect, if not practically impossible at many locations on Earth.

Recent commercial satellites such as Ikonos, QuickBird, partially also Spot 5, and in the future Pleiades offer optical imagery with such a high spatial resolution that the information on land cover types may be derived reliably using image data only, without the need for *in-situ* measurements. However, the images of the super-high resolution satellites are acquired on a “by order” basis. They do not offer globally representative coverage.

The Kioto+ mission is designed to fill in the obvious gaps in global satellite data availability for the derivation of reliable statistical data on forest and land cover.

1.2 Demand-driven objective for the Kioto+ mission

The objective of the Kioto+ satellite mission is to provide a systematic sample from global land cover and forest cover using a super-high resolution optical instrument. The resolution is high enough to enable derivation of reliable statistical information without extensive in-situ measurements or even completely without any in-situ data, depending on the nomenclature.

Also, the changes over time can be monitored reliably. The information can further be utilized to understand the global carbon and water cycles better. The size of the smallest target area for which reliable statistical data can be derived has preliminarily been defined as about 100 000 km^2.

In addition to the sample characteristic, the imagery can largely replace in-situ measurements for the training of the models that use wall-to-wall satellite data with a coarser resolution. Similarly, it can be used for validation purposes.

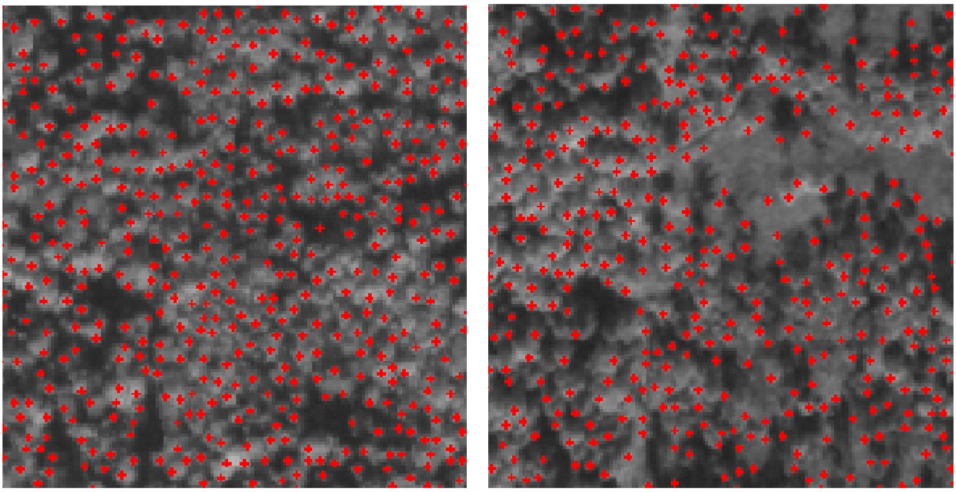


Figure 2. Automatically derived tree locations in September 2002 (left) and June 2005 (right) images after thinning and clear cuttings. Boreal forest, Quickbird panchromatic images.

The key difference with the existing missions and the proposed super-high resolution Kioto+ mission is a completely different data acquisition strategy. Data that alone can give reliable information on global natural resources are collected using a sampling principle.

The policy-driven requirements to the highest required spatial resolution for the Kioto+ mission vary from 0.5 metre to 2 metres depending on the product (Table 1) (Astola et al. 2004). For the principal land cover classification, two-metre resolution in the visible and near infrared spectral bands may be adequate.

The requirements on the spatial resolution increase when variables that are associated with biomass are estimated. Already for the forest type, a higher resolution and the Short Wave Infrared (SWIR) channel are very desirable. Forest type is a key variable when the forest area is transformed to the biomass using the procedure that has been applied by the FAO.

Harvest of individual trees is an activity that causes major uncertainty in the biomass change estimates in the tropics, but its magnitude is poorly known (Brown 1998, Koskela et al. 2000). Detection of selective cuttings requires a very high spatial resolution, and successive observations from the same direction (nadir) (Figure 2). Furthermore, recent research shows that Leaf Area Index (LAI) estimates of forests can be drastically improved when the SWIR band is available (Stenberg et al. 2004). The LAI is a key parameter for the estimation of the Net Primary Productivity (NPP) (Kotchenova et al. 2004).

For most of the products shown in Table 1, biannual or annual observation rate is adequate. However, the accuracy of the estimates can be improved if the seasonal variation can be taken into consideration. The estimation will naturally benefit from as large a sample rate as possible. For the principal estimation for land cover and forest type it is beneficial if the samples do not overlap because this increases the sampling rate, whereas monitoring of change requires multi-temporal observations from the same location.

High radiometric sensitivity is required from the instrument since the reflectance of forest can be as low as 1% in the visible spectral range (Kleman 1986). The low reflectance end is particularly important in the estimation of biomass. However, the highest biomass levels cannot be estimated using spectral data only, and the individual trees have to be separated. This requires as high a spatial resolution as possible.

Table 1. Policy-driven requirements for the Kioto+ mission.

Product	**Spatial resolution**	**Spectral bands**	**Radiometric performance**	**Geometric accuracy**	**Repeat frequency**
Land/forest cover classification	0.5–2 m	Visible, NIR	High	High	Annual
Forest type	0.5–2 m	Visible, NIR, SWIR	High	High	Annual
ARD	0.5 m pan	Visible, NIR	High	High	Biannual to annual
Leaf Area Index	0.5 to 4 m	Visible, NIR, SWIR	High	High	Biannual to annual
Forest biomass for direct carbon storage assessment	0.5 m pan	Visible, NIR, SWIR	High	High	Annual

The Kioto+ mission is principally for the provision of super-high resolution sample data from land areas. Over the oceans the mission can additionally be used to collect continuous observations with reduced spatial resolution for the secondary products.

2. Mission characteristics

2.1 General mission characteristics

The baseline concept is a polar orbiting satellite that regularly acquires super high-resolution images with six spectral bands: panchromatic, blue, green, red, near infrared (NIR) and Short Wave Infrared (SWIR). Since global wall-to-wall mapping with very high resolution is not feasible, a sampling approach is chosen. A grid of sample plots (4 km by 4 km in size) is acquired at a repeat interval of 35 days. The sample plots are located along the satellite orbit in such a manner that an optimal sampling density is achieved (shorter interval close to the equator than near the poles because the orbits approach each other in north and south). The separation of orbits is 75 km at the Equator.

Due to the large amount of high-resolution data, the limiting factor for the mission is the amount of data that can be down-linked to ground stations. The satellite is equipped with an on-board analyzer for cloudy images. In addition to the primary sample A plots, a secondary set B of plots is imaged between the A plots. Whenever a plot in set A is considered cloudy, data for a cloud-free B plot are down-linked instead. Feasibility of lossless onboard compression is also considered. Compression ratios of 1.5–2 are possible with current algorithms. With a compression ratio of 2, the on-board memory can accommodate 913 scenes (the locations of which can be programmed according to the requirements of un-biased sampling strategy in land areas).

