Report

State of the art for tropical forest monitoring by remote sensing

A review carried out for the Ministry for the Environment of Norway and the Norwegian Space Centre


NASA

Report no 1020

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Norut Earth Observation (JOBS) group has largely worked with data from Synthetic Aperture Radar (SAR), but also has long experience with optical and atmospheric instruments. Key skills have been successfully applied to data generated by other imaging instruments such as rontgen and acoustics. In recent years there has also been widespread activity in the use of unmanned aircraft for remote sensing. The JOBS group has recently become particularly engaged in several major EU projects, and has functioned as coordinator for EnviSnow, FloodMan and Eniwave, among others. In addition, the group has been engaged in a number of major projects initiated by the Norwegian Research Council, the Norwegian Space Centre and the Euro Space Agency (ESA).

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Abstract

Norway has undertaken a large initiative for reducing deforestation, in particular in tropical forests which represent a significant carbon store in the Earth system. However, measuring the effects of reducing deforestation, and hopefully also achieving some degree of reforestation, requires effective means of quantifying the results of the measures and giving quick warning if counteractions to negative results are needed. Infrastructure is almost absent in vast regions covered by tropical forests, and the only means to achieve something close to monitoring, with a counteractive and preventive effect, is by using remote sensing. Due to the significant extent of the rainforest areas, particular the Amazon rainforest, even airborne remote sensing can be insufficient, leaving satellite remote sensing as the only effective solution. This report gives an overview of the current state of the art of remote sensing techniques, detailing current relevant sensors and algorithms, usable datasets and information on the leading institutions for R&D on techniques that might lead to operational monitoring of tropical forests.

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Executive summary

Norway has undertaken a large initiative for reducing deforestation, in particular in tropical forests which represent a significant carbon store in the Earth system. However, measuring the effects of reducing deforestation, and hopefully also achieving some degree of reforestation, requires effective means of quantifying the results of the measures and giving quick warning if counteractions to negative results are needed. Infrastructure is almost absent in vast regions covered by tropical forests, and the only means to achieve something close to monitoring, with a counteractive and preventive effect, is by using remote sensing. Due to the significant extent of the rainforest areas, particular the Amazon rainforest, even airborne remote sensing can be insufficient, leaving satellite remote sensing as the only effective solution. This report gives an overview of the current state of the art of remote sensing techniques, detailing current relevant sensors and algorithms, usable datasets and information on the leading institutions for R&D on techniques that might lead to operational monitoring of tropical forests.

Tropical forest logging is carried out by private enterprises that want to use the wood or develop new land for farming. Illegal logging activities occurring deep within the forests are difficult to detect since they are often concealed by the surrounding dense forest. The countries constituting the rainforest belt (including Brazil, Congo and Indonesia) have variable competences and infrastructures for monitoring their respective forested regions by satellite. Brazil is the leading nation of the tropical forest countries with its own operational monitoring program, both for surveying and counteraction. Most other tropical forest countries have none or modest remote-sensing based activities on forest monitoring. In addition to Brazil, the most experienced research and development groups are located in the United States and in Europe. Several universities in the US have carried out quite comprehensive studies of approaches for tropical forest monitoring, especially Carnegie Institution of Washington, South Dakota State University and the University of Maryland. In Europe, the leading groups are SarVision (Wageningen) and the Joint Research Centre (Italy).

Remote sensing of ‘smart’ logging in tropical forests is challenging. Optical remote sensing is limited by cloud cover, which is frequent in these regions. Annual mapping of the ‘state of the forest’ is feasible by combining multiple medium resolution images. However, detecting new logging in an early stage is difficult. An approach combining satellite sensors of different spatial resolutions has been investigated by several groups, and is applied operationally by Brazil. Very high resolution sensors with controllable viewing direction are used for final checking when ‘suspicious’ changes are detected at moderate resolution. This is the current best practice using optical data alone.

Radar sensors, in particular the Synthetic Aperture Radar (SAR), have promising potential for tropical forest monitoring because they can penetrate the cloud cover and are therefore almost weather independent. However, the most appropriate microwave wavelengths for tropical forest monitoring are still not available from spaceborne sensors. The most popular current wavelength is C-band, which does not penetrate very deeply into the canopy. ‘Smart’ logging, selectively removing trees such that the crown cover is affected as little as possible, is hard to discover using such short wavelengths. Longer wavelengths (L- and P-band) would be more relevant to penetrate the canopy for biomass monitoring, but are not available or, in the case of L-band data, have only limited availability. The best of these wavelengths, P-band, penetrates deeply into the canopy, but no satellite to date is equipped with a P-band SAR at this point. A change detection technique comparing old and new imagery could then be used to discover that timber actually has been removed.

Given the currently available spaceborne sensors, a combination of optical and microwave sensors have the best potential for successful tropical forest monitoring. The first approach is to supplement the Brazilian data method with available C-band SAR data. This combination also allows for more sophisticated algorithms with greater potential of detecting the rather subtle changes that take place in the early stages of ‘smart’ logging. Such multi-sensor approaches have been developed for other applications in Norway with great success. This is in particular the case when the multi-sensor approach is combined with multi-temporal, i.e. processing time series of satellite data. ‘All’ available optical and SAR data are then processed together to make the best assessment of the current situation. This is done on a daily basis as new satellite data arrives from global coverage, moderate resolution satellites sensors.

From the perspective of the authors of this report, the logical way forward in order to establish a means of applying satellite remote sensing for tropical forest de- and re-forestration monitoring, is to: 1) establish an international panel of leading experts for sharing their experience of tropical forest monitoring with Norway; and 2) carry out a pilot project in Norway to obtain national experience of applying various algorithms to remote sensing data of tropical forests; and 3) adapt existing monitoring tools to remote sensing data of tropical forests.

Norway is a leading nation, also in a worldwide perspective, in development of remote sensing algorithms and earth observation applications. This is clearly demonstrated in the numerous national and international projects Norway participates in and contributes heavily to. However, for natural reasons, Norway has little experience in analysis of remote sensing data covering tropical forests. Following the three recommended actions above, Norway would quickly come to a position where Norwegian institutes can take a lead in building up tropical forest monitoring competence and systems for this in the tropical forest countries Norway makes agreements with. Additionally this will give Norway the necessary capability to make independent control measurements (spot testing), verifying that the nationally reported results represent the true situation on the ground.

Contents

1 Introduction

1.1 Background

Tropical forests play a crucial role in the global environment. They cover substantial parts of the Earth, and their ecosystems comprise a wide range of biodiversity. The stored carbon in these forests is a key factor in the global carbon balance.

Tropical forests and the land occupied by these forests represent important economic resources at national, regional and local levels. Therefore, these regions are rapidly cleared in many countries in order to utilize the timber and the land in various ways. As there may be conflicting interests and lack of governance in such regions, these activities are not always controlled or properly monitored by legal national authorities. From an environmental conservation and a global climatic change view, there is a serious need to assess the status as well as the current development of tropical forests.

The Norwegian government has taken an initiative to protect tropical forests from deforestation and degradation by providing financial help to encourage governments to take actions to protect their forests. It is necessary to verify that these actions have the right, intended effects. It is, therefore, crucial to identify effective means to establish the status and monitor the development of forest areas that are included in this program. The purpose of this report is to present the state of the art for tropical forest monitoring by means of earth observation (EO) techniques.

Advances in remote sensing techniques allow us to be able to assess these areas, track changes in real time and pinpoint hotspots and specific areas of concern, providing critical knowledge that was not possible prior to this technological development. Through the use of both optical and SAR imagery, we aim to provide much needed information that will aid in monitoring these critical regions and the valuable forests.

Mapping tropical forests presents a number of challenges and consequently requires technical and methodological adaptations. The vegetation is diverse, both in number and type of species but also in its structural organisation, consisting of layers from the forest canopy down to the forest floor. Land cover mosaics rather than straightforward land cover types can be determined and employed to account for this. Weather plays a significant role with clouds often covering the forest and obscuring optical views of the forest, and thus illustrating the value of alternative techniques such as the use of SAR satellites. In the past, the coarse resolution of satellite imagery along with the density of the forest prevented small-scale changes (such as selective logging see Figure 1) from being observed. However, the increasing availability of high-resolution imagery is helping efforts to map the regions in adequate detail and to be able to identify even small areas of change.

Figure 1. Examples of conventional logging (left) and reduced-impact logging (right) in the eastern Amazon.

The challenge is to determine how the world's tropical rainforest areas can be economically developed and protected at the same time. Applying modern remote sensing technology and developing new methods of analysis such as real time monitoring and more sophisticated ways of assessing change will aid greatly in this battle, providing new insight and information that will lead to better management and improved solutions. In terms of research and utilising technology to help in the preservation of critical forest regions, the Amazon region, with its specialised programs and current applications of satellite data, is far ahead of other rainforest regions, particularly Africa but also Southern Asia.

1.2 Main characteristics of tropical forest regions

Tropical rainforests play critical roles in the global ecosystem. They are unparalleled in their biological diversity, containing more than half of the diversity of life on the Earth and providing critical genetic diversity, numerous medicinal plants and sources of many other biological applications. They provide important habitat for specialised and numerous flora and fauna, and support a number of indigenous cultures and peoples. They play a crucial role in regulating global weather patterns, and more importantly, play a critical role in the global carbon cycle, storing vast amounts of carbon and producing great supplies of the Earth's oxygen.

Rainforests are restricted in their location, existing only between the Tropic of Cancer and Tropic of Capricorn, or between 22.5° North and 22.5° South of the equator. The rainforests of the world are found in three main regions (in order of decreasing size): the Amazon, occupying 40% of South America within nine countries, primarily Brazil (the Brazilian component alone represents 30% of the Earth's rainforests); the Congo Basin in central Africa (in Cameroon, the Central African Republic, the Republic of Congo, the Democratic Republic of Congo, Equatorial Guinea and Gabon); and Southern Asia (including Java and Borneo, Malaysia and to the west Burma and India (Figure 2).

Indonesia and the Congo Basin account for another 20% of the global rainforest area and the remaining approximately 50% is scattered throughout these three regions in other tropical zones.

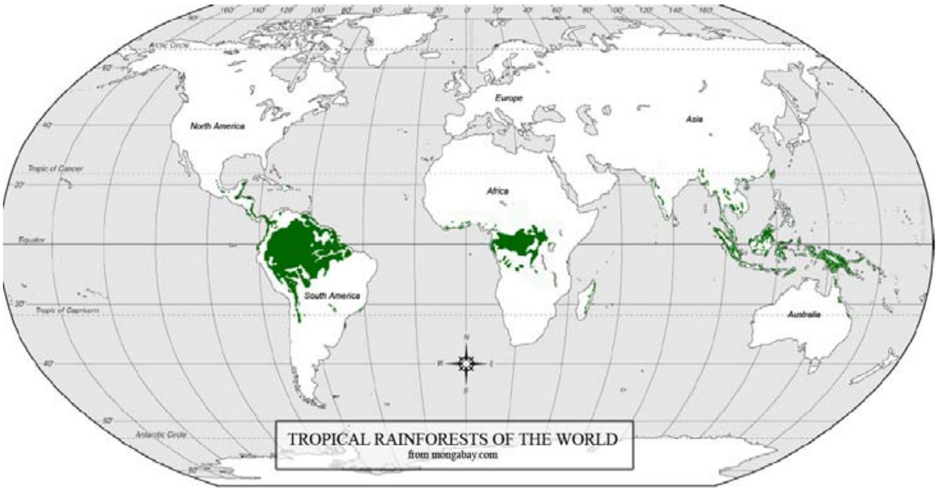


Figure 2. Tropical rainforests of the world.

Rainforests of the world differ in their environments and specific regional environmental characteristics (climate, soil, etc.), local biodiversity and species present, for example, the African rainforests are drier and more seasonal than those in other regions. However, typical generalised environmental characteristics of rainforest regions include well-distributed annual rainfall, substantial annual rainfall typically above 1800 mm but extending to 10,000 mm potentially, very little variation in seasonal temperatures and often a greater variation between diurnal and nocturnal temperatures, consistently warm temperatures, and significant periods of cloud cover but with the possibility of a brief, drier period. The structure of plants and trees follows a layered system: tall, scattered, emergent trees growing above the main canopy (up to about 70m tall); a main umbrella canopy whose density greatly reduces the light penetrating below it (can be divided into two layers with the upper layer reaching heights of approximately 50m); an understory of saplings and shrubs (up to about 15m tall), surviving under low light conditions near the forest floor; and a sparse ground layer containing little vegetation. A variety of vines, lianas, epiphytes, climbers and other specialised plants are found between. A number of tropical forest characteristics can be monitored (Table 1).

Table 1. Common tropical forest monitoring variables

Forest cover	Biomass and carbon	Infrastructure
Forest type change	Stem volume data	Roads
Clear cut maps	Biomass data	Settlements
Forest area	Carbon statistics	Land-use
Forest fragmentation	Carbon change statistics	
Tree and plant species information		

Today less than five percent (6.25 million km^2) of the Earth is covered by tropical rainforest; a few thousand years ago this figure was likely about 12 percent (15.5 million km^2). More than two thirds of the world's rainforests now exist as fragments. The largest unbroken rainforest is found in the Amazon Basin, with more than half of this in Brazil. If current rates of deforestation are not slowed, however, it is estimated that 40% of the Brazilian forest will be gone by 2050. Brazil has already lost about 700,000 km^2 of rainforest since 1970, accounting for 80% of deforestation in the Amazon. Africa has the highest deforestation rates currently.

Rainforests are under threat by activities that appear to be more lucrative or offer economic support to the people that live in the region. Throughout the world's rainforests, logging, road building, and agricultural expansion, whether for the world market or subsistence as is the case in African regions, are the primary activities leading to deforestation. In the Amazon, cattle ranching activity is by far the most serious concern, responsible for about 70% of the loss of rainforest. The number of cattle in Brazil, 55 million, has nearly doubled since 1990. Soya crops in Brazil now cover more than 6 million hectares (60 000 km^2) versus 1.2 million hectares (12 000 km^2) in 1985 while oil palm (a key biofuel) cultivation has expanded in Indonesia from 600,000 hectares (6000 km^2) in 1985 to more than 6 million hectares (60 000 km^2) in 2007 and is expected to reach 10 million hectares (100 000 km^2) by 2010.

1.2.1 Characteristics of tropical forest deforestation

Deforestation of tropical forests has increased dramatically during the last decade. The Brazilian Amazon accounted for 43% of the global net forest loss in the period 2000-2005. Figure 3 gives an example of deforestation in the Brazilian state of Rondônia. In 2001, about 11% of Brazilian Amazonia was deforested, while 47% was under some type of human pressure (Barreto et al., 2006). In 2002-2003 the deforestation rate in Brazilian Amazonia reached a level of 24,000 km^2 per year (Laurance, 2004).

Deforestation is a consequence of a range of legal and illegal human activities, including logging, cattle ranging, slash-and-burn farming, and industrial farming. Due to the huge areas and distances in Amazonia**,** these activities are closely dependent on the transportation infrastructure. Deforestation is therefore likely to happen close to highways and railroads. According to the World Resources Institute (WRI) (Barreto et al. 2006), about 80% of the total deforested areas are within a 30 km buffer from an official road. They relate deforestation to human pressure and distinguish between deforestation related to settlements and to incipient human pressure, respectively.

Figure 3 Deforestation pattern, Ariquemes, Rondônia, Brazil. The image covers an area of approximately 100 × 100 km^2 (Google Maps)

In a review of tropical forest monitoring and remote sensing, Fuller (2006) compares Brazil and Indonesia. While Brazil has an operational EO based system for monitoring deforestation, Indonesia, which is undergoing a very rapid conversion of forest land to other land uses, has no system for monitoring these changes. Likewise Africa has very little activity and research related to monitoring and protection of its rainforests.

1.2.2 Logging

Because of insufficient legislation and weak law enforcement, illegal logging is a significant problem in Amazonia as well as Indonesia. Illegal loggers disregard protected areas and log these areas and legal forest concessions. Illegal logging in the latter has encouraged legal concessionaires in Indonesia to accelerate their logging in order to get the timber before it is harvested illegally (Fuller et al., 2004), compounding the problems of and associated with deforestation. 43% of the timber harvested in 2004 in Brazilian Amazonia is assumed to be from illegal logging, likely an underestimate due to additional unauthorized practices from licensed loggers (Barreto et al. 2006). Conventional logging causes severe damage to the forests, but some loggers have adopted improved practices in order to obtain green certification.

Selective logging refers to areas where only economically valuable tree species are being harvested. The remaining forest has less economic value, and is left by the loggers. Some of the forests will be transformed to agricultural or pasture land as the next step, and others will be exposed to burning (Barreto et al., 2006).

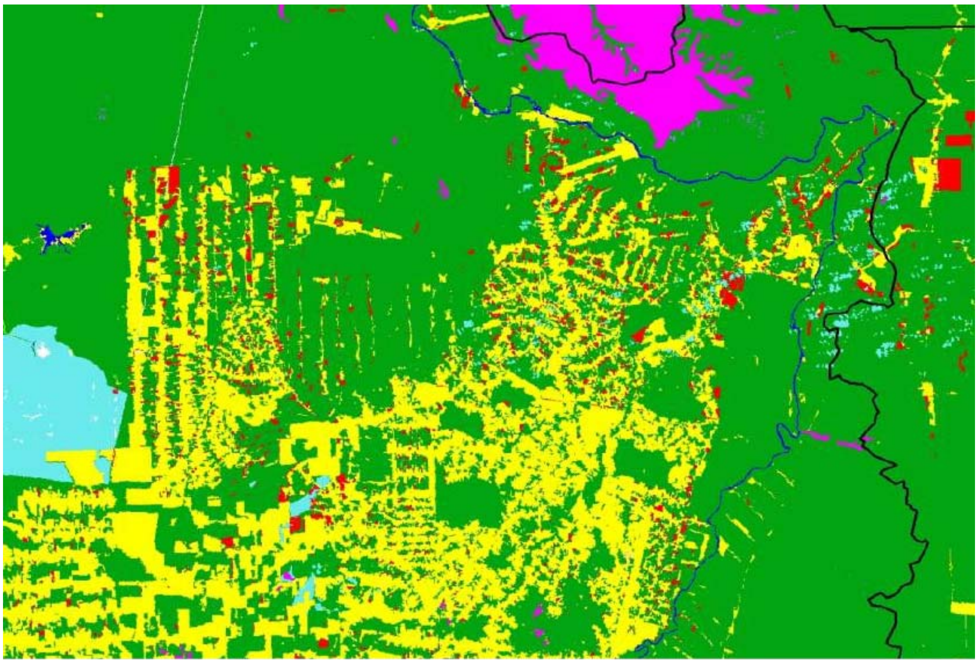


Figure 4. Deforestation in Rondonia, Brazil 2005. Yellow – old, red – new (data by INPE).

