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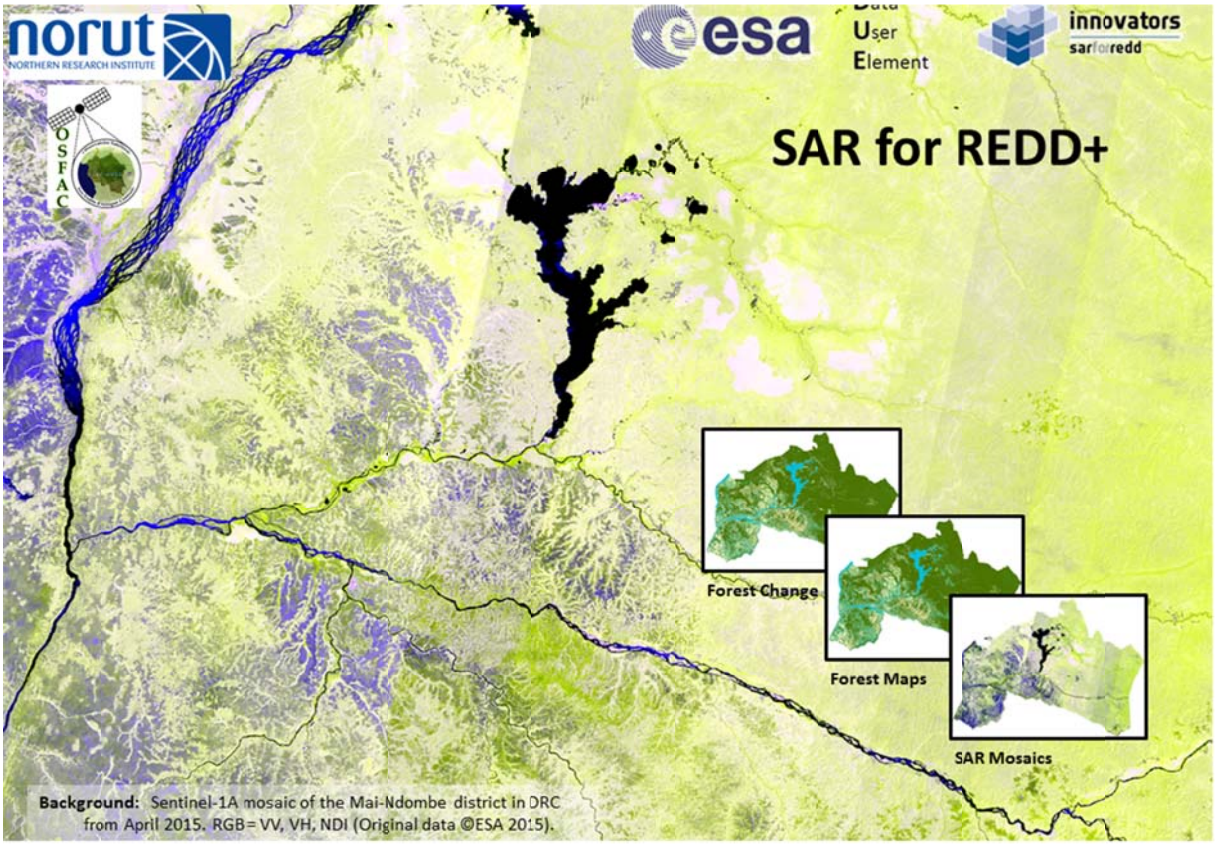
ESA DUE – Innovator III
SAR for REDD

D2.3 – Final Report (FR)



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Summary:

The objective of the ESA DUE Innovator III project "SAR for REDD" is to provide synthetic aperture radar (SAR) pre-processing and analysis capabilities and tools to users in tropical countries that are involved in REDD initiatives for operational tropical forest monitoring. In this project and in cooperation with our user, the Observatoire Satellital des Forêts d'Afrique Centrale (OSFAC), a Congolese NGO, we demonstrate usefulness of SAR on the Mai Ndombe district in the Democratic Republic of Congo in regard to producing mosaics, forest maps and forest change maps.
This final report summarizes the whole project, giving an overview and summary of the delivery reports, presenting the tools and methods, the resulting delivered products, their validation, and concluding with an assessment of the products and the service by both the contractor and the user, including a future outlook.