Figure 3 shows the imaging modes of the proposed satellite system. In addition to the basic high-resolution mode, a 100-m mode is included for sea areas. Stereo imaging can be obtained by rotating a single satellite, or by an optional second satellite in an orbit that enables stereoscopic viewing along-track some 20 to 30 minutes after the first satellite.

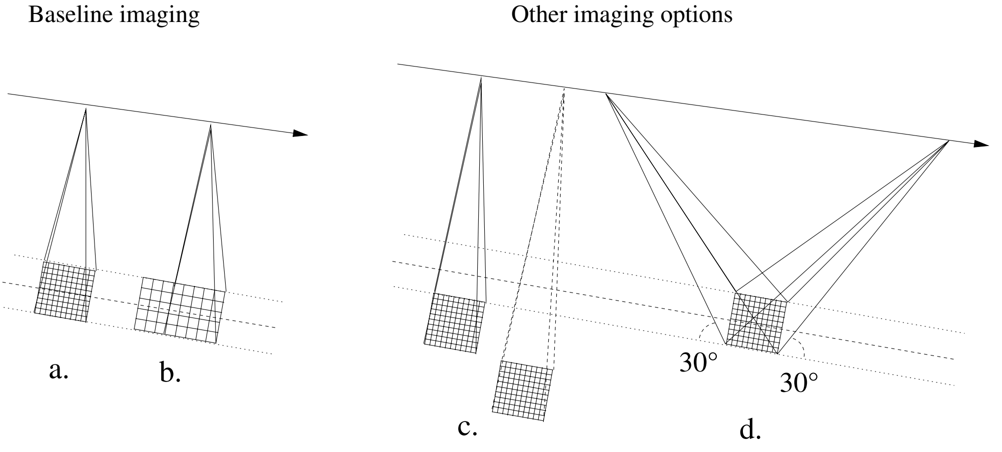


Figure 3. Baseline and optional imaging modes: a. Baseline sample imaging at 0.5 m (panchromatic), 2 m (visible and NIR) and 4 m (SWIR) resolution. b. Continuous-strip baseline imaging over the oceans (100 metre resolution for all channels). c. Possible off-nadir. d. stereoscopic imaging modes. All imaging modes are available for both baseline and optional two-satellite configuration.

The detailed downlink requirements are to be defined later. However, high rate data links are strongly preferred since the downlink budget is foreseen as the limiting element for the number of images that can acquired. The feasibility of an optical link with a capacity of more than 1 Gbps will also be studied during the Kioto+ definition phase. Use of two ground stations at high northern latitudes and one in the south is proposed.

2.2 Mission timeline

Table 2 shows a preliminary mission timeline for the baseline mission (one satellite). In phase C/D, it is proposed to develop an engineering model (EM) and a flight model (FM) for the instrumentation. The total time from Phase A to launch is approximately 59 months. The designed mission lifetime is three plus two years (three years minimum).

Table 2. Mission schedule.

Year	2006				2007				2008				2009				2010				2011			
Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Phase A/B	■	■	■	■	■																			
Breadboard			■	■	■	■	■																	
Negotiation phase								■																
Phase C/D									■	■	■	■	■	■	■	■	■	■	■	■				
Payload design									■	■	■	■												
Payload EM										■	■	■	■											
Payload FM													■	■	■	■								
Payload AIT																	■	■						
Platform design									■	■	■													
Platform FM												■	■	■										
Platform AIT															■	■	■							
Satellite AIT																			■	■				
Launch																					■			
Calibration																					■			
Operational use																					■	■	■	■

2.3 Orbit

Various factors limit the possible orbital parameters (Table 3). The downlink time and the size of the optics are greatly affected by the orbit height.

Table 3. Principal parameters relevant to orbit definition.

Item	**Requirement**	**Notes**
Orbit type	Polar sun synchronous	
Altitude	500 km	Compromise for maximum resolution and minimum atmospheric drag and propellant use
Designed lifetime (minimum lifetime)	5 years (3 years)	Amount of propellant and reliability of the sub-systems set the limit
Repeat cycle	35 days	Provides a representative coverage and also possibility to observe changes in key locations
Downlink connection time	Maximum	Direct ground station overpass provides connection for 10 minutes
Local observation time	12:00 a.m.	Good lighting conditions.

Table 4 lists various orbit-related parameters *vs*. altitude for a sun-synchronous orbit. The amount of fuel to counteract the reduction in orbit velocity due to atmospheric drag is determined for a conventional hydrazine-based thruster with a nominal specific impulse of 230 s. A conservative estimate for satellite mass of 1000 kg and cross-section area of 3 m^2 are assumed in these calculations. Maximum contact times are listed for comparison. Contact times are determined based on a minimum elevation angle of 5 degrees and a direct overpass. The atmospheric densities used are expected worst-case values. Station-keeping manoeuvres are estimated to be needed every 38 revolutions.

Table 5 lists parameters relevant to the instrument design. Also listed are the minimum pointing accuracies required to image the same area and swath with 80% accuracy. A maximum error of 5 metres in orbital information is assumed.

The 500 km altitude orbit seems to be the best trade-off concerning the on-ground imaging resolution of 0.5 metres, major budgets and platform performance.

Table 4. Orbital parameters and propellant masses needed to counter-act atmospheric drag.

Orbit altitude (km)	**Orbit period (min)**	**Orbit inclination (degrees)**	**Maximum contact time (min)**	**Atmospheric density [1] (kg / m^3)**	**Lifetime w/o propulsion [2] (days)**	**ΔV [3] (m/s)**	**Hydrazine fuel [4] (kg)**
300	90.5	96.7	7.3	4.70E-11	58.9	1460	910
400	92.6	97.0	8.7	1.20E-11	269.2	370	180
500	**94.6**	**97.4**	**10.0**	**3.10E-12**	**1150.0**	**94**	**42**
600	96.7	97.8	11.3	1.00E-12	3834.5	30	13
700	98.8	98.2	12.5	3.10E-13	13419.1	9	4

[1] Predicted worst-case values.
[2] Cross-section area of 3 m^2 and mass of 1000 kg have been assumed in the calculation.
[3] Approximate reduction in orbit velocity over a 5-year mission due to atmospheric drag.
[4] Approximate amount of hydrazine propellant to counter-act the atmospheric drag. A specific impulse of 230 s is assumed.

Table 5. Instrument and platform specific parameters vs. the orbit altitude.

Orbit altitude (km)	FOV (mrad)	IFOV (μrad)	Area pointing accuracy[1] (mrad)	Swath pointing accuracy [2] (mrad)
300	13.3	3.3	1.92	2.60
400	10.0	2.5	1.44	1.95
500	**8.0**	**2.0**	**1.15**	**1.56**
600	6.7	1.7	0.96	1.30
700	5.7	1.4	0.82	1.11

[1] 80% repeatability in imaging area and maximum orbit knowledge error of 5 metres are assumed.
[2] 80% accuracy in swath repeatability and maximum orbit knowledge error of 5 metres are assumed.