1.2.3 Burning

Forest burning has been applied as part of a shifting agriculture practice at smaller scales for centuries. The slash-and-burn practice leads to quick fertilization of the ground. However, it is useful for simple agriculture for a short period of time only. After a few years, the burned area must be left as fallow land. When applied at larger scales this practice is not sustainable.

The number of fires in Amazonia doubled between 2000 and 2002, reaching a level of 43,000 fires a year. About 28% of Brazilian Amazonia is within a zone of 10 km from a recent forest fire location. The majority of these areas are close to or within deforested areas.

Only 1/3 of the fire zone is within a 30 km buffer zone from an official road (Barreto et al., 2006). However, a large part of the rest is close to unofficial roads related to logging, ranging or mining.

Forest areas that have been burned or logged may or may not be succeeded by secondary vegetation. Where secondary vegetation is established, the forest may gradually recover and the carbon accumulation may thus continue. Other areas may remain as fallow land for a long time without recovery.

1.2.4 Land use and infrastructure

Even though industrial farming does not necessarily promote clearing of forests directly, it has important indirect impacts on deforestation (Laurance, 2004). First, it may take over cleared land that is already being used for other purposes, and thus push these less intensive land users, like rangers and slash-and-burn farmers, deeper into the forest. Furthermore, the economic impact of industrial farming may trigger large infrastructure projects, e.g. new roads or road paving. This will allow access to the tropical forest areas to other actors. Remaining fragments of forest between patches with other land use are believed to be particularly vulnerable.

In order to identify where deforestation is likely to occur, it is useful to monitor land use changes in the vicinity of the forests. In particular, transitions to industrial agriculture and urban zones in settled areas and construction of transportation infrastructure should be monitored carefully. The latter should include official as well as unofficial roads.

Deforestation and land use changes are mainly driven by human activities, and it is, therefore, useful to approach them with a ‘proximate sources/driving forces’ framework (Roy Chowdhury, 2006). While the former refers to activities that directly cause land cover changes, the latter refers to underlying social and economical processes that trigger these actions. Some of these factors are spatial in their nature, and Roy Chowdhury (2006) shows how data from EO combined with Geographical Information Systems (GIS) and spatial models can be used for identifying such spatial driving forces. These will typically operate on different spatial levels.

2 Related existing international activities

2.1 Key ongoing and recent monitoring projects

2.1.1 PRODES and DETER

To monitor the destruction of the forest, the Brazilian government is employing two systems – PRODES and DETER – both under the management of the National Institute for Space Research (INPE).

Officials can view on their computers at high resolution, small sections of the Amazon based on a series of polygons. They say they can detect instantly the trees being felled and send in teams on the ground to make arrests.

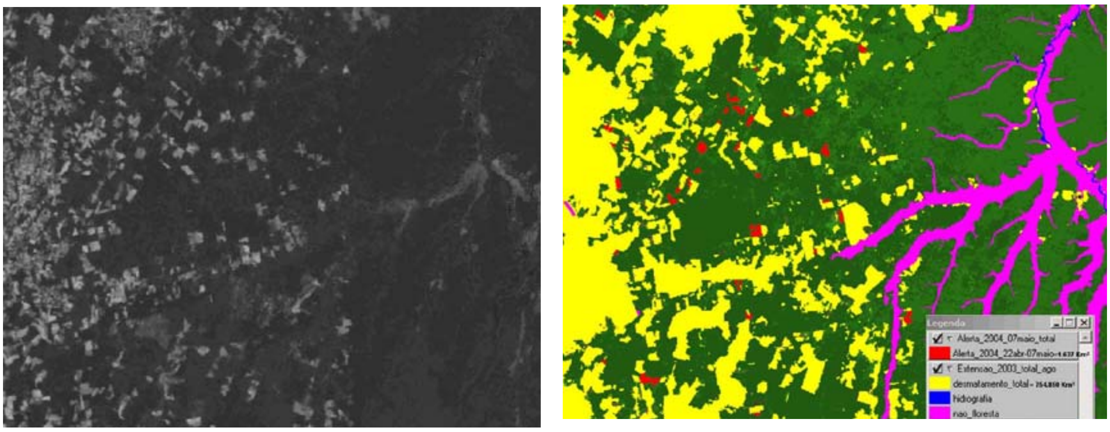


Figure 5. Left: Mosaic of MODIS images, Amazonia, 22 April to 7 May 2004 (data by INPE). Right: Classified MODIS images 22 April to 7 May 2004. Green – forest, yellow – non forest 2003, red – new deforestation (data by INPE).

PRODES (Program to Calculate Deforestation in the Amazon) produces the most accurate images for calculating the annual rate of forest loss, using Landsat TM and CBERS-2 data.

It takes as its reference point data collected in August, in the dry season when images are clearest. Its level of precision is that it can detect areas of deforestation of more than 6.5 hectares (65 000 m^2 or 0,065 km^2), the equivalent of eight football fields.

DETER (Real-time Detection of Deforestation) acts as an alert system throughout the whole year, using MODIS data from the Terra and Aqua satellites. Every fortnight, it sends a report to IBAMA, Brazil's environmental protection agency, detailing the areas of deforestation it has detected. It can detect an area of deforestation of greater than 25 hectares (250 000 m^2 or 0,25 km^2), or 30 football fields. For example, DETER detected an area of deforestation of 3,235 square kilometres in the last five months of 2007.

However, both systems have limitations. The level of cloud cover can impede detection. But the main obstacle is the availability of resources to follow up on the information the systems provide. Helicopters often arrive too late once logging has been spotted. In the whole of the Amazon region there are about 640 government inspectors and other officials, and just four helicopters. Even when an alert goes out, it is very difficult to determine who exactly is responsible for the deforestation, partly because it is difficult to establish who owns which piece of land.

2.1.2 LBA

The Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) is an international research initiative led by Brazil. LBA was designed to create new knowledge needed to understand the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land-use change on these functions, and the interactions between Amazonia and the Earth system. LBA is centred on two general key questions that are addressed through multi-disciplinary research, integrating studies in the physical, chemical, biological, and human sciences:

- How does Amazonia currently function as a regional entity?
- How will changes in land use and climate affect the biological, chemical, and physical functions of Amazonia, including the sustainability of development in the region and the influence of Amazonia on global climate?

An example from the LBA-project: Integrating Coarse and Fine Resolution Satellite Data to Monitor Land Cover Change throughout Amazonia.

The LBA LC-22 team is working to integrate coarse and fine resolution satellite data to monitor land-cover change in the Brazilian Amazon. The team has developed and validated several methods for near-real time monitoring of deforestation using 250 m resolution MODIS data. The team has worked with the MODIS Vegetation Continuous Fields (VCF) tree-cover product to generate training and validation data for various vegetation structures across the gradient from Amazon forest to cerrado savanna-woodland physiognomies. These training data are an integral part of calibration and validation for the VCF product.

The LBA project is a regional initiative in NASA's Land-Cover and Land-Use Change Program (LCLUC), see http://lcluc.umd.edu/.

2.1.3 NASA Landsat Pathfinder Humid Tropical Deforestation Project

The NASA Landsat Pathfinder Humid Tropical Deforestation Project mapped global deforestation for the humid tropics. Data sets from both Landsat TM (Thematic Mapper) and MSS (Multispectral Scanner System) were used for three time periods in the 1970s, 1980s, and 1990s. The project focused on the three regions where most of the tropical deforestation in the world has occurred - the Amazon Basin, Central Africa, and Southeast Asia. Mapping deforestation in these three regions accounts for the majority of deforestation activities in closed tropical forests worldwide. These products are country-based representations of forest cover change.

2.1.4 GMES "Forest monitoring"

GMES “Forest monitoring”, lead by GAF (http://www.gmes-forest.info/index.htm) GSE Forest Monitoring is a European Space Agency (ESA) funded project. It forms part of the Global Monitoring for Environment and Security Services Element (GSE). The GSE FM consortium was set up to address policy related demands for securing ecological functions in the forestry and land-use sectors. The first stage (2003-2004) consolidated services related to information needs of environmental policies such as the United Nations Framework Convention on Climate Change (UNFCCC). Additionally, existing infrastructural systems and data sources were reviewed and utilised in order to develop forest monitoring services such as yearly carbon balance information, forest disturbance data, as well as products for practical forest and land use management. A service portfolio of validated products and services was provided by the monitoring service and standardised, spatially referenced, quality products were delivered e.g. maps, which are cost effective, readily accessible and transparent to users, thereby promoting key applications and good governance within the forestry sector with sustainability as a paramount consideration.

2.2 Key active institutes

2.2.1 Instituto Nacional de Pesquisas Espaciais, Brazil

The Brazilian National Institute for Space Research (INPE) developed a monitoring system through the PRODES (Brazilian Amazonian Forest Monitoring by Satellite) program. More recently, the DETER (Real Time Deforestation Detection System) program was launched to give a faster response (twice a month). PRODES uses Landsat TM and Brazilian-Chinese CBERS data, while DETER uses MODIS sensors onboard NASA's Aqua and Terra satellites. INPE has also in recent years developed a contract with DMC International Imaging to acquire high-resolution satellite images of the entire Amazon rainforest. Images are provided by the international, five-satellite Disaster Monitoring Constellation (DMC). These micro-satellites use wide area cameras to capture high-resolution images. For more information see http://www.inpe.br/ingles/index.php.

2.2.2 Laboratory for Regional Ecological Studies, Carnegie Institution of Washington, USA

The institute has carried out extensive work on tropical forests, especially focussing on selective logging (http://asnerlab.stanford.edu/). Most of the work has been done using Landsat ETM+ imagery and field studies, (Asner et al., 2002, 2004), but there also have been studies using finer resolution data (Asner and Warner, 2003). An overview of work done with deforestation and logging in the Amazonas can be found at http://asnerlab.stanford.edu/highlights/amazon_logging2/. An operational system for studies of regional and global forest disturbance, CLAS, has been developed. It is based on Landsat data, see http://asnerlab.stanford.edu/highlights/amazon_logging2/clas.pdf.

2.2.3 Geographic Information Center of Excellence, South Dakota State University, USA

The Geographic Information Science Center of Excellence (GIScCE) is based on collaboration between South Dakota State University (SDSU) and the US Geological Survey EDC with a focus on earth observation and monitoring. EDC is the world's largest repository of remotely sensed data sets. The GIScCE is a research partnership that employs the capabilities of geographic information science (GISc) to document and understand the changing earth. Through the combined resources of many disciplines, the GIScCE seeks to investigate important questions regarding the dynamic earth system. These include studies of land cover and land cover change, (e.g. Hansen et al., 2002; Hansen et al., 2008).

2.2.4 Department of Geography and Institute for Advanced Computer Studies, University of Maryland, USA

At the Department of Geography (http://www.geog.umd.edu/) strategies for monitoring land cover by satellites and use of moderate resolution data from sensors, like AVHRR and MODIS, in classification and detection of land cover changes have been studied for many years (Townshend and Justice, 1988; Townshend et al., 1991; Tucker and Townshend, 2000; Zhan et al, 2002). The department has been working on the MODIS vegetation products VCC and VCF. A description of Enhanced Land Cover and Land Cover Change Products from MODIS is found at http://www.geog.umd.edu/research/projects/Townshend_Modis.htm. The institute is also engaged in the Global Land Cover Facility, which provides data and products to help better understand global environmental systems. At http://glcf.umiacs.umd.edu/data/ there are links to various satellite data and products, including forest change products for the Amazon Basin, Central Africa, and Paraguay. There are also links to MODIS VCC and VCF.

2.2.5 Department of Geography and Regional Studies, University of Miami, USA

Research at the department of Geography and Regional Studies in Miami is described at http://www.as.miami.edu/geography/research/. Two professors undertake research that is relevant to rainforest regions and related issues. Professor Douglas O. Fuller specializes in remote sensing, GIS, land-cover change, and human-environment interactions in Southeast Asia and Africa. He uses imagery from weather satellites to examine inter-annual phenomena associated with weather and climate change. His research projects include fires and deforestation in Indonesia and eco-regional planning in Indonesia. Professor Rinku Roy Chowdhury focuses on landscape and ecosystem transformations in tropical forest/agricultural mosaics. She applies remote sensing and GIS in explanatory models, which links land-use decisions to the socioeconomic and biophysical driving forces of land-use change. The ecological consequences of those decisions are evaluated at multiple scales.

2.2.6 Woods Hole Research Center, Woods Hole, USA

The centre (http://www.whrc.org) carries out research programs dealing with forests and carbon cycles around the world, concentrating on the Amazon Basin of Brazil. Their work extends from the details of physiology of trees to major issues of land and water management to assure the stability of the resources of the region. They collaborate with Brazilian colleagues and local communities towards economic development under circumstances that provide for sustainable use of the landscape. The centre has parallel programs dealing with the forests of the Congo Basin and Russian Asia, where the emphasis is heavily on satellite imagery as the basis for appraising changes in the landscapes.

2.2.7 Global Forest Watch at the World Resources Institute

Global Forest Watch (http://www.globalforestwatch.org/) is an initiative of the World Resources Institute (WRI). The entity monitors the forests at a global level. This includes threats and conservation values as well as current status and development. Their methods include the use of GIS and EO. The WRI (see http://www.wri.org) defines itself as an environmental think tank that goes beyond research to find practical ways to protect the earth and improve people's lives. One of its main goals is to protect the global climate system from further harm due to emissions of greenhouse gases and help humanity and the natural world adapt to unavoidable climate change.

2.2.8 SarVision, Wageningen, The Netherlands

SarVision (http://www.sarvision.nl/) is a spin-off from Wageningen University (WUR) based in the Netherlands. SarVision carries out operational application of systematic satellite and airborne monitoring and mapping for environmental and natural resource management. They provide maps and information on land and forest cover, change, fire and hydrology, updated on a regular basis (monthly to yearly). Their key application fields include mapping of biodiversity, legal and sustainable timber and agro-industrial crop, carbon storage, fire risk, hydrological monitoring, ecosystem services payment contracts monitoring, etc.

2.3 Key datasets

Existing digital cartographic and environmental data are useful as base maps for change detection analyses and a variety of other GIS and mapping applications.

2.3.1 MODIS land cover products

The Land Processes Distributed Active Archive Center (LP DAAC) was established as part of NASA's Earth Observing System (EOS) Data and Information System (EOSDIS) initiative to process, archive, and distribute land-related data collected by EOS sensors. The role of the LP DAAC includes the higher-level processing and distribution of ASTER data, and the distribution of MODIS land products derived from data acquired by the Terra and Aqua satellites.

2.3.1.1 Vegetation Cover Conversion

The MODIS Vegetation Cover Conversion (VCC) product is produced on a quarterly basis comparing data from 3 months of the current year to the same 3 months of the previous year. The input for the quarterly VCC is an intermediately produced 250 m resolution composite derived from 16 days of daily data by performing a quality based per pixel method, which selects the most cloud-free data. Each of these composites is processed separately and change is detected by comparison of the images.

2.3.1.2 The MODIS/Terra Vegetation Cover Conversion

Quarterly L3 Global 250m SIN Grid product, MOD44A, currently reports only change from forest to non-forest (deforestation) for the humid tropical regions of the globe (30° north latitude to 30° south latitude). In future versions, change will be reported for deforestation for the rest of the globe and for flooding on a global scale. Forest cover is defined by using the Vegetation Continuous Fields product (MOD44B) and considering anything with 60% tree cover or more to be forest. This is consistent with the IGBP classification of a forest. Non-forest is defined as less than 40% tree cover. Any pixel that was identified as forest in year one and was then identified as non-forest in year two is flagged and recorded in one of the metrics layers. When all of the 16-day periods have been processed, the metrics (intermediate classification comparison) layers are compared. Any pixel that has been flagged in at least two of the metrics layers is recorded in the "labelled land cover change" layer. Categorical quality assurance, determined by the quality of the input data, is provided in the "labelled land cover change QA" layer. A description is found at http://edcdaac.usgs.gov/modis/mod44av4.asp and http://glcf.umiacs.umd.edu/data/vcc/. A user's guide can be found at http://glcf.umiacs.umd.edu/pdf/VCCuserguide.pdf.Vegetation Continuous Field

Proportional estimates of cover are developed from global training data derived using high-resolution imagery. The training data and phenological metrics are used with a regression tree to derive percent cover globally. The model is then used to estimate area proportions of:

1) life form (proportion of woody vegetation, herbaceous vegetation, or bare ground),

2) leaf type (proportion of woody vegetation that is needle-leaf or broadleaf),

3) leaf longevity (proportion of woody vegetation that is evergreen or deciduous).

The current version of the MODIS Vegetation Continuous Fields product contains only percent tree cover, percent non-tree vegetation, and percent bare land, with the other layers to follow in later releases. This product was generated from monthly composites of 500 m resolution MODIS data. The MOD09A1 Surface Reflectance 8 day composites were used as inputs to the 32 day composites. Compositing was based on the second darkest albedo to remove clouds and cloud shadow. All 7 bands of 500 m resolution were used to derive metrics for the calculation of percent tree cover with metrics derived from bands 1 and 3 providing the most discriminatory power. Description is found at http://edcdaac.usgs.gov/modis/mod44bv4.asp and http://glcf.umiacs.umd.edu/data/vcf/. A user's guide is found at http://glcf.umiacs.umd.edu/data/guide/technical/MOD44B_User_Guide_v3.0.0.pdf.

2.3.2 Global Rain Forest Mapping project

The Global Rain Forest Mapping project (GRFM) was an effort led by the Japanese National Space Development Agency (NASDA) in cooperation with, among others, the NASA/Jet Propulsion Laboratory (JPL), the Alaska SAR Facility (ASF), the Space Applications Institute of the Joint Research Centre of the European Commission (JRC/SAI), the University of California, Santa Barbara (UCSB), the Brazilian National Institute for Space Research (INPE) and the National Institute for Research of the Amazon(INPA). Its goal was to acquire contiguous Synthetic Aperture Radar (SAR) data sets of the major rain forest of the Earth using the Japanese Earth Resources Satellite (JERS-1 or FUYO-1), and a global rainforest mosaic was produced (subsection shown in Figure 6). The mosaic divided the Earth into three geographical regions: South and Central America, Central and Western Africa, and South-East Asia and Northern Australia. Each region was observed at least once during a "single season" between September 1995 and January 1997. Examples of the data set can be found at http://southport.jpl.nasa.gov/GRFM/.