Keywords: SAR, REDD, Tropical Forest, land cover, forest change, ENVISAT ASAR, SENTINEL-1, ALOS PALSAR, ALOS-2 PALSAR-2

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1.1	18.01.2018	Final	Correction of typos and contract number (header)

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1 Executive Summary

1.1 Scope of this delivery

This the final report of the ESA DUE Innovator III project "SAR for REDD" (Figure 1) and summarizes the whole project, giving an overview and summary of the delivery reports, the delivered products, their validation, and concluding with an assessment of the products and the service by both the contractor and the user, including a future outlook.

1.2 Project Objective

The objective of "SAR for REDD" is to provide synthetic aperture radar pre-processing and analysis capabilities and tools to users in tropical countries and primarily in Africa that are involved in REDD initiatives for operational tropical forest monitoring and to demonstrate its usefulness on the Mai Ndombe district in the Democratic Republic of Congo in regard to producing mosaics, forest maps and forest change maps.

1.3 Project Executive Summary

The overall goal of "SAR for REDD" is to provide satellite synthetic aperture radar (SAR) pre-processing and analyzing capabilities and tools for operation tropical forest monitoring to REDD countries and primarily in Africa.

The UN initiative Reducing Emissions from Deforestation and Forest Degradation, including conservation, sustainable management of forests and enhancement of forest carbon stocks (REDD+), is an effort to create a financial value for the carbon stored in forests, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development. A necessity to implement REDD+ is the development of consistent and accurate monitoring, reporting and verification (MRV) systems based on both remote sensing and in-situ measurements.

As persistent cloud cover in the humid tropics prevent reliable observations at any time with optical satellite sensors, cloud-penetrating SAR imagery has proven to be a useful tool for interoperability and/or to complement optical satellite forest monitoring systems. For forest applications, L-band (1.27 GHz, ~23.6 cm wavelength) SAR is generally better suited than C-band (5.3 GHz, ~5.6 cm wavelength) since its signal penetrates deeper into the forest canopy and thus, also provides more information on biomass. However, with the launch of Sentinel-1A in 2014, ESA's C-band SAR has evolved from a research purpose to a fully operational satellite with higher coverage and revisit frequencies to establish denser time-series, increased radiometric accuracy and free data policy.

SAR pre-processing and analysis has not been at the reach for everybody and there is still a strong need for technical and human capacity in developing countries for this sensor type to be fully used. Since the 1990, Norut has developed automatic SAR pre-processing and analysis tools and set up operational SAR-based monitoring system for several environmental monitoring projects.

In this project, Norut will therefore not only provide already processed remote sensing products in the form of radiometric calibrated and geo-referenced SAR images and mosaics, forest/non-forest maps and forest change maps for specific periods, but also provide those necessary tools for mosaicking, temporal averaging and classification. The system will be able to process the main historical and current SAR sensors: ERS-1&2 SAR, ENVISAT ASAR, ALOS PALSAR (1&2), Radarsat-2 and Sentinel-1. This will give REDD countries the possibility to process and analyze historical and future SAR imagery and implement SAR into their operational forest monitoring systems to improve their monitoring, reporting and verification of REDD activities.

Interoperability and complementarity with optical remote sensing will also be investigated benefitting the SPOT5/TAKE5 program. The project also includes a validation field campaign where forest plots, ground and aerial photography will be collected, as well as a user workshop to insure the implementation of the SAR processing tools at the user's premises.

The pilot focus region is the Mai-Ndombe district in the Democratic Republic of Congo and the service user is the Observatoire Satellital des Forêts d'Afrique Centrale (OSFAC), a Congolese NGO. OSFAC has been a close collaborator and already a user in the EU FP7 project ReCover where Norut was the responsible service provider for DRC and responsible for the development of SAR based forest products. OSFAC's primary objective is to support the management of natural resources and promote sustainable development by producing reliable land cover products, distributing satellite data, building capacity and providing technical assistance to implementing partners. Among those partners are the environmental ministries of several Congo Basin countries which are responsible for the REDD implementation and development of tropical forest monitoring systems in these countries.