2.4 Ground segment requirements

The critical component in data acquisition of Kioto+ is the ground segment. The satellite can acquire more data that can be transmitted to ground with a foreseen number of receiving stations. High latitude locations for ground stations provide frequent contact times for telemetry, tracking and command (TTC) capabilities. The locations should be as free of interference signals as possible. To provide ideal coverage, the ground segment should contain at least two stations in a 45 to 90 degrees angle in the longitude direction in the polar area and a third one in the southern hemisphere. The infrastructure should contain all the necessary components for the ground station, along with maximum data transmission capability.

Of the three ground stations, one would be the primary TTC station and should be supported by one back-up TTC station. In addition, one of the receiving stations should be considered as the data centre where all the data are gathered, processed, archived and distributed to the customers. The raw and/or pre-processed data are archived at the receiving stations, and delivered to the data centre for processing and distribution to customers. Optionally, the receiving stations should be prepared for receiving two separate but similar satellites having a 20 to 30 minute gap between receptions. Data transmission should be fast enough for this amount of data, as well as very large storage capacity at the archiving and receiving environment.

3. Technical concept

3.1 Technical concept overview

The required on-ground imaging resolution of 0.5 metre is a driver for the optics design, major budgets and platform performance (Table 6). A reasonably low flying platform of 500 km altitude is proposed. The high on-ground imaging resolution in the panchromatic band can be achieved with a narrow swath width by using a split focal plane and a mutual shift of CCDs by half a pixel in both row and column directions. The use of two-dimensional image sensors instead of line sensors makes the Kioto+ instrument potentially less sensitive to pointing instabilities than for example Spot, Rocsat2 and Pleiades imagers based on line CCDs.

Table 6. Kioto+ mission major budgets.

Parameter	Value	Remarks
Satellite type		3-axis stabilized, medium sized satellite in a sun-synchrounous orbit
Satellite mass range	680–800 kg	The system mass depends on instrument mass and power consumption.
Payload mass range	180 kg	This figure may be reduced with future development.
Payload dimensions	L = 1750 mm W = 800 mm H = 850 mm	
Payload power consumption	170 W	In active mode. The instrument average power consumption is less.

3.2 Payload

The diameter of the telescope main mirror is 500 mm, which is adequate to provide 0.5 m optical ground resolution assuming nearly diffraction-limited optics. The ground sampling distance is 0.7 m with the half a pixel mutual shift of the two panchromatic CCDs (Figure 4). Methods to construct a super resolution image are presented in the PhD thesis of Nhat Xuan Nguyen (2000). One alternative for constructing a super resolution image from images shifted on the ground by sub-pixel width is explained in Figure 5. In the paper of Xinping et al. (2000), a high resolution imaging technique similar to the Kioto+ concept is presented. The feasibility of the imaging method was demonstrated by computer simulations and experimental results. The target resolution of 0.5 m provided by the optics enables the construction of 0.5 m ground pixel images by interpolation from the two images shifted 0.7 m on the ground in a similar way as the algorithm used for SPOT-5 images (Terra Engine 2005).

The ground sampling distance is 0.7 m. A stereo imaging capability is arranged by manoeuvring the satellite line-of-sight along-track to image the same area from two different angles. If the optional second satellite is implemented, near-simultaneous stereo imaging of the same area is also possible. The absolute pointing accuracy requirements of Kioto+ are important but they can be fulfilled with the technology available in the near future.

All CCD detectors are proposed to be Time Delayed Integration (TDI) devices to enable adequate exposure times for all spectral channels. In Europe E2V Technologies is developing CCD91-72 sensors for the GAIA-mission (ESA Science & Technology 2005). These devices could be modified for the Kioto+ mission. Fairchild Imaging has developed both line and 2D TDI CCD sensors for NASA (Fairchild Imaging 2005). The TDI 2D CCDs require a shutter. To avoid a shutter an optical configuration based on TDI line CCDs (similar to the devices used in Pleiades) is also a feasible concept for Kioto+. For the SWIR channel detectors, the HgCdTe detectors developed for PRISM are proposed (Chorier et al. 2001). An alternative would be the Monolithic InGaAs-on-silicon Short Wave Infrared detectors that are developed in the USA (NASA 2002).

The preliminary payload concept assumes that major specifications for the mission are as shown in Table 7.

Table 7. Preliminary instrument characteristics.

Parameter	**Value range**	**Remarks**
Spectral bands	Panchromatic, BGR, NIR, SWIR	BGR, NIR 0.45 .. 1.1 μm as for Landsat, SWIR 1.4 .. 1.6 μm, Pan 0.45 .. 0.72 μm.
Ground resolution at nadir	0.5 m Pan, 2 m BGR&NIR, 4 m SWIR	Ground resolution at nadir 0.5 m Pan, 2 m BGR&NIR, 4 m SWIR. 0.5 m resolution can be achieved with the half a pixel mutual shift of the two panchromatic CCDs and with a re-sampling on the ground. The ground sampling distance is 0.7 m.
Image size	4 km x 4 km	With two 4000 x 4000 pixel CCD arrays for Pan.
Total Field of View, FOV	8 mrad	At 500 km altitude.
Focal length of the optics	6 m	At 500 km altitude.
IFOV	2 μrad	For a 500 km altitude LEO satellite this imposes strict requirements on pointing stability.
Exposure time	4–7 ms	For adequate SNR, TDI integration will be used.
Dynamic range of image data	12 bit	High SNR for biomass, LAI mapping and conifer forests.
Data per one exposure of all channels (2x PAN, 1x B, 1x G, 1x R, 1x NIR, 1xSWIR)	588 Mbit (73.5 Mbyte)	Pan: 2x4000x4000 pixels; BGR: 3x2000x2000 pixels; NIR 1x2000x2000 pixels; SWIR: 1x1000x1000 pixels. Dynamic range for all channels is 12 bit.
Image data compression ratio	2	Lossless compression preferred
Compressed data per image of all channels	<u>294 Mbit</u> (36.8 Mbyte)	