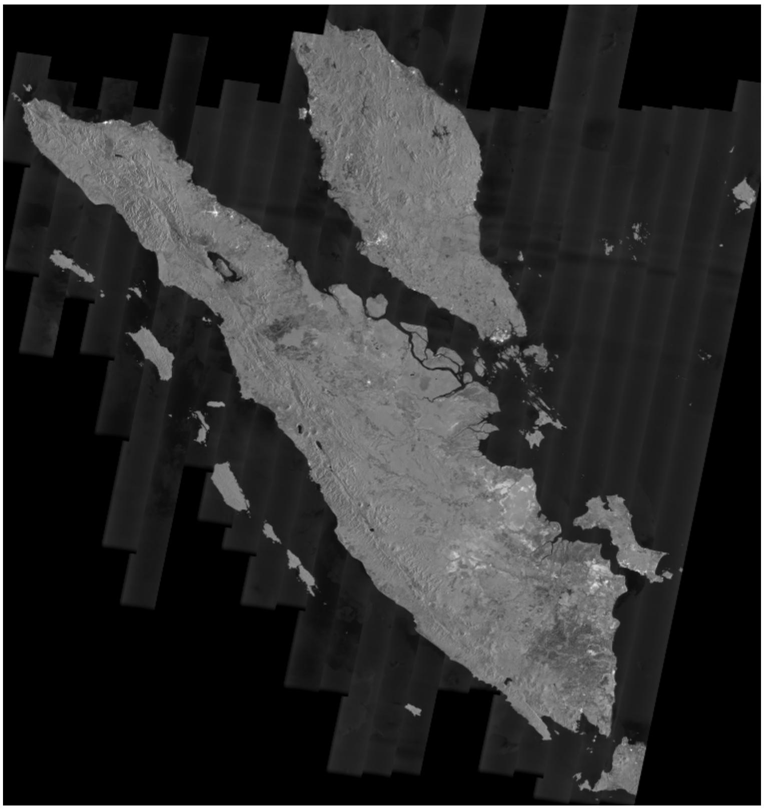


Figure 6. JERS mosaic over Sumatra, 1998. (http://www.eorc.nasda.go.jp)

2.3.3 The Geography Network

A main source of digital datasets is the metadata service "The Geography Network" (http://www.geographynetwork.com/), a global network of geographic information users and providers, managed and maintained by the ESRI GIS company. These maps can be previewed in ArcGIS, and some of the datasets can be downloaded. On a world scale important maps concerning rain forests include maps from the World Wildlife Fund (WWF) covering almost 25,000 ecoregions of the world with themes such as biological distinctiveness and degree of threat, and the Global Forest Watch maps, "The Last Frontier Forest". In addition, there are links to several global vegetation maps and climatic maps, as well as Landsat mosaics. Also on a country scale several different environmental themes can also be found on the Geography Network site. Finally, GIS-ready data, DEMs, geological data, political maps, satellite data, and other relevant data for the entire world can be bought from East View Cartographic (http://www.cartographic.com/).

2.3.4 Food and Agriculture Organization

Several different United Nations (UN) programmes provide data and useful information. The Food and Agriculture Organization (FAO) project "Africover" (www.africover.org/), provides metadata and web-maps of basemaps and environmental data for various African countries, including Congo, Rwanda, and Uganda. At present the FAO project, "Asiacover", does not provide any downloadable maps. The UN connected Global Mapping project (www.iscgm.org), includes most of the countries with rain forests, and provides vegetation maps that can be downloaded. The UN program UNOSAT offers satellite data and geographic information, however, it focuses on hazards and risk detection. Google Earth provides some data from the "Atlas of Our Changing Environment", produced by the UN program Environment for Development. Some of these sites provide time series of Landsat images from selected areas of the world, including rainforests (see also: http://na.unep.net/digital_atlas2/google.php). However, these Google Earth maps cannot easily be added into GIS systems.

2.3.5 Various other data sets

The European Space Agency (ESA) is involved in the GlobeCover project, which aims to provide standardized vegetation maps of the world based on MERIS satellite data with 300 m spatial resolution. For historical data on deforestation, the Global Land Cover Facility at the University of Maryland provides downloadable Landsat mosaics which show forest changes in Amazon and Central Africa during the 1970s, 1980s, and 1990s (http://glcf.umiacs.umd.edu/data/pathfinder/). Recently, the entire USGS Landsat archive was released at no charge (http://glovis.usgs.gov/), where RGB scenes can provide information on deforestation over the last 35 years.

The ESA project GlobWetLands may also provide some data sets of value (e.g., http://www.esa.int/esaCP/SEMECNOFGLE_Protecting_0.html). This project had a focus on the preservation of large global wetlands, and in particular interacted with users in Africa. One of the products that was highly rated by users was s set of deforestation maps (there is an intimate relation between preservation of forests and wetlands on a global scale). On a national level, cooperation with the relevant counties' national mapping authorities must be established. For instance, in Indonesia it is the National Atlas Centre, Bakosurtanal, and in Brazil it is the Instituto Brasileiro de Geografia e Estatistica. Other useful links to Amazonas are Imazon (www.imazon.org.br) and The National Brazilian Institute of Space Research (INPE) (www.inpe.br/).

With specific relevance to SAR, the Shuttle Radar Topography Mission (SRTM) digital elevation model is an important dataset for SAR processing (geocoding). Using a modified radar system that flew on the space shuttle ‘Endeavour’ in 2000 and interferometry techniques, a near-complete high-resolution digital topographic database of Earth was produced. The SRTM was a joint effort by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). Two antenna panels, C-band and X-band, were used, the former creating the near-global DEMs, and the latter creating higher resolution DEMS but without global coverage. The global data are being distributed through the United States Geological Survey's EROS Data Center and the X-band derived data are being distributed by the German Aerospace Center, DLR. A version of substantially corrected SRTM DEMs, Version 2, is now available.

3 The potential of different sensor types

3.1 Optical remote sensing

3.1.1 Relevant regions of the electromagnetic spectrum

Optical sensors detect reflected sunlight or emitted electromagnetic radiation. The region of reflected visible light is from blue to red (~0.45 - 0.75 µm). As vegetation and tree canopies have different colours than bare ground, roads, buildings, etc., visible light is useful for separating the different object types. Blue/green is useful for differentiation between soil and vegetation, as well as distinguishing forest types. Green light can measure green reflectance from healthy vegetation and the red band is suitable for detecting chlorophyll absorption in vegetation.

Vegetation reflects strongly in the shortwave, near infrared (NIR, 0.75 - 1.4 µm). Therefore, it is common for satellite sensors to have detectors for visible and near infrared light (VNIR). A common measure for vegetation is the Normalized Difference Vegetation Index (NDVI). It can be given as (R – IR)/(R + IR) where R is the measured signal in a sensor's red band and IR the corresponding signal in the near infrared band. A high value of NDVI means a high percent of green vegetation.

The next wavelength regions are called short-wave infrared (SWIR, 1.4 - 3 µm), mid-wave infrared (MWIR, 3 - 8 µm), long-wave infrared (LWIR, 8 - 15 µm) and far infrared (FIR, 15 – 1000 µm). NIR and SWIR are sometimes called reflected infrared, while MWIR and LWIR are sometimes referred to as thermal infrared (TIR).

The SWIR region is useful for vegetation and soil moisture studies, while bands in the TIR region can be used for thermal mapping, soil moisture and vegetation studies. The thermal region can also be used for detection of forest fires.

The most serious problem with optical wavelengths is that they do not penetrate clouds. In totally overcast conditions, optical sensors in satellites will get no signals from the ground. In partly cloudy weather, clouds will cover parts of the surface and cloud shadows will further reduce the reflected light from the ground. Under such conditions, it is necessary to detect the clouds and treat the sunlit and shaded areas in different ways. In areas with tropical forests there are many days with cloudy weather, which makes continuous monitoring with optical sensors impossible.

The Laboratory for Regional Ecological studies at Stanford University has done a study of cloud cover in the Brazilian Amazon region and found that it varies throughout the year and over the region. In the "best" months of July and August, only 13 % and 6 % respectively of the entire region had a 90-100 % chance of a successful surface imaging, using a 16 day satellite revisit frequency and a maximum acceptable cloud cover of 30 %.

3.1.2 Optical sensor types

Sensors can be classified as single band, multispectral and hyperspectral.

3.1.2.1 Single band

A few optical sensors have only one wavelength band. It is usually a panchromatic band with wavelengths in the region from 0.45 to 0.9 µm, i.e. from blue to NIR. The image will look like a black and white image. With resolution of 1 m or less, a panchromatic band is very useful for detecting small details and minor changes.

3.1.2.2 Multispectral

A multispectral sensor has a number (typically 4 - 36) of bands covering different wavelength regions. In addition, many sensors have a panchromatic band covering the VNIR region. Many satellites have multispectral sensors with four bands in the visual and NIR region. The wavelength regions are usually close to those shown in the table below.

Table 2. Typical wavelengths for multispectral sensors (Quickbird)

Name	Wavelength min (µm)	Wavelength max (µm)
Blue	0.45	0.52
Green	0.52	0.60
Red	0.63	0.69
Near-IR	0.76	0.90

Other sensors have a larger number of spectral bands covering the wavelengths from blue to TIR (36 for MODIS). The wavelengths and bandwidths are chosen for their ability to detect specific materials or properties of the observed objects.

3.1.2.3 Hyperspectral

A sensor is called hyperspectral when it has a large number of spectral bands with small bandwidths (220 for Hyperion). With such a sensor it is possible to get a nearly continuous spectrum of the reflected light from the observed objects. This detail can be used for precise parameter retrieval, classification and detection of minor changes in the properties of the objects.

3.2 Microwave sensors

3.2.1 Synthetic Aperture Radar

Spaceborne Synthetic Aperture Radar (SAR) is an imaging radar type that is widely used for monitoring the land and sea surface with medium (30–100 m) to high (1–10 m) spatial resolution. It is particularly useful due to its weather and light independency, which, for example, allows visibility through clouds and haze, common in tropical rainforests.

A spaceborne SAR images the Earth’s surface in a sideways-angled geometry as shown in Figure 7. The radar antenna has a beam pattern for a given point in time, where the corresponding imaged area is called the antenna footprint. As the SAR moves along its straight path, it illuminates a swath on the ground by transmitting a series of microwave pulses. The SAR receiver detects the stream of echoes reflected from the Earth's surface and separates them into individual echoes, corresponding to the transmitted pulses. These echoes are produced because the terrain consists of different scatterers such as trees, rocks, or buildings that interact with the incoming microwave radiation. The energy scattered back towards the radar is called backscatter. A strong scatterer reflects more energy than a weak one. The received amplitude is characterized by the efficiency of the scatterer, as well as geometrical factors.

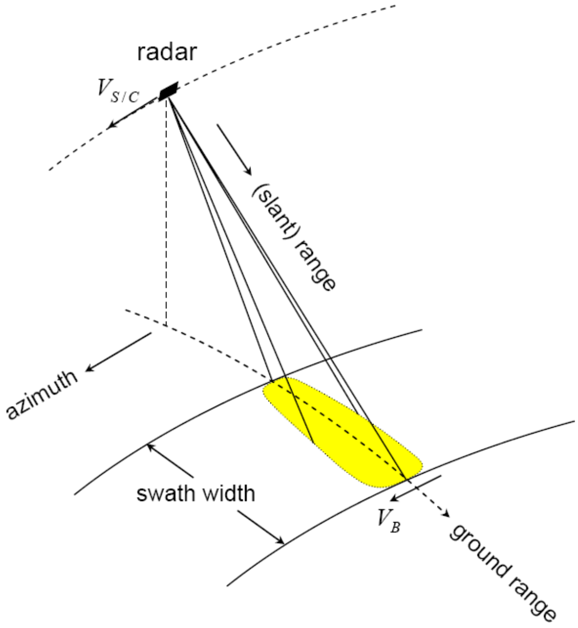


Figure 7. SAR side-looking geometry

A SAR transmits energy at radar frequencies and analyses the return from the Earth's surface to generate an image of the mapped area. SAR penetrates clouds with almost no disturbance and has some capabilities of also penetrating biomass, although present day C-band SAR (5 GHz) is effectively absorbed by thick forest stems. Novel SAR technology, radiating at lower frequencies, like L-band (1-2 GHz) and P-band (500-1000 MHz), have better capabilities for detection changes in the observed biomass, but are unfortunately not operational like C-band SAR, which has been flown for over 20 years.

Japan has a L-band SAR (PALSAR) on board the ALOS satellite. This research satellite will provide valuable data, with hopefully worldwide coverage once per year. The observation program could be used over tropical rainforests to detect subtle changes in the biomass caused by "smart deforestation", i.e. forest logging that aims to not be detected by conventional means (by thinning out the forest so that the forest crowns still cover the underlying soil). It is questionable whether C-band SAR can detect such activity before it is too late, but advanced SAR processing techniques using multitemporal imagery to create "super-resolution images" might have the potential.

A P-band SAR is in many respects the ideal sensor for the task of detecting deforestation. It has the ability to penetrate both the crowns and the stems and can also provide a quantitative measurement of the biomass. The problem is, however, that such a satellite sensor has never been flown. There is ongoing activity in ESA to evaluate the potential of this sensor concept (the proposal BIOMASS in ESA's Earth explorer mission program). There are, however, some questions with regards to the feasibility of building the sensor with the present technology. If the sensor was selected by ESA to be built, it would still be a research sensor with limited global monitoring capability.

In order to set up an observation program for detecting deforestation, we need to decide what kind of lead-time for alarm sounding is acceptable. If the lead-time is of the order of one year, L-band SAR from ALOS could be an acceptable choice. If the lead-time is much shorter, e.g., of the order of one month, we strongly argue that a C-band SAR solution is presently the best choice. Current operational C-band SARs (ASAR, Radarsat-1/2) could provide a total coverage over the rainforest belt within ~30 days. Rapid and trustworthy change detection could subsequently be used to provide local authorities with usable information that they can act upon.

An important part of SAR processing is to decrease the resolution of the imagery. This is achieved by range-compression which takes advantage of the fact that as the satellite moves, the same target is illuminated from different positions by different transmitted pulses. This is equivalent to a single pulse reception by a very large antenna (several km), thus the name *synthetic aperture*. The resolution is in particular important for the purpose of detecting deforestation. The better the resolution, the better the ability to detect small changes in the forested areas.

When topographic features exist, foreshortening effects can appear on the front and backside of a hill, resulting in compressed and expanded pixels on the ground. In an extreme case, layover appears when the top of a hill is closer to the radar than the foot of the hill. This occurs when the local surface slope is higher than the incidence angle.

SAR speckle (or multiplicative noise) is a phenomenon inherent in coherent imaging systems with spatial resolution greater than the transmitted wavelength. Due to the roughness of the imaged surface, each resolution cell will contain several scatterers, and the resulting image will have a granular appearance due to constructive and destructive interference. The granular nature of speckled images makes them hard to interpret, both for the human eye and automated segmentation and classification algorithms. Several methods have been developed to reduce speckle noise.

3.2.2 Polarimetry

Radars may transmit and/or receive at vertical or horizontal polarization. Polarimetric SAR systems may hence provide up to four independent measurements (HH, HV, VH and HV) of the same area instead of the normal case where only one polarization is available (typically VV or HH). The increased information content gained by measuring at different polarizations can be used to improve understanding of the object studied. In forests, polarimetry has been used to separate the backscatter from leaves and stems, improving for example, methods for land use classification. There is, however, a price for using polarimetry since the swath width of the SAR will be smaller. Some new methods that may alleviate this problem have been suggested (dual-pol and compact polarimetry).Until recently, polarimetric data were available only from airborne instruments, thus limiting their potential use. In January 2006, the Japanese Aerospace Exploration Agency (JAXA) launched the Advanced Earth Observation Satellite (ALOS) with the fully polarimetric instrument PALSAR. This is a scientific satellite with many modes, and it will operate in fully polarimetric mode only for limited time periods, thus reducing the commercial usability. Nonetheless, it will provide valuable data for research on how to exploit these kinds of data, and for some mapping purposes that are not dependent on a time series of images, this may be sufficient.

3.2.3 Interferometry

The phase measured by a SAR is primarily dependent on the distance between the satellite and the ground target. However, water content in the atmosphere may also affect the phase. Interferometric SAR (InSAR) exploits the phase difference between two complex-valued SAR images, acquired from different orbit positions and/or at different times. For two SAR images to be suitable for InSAR processing, at least one imaging parameter must be different. This can be, e.g., flight path, time of acquisition, or radar wavelength. This information defines the type of the interferometer. There are in principle two types of interferometers, across-track, and along-track. A variant of the across-track mode is often called repeat-track interferometer. Repeat-track interferometry requires only one antenna, and is thus suitable for spaceborne systems.

The potential of using InSAR decorrelation techniques to assess deforestation have been studied in ESA’s Dragon project by University of Jena, Chinese Academy of Forestry in East Asia (see Figure 8).

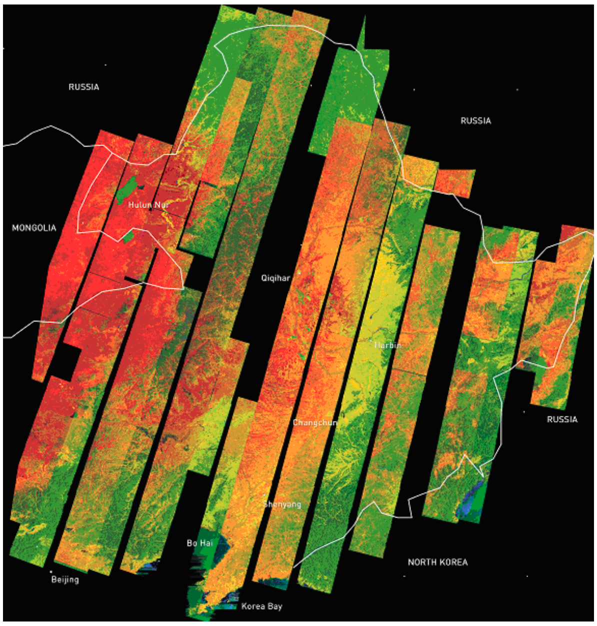


Figure 8: Mosaic based on ERS-1/2 data With more than 500 radar images acquired between 1995 and 1997. The false colour composite, red corresponds to the ERS-1 and -2 coherence (matching data), green to the ERS-1 SAR intensity and blue to the ERS-1 and -2 intensity difference. Forests appear in green; agricultural areas appear in orange or yellow, depending on whether the images were acquired in winter or not; steppe and marsh land surfaces along the Mongolian border appear in red. The green patches in the centre of these regions correspond to the frozen surfaces of lakes Hulun Nur and Buir Nur.