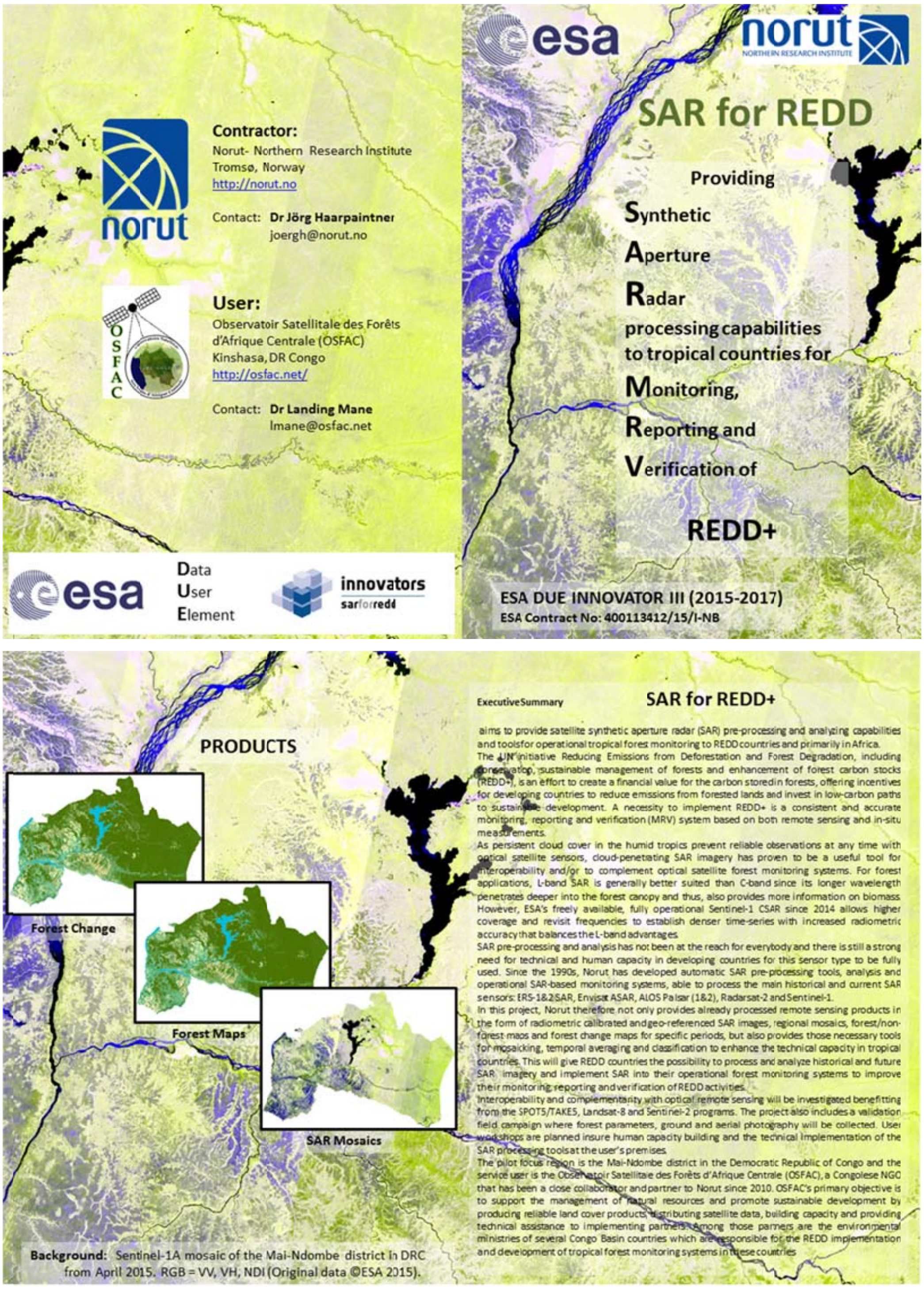

Figure 1. SAR for REDD leaflet

2 Introduction

2.1 Scientific background

Tropical forest represents the most important above ground carbon pool and plays a crucial role in biodiversity, hydrological and biochemical cycles and socio-economics for local communities. Deforestation and forest degradation is estimated to account for up to 17% of the global anthropogenic greenhouse gas emissions [Van der Werf et al., 2009]. This shows the necessity of including the forest sector in climate policies [Gullison et al., 2007]. The UN initiative Reducing Emissions from Deforestation and Forest Degradation, including conservation, sustainable management of forests and enhancement of forest carbon stocks (REDD+), is an effort to create a financial value for the carbon stored in forests, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development [Sukhdevb et al., 2012]. A necessity to implement REDD+, is the development of consistent and accurate monitoring, reporting and verification (MRV) systems based on both remote sensing and in-situ measurements [Herold & Skutsch, 2009]. The Group on Earth Observations Forest Carbon Tracking Task (GEO FCT) [http://www.geo-fct.org/] has been established to support countries to do so by coordinating CEOS satellite data acquisitions and establishing a scientific network to set up technical standards following IPCC guidelines. GEO-FCT has evolved into the Global Forest Observation Initiative (GFOI; http://gfoi.org/) which has reviewed and defined research and development (R&D) topics to improve MRV [GFOI, 2013]. As persistent cloud cover in the tropics prevents reliable observations at any time with optical satellite sensors the development of methods to use synthetic aperture radar (SAR) is one of the main R&D topics in this report, specifically the interoperability and complementarity of SAR with optical data, and the potential generation of products from SAR time-series. Both, C- and L-band SAR have proven to be a useful tool to monitor forests in humid tropics due to its ability to penetrate cloud cover [Hoekman et al., 2010; Almeida-Filho et al., 2009; Haarpaintner et al., 2009]. L-band (1.27 GHz, ~23.6 cm wavelength) SAR is generally much better suited than C-band (5.3 GHz, ~5.6 cm wavelength) since its signal penetrates deeper into the forest canopy and thus, also provides more information on biomass [Mitchard et al., 2009].With the launch of Sentinel-1 however, ESA's C-band SAR has evolved from a research satellite into a fully operational monitoring purpose set-up with a projected much higher satellite data availability to establish denser time-series, increased radiometric accuracy and free data policy. L-band from ALOS-2 PALSAR unfortunately is only available on a commercial basis or in limited amount through research proposals. According to GFOI Review of priority R&D topics [GFOI, 2013], optimizing information extraction from synthetic aperture radar, both L and C-band, is one of the high priority R&D issues for sensor interoperability and sensor complementarity. Specifically dense time series of C-band SAR from Sentinel-1 will be a primary source of RS data as Sentinel-1 data will be freely available.