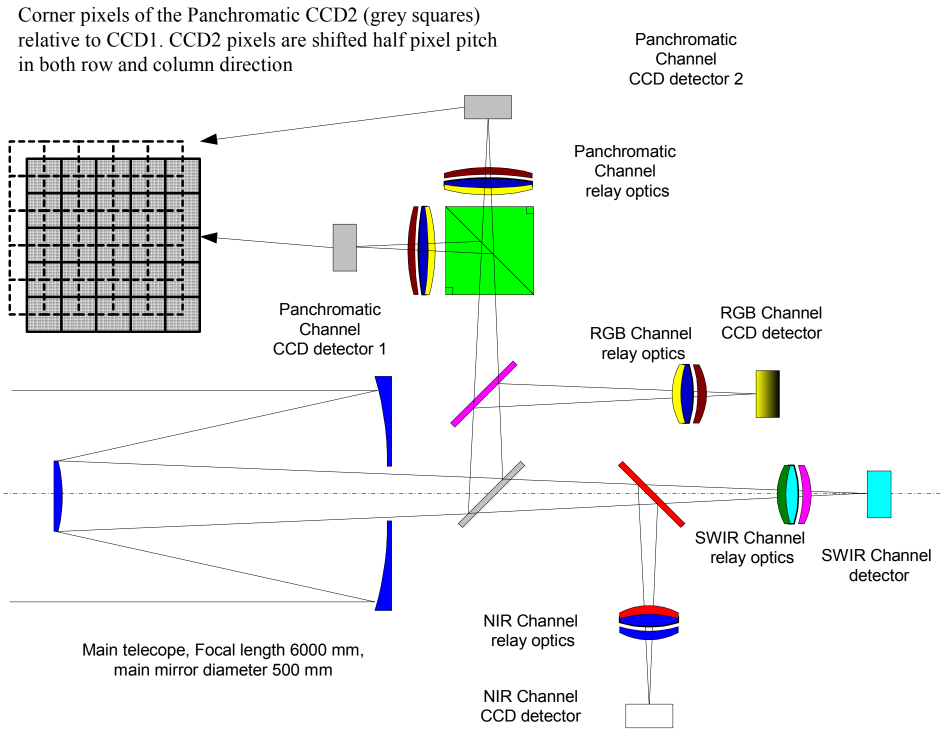


Figure 4. Kioto+ Payload concept based on 500 km altitude and 0.5 m ground resolution achieved with staggered 2 dimensional CCD detectors.

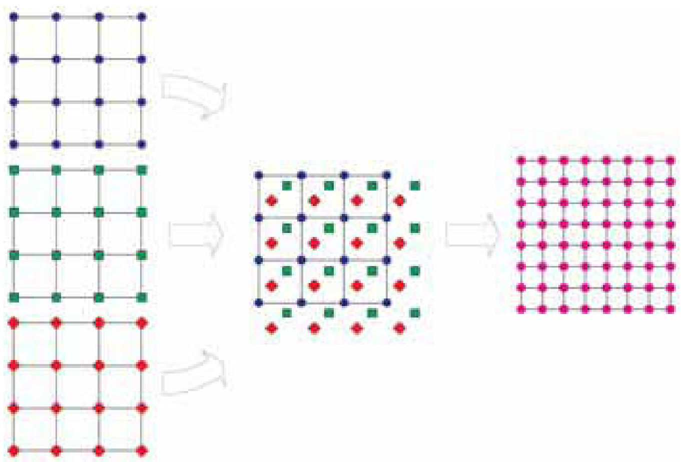


Figure 5. The principles of the super-resolution image reconstruction. First, a sequence of images is taken from the same target with the mutual sub-pixel shifts. Then a thicker super-resolution grid is created and pixel values are interpolated from the single images.

The Kioto+ instrument has the following operational modes:

- launch mode in which the instrument is switched off;
- commissioning mode in which the initial power is on and calibration procedures are performed;
- pause mode which is used both as waiting condition and as intermediate step when switching between different modes;
- nominal mode (measurement mode) for which the instrument has three sub-modes:
    - full resolution (sampling) imaging mode over land;
    - strip imaging mode with 100 metre resolution over the sea;
    - stereo imaging mode.
- stand-by mode for reduced power consumption;
- safe mode to which instrument enters in case of malfunction or for protection purposes;
- software update mode in which the instrument receives from the ground data about orbit forecast and if necessary software updates.

Payload electronics

Kioto+ detectors are located in the focal plane of the optics (Figure 6). To obtain the required on-ground resolution, 5 detector arrays are used in total. The payload electronics consists of three main sections:

- The focal plane assembly (FPA) electronics containing the CCD clock drivers and CCD analogue video signal pre-amplifiers. Gain switching of the analogue video signal is optional and to be studied later.

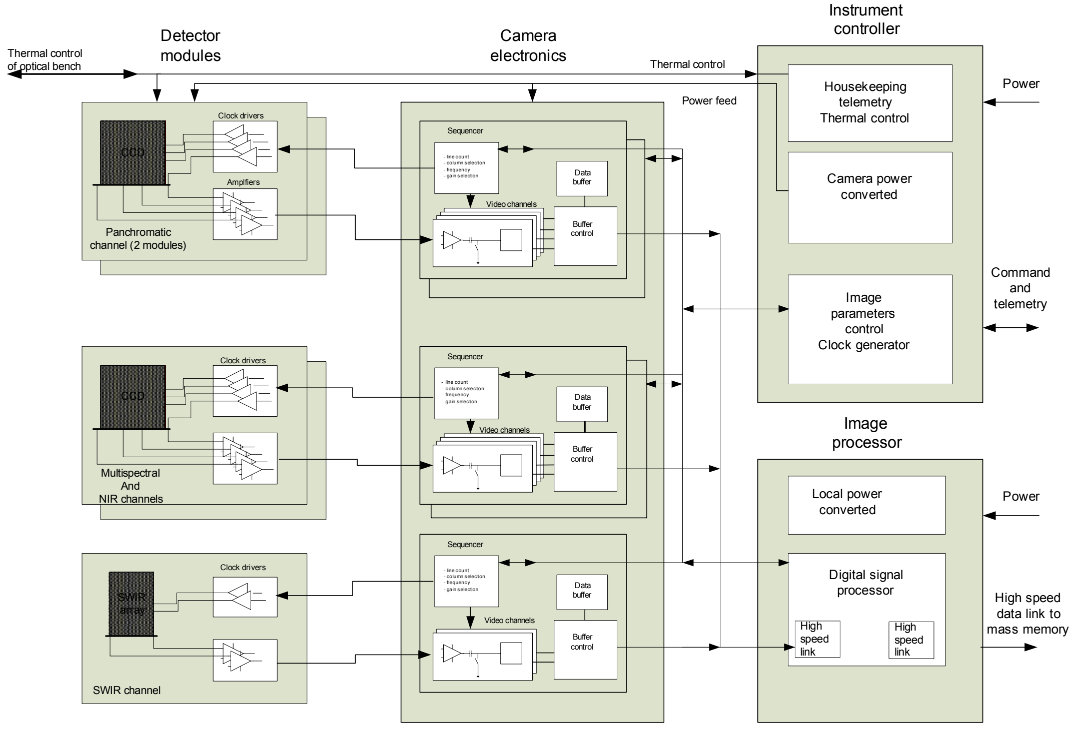


Figure 6. Block diagram of electrical system of the Kioto+ payload.

- Camera electronics containing the video chains for the digitisation of the analogue video signals. The sequencers generate the CCD clocking signals according to the programmed raw image parameters. A local image data buffer stores the data from each of the CCDs.
- The instrument controller contains common data processing, housekeeping and power conversion functions. A dedicated image processor performs on-board image analysis to reject images with large cloud coverage.

The satellite mass memory unit is also an essential part of the payload data path. The instrument control computer commands data transfers from the image processor to the mass memory. Depending on the imaging sequence, the image processor will evaluate the image content before the data transfer. For short imaging intervals, the image is first transferred to mass memory and analysed by the image processor later in a suitable time slot.

As a first estimate, the Kioto+ payload electric power consumption is divided between optics thermal and focus control (40 Watts), the focal plane electronics (30 Watts), and camera electronics (90 Watts). In total, 170 Watts is estimated at this phase including 10 Watts contingency.