3.2.4 Polinsar

Polarimetric interferometry is performed using two polarimetric SAR images acquired from slightly different directions. The study of these data sets permits us to retrieve parts of information related to the 3-D structure of the observed scene, such as topography or forest biomass.

The joint use of polarimetric and interferometric techniques permits us to characterize accurately the different kinds of natural media. New polarimetric radar sensors, such as RADARSAT-2 and ALOS-PALSAR, will provide such information. The recently launched ENVISAT ASAR is providing simultaneous dual polarisation capability as a forerunner of fully polarimetric radars.

Polinsar techniques are very promising and provide data sets with amazing detail richness, which will allow new insight into the problem of rain forest monitoring. It is, however, our judgement that at the present stage the technology is not yet suitably advanced.

3.2.5 Pre-processing microwave data

SAR data is usually only available from satellite providers as Level-1B data. This is focussed SAR backscatter cross sections. These data have to be transformed to a map projection with high-precision geocoding software in order to be useful.

Radiometric calibration of the SAR data is needed in order to establish a relation between the radar cross-section and the properties of the Earth's surface. This requires corrections of the relief distortions, the main task of geometric calibration. Finally, the SAR data must be transformed into a cartographic reference system (map projection) for further multi-temporal or multi-sensor integration. Therefore quantitative use of SAR data requires radiometric and geometric calibration of SAR data. These are often referred to as geocoded products.

Norut has developed geometric and radiometric calibration algorithms applicable to both spaceborne and airborne SAR sensors from different platforms. The algorithm has successfully been used for studying the capabilities of snow cover mapping using SAR in alpine regions (Guneriussen, et. al., 2001). There are of course also commercial geocoding software packages. Gamma Remote sensing software (http://www.gamma-rs.ch/geo.php) seems to have software for a lot of SAR processing tools, including DEM generation, precision image registration, interferometric processing, radiometric calibration and geocoding. SARscape is another commercial geocoding software that is bundled with the familiar Envi-software software system for processing Earth observation data (http://www.ittvis.com/envi/SARscape.asp) and that provides orthorectified SAR backscatter images.

4 The potential of existing sensors and satellites

4.1 Optical sensors

4.1.1 NOAA AVHRR

A number of NOAA satellites have been in orbit since the first was launched in 1979. At the present time NOAA 14, 15, 16, 17 and 18 are active. AVHRR (Advanced Very High Resolution Radiometer) has a red and a NIR band in addition to two bands in SWIR and two in TIR. The spatial resolution is 1.1 km at nadir. The resolution is low, and the sensor is probably not well suited for detection of small land cover changes. However, the satellites have been in operation for nearly 30 years, and there exists time series for the whole period which can be used for an overview of forest development.

4.1.2 Spot Vegetation

SPOT 4 was launched on 24 March 1998. The vegetation sensor has 4 bands in VNIR and 1 in SWIR with resolution 1165 m and swath width of 2250 km. The Vegetation Instrument system is an essential tool for studies on global vegetation. It has also been designed for decision support in the fields of agriculture, early warning systems, follow-up of deforestation and forest degradation and the management of natural resources. Studies of the greenhouse effect caused by the accumulation of carbon dioxide in the atmosphere are also being aided by SPOT 4 Vegetation Instrument imagery. With its large swath width it is usable for continuous monitoring. It could be a supplement to MODIS. The low resolution makes it more suitable for an overview of forest development than for real time detection of new logging areas.

4.1.3 MODIS

The Terra satellite is equipped with a number of sensors. The most important is MODIS (Moderate Resolution Imaging Spectroradiometer). The sensor has a red and a NIR band with 250 m resolution, 5 bands in blue, green, NIR and SWIR with 500 m resolution and 29 bands throughout the wavelength region from 405 to 14385 µm with 1 km resolution. The 250 m and 500 m bands are designed for land cover use and also clouds and aerosols. The 1 km bands are mainly for studies of oceans, atmosphere, clouds and temperature. The swath width is 2330 km and 1–2 images each day of any area are possible, depending on the latitude (below 70 degrees). The images are free and can be downloaded from the Internet. The MODIS sensor is also installed in the Aqua satellite, launched on 4 May 2002. The resolution of 250 m, the daily images and the simple and free downloading from Internet has made MODIS images the most popular set of satellite image data all over the world. It is perfectly suited for continuous monitoring of tropical forest cover. Although the resolution is not the finest, change in forest cover at some level can be detected. A sensor with higher resolution could be used to find the finer details.

4.1.4 MISR

MISR (Multiangle Imaging SpectroRadiometer) has 4 bands in VNIR with a resolution of 275 m. The swath width is 400 km. The sensor is looking at the Earth from 9 different view angles. It is used to study cloud forms and land cover. It has been used in forest investigations to find fractional woody plant cover, plant number density, mean crown radius, mean canopy height and estimate of aboveground woody biomass. This study has been done on forests in Arizona and New Mexico, but it can likely also be used on tropical rain forests.

4.1.5 ASTER

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) has 3 bands in the VNIR with 15 m resolution, 6 bands in SWIR with 30 m and 5 bands in TIR with 90 m resolution. The swath width is 60 km. ASTER can be used to study in detail, at the same time, parts of an area which are covered by MODIS. However, the data show just a narrow corridor in the middle of the MODIS coverage. The bands in ASTER are designed to monitor a wide array of global change-related applications, including vegetation and ecosystem dynamics. Land cover changes like changes in tropical rain forests can be studied in detail. ASTER is unique due to having a number of bands in SWIR and TIR. Other sensors with the same spatial resolution usually have none or one band in TIR.

4.1.6 Landsat

Landsat is a program consisting of a number of satellites, with the first Landsat 1 launched in 1972. At present, there are two Landsat satellites delivering images, Landsat 5, launched 1 March 1984, and Landsat 7, launched 15 April 1999. Landsat 5 has two sensors MSS (Multispectral Scanner) and TM (Thematic Mapper). The TM sensor is still working. Landsat 7 has one scanner called ETM+ (Enhanced Thematic Mapper). The TM sensor has 4 bands in VNIR with the commonly used wavelengths, 2 bands in SWIR, all with spatial resolution of 30 m. In the thermal region there is 1 band with resolution of 120 m. The swath width is 185 km. The ETM+ sensor has the same 7 bands as TM, but the TIR band has a resolution of 60 m. In addition it has a panchromatic band with resolution of 15 m.

There is a long tradition of using Landsat for land cover observations. The bands are suitable for vegetation monitoring, and the resolution is good enough for detecting even small changes. In fact studies have shown that all changes due to forest logging activities are detectable in Landsat images. While Landsat 5 images could only be used by the buyer, Landsat 7 images are free to distribute once they have been bought. The images became very popular and have been used in several studies of rain forest classification, cover change and logging. In 2003, however, a malfunction occurred in the ETM+ sensor, and the images have since then been delivered with some data partly missing. Even if most of the image can be used, it is not a satisfactory product for detection of cover change. Landsat 5 images can still be used as a supplement to images with coarser resolution. The observed area is much larger than for the high resolution satellites, and all interesting changes should be visible in the Landsat images.

4.1.7 CBERS-2

CBERS-2 (China-Brazil Earth Resources Satellites) was launched 21 October 2003. It has 3 optical sensors with different resolutions. We do not know how easy it is to get images from this satellite. It is used by the Brazilian National Institute for Space

Research (INPE) in the PRODES (Program to Calculate Deforestation in Amazon) project. The WFI (Wide Field Imager) sensor has 2 bands in read and NIR of spatial resolution of 260 m and a swath width of 890 km. It should have the same properties as the 250 m resolution bands of MODIS, but the swath width is much lower, so images for the whole world are not available each day. The HRCC (High Resolution CCD Camera) sensor has 1 panchromatic band and 4 bands in VNIR of spatial resolution 20 m and 113 km swath width. It should be fully usable for vegetation monitoring and detecting cover changes in specified areas. The resolution is better than Landsat, but the swath width is lower. The IRMSS (Infrared Multispectral Scanner) sensor has a panchromatic band which goes out in the NIR, and 2 bands in SWIR with 80 m resolution. In addition it has a TIR band with resolution of 160 m. The swath width is 120 km. This sensor is probably not suitable for small change detections, but the TIR band could be used for detection of forest fires.

4.1.8 SPOT 5 HRG

The satellite was launched 3 May 2002. It has a panchromatic band with resolution 2.5 and 5 m, 3 bands in VNIR with 10 m resolution and 1 SWIR band with 20 m resolution. The swath width is 60 km. This sensor is fully capable of detecting small changes in the forest cover.

4.1.9 ALOS

ALOS is a Japanese satellite, launched 24 January 2006. It has 1 radar and 2 optical sensors. The PRISM Panchromatic sensor has resolution 2.5 m and swath width 70 km. The AVNIR-2 multispectral sensor has 4 bands in VNIR with resolution 10 m and swath width 70 km. The optical bands are usable for detection of small changes in vegetation cover.

4.1.10 Ikonos

The satellite was launched 24 September 1999. It has a panchromatic band with resolution of 0.82 m at nadir and 1 m at 26° off nadir, and 4 bands in VNIR with 0.32 m resolution at nadir and 4 m at 26° off nadir. The swath width is 11 km at nadir and 13.8 km 26° off nadir. The capability of the sensors to view off nadir reduces the revisit time. It is approximately 3 days at 40° latitude. The high resolution makes the sensors very suitable for discovering details and small changes in all kind of objects on the ground. The swath width is too low, however, to make the satellite useful for continuous monitoring of large areas.

4.1.11 Quickbird

The satellite was launched 18 October 2001. It has a panchromatic band with resolution 0.61 m at nadir and 0.72 m at 25° off nadir, and 4 bands in VNIR with resolution 2.44 m at nadir and 2.88 m at 25° off nadir. The swath width is 16.5 km at nadir. The capability of looking off nadir makes the revisit time 1-3.5 days, depending on the latitude, for 30° off nadir. Maximum offset is 45°. Quickbird has the same potential as Ikonos for detecting small changes in forest cover. The resolution is even better and the swath with is larger than for Ikonos. Still, the swath width is too low to make the satellite useful for continuous monitoring of large areas.

4.1.12 WorldView 1

The satellite was launched 18 September 2007. It has a panchromatic band with resolution of 0.50 m at nadir and 0.55 m at 20° off nadir. The swath width is 17.6 km at nadir. It has the finest resolution and the largest swath width of the sensors with very high resolutions, but it has no multispectral bands. For some applications this is a disadvantage, but for confirmation of a probable forest cover change, detected by sensors with coarser resolution, the sensor will probably work very well.

4.2 Microwave sensors

4.2.1 ERS-1/2

ERS-1 and-2 were launched by ESA in 1991 and 1995, respectively. They use the C-band (5.3 GHz) with VV polarization. The orbit altitude is 790 km with a 35 day repeat cycle and they cover incidence angles 21-26 degrees. The nominal ground resolution is 22×5 m, the swath-width was 100 km. ERS is used a lot for interferometric and change-detection purposes due to its relatively long time-series.

4.2.2 JERS-1

JERS was an L-band SAR (1.2 GHz) launched by Japan in 1992. It was operational until 1998. The orbit altitude was 570km and it had 75 km swath-width. The ground resolution was 18×6 m.

4.2.3 Radarsat

The Canadian satellite Radarsat launched in 1995 was the first steerable SAR with down to 10 m ground resolution. It operates on C-band with HH polarization, and has many different acquisition modes ranging from fine resolution imagery with 10 m resolution to ScanSAR images covering 500 km swaths with 100 m resolution.

4.2.4 Envisat ASAR

The European research satellite Envisat was launched by ESA in 2002, and has several sensors, but ASAR is the main instrument. This is a steerable SAR with a long list of acquisition modes ranging from 30 m precision images to 500 km wide-swath images with 100 m resolution. ASAR has been used frequently to demonstrate satellite based services such as sea ice, ocean, glacier, snow and land use monitoring (e.g. Figure 9).

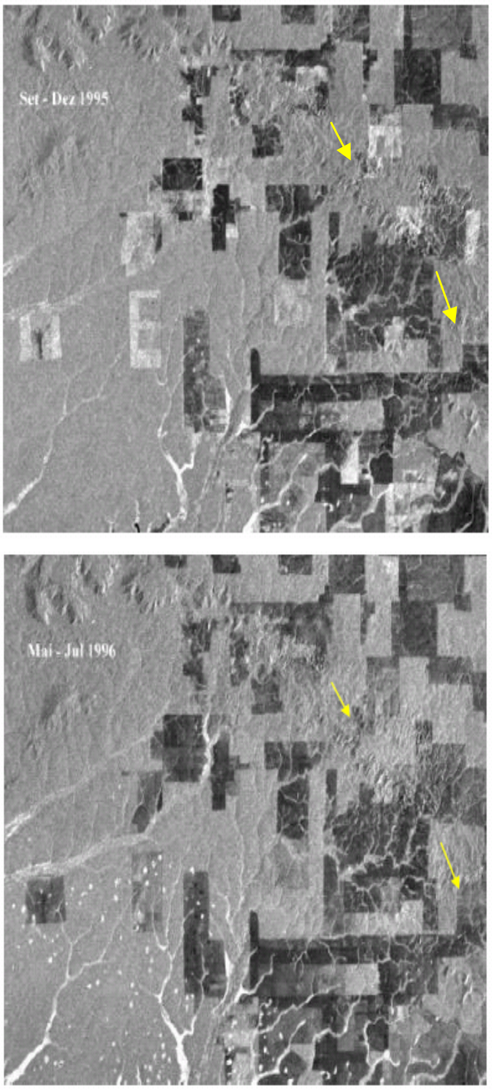


Figure 9. Detection of deforestation by L-band SAR from JERS-1 mosaic

4.2.5 PALSAR

PALSAR is an L-band sensor on the ALOS satellite that was launched by Japan in 2007. It has full polarimetric capabilities, and high spatial resolution. This sensor is well suited for detecting deforestation, but since it is a research satellite, it has limited capabilities for frequent coverage, in particular at equatorial latitudes.

4.2.6 TerraSAR-X and Cosmo-Skymed

TerraSAR-X from Germany and Cosmo-Skymed from Italy are both private X-band (9.5 GHz) SAR sensors. They were both launched in 2007. Cosmo-Skymed will also launch 2-3 similar satellites to provide very frequent temporal coverage. Due to the high radar frequency and narrow swath-widths, these radars are not well suited for rainforest monitoring.

4.2.7 Radarsat-2

Radarsat-2 was launched in 2008 by Canada. The SAR is a C-band SAR, and it has a long list of advanced SAR modes (see Table 3), including very high resolution imaging of 5 m.

Table 3. Table of historical and present SAR satellites

Mission	**ERS-1**	**ERS-2**	**JERS-1**	**ASAR**	**Radarsat**	**Palsar**	**Terrasar-X**	**Rsat-2**
Country	ESA	ESA	Japan	ESA	Canada	Japan	German	Canada
Launch date	1991	1995	1992	2002	1995	2006	2007	2008
Life time	2000	2006	1998	-	-	-	-	-
Frequency [GHz]	5.3	5.3	1.2	5.3	5.4	1.2	9.65	5.3
Polarization	VV	VV	HH	Alt.pol	HH	Full	Dual.pol	Full
Orbit altitude	790	790	570	790	800	690	514	800
Incidence angle [deg]	21–26	21–26	32–38	21–26	20–60	8–60	20–45	20-60
Swath width [km]	100	100	75	100–500	45–305	40–350	5–100	10-500
Ground resolution [m] (range, azimuth)	22x5	22x5	18x6	22x5	8x8	9x9	1x1	1x1
Repeat cycle [days]	35	35	44	35	24	46	28	24

4.2.8 Sentinel 1

The upcoming Sentinel-1 series of satellites from ESA (GMES) will address the issue of data continuity for SAR data at large. The immediate priority is to ensure such continuity for C-band data. Under the current scenario, provision of ENVISAT data to feed SAR-based services is likely to cease in the 2008-2010 timeframe. The experience with ERS, Envisat and Radarsat constitutes the basis for the Sentinel-1 mission requirements and concept. The sensor will most probably have limited numbers of modes in comparison to Envisat and Radarsat, but will provide the same type of data over large areas. This ensures global coverage. The preferred land mode is wide swath mode.

4.2.9 Tandem-X

The German space agency DLR - has planned to launch a satellite similar to TerraSAR-X in 2012. This satellite will together with TerraSAR-X constitute a tandem SAR interferometric system with unique capabilities in performing interferometric measurements. These measurements can be used to measure the elevation of the land surface with high accuracy, and it is expected that one of the outcomes will be a global digital elevation model (SRTM covers only latitudes from 60 degrees North to 60 degrees South). Another application will be to detect deformations of the Earth surface due to geological activity, and land slides. As indicated before, X-band SAR does not have any obvious applicability for rainforest monitoring.

4.2.10 ALOS Palsar continuation

There are some ongoing plans in the Japanese Space Program (JAXA) to launch a follow-up to ALOS Palsar. Such a system could play an important role for rain forest monitoring since it will grant the continuation of L-band SAR data, and in a period when both the predecessor, ALOS Palsar, and the continuation are operational, providing extended coverage over the rainforests.

4.2.11 C-SAR constellation

The Canadian Space Centre has indicated interests in launching a constellation of 3 C-band SAR sensors that could provide unprecedented temporal coverage over the polar regions. The main motivation would be sea ice monitoring, but it will also provide improved coverage over the rainforests, and could be used together with the Sentinel-1 program to give almost daily satellite coverage over the rainforest belt.

5 Future operational satellites

Most planned satellite missions are experimental. However, the GMES initiative has initiated the development of a series of operational satellites that potentially could be very important for operational tropical forest monitoring in 3-4 years. In contrast to experimental and commercial satellites, the GMES satellites will provide regular and relatively frequent coverage over the rainforest belt.

5.1 Sentinel missions

The ESA Sentinels constitutes the first series of operational satellites responding to the Earth Observation needs of the EU-ESA Global Monitoring for Environment and Security (GMES) programme. The contracts of the construction of the three first satellites have been signed, and according to plans they will be launched in 2011-2012.

The satellites have been designed for global monitoring of land and ocean and are expected to be operative for 7-8 years. There are plans for more satellites in this programme. Sentinel-4 and -5 are designed to keep an eye on quality and pollution of the atmosphere.

5.1.1 Sentinel-1

As part of the GMES space component, ESA is undertaking the development of a European Radar Observatory (Sentinel-1), a European polar orbiting satellite system for the continuation of SAR operational applications. Sentinel-1 is an imaging radar mission at C-band, aimed at providing continuity of data for user services. The satellite will take over many of the tasks of the radar instrument on board Envisat. Special emphasis is placed on services identified in ESA's GMES service elements (GSE) program. Three priorities (fast-track services) for the mission have been identified by user consultation working groups of the European Union: Marine Core Services, Land Monitoring and Emergency Services.