3.3 Platform

The selection of platform options for the Kioto+ mission is based on platforms available or selected for similar kinds of missions (Table 8). The Alcatel Proteus LEO platform, the Ball Aerospace Commercial Platform 2000 (BCP 2000) and Astrium Leostar platform are flight proven, whilst the Astrium Pleiades platform is under development.

The requirement for the mass memory capacity for the instrument parameters given is determined by:

- requirement for the maximum non-contact time between the satellite and ground stations;
- specified ground contact data downlink rate.

As a minimum, a mass memory capacity of 256 Gbit is required and taken into account in the in-flight system budgets.

Table 8. Platform examples.

Platform (Missions)	**Power**	**Downlink**	**Pointing accuracy / knowledge**	**Orbits**	**Spacecr aft mass**	**Slew rate**
Proteus (Jason-1, SMOS)	450 W	S-band 690 kbps (X-band optional)	0.035° / –	600–1500 km	600 kg	Unknown
Pleiades (Pleiades HR)	1400 W	X-band 10 Mbps	<0.0041° / <0.0016°	680 km	1000 kg	3 deg/s
Leostar 500 XO (Rocsat 2)	900 W	X-band 120 Mbps	0.12° / 0.02°	450–1500 km	1000 kg	0.4–0.75 deg/s
BCP 2000 (Quickbird)	730 W	X-band 320 Mbps	0,016° / 0.0008°	400–900 km	1000 kg	Up to 4 deg/s
Astrobus (Aeolus)	2400 W	X-band 10 Mbps	0.01° / 0.0026°	408 km	1100 kg	Unknown

3.4 Launcher

The mission will probably need a dedicated launcher. A piggy-back or shared launch with another satellite mission might be difficult due to specific orbit requirements. Some possible launchers for a sun-synchronous LEO with orbital height of 500 kilometres for a 400–1000 kg satellite include the following (Table 9):

Table 9. Launcher options for Kioto+ satellite.

Launcher	LEO performance	Launch site	Notes
Rockot	800 kg to 1200 km	Plesetsk	Selected for first three ESA Earth Explorer missions.
Vega	1500 kg to 700 km	Kourou	First launch 2007. Option for Pleiades.
Soyuz	7000 kg to LEO	Baikonur (Kourou)	First launch in Kourou 2007. Option for Pleiades.
Delta II	2600 kg to LEO	Vandenberg, Cape Canaveral	Selected for two Proteus platform launches.
Taurus	1450 kg to LEO	Vandenberg	Option for Ball CP 2000
Cosmos SL-8	1350 kg to LEO	Plesetsk	Option for Ball CP 2000
Dnepr	1700 kg to 500 km	Baikonur	Option for Aeolus

3.5 Ground segment

Table 10 shows how the location of the receiving station(s) and the number of stations correspond to the estimated contact times/day from satellite to ground segment.

Table 10. Estimated daily receiving capabilities with 15 satellite orbits/day.

Number of stations and location latitude	Average contact time/day	Data received/day with 100 Mb/s	Data received/day with 300 Mb/s
1 station at 67˚	100 minutes	76 GB	225 GB
1 station at –30˚	40 minutes	30 GB	90 GB
2 stations at 67˚ with 45˚ separation angle in longitude	160 minutes	120 GB	360 GB
2 stations at 67˚ with 90˚ separation angle in longitude	180 minutes	135 GB	405 GB
2 stations at 67˚ with 45˚ separation angle in longitude, and 1 station at –30˚	200 minutes	150 GB	450 GB
2 stations at 67˚ with 90˚ separation angle in longitude, and 1 station at –30˚	220 minutes	165 GB	495 GB

As was shown in Table 7, the raw image data size per one exposure of all channels (2x PAN, 1x B, 1x G, 1x R, 1x NIR, 1xSWIR) is 588 Mbit or 73.5 MB. Due to framing overheads in data transmission from satellite to ground station the total amount of data per image increases 20–25% up to 92 MB. For example, with 2 receiving stations at 67˚ with 45˚ separation angle in longitude and 1 station at –30˚ and with 300 Mbit/s downlink the ground segment will be able to receive almost 5000 exposures/day.

The annual number of images using two or three ground stations is estimated to be as follows (maximum achievable downlink time limits the amount of images):

⇒ 100 Mbps link:

- 1 station: 780 000 compressed images (including all six channels);
- 2 stations: 1 092 000 to 1 400 000 compressed images;
- 3 stations: 1 560 000 to 1 720 000 compressed images.

⇒ 300 Mbps link:

- 1 station: 2.2 million compressed (lossless) images;

- 2 stations: 3.2 to 4.2 M compressed (lossless) images;
- 3 stations: 4.6 to 5.2 M compressed (lossless) images.

Thus, if we assume two-thirds of the images being cloudy or invalid for other reasons despite an intelligent acquisition concept with on-board cloud detection, it is possible to collect at least one million valid images annually using two receiving stations and lossless on-board image compression. A sample size of one million means an image every 12 km by 12 km on all land areas excluding the Antarctica.

Processing environment and archiving

All hardware and software architecture in receiving stations and the main data centre should be based on up to date technology at the time of launch. All receiving stations archive the raw data, and the data are also processed at the station. One of the receiving stations operates as the main data centre, which will archive all received raw and processed data. Also this data centre is responsible for data dissemination and customer services.

3.6 Products

The primary products of the Kioto+ mission are related to land cover, forest cover characteristics, and carbon storage of forest vegetation (Table 11). These characteristics are determined for each sample plot (image) by applying the full spatial resolution of each measurement channel. Additionally, an experimental mission mode is able to provide observations from the same sample plots with two different angles of observation (stereographic images). These data can be applied for example to map tree canopy structure of dense forests.

Table 11. Preliminary products.

Product level	Product	Geocoding	Characteristics	Provider
Level 1B	TOA reflectance and radiance	Applying orbit parameters	Percentage units, $W/m^2/Sr$	ESA
Level 2	Atmospherically corrected surface reflectance	Applying orbit parameters	Percentage units	ESA
Level 3	Forest cover	Improved geocoding for multi-temporal samples	Canopy closure for each sample plot, size *e.g.* 50 m by 50 m (from 0 to 100% incl. conf. interval)	Product specific data provider
Level 3	Land cover classification	Improved geocoding for multi-temporal samples	Spatial resolution of 50 m by 50 m, forest/non-forest classes, information on tree types, conf. intervals	Product specific data provider
Level 3	Tree map / individual tree harvest product (ARD)	Improved geocoding for multi-temporal samples	Individual trees within a selected sample plot at the spatial resolution of 0.5 m	Product specific data provider
Level 3	Leaf Area Index	Improved geocoding for multi-temporal samples		Product specific data provider
Level 4	Forest biomass for direct carbon storage assessment	Improved geocoding for multi-temporal samples	Using spectral data with SWIR possible up to approximately 100 tons dry matter, but with individual tree detection can be extended to higher biomass levels	Product specific data provider

The secondary products of the mission are obtained for ocean and coastal areas using a continuous sampling principle. These products provide information on the water quality characteristics, such as chlorophyll-a concentration (chl-a) in ocean waters, and total suspended solids concentration (TSSN) in coastal and lake waters. The instrument images a line below the flight track with a coarse pixel size of 100 m (for all channels). Thus, each image line consists of 40 pixels in the across-track dimension (total line width 4 km). The data amount for the secondary product is roughly 200 Mbits per orbit.

The accuracies of the Kioto+ based estimates were simulated using the Corine land cover database (JRC-EEA 2005). At the global level, the accuracy in all cases is very good. Even for an area of 30 000 km^2 the accuracy is quite satisfactory, as is demonstrated in Table 12, which presents the estimated coefficients of variation (the standard error of the estimated area of a land cover class in percentage units for a land cover area) for the different area sizes and proportions of land cover classes. The simulations were based on a sampling rate of 11% (globally one million on land area excluding Antarctica). The higher is the area proportion of a land cover class and the larger the region, the better is the accuracy. The accuracy of a single observation in the land cover class definition was assumed to be 95 to 98%, depending on the nomenclature (*i.e.* definition of forest classes). This level of accuracy should easily be met at least in interactive image interpretation.

Regarding the biomass estimation, the *sampling error* is foreseen to be of the same order of magnitude as in the land cover classification into two classes (*i.e.* forest and non-forest). The actual main error source is the *model* that is used to transform the image data to biomass estimates. (*N.B.* In land cover estimation [Häme et al. 2000, Sirro et al. 2002] the model error can be avoided in the interactive image analysis because the observations resemble *in-situ* measurements.)

Table 12. Estimated coefficient of variation for the different area sizes and proportions of land cover classes. The simulations are based on a sample size of one million on land area excluding Antarctica (11% sampling rate).

	Proportion of forest or another land cover class						
Area of region	10%	20%	30%	40%	50%	60%	80%
30,000	6.8	4.5	3.5	2.8	2.3	1.8	1.1
100,000	3.7	2.5	1.9	1.5	1.2	1.0	0.6
1,000,000	1.2	0.8	0.6	0.5	0.4	0.3	0.2
10,000,000	0.37	0.25	0.19	0.15	0.12	0.10	0.06
global	0.12	0.08	0.06	0.05	0.04	0.03	0.02

4. Discussion

4.1 Scientific benefit of the Kioto+ mission

The mission responds to most of the new challenges that are presented in the Science Priority document (ESA/Explorer/CCM-02 – ANNEX A, Chapter 4). It focuses on the acquisition of global information. Very high spatial resolution makes it possible to integrate models and data in a more reliable manner using assimilation methods. The global monitoring capability of the mission helps greatly to include the human dimension in Earth system models.

The relevant focus areas of the Kioto+ mission are the global water cycle, the global carbon cycle, and the human element in the Earth system. All the listed focus areas (including atmospheric chemistry) are anyway interconnected.

The data from the Kioto+ mission can be used to help estimation of the evapotranspiration over land through vegetation and soil mapping. In the global carbon cycle and human impact estimation, the usefulness of the data is obvious through the forest area species and biomass mapping, and through land cover class monitoring. The data could not only be used for scientific carbon cycle studies, but could also be utilized to help the implementation of the successor treaties of the Kyoto Protocol to the UNFCCC because the images can be used to accurately estimate forest area and its changes.

Regional Authorities may also be final users of Kioto+, as their forest services are interested in quantitative estimations of forest parameters such as the area of forest and ARD. Moreover, Kioto+ products can be used to reliably estimate the extent of burnt area, support watershed characterization activities, and provide inputs to hydrological models.

4.2 Need, usefulness and excellence

The Kioto+ sampling mission will offer more accurate and reliable information on global land cover, forest cover and forest biomass than any other data source thus far. The statistical sample from the Kioto+ mission will also make it possible to calibrate the wall-to-wall maps from coarser resolution satellites so that the proportions of the land cover classes in those maps correspond to the reality.

The mission responds to the needs that follow from the implementation of the international policies as discussed in Chapter 1. As indicated in Table 12, very high accuracies can be achieved in forest and land cover estimation and the changes between the land cover classes and within them including afforestation and deforestation. The accuracy for the biomass estimation is automatically lower than the accuracy of the land cover class estimation because the biomass estimation requires utilization of a model that involves an error (the error due to the model is also included in the ground-based estimation). However, compared to the present accuracy of the estimates the improvement may be most dramatic in the biomass.

Land cover can be described using the super-high resolution data without utilizing any model. The estimation performance in forest cover may be even better than in ground-based surveys because the estimation of crown cover area for the nadir images is easy and can be automated.

The potential final users of the information from the mission include FAO, The Global Carbon Project of the IGBP, The European Environment Agency, European Forest Institute, also national authorities that are responsible for the implementation of the international climatic treaties, and naturally the science community that is involved in global carbon cycle and water cycle studies, including the WCRP.

The 0.5 metre resolution of the panchromatic band together with the other spectral channels (particularly the SWIR channel) makes the data very effective to estimate the primary production through the Leaf Area Index (LAI) estimation. Involvement of the SWIR band has been proven to drastically improve the LAI estimation accuracy in (boreal) forests. The SWIR band has also been often the most effective spectral band in forest biomass estimation using reflectance-based (non-textural) estimation.

The Kioto+ payload concept makes it possible to use a matrix detector instead of a line detector. This solution makes the pointing accuracy requirement more relaxed, thus decreasing the risk of blind spot areas in the image. Manufacture of such detectors is a proven concept for airborne imaging. Such a detector for space-borne use is a technical challenge for the European space industry that will help to develop the competitiveness of the industry but is not too risky.

4.3 Uniqueness and complementarity

As discussed in Chapter 1, no other missions for the same purpose as Kioto+ exist or are planned. The Pleiades mission has technological similarities but its purpose is different and it thus cannot fulfill the need of statistical sampling which is crucial for the derivation of reliable global statistics on natural resources. The Kioto+ satellite also has the SWIR band that is not available in other super-high resolution satellites.

On the technological side, an important innovation is the use of a matrix Time Delayed Integration detector instead of a line detector. The shutter required by a TDI matrix detector is a major technological challenge in the Kioto+ instrument development.

Kioto+ would complement the GMES Sentinel program (particularly Sentinel 2) by provision of reliable reference data for wall-to-wall mapping as discussed above.

4.4 Degree of innovation and contribution to the advancement of European EO capabilities

The principal innovation of the Kioto+ mission is that it offers objective global data to near-in-situ-measurement accuracy on land cover and forest cover. The observations can be considered as *in-situ* measurements from space, which gives European advantage over the US IEOS (Integrated Earth Observation System) program. The super-high resolution data collected using a statistical sampling principle will make it possible to produce also reliable wall-to-wall maps using the GMES Sentinel satellites. Thus, it gives a significant contribution to the GMES program and consequently to the international GEOS initiative. The Kioto+ mission would be the world leader in the provision of super-high resolution space-borne data globally.