5.1.1.1 Technical specification

Sentinel-1 will be in a near-polar sun-synchronous orbit with a 12 day repeat cycle and 175 orbits per cycle.

Sentinel has four operational modes designed for inter-operability with other systems.

1. Stripmap MODE (SM) with 80 km swath and 5 × 5 meter spatial resolution
2. Interferometric Wideswath Mode (IW) with 250 km swath, 5 × 20 meter spatial resolution and burst synchronisation for interferometry
3. Extra-wide Swath Mode (EW) with 400 km swath and 25 × 100 meter spatial resolution
4. Wave Mode (WV). Sampled image mode with low data rate and 5 × 20 meter spatial resolution.

Sentinel-1 has selectable single polarisation (VV or HH) for the Wave Mode and selectable dial polarisation (VV+ VH or HH + HV) for all other modes.

Sentinel-1 is anticipated to work largely in a pre-programmed fashion imaging all global land masses, coastal zones, shipping routes in full resolution (IW mode), and covering the global ocean with imagettes (WV mode). To satisfy revisit requirements a constellation of satellites is required with two satellites as a minimum. With both satellites operating for 20 minutes per orbit, ESA's member states and Canada will be fully imaged every two days or better – dependant on latitude – in full imaging mode, and the remainder of the world every six days or better.

The Sentinel-1 IW-mode will be a suitable mode for monitoring deforestation. The combination of frequent repeated measurements and relatively high resolution will allow detection of clear cutting over vast areas. Norwegian authorities should indicate that the rainforest belt needs to be prioritized in the observation plans for Sentinel-1, and preferably be monitored for each orbit that covers the rainforests.

5.1.2 Sentinel-2

The Sentinel-2 mission provides continuity to services relying on multi-spectral high-resolution optical observations over global terrestrial surfaces. Sentinel-2 will capitalise on the technology and the vast experience acquired in Europe and the US with systems such as SPOT and Landsat families over the past decades. The start of operations in 2011/2012 will ensure continuity to currently existing sensors SPOT and Landsat.

Sentinel-2 is mainly designed to keep an eye on the earth's vegetation, but can also be used for other purposes.

The satellite is planned to take images with resolution between 10 and 60 m and with a swath of 320 km.

5.1.2.1 Technical specification

The optical sensor in Sentinel-2 is planned to have bands in the optical, NIR and SWIR with different spatial resolutions according the use of the bands. The centre wavelength, spectral width and spatial resolution can bee seen in Table 1.

Table 4. Spectral and spatial resolution of the Sentinel-2 spectral bands

Band #	Centre wavelength (nm)	Spectral width (nm)	Spatial resolution (m)
1	443	20	60
2	490	65	10
3	560	35	10
4	665	30	10
5	705	15	20
6	740	15	20
7	775	20	20
8	842	115	10
8a	865	20	20
9	940	20	60
10	1375	20	60
11	1610	90	20
12	2190	180	20

Bands 1, 9 and 10 are sampled at 60 m spatial resolution as they are devoted to atmospheric correction purposes, Bands 2, 3, 4 and 8 are sampled at 10 m to ensure higher resolution products for specific applications (e.g. soil sealing mapping, forest mapping for Kyoto Protocol inventory). The rest of the bands are specified at 20 m spatial resolution, sufficient for the rest of the potemtial applications.

A number of service products are specified to be available for final users. Service providers are officially recognised entities in charge of delivering more refined products or products specific for certain applications in the frame of the GMES programme. The list of planned main products contains a number of products useful for forest monitoring:

- Land Cover Map
- Change Detection Map

- Leaf Area Index
- Fraction of Vegetation Cover
- Fraction of Absorbed Photosynthetically Active Radiation
- Leaf Chlorophyll Content
- Leaf Water Content
- Snow Cover

5.1.3 Sentinel-3

The pair of Sentinel-3 satellites will provide global, frequent and near –real-time ocean, ice, and land monitoring. It continues Envisats altimetry, the multispectral, medium-resolution visible and infrared ocean, ice and land-surface observations of ERS, Envisat and SPOT, and includes enhancements to meet operational revisit requirements and to facilitate new products and evolution of services. While Sentinel-2 is mainly meant for studies of vegetation and land cover, the main objective for Sentinel-3 is analysis of the oceans. It is equipped with two optical instruments and a topographic package.

5.1.3.1 Technical specification

The satellite has two optical instruments.

- Ocean and Land Colour Imager (OLCI)
- Sea and Land Surface Temperature (SLST)

The OLCI sensor is based on the MERIS sensor and shall be optimised to measure the ocean colour over the open ocean and coastal zones, however, it shall not saturate over land targets. The spectral bands for OLCI are in the visible to the near infrared as shown in Table 2.

Table 5. Wavelength and band width for OLCI spectral bands

Band	Centre Wavelength (nm)	Band-width (nm)
O1	413	20
O2	443	10
O3	490	10
O4	510	10
O5	560	10
O6	620	10
O7	665	10
O8	681	7.5
O9	709	10
O10	754	7.5
O11	761	3.75
O12	779	15
O13	865	20
O14	885	10
O15	900	10
O16	1020	40

The spatial resolution is 1 km over open ocean and sea ice, and 0.25 km over costal zones and land.

The SLST sensor measures sea- and land-surface temperatures, following the AATSR concept.

Its rotary scan mirror mechanism produces the wide swath of 750 km. It features ~1 km resolution at nadir for thermal-infrared channels and 500m for visible and shortwave infrared channels.

Table 6. Wavelength and band width for SLST spectral bands

Band	Centre wavelength (µm)	Band-width (nm)
S1	0.555	20
S2	0.659	20
S3	0.865	20
S4	1.375	15
S5	1.61	60
S6	2.25	50
S7	3.74	380
S8	10.85	900
S9	12.0	1000

The topographic payload consists of the

- Synthetic Aperture Radar Altimeter (SRAL)
- Microwave Radiometer for Atmospheric Correction (MWR)
- Precise Orbit Determination Package (POD)

These instruments will determine very accurately the height of the Earth surface, and in particular the sea surface, relative to a precise reference frame.

SRAL is a dual-frequency nadir-looking microwave radar altimeter employing technologies form the CryoSat and Jason altimeter missions. The main range measurements are performed at 13.575 GHz Ku-band, while a second frequency at 5.41 GHz C-band allows compensations for ionospheric effects.

MWR measures the thermal radiation emitted by Earth. The received signal is proportional to the abundance of the atmospheric component emitting at the observed frequency and the sea-surface reflectivity. This information reveals the delay added to the altimeter pulses by moisture in the troposphere.

The POD equipment is a satellite navigation receiver supplemented with a laser retro-reflector. It provides the satellite altitude to an accuracy of 2 cm.

Sentinel-3 will support the routine generation of a general suite of high-level geophysical products with priority on:

- ocean, ice, land and inland water surface topography
- sea-surface temperature

- ocean colour
- land surface biophysical properties
- land surface temperature

6 Evaluation of existing retrieval algorithms

6.1 Algorithms for optical data

6.1.1 MODIS vegetation algorithms

The MODIS Vegetative Cover Conversion (VCC) product is designed to serve as an alarm, where rapid land cover conversion, once detected, can subsequently be analyzed with data from higher resolution sensors such as Landsat, Ikonos and Quickbird.

Currently three types of changes are detected: deforestation, change due to burning and change due to flooding. Each type is identified by a separate algorithm. VCC-Deforestation is generated using decision tree models to classify the input data.

The algorithms have been tested on MODIS Level 1B 250 m data for all types of changes for some selected areas (Zhan, 2002). Five different methods have been used to detect the changes. Three methods utilize the spectral domain and two are based on texture. The methods are:

- Red-NIR space partitioning method
- Red-NIR space change vector method
- Modified delta space thresholding method
- Changes in spatial textures
- Changes in linear features

Details of these methods are given by Zhan et al. (1998, 2000).The evaluation of the methods showed that detection of small-scale deforested areas is relatively difficult compared to detection of large-scale flooding or burning. The change vector seemed to be the best method, and for deforestation, the performance of integration of all methods was not as good as for the change vector method alone. The linear feature method did not work for the selected areas in this study. It will have more value in areas with active road building.

The MODIS Vegetation Continuous Fields product has a sub-pixel estimate of the percentage cover of woody, herbaceous and bare; leaf type; leaf longevity; crop cover; and water cover. The present product has a 500 m spatial resolution but in the next version it will change to 250 m. The product is updated annually. A VCF percent tree product with 250 m resolution has already been used as a reference data set for training of Landsat imagery (Hansen et al, 2008).

An annually updated product is suitable as a reference, but for continuous monitoring one hopefully can use the same or similar methods for representing percent tree cover in a single MODIS image. Also, change in cover between two images from different times should be possible to detect with resolution of 250 m. There are, however, some problems. As MODIS has a large swath width, an area can be covered at least once a day. The position of the satellite will be different from day to day, and so the view angle for a point on the ground will vary, as will the size of the pixel containing this point. This means that the reflectance value of the pixel may vary from image to image even if there are no changes in land cover.

Parts of the image that are far from nadir positions of the satellite track should not be used. As the satellite track has a period of 16 days, many of the MODIS products use a 16 or 8 day composite to take the variation of view angle into account and present mean values of the presented variables. In 16 days there is also a chance that not all images are covered with clouds. In a composite image, small details may be smeared out because of varying pixel sizes, and also because of small errors in position data.

To detect real changes on the ground single images taken with the satellite in approximately the same track should be used if possible.

6.1.2 CLAS algorithms

The Carnegie Landsat Analysis System (CLAS) uses Landsat (ETM+) data and a fully automated version of the 6S atmospheric radiative transfer model. The 6S program is integrated into the CLAS processing stream and uses monthly averages of aerosol optical thickness and water vapour values from the MODIS sensor onboard the NASA Terra spacecraft. The CLAS process decomposes each image pixel into a fractional cover estimate (0-100% cover) of photosynthetic vegetation (PV) canopy, non-photosynthetic vegetation (NPV), and bare substrate.

6.1.3 Combinations of reflectance data and texture analysis

Asner et al. (2002) combined a detailed field study of forest canopy damage with calibrated Landsat 7 Enhanced Thematic Mapper Plus (ETM+) reflectance data and texture analysis to assess the sensitivity of basic broadband optical remote sensing to selective logging in Amazonia. The field study encompassed measurements of ground damage and canopy gap fractions along a chronosequence of post-harvest regrowth of 0.5-3.5 years. They found that canopy damage and regrowth rates varied according to the logging method used - conventional logging or reduced impact logging. Areas used to stage felled trees prior to transport, log decks, had the largest gap fractions immediately following cutting. Log decks were quickly colonized by early successional plant species, resulting in significant gap fraction decreases within 1.5 years after site abandonment. Although log decks were the most obvious damage areas on the ground and in satellite imagery, they accounted for only 1-2% of the total harvested area of the blocks studied.

Other forest damage features such as tree-fall gaps, skid trails, and roads were difficult to recognize in Landsat reflectance data or through textural analysis. These landscape features could be only crudely resolved in the most intensively logged forests and within about 0.5 years following harvest. It was found that forest damage within any of the landscape strata (decks, roads, skids, tree falls) could not be resolved with Landsat reflectance or texture data when the canopy gap fraction was <50%. The basic Landsat ETM+ imagery lacks the resolution of forest structural features required for quantitative studies of logging damage. Landsat textural analyses may be useful for broad delineation of logged forests, but detailed ecological and biogeochemical studies will probably need to rely on other remote sensing approaches. Until spatial gradients of canopy damage and regrowth resulting from selective logging operations in tropical forests in the Amazon region are resolved, the impacts of this land use on a continental scale will remain poorly understood.

6.1.4 IKONOS used for studying canopy structure and logging impacts

With 1 m resolution it is possible to study single trees in forests. Asner et al. (2003) studied the magnitude and variability of canopy shadows with observations from the IKONOS satellite over tropical regions. Knowledge of canopy structure and shadows is essential in detection of selective logging. Read et al. (2003) studied the application of IKONOS 1 m and 4 m resolution merged data to research and management in tropical forests.

An automated tree crown analysis algorithm using 1 m panchromatic IKONOS images has been developed by Palace et al. (2008). The algorithm was used to estimate crown dimensions and forest structural properties in 51 forest stands (1 km²) throughout the Brazilian Amazon. Sources of observed errors included an inability to detect understory crowns and to separate adjacent intermingled crowns. Nonetheless, the technique can serve to provide information about structural characteristics of large areas of unsurveyed forest throughout Amazonia and other rainforest regions.

6.2 Algorithms for SAR data

Rosenqvist (2003): “Space-borne SAR data may also prove useful for detecting land cover change and quantifying canopy closure”. For example, shorter wavelength (~5.5 cm) C-band and longer wavelength (~23.5 cm) L-band and SAR backscatter data are sensitive to the amount of foliage/small branches and woody (branch/trunk) components respectively and time-series of these data could be used for quantifying changes in vegetation through ARD activities. Even so, confusion with rough surfaces and herbaceous grasslands may occur with C-band. If limited to one band, the detection and quantification of ARD areas is best addressed using longer wavelength L-band SAR systems, which are more sensitive to the range of vegetation structures associated with different growth stages of forests. However the only L-band SAR satellite in orbit is the ALOS PALSAR satellite which is still a research satellite and does not have the same operational setup and availability as the C-band Envisat ASAR sensor.

The integration of longer and shorter wavelength SAR data also improves the capacity for vegetation distinction as demonstrated through studies using the 1994 multi-band, polarimetric space Shuttle Imaging Radar (SIR-C SAR) data (Ranson and Sun, 1994; Way et al., 1994). Although no space-borne multi-band missions are yet planned, polarimetric and dual-band data are available through the synergistic use of the Advanced Land Observing Satellite (ALOS) Phased Array L-band SAR (PALSAR), and the C-band ENVISAT Advanced SAR (ASAR) and RADARSAT-2/3 SAR. A prerequisite for successful utilisation of data from different sensors, however, is that the data are acquired during the same time periods, thus calling for joint observation campaigns and close collaboration between satellite operators, which currently is not typically the case.

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

The saturation of C- and L-band data at relatively low levels of biomass limits the use of these data for routinely quantifying biomass, particularly as the majority of forests and woodlands globally support an above ground biomass of >100Mgha−1. Even so, these data may be useful for quantifying the biomass of vegetation <100Mgha−1, particularly those associated with A, R and re-vegetation activities after 1990.

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

6.2.1 L-band SAR (JERS-1 and ALOS PALSAR)

The Global Rain Forest Mapping Project (GRFM) (http://southport.jpl.nasa.gov/GRFM/) is an international collaborative effort initiated and managed by the National Space Development Agency of Japan (NASDA). The main goal of the project is to produce a high-resolution wall-to-wall map of the entire tropical rain forest domain in four continents using the L-band SAR onboard the JERS-1 spacecraft. The processing phase, which entails the generation of wide area radar mosaics from the raw SAR data, was split according to the geographic area. The GRFM project's goal calls for the coverage of a continental scale area of several million km2 using a sensor with the resolution of tens of meters. In the case of the African continent, this entails the assemblage of some 3900 high-resolution SAR scenes into a bi-temporal mosaic at 100 m pixel spacing and with known geometric accuracy. While this fact opens up an entire new perspective for vegetation mapping in the tropics, it presents a number of technical challenges. DeGrandi et al. (2000) report on the solutions adopted in the GRFM Africa mosaic development and discusses some quantitative and qualitative aspects related to the characterization and validation of the GRFM products. In particular, the mosaic geolocation and its validation are discussed in detail. Indeed, the internal geometric consistency (subpixel accuracy in the coregistration of the two dates), and the absolute geolocation (residual mean squared error of 240 m with respect to ground control points) are key features of the GRFM Africa mosaic. Other important aspects that are discussed are the multi-resolution decomposition approach, which allows for tracking the evolution of natural phenomena with scale; the internal semi-automatic radiometric calibration, which minimizes artefacts in the mosaic; and the thematic information content for vegetation mapping, which is illustrated by a few examples elaborated by visual interpretation. Experience gained so far indicates that the GRFM products constitute an important source of information for global environmental studies (DeGrandi et al. 2000).

Shimabukuro et al. (2005) discuss the use of a JERS-1 (Japanese Earth Resources Satellite) L-band Synthetic Aperture Radar (SAR) time-series for mapping and monitoring land cover in a test site in the region of Corumbiara, Rondônia State, western Brazilian Amazonia. In order to support JERS-1 data analysis, land cover maps were obtained by digital classification of Landsat TM images acquired from 1993 to 1997 period, following a procedure based on image segmentation, unsupervised classification, and post-classification image edition. The comparison of these products with JERS-1 images shows that clean deforested areas are well identified presenting a low backscattering response as expected. However areas that have been cleared and even burned but with remaining forest material left on the ground present high backscattering response opposed to expected. Considering these observations and user interpretation expertise, JERS-1 SAR images could be used to map and monitor land cover changes in Amazonia, but unambiguous detection of deforested areas seems to be possible by their method only if the entire clearing process, which involves slash, burn, and removal of trunks and branches, had already been concluded (Almeida-Filho et al., 2005).

Woods Hole research centre (www.whrc.org) has demonstrated how ALOS Palsar data can be used. They state that “The ALOS observation plan will ensure that these high-resolution data are acquired several times per year for years to come. With a strong sensitivity of the ALOS radar imaging sensor to vegetation structure, this marks a new era in remote sensing of natural resources.

The response of the L-band ALOS PALSAR sensor to artificially wind-thrown forest and clear-felled forest was studied on spruce forest stand in Sweden (Fransson et al., 2007). Test sites of the spruce forest were artificially wind-thrown by cutting in August 2006 and the debris was then cleared in December 2006. The drop in backscattering coefficient between the reference and the clear-felled stands (winter images) was on average 2.1 dB, and the corresponding decrease between the reference and the artificially wind-thrown stands (fall images) was 1.6 dB. Moreover, the difference in backscattering coefficient between the averaged summer images and the winter images was found to be 2.7 dB for the treated stands, whereas the corresponding difference for the reference stands was 1.0 dB.

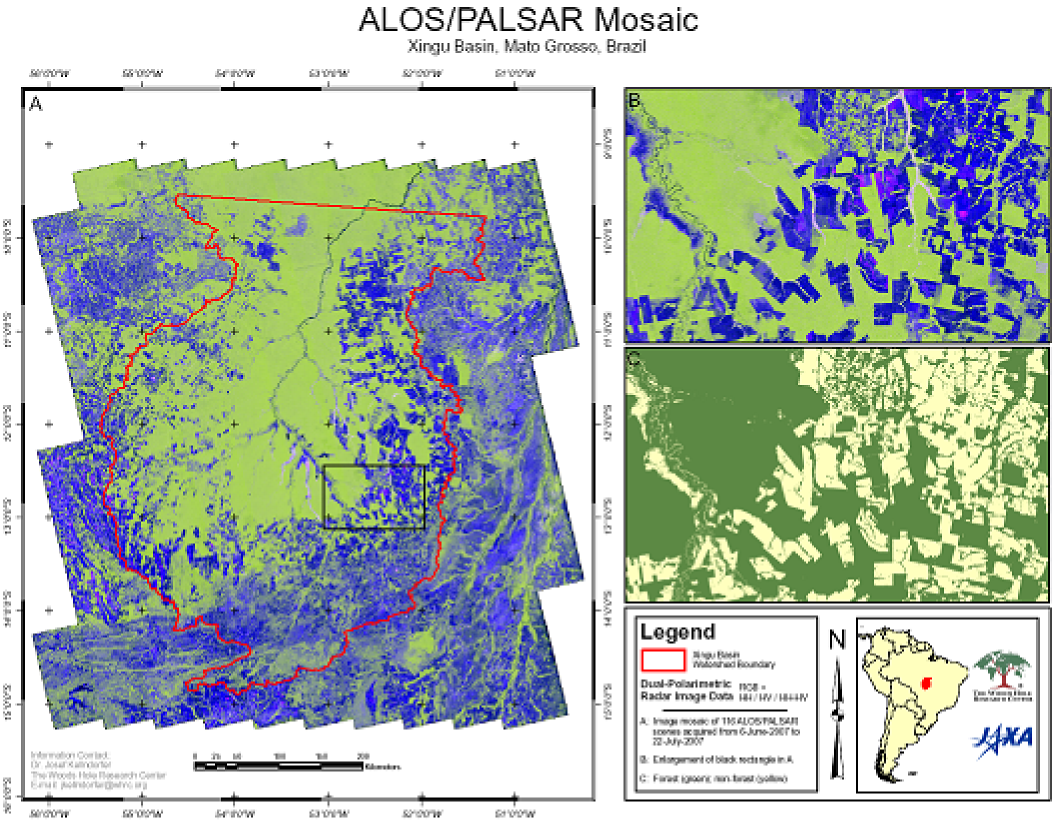
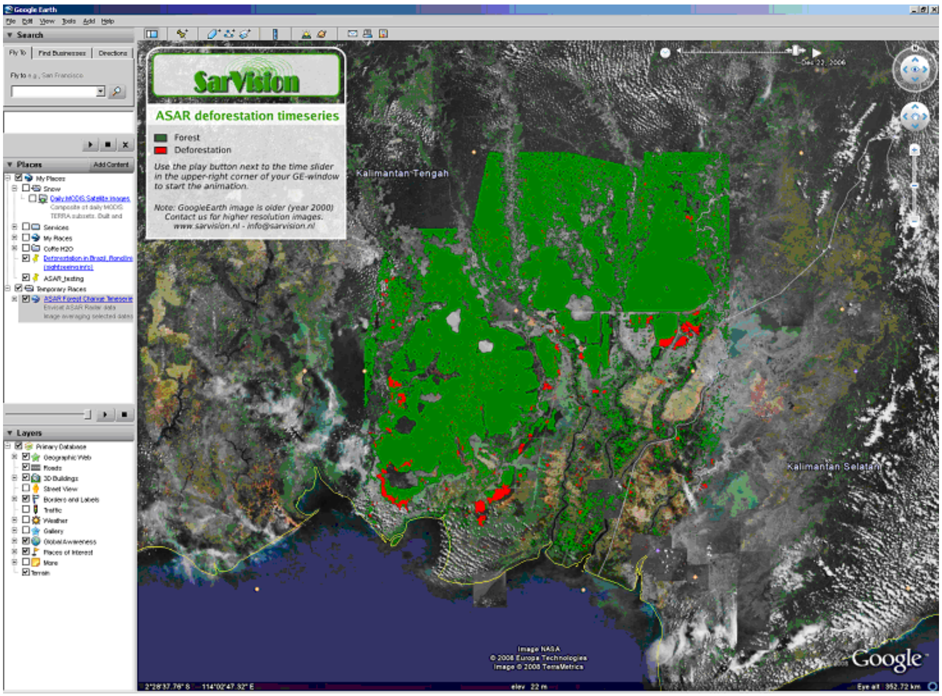


Figure 10. **ALOS/PALSAR mosaic of the Xingu river basin in Mato Grosso, Brazil. The image mosaic is a composite of 116 individual images acquired between June 8 and July 22, 2007.**

6.2.2 C-band SAR

Henry et al. (2006) used ESA's ERS-1 and Envisat ASAR imagery to map forests in French Guiana. The reprocessing of the ERS-1 data with the new PGS ASAR processor instead of the old ERS VMP processor combined with the co-registration method developed in the GBFM (Global Boreal Forest Mapping) project allowed better geometric quality and geolocation. The Autochange method, presented by Häme et al. (1998), has then been applied using average amplitude and temporal variability as input channels, with PGS-reprocessed ERS and ASAR images on the one hand, and with VMP processed ERS and ASAR images on the other hand. The reprocessing of ERS images from 1992-1993 period provide a better accuracy of geolocation information, even if additional adjustments were necessary to ensure the best co-registration within and between image stacks. It also enables a better definition of temporal SAR features and, consequently, a better quality of change maps computed with an unsupervised method.

Another institute that has focused on the practical use of C-band SAR for deforestation detection is the company SARVision located in Wageningen, the Netherlands (http://www.sarvision.nl/). They have shown applications of change detection using both L- and C-band SAR in tropical rainforests. A prototype system for operational monitoring of the Central Kalimantan in Indonesia with Envisat ASAR (C-band) was demonstrated at the Bali Conference in 2007. Maps are also exported to Google Earth.



Use the play button next to the time slider in the upper-right corner of your GE-window to start the animation.

Note: GoogleEarth image is older (year 2000) Contact us for higher resolution images. www.sarvision.nl - info@sarvision.nl

Figure 11. Google Earth screen dump of the prototype service provided by SARVision over Laimantan in Indonesia. Red areas are interpreted as areas being deforested in the period 1 January 2006 to 22 December 2006.

6.3 Multi-source algorithms

6.3.1 Multi-sensor algorithms

MODIS and Landsat data have been combined for monitoring of forest cover and change in the Congo Basin (Hansen *et al*, 2008). Work has been done to explore techniques to improve land cover classification accuracy through a comparative analysis of different combinations of spectral signatures and textures from Landsat ETM+ and Radarsat data. A wavelet technique was used to integrate Landsat ETM+ multispectral and panchromatic data or Radarsat data. Gray level occurrence matrix (GLCM) textures based on Landsat ETM+ panchromatic or Radarsat data and different sizes of moving windows were examined. The incorporation of data fusion and textures increases classification accuracy by approximately 5.8 - 6.9 % compared to Landsat ETM+ data (Lu *et al*, 2007). Haack *et al.* (2000) mapped land-use in Africa and concluded that a merger of optical and radar sensors improved the ability to map surface features, compared to using only one of the sensor types.

In a regional study in the Guarayo region (Bolivia), Ferrufino-Ugarte et al. (2007) applied a multi-temporal multi-sensor change detection algorithm “RCEN multi-spectral” using 2001 data from ETM+/Landsat-7 and 2006 data from CCD/CBERS-2 (China-Brazil Earth Resources Satellite). Both sensors acquire data in the red, green and NIR bands and change is detected through the radiometric rotation between the two multi-spectral data sets between 2001 and 2006. The advantage of this method is that no complicated radiometric correction is necessary combining two spectral sensors, although water bodies have to be masked out.

6.3.2 Time-series algorithms

A detailed study of selective logging operations was conducted near Sinop, State of Mato Grosso, Brazil, one of the key Amazonian logging centres. An 11-years series of annual Landsat images (1992–2002) was used to detect and track logged forests across the landscape. A semi-automated method was applied and compared to both visual interpretation and field data. Although visual detection provided precise delineation of some logged areas, it missed many areas. The semi-automated technique provided the best estimates of logging extent that are largely independent of potential user bias. Multitemporal analyses allowed the authors to analyze the annual variations in logging and deforestation, as well as the interaction between them. It is shown that, because of both rapid regrowth and deforestation, evidence of logging activities often disappeared within 1–3 years.

Nearly 3% of logged forests were rapidly deforested during the year in which logging occurred, indicating that even annual monitoring will underestimate logging extent. Great care will need to be taken when inferring logging rates from observations greater than a year apart because of the partial detection of previous years of logging activity (Matricardi *et al*, 2005)

6.3.3 Multi-scale algorithms

Multiscale texture has been applied in classifying JERS-1 radar data over tropical vegetation. In a work by Podest and Saachi (2002), a multiscale texture-based classifier for mapping tropical forest cover types is discussed. The classifier was implemented using the Japanese Earth Remote Sensing Satellite (JERS-1) 100 m resolution radar data acquired over the Amazon Rainforest as part of the Global Rainforest Mapping (GRFM) Project. Demonstrated here is the use of the information content present in different texture measurements at different scales to separate three categories of land cover types: forest from non-forest, terre firme from floodplain vegetation, and grassland from woodland savannah. Various combinations of first-order image statistics known as texture measures were used at different scales as feature dimensions to aid the class discrimination. Eight of the most common first-order texture measures found in the literature was used. The best combination of texture measures at each scale was determined by employing class separability tests using the Bhattachuryya distance. The results were then used as input images into a supervised multiscale maximum likelihood estimation classifier. The classified maps were validated against independent test sites, and by comparison with a Landsat Thematic Mapper (TM) classification. It was found that JERS-1 backscatter and texture measures can discriminate forest from non-forest types with very high accuracy (above 90%). Old secondary forest or regrowth areas were often mixed with forest. Radar backscatter alone was able to separate terre firme and floodplain vegetation. However, texture measures were important in separating open from dense floodplain vegetation. Similarly, the backscatter sensitivity to low biomass values was instrumental in separating woodland from grassland savannah. Texture had a lesser role in separating these two vegetation types but was important to separate the woodland savannah from dense evergreen forest and secondary forests.

Supervised classification-based forest mapping from remote sensing data are limited by lack of ground truth and spectral-only-based methods. In a paper by Ouma *et al*, (2008) the first results of a methodology to detect change/no-change based on unsupervised multi-resolution image transformation are presented. The technique combines directional wavelet transformation texture and multispectral imagery in an anisotropic diffusion aggregation or segmentation algorithm. The segmentation algorithm was implemented in unsupervised self-organizing feature map neural network. Using data from Landsat TM (1986) and ETM+ (2001), change detection results for part of Mau forest in Kenya are presented. An overall accuracy for change detection of 88.4 % was obtained. The method is able to predict the change information a posteriori as opposed to the conventional methods that require land cover classes a priori for change detection. Most importantly, the approach can be used to predict the existence, location and extent of disturbances within natural environmental systems.

The characterization of landscape objects can vary when considering different spatial resolution and different deforestation patterns in the Amazonia. An evaluation of the effects of spatial resolution and different deforestation patterns on the performance of landscape metrics, has been done by da Silva *et al* (2007). Deforestation maps from MODIS (250 m) and TM (30 m) sensors were used in this study. The experiments were performed in the region “Terra do Meio”. The results have shown, with good accuracy, that similar landscape metrics sets can be used, extracted from coarser spatial resolution images, to characterize landscape objects extracted from higher spatial resolution images and vice-versa.

7 Evaluation of available software

7.1 Norut and NR's common processing framework

Norut has been coordinating international consortiums for pre-operational European monitoring services like EnviSnow (http://projects.itek.norut.no/EnviSnow/) and Floodman (http://projects.itek.norut.no/floodman/), based on optical and active microwave satellite sensors. Through long cooperation, Norut and NR have developed a module based ENVI/IDL platform for snow cover area monitoring based on MODIS and Envisat ASAR. Norut has been mainly responsible for the operational SAR processing software and NR for the MODIS processing. The SAR software includes geocoding and algorithms for monitoring floods, snow cover area and, recently, also sea ice. The principals of change detection algorithms and the overall ENVI/IDL platform and framework developed should be easily transferable to rainforest monitoring.

The monitoring processing line (Figure 12) has been operational for hydro-energy companies since 2006 for most of Scandinavia.

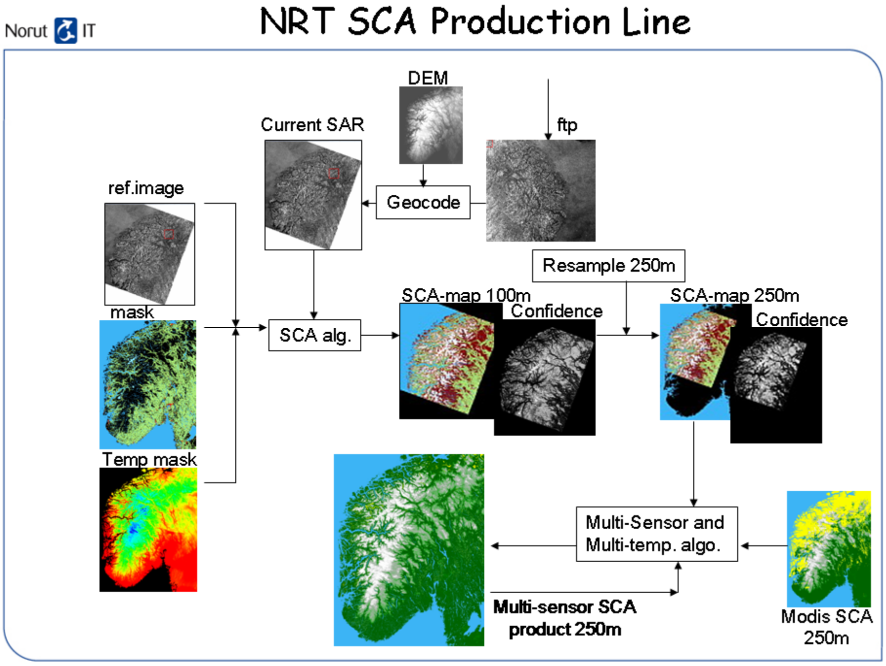


Figure 12. Complete monitoring processing line developed by Norut and NR

7.2 Norut's processing software

7.2.1 Geocoding

All satellite image algorithms that are based on multi-temporal change detection methods, as is the case for flood, snow cover and rainforest monitoring, are dependent on reliable and accurate geocoding software. Norut has developed state of the art in-house geocoding software that allows correct geocoding of data from all available SAR satellites, i.e. ERS-1/2 SAR, Envisat ASAR and Radarsat-1/2. The software requires access to DEMs and the correct flight and position parameters from the satellite in order to support different kinds of output data products. The software generates a primary output product ortho-SAR and several secondary products listed below:

- backscatter image in UTM projection i.e. ortho-SAR.
- simulated backscatter image in UTM
- local incidence angle image in UTM
- image of angle between surface normal and local image plane normal in UTM
- local look angle image in UTM
- global look angle image in UTM
- layover/shadow image mask in UTM
- arrays holding the DEM and the corresponding input SAR image indexes.

The geocoding module is the first and most important step in the change detection processing line.

7.2.2 Reference data set

The next step in studying change detection is to build a reference data set with the initial ground situation. For flood and snow cover monitoring, Norut has already developed different methods to establish suitable reference data sets. It is not only important that the reference data set is correctly geolocated so it can be compared to the study data set, but the reference data set also often needs to satisfy several conditions to qualify as a good reference data set. For example, in snow cover monitoring which detects wet snow compared to dry snow, it has to be ensured that the reference data has been taken during no-snow conditions (summer images) or conditions below the freezing point in order to ensure dry snow. This is done with the integration of daily meteorological data from the Norwegian and Swedish Meteorological Institutes that are interpolated and combined with a DEM in a temperature map that is then used as a quality check in the construction of the reference data (Figure 13).

Similar auxiliary data sets for rainforest monitoring might be necessary in order to ensure that the change detection is not influenced by abnormal meteorological conditions of long humid or dry periods in seasons when they typically do not occur.

Modules that average good reference data sets, weighing them based on quality to ensure the best reference data set, have also been developed.

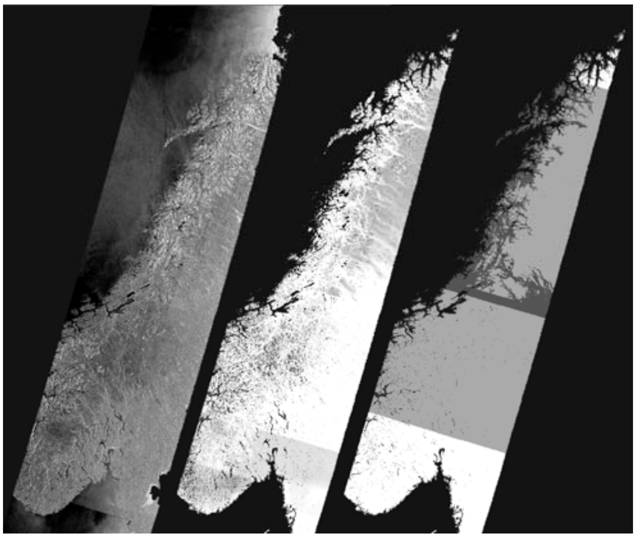


Figure 13. Reference data set from left to right: Average backscatter reference, confidence level and number of images that were used to construct each pixel.

7.2.3 SAR change detection

Norut has developed operational change detection software for flood and snow cover area monitoring. These are mostly based on detecting changes in backscatter between multi-temporal data sets (or one data set and a reference data set) and applying thresholds for these changes. These change detection algorithms should be easily transferable to rainforest monitoring

For snow cover detection, the software detects a decrease of about 3 dB in SAR backscatter due to the absorption of the radar signal in wet snow. By combing the result with a DEM, dry snow that lies at higher altitude and could not directly be detected is then inferred by simple modelling and the use of auxiliary meteorological data. Similar change detection techniques are used for flood monitoring when images of flood conditions are compared to earlier images when there was no flooding. Figure 14 shows examples of a SAR-based snow map and flood inundation map, based on SAR change detection techniques as illustrated. Figure 15 shows a preliminary example of change detection over a rainforest area. It must be stressed that this is a preliminary example based on non-calibrated data and software simply to demonstrate the potential.