The Kioto+ mission is run by an international organization and not by commercial companies or national agencies, which means that the mission can fully focus on the information collection for the global carbon and water cycles, as well as on the sustainable use of natural resources.

4.5 Feasibility and level of maturity

We believe that the mission would be feasible and that the level of scientific maturity is high. The scientific concept is based on research over many years on the estimation of land surface variables using high resolution optical imaging data. The mission and the satellite platform have similarities with several high resolution imaging missions being developed and also manufactured in Europe. The absolute pointing accuracy will require special attention during the development but is still well in line what is available in the near future. System mass and power budgets are quite conservative, with total satellite mass estimated in the range of 680–800 kg.

Careful design of Kioto+ instrument optics is required to obtain the required resolution and long-term stability. However, owing to the relatively low orbit and mission time many requirements on the payload can be relaxed somewhat. The detectors will require technical development in terms of space qualification. This work is already performed in Europe for several near-future missions. An internal signal is used to calibrate the camera electronics in flight. In-flight calibration of the optics and detectors requires on-ground test areas with known spectral properties and illumination conditions.

The total number of images is limited by the data downlink budget. This could be improved by using several ground stations, including one in the southern latitudes. However, availability of a southern ground station for this mission is not a technological but rather an economic and political issue.

4.6 Timeliness

The mission would be timely considering the urgent need for a better characterisation of forest cover and its role in climate change. In addition, a launch in year 2011 would offer complementarities to the GMES Sentinel 1 and Sentinel 2 missions, as well as to a range of other optical and SAR EO missions already planned. There is no specific technical timing constraint for this mission. It will, however, benefit from overlap with other coarser spatial resolution sensor missions.

4.7 Programmatics

Schedule and cost estimates are based on a proto-flight model philosophy, supported by specific breadboards and test activities. The schedule envisages a Phase C/D of about 36 months duration.

The mission duration is planned to be 3 years and thus is compliant with the objective of the Explorer program. An additional margin of 2 years has been planned which means that the payload and platform have been designed to operate for 5 years. The margin will allow an adequate time for the testing and verification of the mission operation. During the 3 year time of operation the global land cover and forest cover can be accurately estimated, and the capability of the Kioto+ mission for change monitoring demonstrated for future operative missions. With a relatively low additional investment, the lifetime of Kioto+ could be extended which would make it possible to achieve more information on the dynamics of the ecosystems.

Development and procurement of the Kioto+ instrument detectors is one of the time critical items. The cost of the detectors depends quite a lot on other similar activities at the time of the Kioto+ development. However, the present Kioto+ budget estimate assumes no other supporting activities.

References

ASAR 2005. http://envisat.esa.int/instruments/asar/, latest update 21.1.2005.

Astola, H., Bounsaythip, C., Ahola, J., Häme, T., Parmes, E., Sirro, L. and Veikkanen, B. 2004. HIGHFOREST – Forest Parameter Estimation from High Resolution Remote Sensing Data. Proceedings of the International Society for Photogrammetry and Remote Sensing XXth Congress. Volume XXXV, Part B, DVD. Pp. 335–341.

BCP 2000. Available: http://rsdo.gsfc.nasa.gov/rapidii/Specs/bcp2000.pdf.

Bonan, G. B. and van Cleve, K. 1992. Soil temperature nitrogen mineralization, and carbon source-sink relationships in boreal forests. Canadian Journal of Forest Research, Vol. 22, pp. 629–639.

Bonan, G. B., Pollard, D. and Thompson, S. L. 1992. Effects of boreal forest vegetation on global climate. Nature, Vol. 359, pp. 716–718.

Brown, S. 1998. Present and Future Role of Forests in Global Climate Change. In: Gopal, P., Pathak, P. S. and Saxena, K. G. (Eds.). Ecology Today: An Anthology of Contemporary Ecological Research. Pp. 59–74. New Delhi: International Scientific Publications.

Chorier, P., Tribolet, P., Sofradir, 2001. High performance HgCdTe SWIR detectors for hyperspectral instruments. SPIE Proc. Vol 4540-47.

CLC (Corine Land Cover) 2000. http://image2000.jrc.it/clc/index.html, latest update 18.5.2004.

ERS 2005. http://earth.esa.int/ers/, latest update 16.11.2005.

ESA Science & Technology 2005. http://sci.esa.int, July 2005.

European Space Agency 2005. Earth Observation Programme Board 2005. The call for ideas for the next Earth Explorer core missions. ESA/PB-EO(2005)22 Att. Annexes A & B Paris, 14 February 2005 (Original: English). 13 p.

Fairchild Imaging, Aerospace. Available:
http://www.fairchildimaging.com/main/apps_aerospace.htm, viewed at September 2005.

FAO 2005. State of the World's Forests 2005. Available:
http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/007/y5574e/y5574e00.htm, viewed at May 2006.

FRA 2000. Forest Resources Assessment. Available:
http://www.fao.org/forestry/foris/webview/forestry2/index.jsp?siteId=2921&sitetreeId=7947&langId=1&geoId=0, viewed at May 2006.

FRA 2005. Global Forest Resources Assessment 2005. Available:
http://www.fao.org/forestry/foris/webview/forestry2/index.jsp?siteId=101&sitetreeId=16807&langId=1&geoId=0, viewed at May 2006.

Finnish Statistical Yearbook of Forestry 2003. Finnish Forest Research Institute. SVT Agriculture, forestry and fishery 2003:45. 388 p. ISBN 951-40-1894-X.

GLOBCOVER 2005.
http://www-gvm.jrc.it/tem/Mapping_land_cover/activities/globcover2005.htm, viewed at 27.1.2006.

GSE-FM 2006. GSE Forest Monitoring (http://www.gmes-forest.info/), latest update January 2006.

Häme, T., Sirro, L., Rauste, Y., Ahola, H., Wegmüller, U., Wiesmann, A., Brusselen, J., Schuck, A. and Karjalainen, T. 2003. Treaty Enforcement Services using Earth Observation. Theme Carbon. Final Report. ESA/ESRIN Contract No.: 15557/01/I-LG. 39 p. http://www.vtt.fi/tte/research/tte1/tte14/proj/teseo/.

Häme, T., Parmes, E., Lohi, A., Räsänen, T. and Stenberg, P. 2000. Combining digital airborne data and satellite images for stand-wise stand variable estimation. Proceedings of the Forestry Information Systems 2000, 16.–20.5.2000, Hyytiälä, Finland.

IGBP 2006. International Geosphere-Biosphere Programme (http://www.igbp.kva.se/), viewed at 27.1.2006.

JRC-EEA 2005. Image 200 and CLC2000. Products and methods. Report EUR 21757 EN.

Kauppi, P. E. 2003. New Low Estimate for Carbon Stock in Global Forest Vegetation Based on Inventory Data. Silva Fennica, Vol. 37, No. 4, pp. 451–457. Available: http://www.metla.fi/silvafennica/full/sf37/sf374451.pdf.

Kleman, J. 1986. The spectral reflectance of stands of Norway spruce and Scots pine, measured from a helicopter. Remote Sensing of Environment, Vol. 20, No. 3, pp. 253–265.