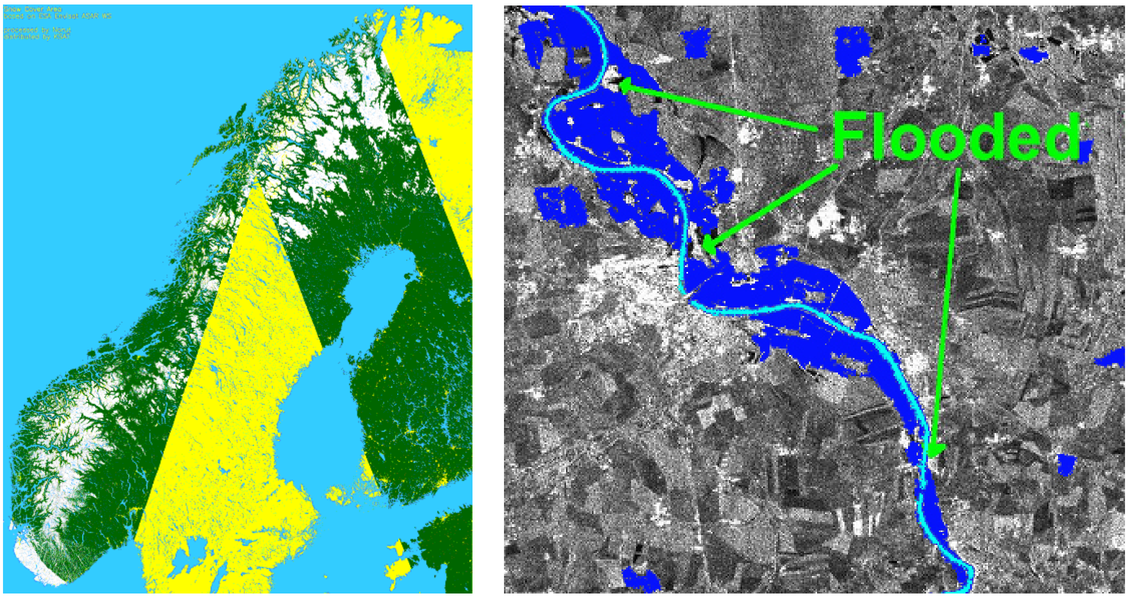


Figure 14. Examples of SAR based snow map and flood inundation map based on SAR change detection techniques, Norut.

7.2.4 Multi-sensor algorithms

An important aspect of rainforest monitoring will be the use of multi-sensor algorithms, combining optical and SAR data. Norut and NR have significant experience with this. In the current monitoring processing line, there is also a module to combine the results from different satellites, i.e. Envisat ASAR and MODIS. The software includes different resampling algorithms to co-locate the different resolution of the sensors on a common grid and combing the results weighed with additional confidence images that are dependent on cloud cover, temperature, the confidence level of reference images, etc. These multi-sensor algorithms should also be very useful when combining optical and SAR images for rainforest areas.

7.2.5 Unsupervised segmentation

For segmentation over large rainforest areas at high temporal resolution, some type of automatic segmentation algorithm is necessary. For monitoring of floods in no-forest areas, as well as for segmenting sea ice from ocean, Norut has developed automatic unsupervised classification algorithms based on SAR texture analysis. The algorithms include an automatic analysis of the backscatter histogram detecting the number of modes (i.e. classes) in the image and searching for the ideal threshold between the two major classes in order to segment the image. These algorithms could serve as a starting point for different segmentation purposes in rainforest classification.

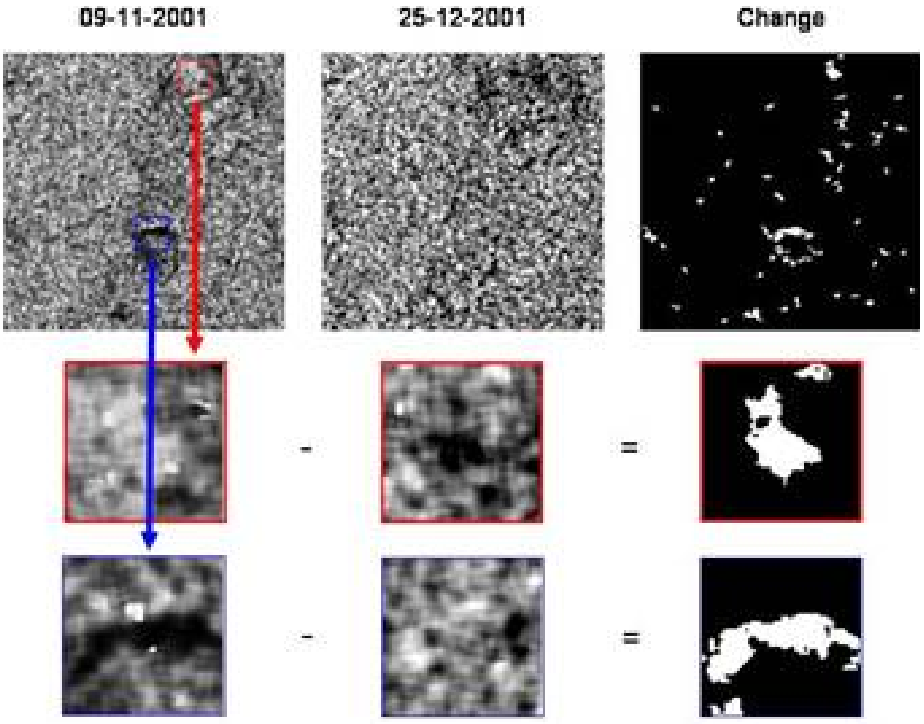


Figure 15. Change detection in tropical rainforest using C-band SAR.

7.2.6 Vegetation mapping and change detection technology at Norut

Norut has substantial experience in vegetation mapping and change detection based on optical satellite data. The same basic techniques can be transferred to the rainforest.

One important, recent mapping development by Norut was a generalized, consistent, and seamless vegetation map for all of mainland Norway, based on satellite images. A total of 45 Landsat TM/ETM+ images were being processed during six operational stages: (1) spectral classification, (2) spectral similarity analysis, (3) generation of classified image mosaics, (4) ancillary data analysis, (5) contextual correction, and (6) standardization of the final map products. Analysis performed on the spectral-only data is often denoted the pre-classification stage of the process, whereas the post-classification process involves analysis and subsequent contextual corrections of the pre-classified image using ancillary data. The quality of the ancillary data sets greatly affects the quality of the final vegetation map. For Norway, high-quality ancillary data are available. In the final standardisation part of the process, the defined classification units are related and described according to a classification schemes well adapted in the Norwegian botanical tradition. The vegetation mapping process used is illustrated in Figure 16.

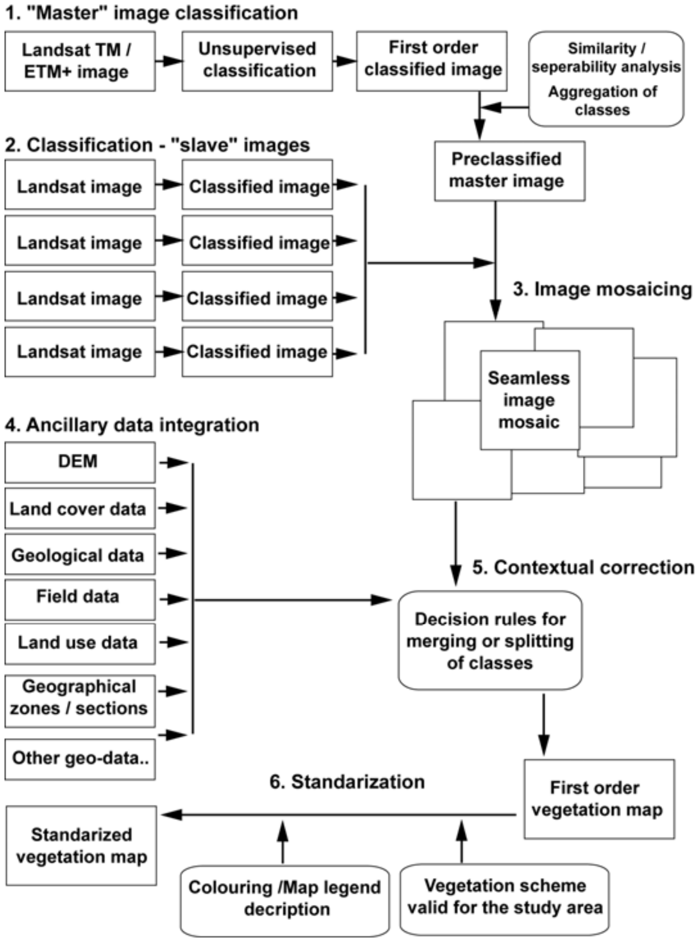


Figure 16. The overall production line is divided into six different operational stages involving image classification, similarity and separability analysis, image mosaicing, ancillary data integration and a final standardization of the end product.

The maps produced portray the Norwegian landscape at different levels. At the most detailed level a seamless vegetation map was created with a ground resolution of 30 m (Figure 17). The products will in the future serve as references for a wide range of studies where spatial information is needed. New and improved delineation of vegetation zones and sections can be extracted. The map will provide input for research fields such as grazing studies, climate and pollution impact studies, as well as studies of land degradation. The maps will further serve as an important source of information when new types of satellite data and sensors are to be evaluated and validated, and also for change detection purposes.

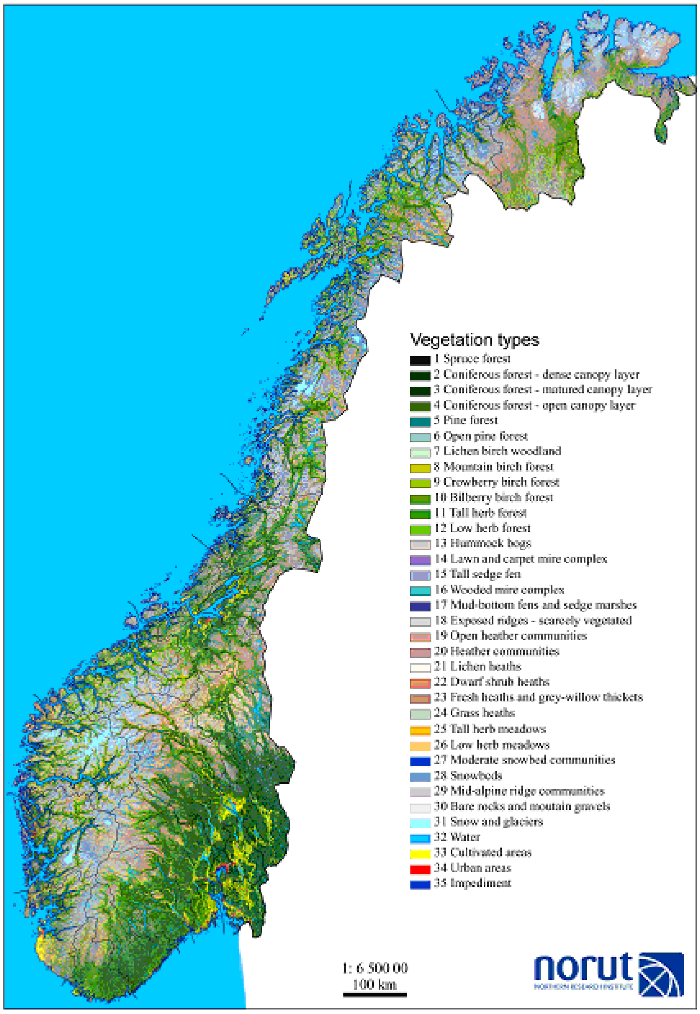


Figure 17. Vegetation map of Norway based on Landsat-TM/ETM data

Norut has much experience in change detection studies, both detecting effects of pollution from the nickel smelters on the Norwegian - Russian border, and effects of overgrazing of reindeer at Finnmarksvidda. Figure 18 illustrates the overall change detection procedure. In Figure 19, the change in vegetation cover due to pollution effects from 1973 to 1985 in Sør-Varanger, northern Norway is shown. Red areas are where the forest has died, due to increases in SO_2 emissions from the Russian smelters.

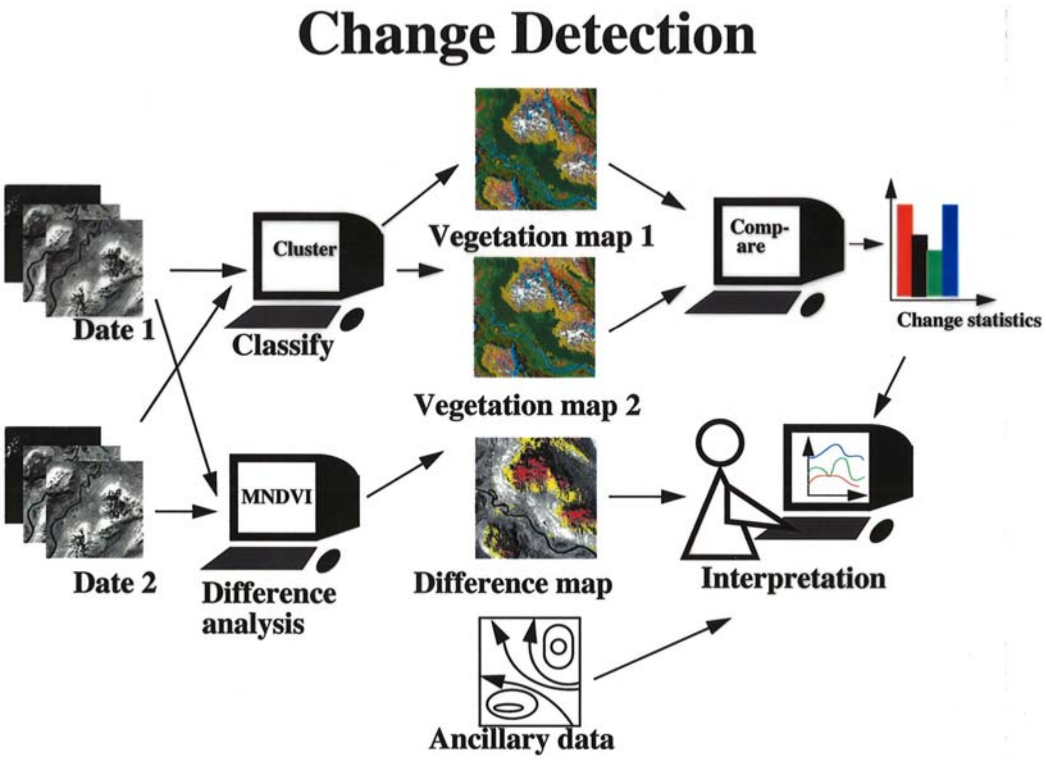


Figure 18. Change detection based on vegetation maps, vegetation indices and ancillary data.

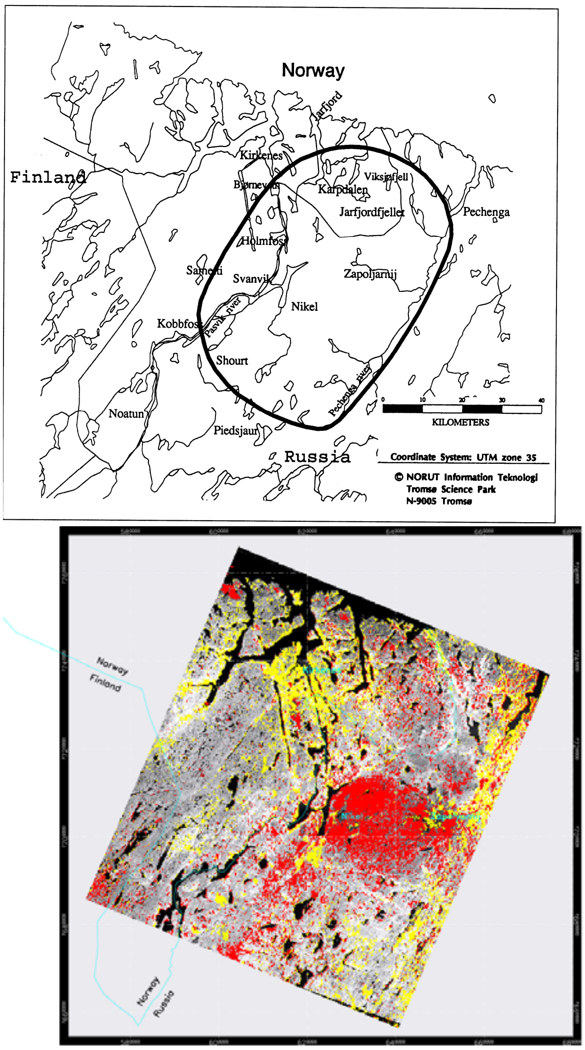


Figure 19. Change detection in Sør-Varanger 1973-1985. Red areas are where the vegetation has decreased or died, due to SO2 emission increase. Yellow areas depict an increase in green vegetation, caused by a transition from lichen to other vegetation types (also a result of the pollution).

7.3 NR's algorithms and processing software

7.3.1 Phenological alignment of growth seasons

This algorithm and corresponding software concern phenological alignment of growth seasons based on satellite data acquired over several years. Vegetation classes are often characterized by their temporal evolution through a growth season. Data of high spatial resolution, like Landsat data, are often temporally sparse. In order to get a longer sequence of images, data from different years can be combined into one single synthetic sequence.

We have developed a method for determining the correspondence between the chronological time of the image acquisition and the time at which the phenological state of the vegetation cover shown in the image would typically occur (Huseby et al. 2005). The task is considered as a minimization problem and is solved by dynamic programming. The methodology is based on the normalized difference vegetation index

(NDVI) computed from data having a coarse spatial resolution such as MODIS or AVHRR data.

The methodology has been tested on data from several years in Norway including in mountainous areas. By applying the time warping methodology to adjust the time scale within each year, the shifts become less apparent. The methodology can be used for alignment of growth seasons from satellite data as a pre-processing step in multi-temporal classification (see below).

7.3.2 Phenological multi-temporal satellite image classification

Ground cover classification based on a single satellite image can be challenging. In practice, some spectral signatures for various vegetation classes will always be very similar. Therefore, we have developed a methodology and corresponding software for multi-temporal satellite image data to alleviate this problem (Aurdal et al. 2005). We consider the problem of vegetation mapping and model the phenological evolution of the vegetation using a Hidden Markov Model (HMM). The different vegetation classes can be in one of a predefined set of states related to their phenological development. The characteristics of a given class are specified by the state transition probabilities as well as the probability of given satellite observations for that class and state. Classification of a specific pixel is thus reduced to selecting the class that has the highest probability of producing a given series of observations for that pixel. Compared to standard classification techniques such as maximum likelihood (ML) classification, the scheme is flexible in that it derives its properties not only from image specific training data, but also from a model of the temporal behaviour of the ground cover. It is shown to produce results that compare favourably to those obtained using ML classification on single satellite images; it also generalizes better than this approach.