Koskela, J., Nygren, P., Berninger, F. and Luukkanen, O. 2000. Implications of the Kyoto Protocol for tropical forest management and land use: prospects and pitfalls. Tropical Forestry Reports 22. Helsinki: University of Helsinki. Department of Forest Ecology. 103 p.

Kotchenova, S. Y., Song, X., Shabanov, N. V., Potter, C. S., Knyazihkin, Y. and Myneni, R. B. 2004. Lidar remote sensing for modelling net primary productivity of deciduous forests. Remote Sensing of Environment, Vol. 92, pp. 158–172. Available: http://cybele.bu.edu/download/manuscripts/skotchen02.pdf.

Landsat 2006. http://landsat.gsfc.nasa.gov/, latest update 9.1.2006.

Liski, J., Korotkov, A. V., Prins, C. F. L., Karjalainen, T., Victor, D. G. and Kauppi, P. E. 2003. Increased Carbon Sink in Temperate and Boreal Forests. Climatic Change, Vol. 61, No. 1–2, pp. 89–99.

Miller, N. L., King, A. W., Miller, M. A., Springer, E. P., Wesely, M. L. and others. 2005. The Doe Water Cycle Pilot Study. Bulletin of the American Meteorological Society, Vol. 86, No. 3, pp. 359–374.

Myneni, R., Dong, J., Tucker, C. J., Kaufmann, R. K., Kauppi, P. E., Liski, J., Zhou, L., Alexeyev, V. and Hughes, M. K. 2001. A large carbon sink in the woody biomass of Northern forests. Proceedings of National Academy of Sciences of USA, PNAS 98 (26). Pp. 14784–14789.

NASA, Infrared Detector Development Program, 2002. Available: http://irtek.arc.nasa.gov/IRprog.html, last updated 7.1.2002.

Nhat Xuan Nguyen 2000. Numerical Algorithms for Image Super-resolution. PhD thesis, Standford University, July 2000.

Radarsat 2005. http://www.space.gc.ca/asc/eng/satellites/radarsat1/, latest update 4.11.2005.

Sirro, L., Häme, T. and Andersson, K. 2002. A method for forest stem volume Estimation 2002. ForestSAT 2002 Conference: Operational tools in forestry using remote sensing techniques. Edinburgh, GB, 5–9 Aug. 2002. CD-ROM. Forest Research, GB (2002).

Stenberg, P., Rautiainen, M., Manninen, T., Voipio, P. and Smolander, H. 2004. Reduced simple ratio better than NDVI for estimating LAI in Finnish pine and spruce stands. Silva Fennica, Vol. 38, No. 1, pp. 3–14. Available: http://www.metla.fi/silvafennica/full/sf38/sf381003.pdf.

TBFRA 2000. Temperate and Boreal Forest Resources Assessment. http://www.unece.org/trade/timber/fra/welcome.htm. Last update 15.6.2005.

Terra Engine 2005. Spot 5 supermode. Available: http://www.terraengine.com/Eng/Technical/supermode.cfm, viewed at September 2005.

Xinping et al. 2000. Sub-pixel imaging method with area-array CCD sensors and experiment. Chinese Science Bulletin, Vol. 45, No. 2, p. 3, January 2000.

Published by

Series title, number and report code of publication

VTT Publications 599
VTT–PUBS–599

Author(s)
Häme, Tuomas, Aulamo, Osmo, Gallego, Javier, Hallikainen, Martti, Kauppi, Pekka, Lahtinen, Panu, Miller, Norman, Pulliainen, Jouni, Saari, Heikki, Sephton, Tony, Stenberg, Jari & Warren, Carl

Title

Kioto+ mission

Global and accurate monitoring of forest, land cover and carbon

Abstract

This publication is a feasibility study on a proposed super-high resolution satellite mission Kioto+. It was conducted as a response to the 2005 call for ideas for the Earth Explorer missions of the European Space Agency (ESA).

Kioto+ offers objective global data to near *in-situ* measurement accuracy on land cover and forest cover and their development over time. A super-high resolution optical instrument is proposed for the derivation of statistically representative and reliable information. The information will greatly improve our understanding of the global carbon and water cycles, and the credibility of estimates of terrestrial carbon storage. The imagery will also give globally accurate training and validation data for wall-to-wall imaging instruments. The mission is named Kioto+ because the projected timescale of the mission (post-2011) means that it will primarily have relevance to successor treaties of the Kyoto Protocol to the FCCC of the United Nations.

Keywords
Kioto+, forests, vegetation, monitoring, super-high resolution satellites, satellite technology, remote sensing, earth observation, terrestrial carbon sinks, carbon cycles, carbon storage

ISBN
951–38–6832–X (soft back ed.)
951–38–6833–8 (URL: http://www.vtt.fi/publications/index.jsp)

Series title and ISSN			Project number
VTT Publications 1235–0621 (soft back ed.) 1455–0849 (URL: http://www.vtt.fi/publications/index.jsp)			1301
Date	Language	Pages	Price
June 2006	English	42 p.	A

Name of project	Commissioned by
	Tekes, the Finnish Funding Agency for Technology and Innovation

Contact	Sold by
VTT Technical Research Centre of Finland P.O. Box 1000, FI-02044 VTT, Finland Phone internat. +358 20 722 111 Fax +358 20 722 7024	VTT Technical Research Centre of Finland P.O.Box 1000, FI-02044 VTT, Finland Phone internat. +358 20 722 4404 Fax +358 20 722 4374

VTT PUBLICATIONS 599 Kioto+ mission. Global and accurate monitoring of forest, land cover and carbon

This publication presents the results of a feasibility study on a proposed super-high resolution satellite mission Kioto+. The study was conducted by an international consortium as a response to the 2005 call for proposals for the Earth Explorer missions of the European Space Agency (ESA).

Kioto+ offers reliable and global data to near *in-situ* measurement accuracy on land cover and forest cover. It also gives information about their development over time. A super-high resolution optical instrument is proposed to achieve statistically representative and precise measurements. The information will greatly improve our understanding of the global carbon and water cycles, and the credibility of the estimates about the terrestrial carbon storage. The imagery will also give globally accurate training and validation data for wall-to-wall imaging instruments. The mission is named Kioto+ because the projected timescale of the mission (post-2011) means that it will primarily have relevance to successor treaties of the Kyoto Protocol to the FCCC of the United Nations.

Tätä julkaisua myy	Denna publikation säljs av	This publication is available from
VTT PL 1000 02044 VTT Puh. 020 722 4404 Faksi 020 722 4374	VTT PB 1000 02044 VTT Tel. 020 722 4404 Fax 020 722 4374	VTT P.O. Box 1000 FI-02044 VTT, Finland Phone internat. +358 20 722 4404 Fax +358 20 722 4374

ISBN 951-38-6832-X (soft back ed.)
ISSN 1235-0621 (soft back ed.)

ISBN 951-38-6833-8 (URL: http://www.vtt.fi/inf/pdf/)
ISSN 1455-0849 (URL: http://www.vtt.fi/inf/pdf/)