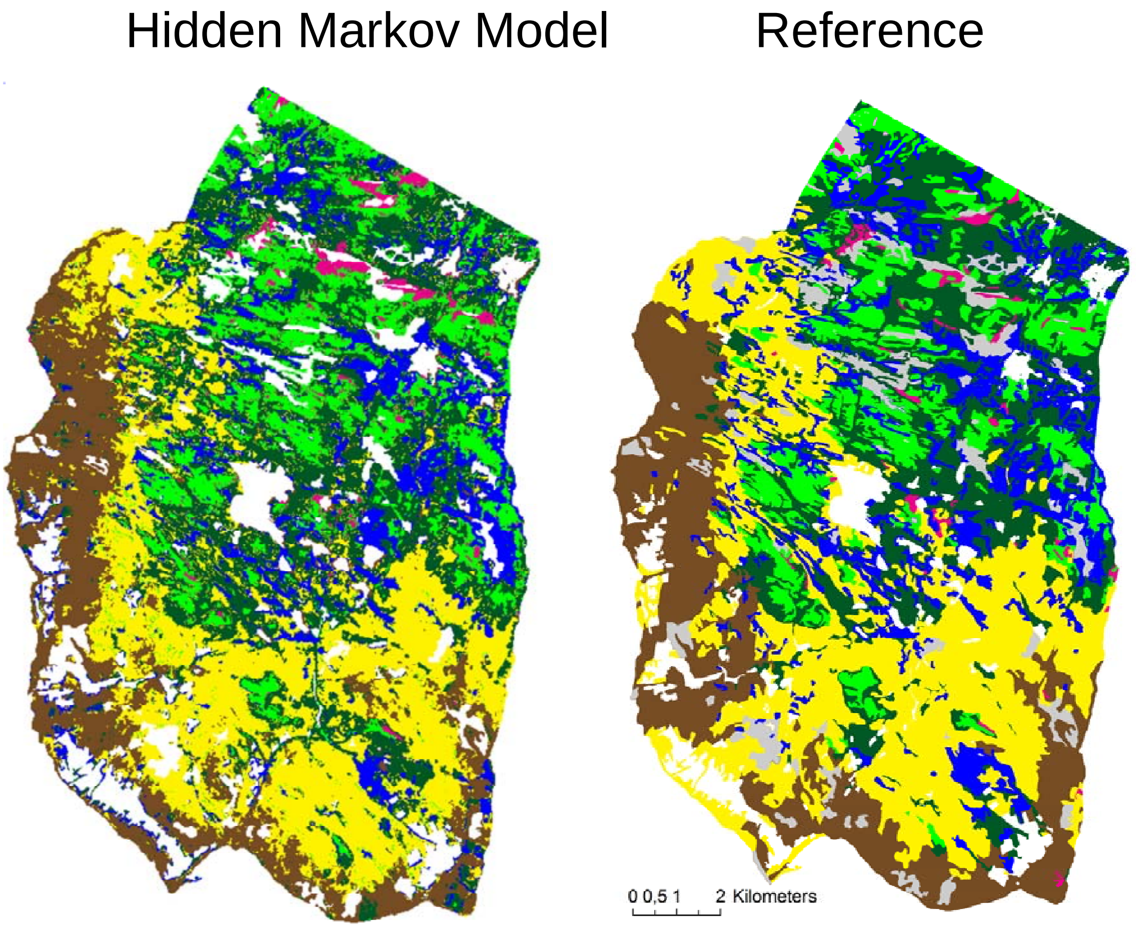


Figure 20. An example of multi-temporal classification using the Hidden Markov Model approach. Classification result to the left and vegetation map from NIJOS to the right. (NR)

7.3.3 Methodological framework for multisource retrieval

Retrieval of vegetation classes and other variables from remote sensing data would in many cases be significantly improved by multiple observations, in some cases by different sensors at different times and at different scales. Spectral properties are often not enough to discriminate between two vegetation classes, while multiple observations through the snow-free season would in many cases add significantly to the discrimination power since spectral features then could be combined with other features in a multi-temporal approach. The combination of sensors of different sensing properties increases the discrimination power further. While optical sensors retrieve spectral reflectance properties, a Synthetic Aperture Radar (SAR) microwave sensor is sensitive to the geometric and dielectric properties of the medium observed. A multi-sensor retrieval approach is very powerful when a reflectance/backscatter model of the medium observed is the basis of the retrieval algorithm (see Solberg et al. 2008 for an example of snow cover retrieval). Due to technical limitations of satellite remote sensing sensors and data transmission bandwidth from satellites to ground stations, there is a trade-off between temporal acquisition frequency and spatial resolution. This trade-off calls for the multi-scale approach where a relationship (a model) is established between the spatial scales. When a model is established, properties at the high spatial resolution could then be predicted from data of lower spatial resolution. This is in particular important when high temporal frequency is needed to monitor the temporal development of the surface cover (in particular vegetation).

In order to utilize the available information in multisource data, NR has developed a framework for data fusion techniques handling multi-sensor, multi-temporal and multi-scale analysis of remotely sensed data. Fusion can be performed at signal-, pixel-, feature-, or decision-levels. The techniques can be applied separately or together (like the combination of multi-sensor and multi-temporal).

8 Discussion

8.1 Optical sensor characteristics versus forest monitoring

The potential application of a sensor depends on its spectral and spatial resolution. A sensor may have a number of detectors that measure incoming radiation in one or a number of wavelength regions (bands). The spectral characteristics are described by the number of bands, and the centre wavelength and width of each band. An optical sensor should have one or more bands in the wavelength regions suited for forest monitoring, i.e. VNIR or possibly SWIR and TIR. With a number of bands, a sensor can record many different properties of the observed objects, and can separate the observed area into different types of land cover. Different objects have different spectral characteristics, and with a suitable selection of bands, it is possible to distinguish forest from other natural or man-made features. Different types of vegetation, and even different species of trees, can be classified. With bands in the thermal area, ongoing or recent fires can also be detected.

A second key aspect of a sensor is its spatial resolution. For the relevant optical sensors, the size of the pixels on the ground varies from 1 × 1 km down to 0.5 × 0.5 m. With a resolution of 0.5 to 10 meters it is possible to distinguish single trees in the forest. Small roads or skids and minor changes in the forest population can easily be detected.

With a medium resolution of 10 to 100 meters, it is possible to detect most of the results of logging activity. Roads, log decks and small clearings are observable in the satellite images.

With a resolution of 100 m to 1 km, the smallest changes are not directly observable. One may classify an image into two classes, forest or non-forest. A change in the forest, for instance a new clearing with an area less than a pixel size, may not result in a pixel completely without forest, and may not be visible. But it is possible to let the fraction of forest cover within each pixel determine the pixel value in the image. Then even a small change in the forest cover can be detected, although not in detail. It has been shown that with a pixel size of 250 m one is capable of detecting most of the changes in the forest caused by logging activity. This, however, does depend on the type of logging activity, e.g. clear cutting versus selective.

In addition to the spatial resolution, the coverage of the sensor on the ground is important. The sensors in the satellites scan the ground from side to side. The swath width will vary with the spatial resolution. Due to the amount of data to be transferred to the ground, the swath width will be largest for the sensors with coarse resolution and smallest for the sensors with very fine resolution. Typical swath widths are 890–2330 km for 250 m to 1 km resolution, 60–185 km for 30 m resolution and 11–18 km for 1 m and less. This means that a sensor with a moderate resolution covers a much larger area in each orbit than a sensor with very high resolution. For continuous monitoring of a large region, a coarse resolution sensor is required. Finer resolutions can be used for specified smaller areas. Most of the relevant satellites take 16 days to return to the original track. With a small swath width it may take 16 days to cover the same area again, but with a coarse resolution and large swath width there may be overlap in two succeeding passes. The time between revisits of the same area will increase with finer resolution, but some of the satellites can move the line of sight up to 45° off nadir and in this way reduce the revisit time.

8.2 Radar wavelengths

Radar waves interact with biomass, and short wavelengths like X-band (2.5–3.75 cm) and C-band (3.75– 7.5 cm) are more influenced than longer wavelengths like L-band (15–30 cm) and P-band (30–60 cm). It is hence easy to understand that longer wavelengths in a certain sense are preferable to short wavelengths. In brief, X- and C-bands are absorbed in the canopy of the forest due to the water content of the leaves, while L-band is mainly absorbed by the stems. In order to penetrate the canopy all the way down to the soil, there is a need for very long wavelengths like P-band.

The dependence of microwave backscatter on total above-ground biomass has been documented by several researchers with studies all showing the same results: (1) the sensitivity of microwave backscatter to biomass variations saturates after a certain level is reached; and (2) the biomass dependence of microwave backscatter varies as a function of radar wavelength and polarization (Figure 21). In summary, the saturation point is higher for longer wavelengths, and the HV polarization is most sensitive and VV least sensitive.

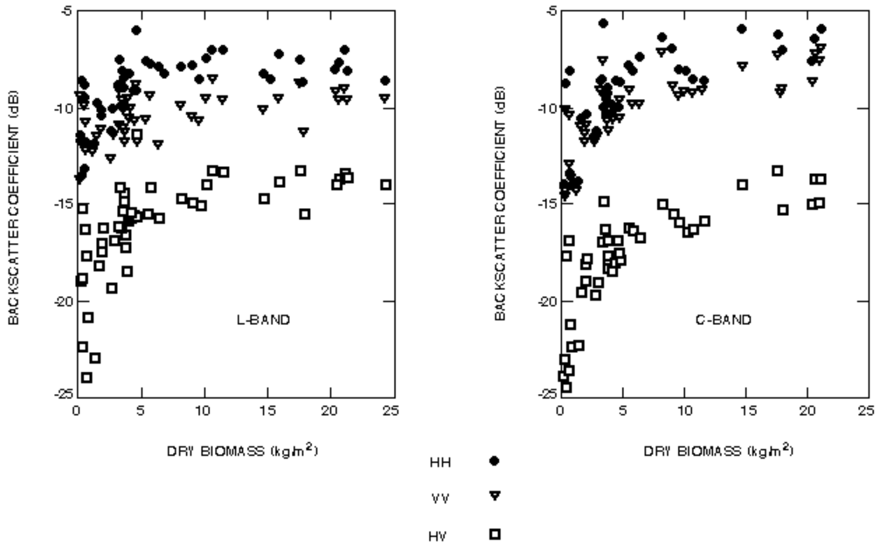


Figure 21. Dependence of L- and C-band backscatter on above ground biomass (from Dobson et al. 1995). L-band and HV polarization is preferable since the signal saturates slowly as a function of biomass.

Since no P-band radar systems are available currently for regular monitoring of tropical forests, we need to study whether C- or L-bands are preferable. L-band is currently only available on the ALOS satellite, a research satellite that does not focus on operational monitoring. At the best we can hope to have annual coverage over the rainforest belt, maybe somewhat more often in certain special interest areas. C-band radars are for the moment more widespread. Both the ERS/Envisat ASAR and the Radarsat-1/2 sensors provide relatively frequent datasets over rainforests. It is realistic to expect at least monthly coverage over the rain forest belt. Considering the advantages of such frequent observations, it seems clear that C-band would be preferable until more operational L-band SARs are launched. Additionally, the Sentinell-1 program, which will allow weekly observations in 2012, seems to make this option most attractive.

8.3 Temporal and spatial geographical coverage with SAR

Today, space-borne SAR systems are polar orbiting, yielding global coverage but with relatively long repeat cycles of 24 and 35 days for Radarsat and Envisat, respectively. By using variable incidence angles, Radarsat and Envisat are capable of acquiring images for a given location with shorter intervals than the orbit repeat cycles. The frequency of how often a satellite SAR can cover a given area is dependent on the geographic location (latitude). The following table shows the typical revisit times for Radarsat.

Latitude	Days	Latitude	Days
0°	2–5	50°	1.5–2.5
10°	2–4.5	60°	1–1.5
20°	2–4	70°	1
30°	1.5–4	80°	0.5
40°	1.5–3		

Table 6. Latitude and incidence angle dependence revisit times for Radarsat

We observe that it is generally impossible to get daily coverage with just one satellite, even with variable incidence angles. If we are able to utilise both Envisat and Radarsat the temporal coverage will, of course, be much better. Thus, to obtain the best temporal coverage for detecting features in SAR images, we need algorithms which work at any incidence angle and with any available satellite.

Sentinel-1 will have a 12 day repeat cycle. When the Sentinel-1 program is active with two satellites, it will cover the equator every 3 days.

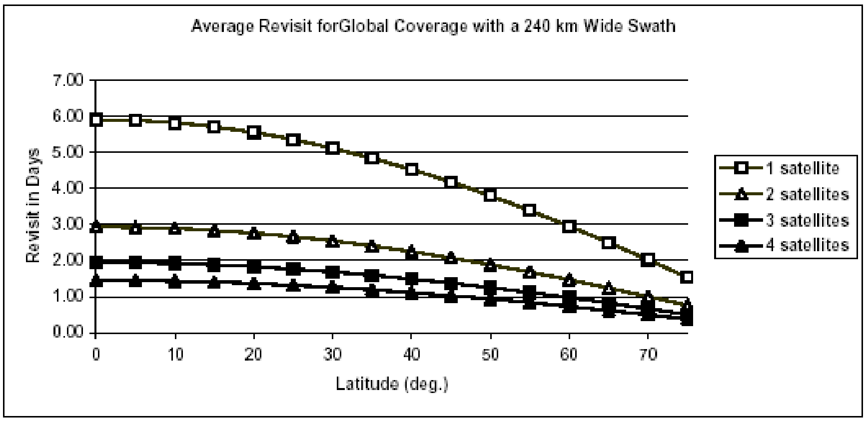


Figure 22. Average revisit as a function of latitude and numbers of satellites (Sentinel-1 Mission Requirement Document, ESA 2005)

9 Conclusions

Key variables for monitoring of tropical rainforests are land-cover, land-cover change, forest cover, clear-cut area, tree species, stem-volume data and biomass data. The first four variables can be measured appropriately with state-of-the art earth observation sensors, while the latter three require further development of methodology and/or new sensors.

Medium- and high-resolution optical satellites are attractive for classification purposes (e.g., tree species). However, they have a major limitation due to cloud cover and haze that often obscure the rainforest. For the purpose of near real-time monitoring, MODIS-type data can be used (e.g., the DETER system in Brazil) since it offers almost daily coverage. Some regions are, however, so affected by clouds that even daily coverage is insufficient. Another problem with MODIS data is the relatively low spatial resolution (250 m), which gives rather low sensitivity to clear cutting, in particular in the case of selective logging.

The Synthetic Aperture Radar (SAR) sensor resolves the cloud cover problem that optical sensors have, but the imagery is not as easy to interpret. A low-frequency SAR (P- or L-band) is preferable due to its ability to penetrate the canopy, and to some extent, the trunks. These sensors are, however, not operational and offer less frequent revisits. C-band SAR would be an appropriate alternative since there are several operational sensors andthe spatial resolution is sufficient to detect clear-cutting and selective logging.

The current most promising approach seems to be a multi-sensor multi-temporal approach. Such multi-sensor approaches have been developed for other applications in Norway with great success. ‘All’ available optical and SAR data are then processed together to make the best assessment of the current situation. This is done on a daily basis as new satellite data arrive from global coverage moderate resolution satellites sensors.

Brazil is the leading nation of the tropical forest countries with its own operational monitoring program, both for surveying and counteraction. The Brazilian National Institute for Space Research (INPE) has developed a monitoring system through the PRODES (Brazilian Amazonian Forest Monitoring by Satellite) program. More recently, the DETER (Real Time Deforestation Detection System) program was launched to give faster response (twice a month). PRODES uses Landsat TM and Brazilian-Chinese CBERS data, while DETER uses MODIS data. INPE also has a contract with DMC International Imaging to acquire high-resolution satellite images of the entire Amazon rainforest. Images are provided by the five-satellite, international Disaster Monitoring Constellation (DMC). These micro-satellites use wide area cameras to capture high-resolution images.

Most of the other tropical forest countries have none or modest remote-sensing based activities on forest monitoring. In addition to those in Brazil, the most experienced research and development groups are located in the United States and in Europe. Several universities in the US have carried out quite comprehensive studies of approaches for tropical forest monitoring, especially the Carnegie Institution of Washington, South Dakota State University and University of Maryland. In Europe, the leading groups are SarVision (Wageningen) and the Joint Research Centre (Italy).

The problems related to monitoring rainforest deforestation and degradation are complex and need to be approached on a broad front. There is a need to work bilaterally with the countries that have tropical forests even though the problem might have to be approached differently in different countries. In Brazil, there is a need to extend the current approach with SAR data and apply a multi-sensor multi-temporal approach. In Congo, the requirements are much greater with the need to build up a monitoring capability almost from scratch.

Norwegian research institutes have experience with relevant methods for processing and interpretation of SAR and optical data. Prototypes based on previous experience in change detection could with relatively small resources be adapted to rainforest monitoring. For operational SAR monitoring of tropical rainforests, the processing framework as well as the necessary software are already established from other applications. Algorithms would have to be adapted to the special conditions observed in rainforests andreference datasets would need to be collected and statistically analysed.

We suggest in the first instancea project with Brazil (INPE), including Envisat ASAR data and the use of a multi-sensor multi-temporal data analysis approach. An existing prototype processing chain could with moderate resources be adapted to and tested on a limited area. Furthermore, a multi-scale analysis approach could be introduced, carrying out a synthesised analysis of data at Landsat/ERS scale with data at MODIS/ASAR scale.

The logical way forward to establish the application of satellite remote sensing in tropical de- and re-forestration monitoring, is to: 1) establish an international panel of leading experts to share experience in tropical forest monitoring with Norway; and 2) carry out a pilot project in Norway to obtain national experience with applying various existing algorithms; and 3) adapt existing monitoring tools to remote sensing of tropical forests.

Norway is a leading nation, also in a worldwide perspective, in development of remote sensing algorithms and earth observation applications. This is clearly demonstrated in the numerous national and international projects Norway participates in and contributes heavily to. However, for obvious reasons Norway has little experience in analysis of remote sensing data covering tropical forests. Following the three recommended actions above, Norway would quickly reach a position where Norwegian institutes can take a lead in building up tropical forest monitoring competence and systems in the tropical forest countries Norway chooses to make agreements with. Additionally, this will give Norway the necessary ability to make independent control measurements (spot testing), checking that the specific nationally reported results reflect the actual national situations. References

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