Main objectives of AfriGEOSS is to increase awareness of Earth Observation and the EO capacities in African countries and reinforce GEO in Africa [GEO, 2013]. As the overall goal of this project is to provide synthetic aperture radar pre-processing and analysis capabilities and tools to users in tropical countries in Africa that are involved in REDD initiatives for operational tropical forest monitoring, it is perfectly in line with objectives of the GEO initiatives, GFOI R&D topics and AfriGEOSS.

2.1.1 User requirements

Implementing large operational data sets in a MRV tropical forest monitoring system needs automatic operational pre-processing capabilities that are still lacking in most tropical countries and in specifically in Africa. Several REDD countries have expressed their interest in getting such SAR pre-processing capabilities. A main basic issue for many EO users, including OSFAC, interested in SAR is the relatively complex pre-processing task to precisely geo-reference and radiometric calibrate the SAR data and to do this on an operational basis with large data sets with non-commercial software.

OSFAC has been a close collaborator and already a user in the EU FP7 project ReCover [Häme & Lönnqvist, 2011; Haarpaintner et al., 2012] where Norut was the responsible service provider for DRC and responsible for the development of SAR based forest products.

OSFAC has expressed their wish to participate as an end-user in this tender and has provided a User Requirement Document (URD) and a Letter of Commitment.
OSAFC request tools for pre-processing and analysis of SAR data specifically from Sentinel-1 and ALOS-2 in order to complement their optical satellite sensor monitoring activities. The user requirements are specified in Delivery "D1.1 - Requirement Baseline (RB)" [Haarpaintner & Mane, 2016]. In addition to pre-processing capabilities, the user also requests modules for automatic mosaicking and seasonal temporal averaging to reduce speckle and seasonal effects that would enhance the use of large data sets and dense time series in order to produce higher level satellite products for forest and forest change mapping. Requested demonstration products are yearly SAR mosaics, forest land cover product and forest change products for the Mai-Ndombe district in DRC.

2.1.2 Proof of concept

Norut is the leading institute in Norway on SAR application covering the whole processing chain from pre-processing to geophysical extraction and time-series analysis. Norut has its in-house developed generic SAR processing software and has already established such an automatic pre-processing system for earlier SAR satellites and has used such an operational automatic set-up for environmental monitoring primarily in Scandinavia. Norut's in-house developed software tool Generic SAR (GSAR) is an extensive suite of modules for SAR/InSAR processing that can be tailored to specific user needs.
A precision SAR geocoding module is the bases of GSAR. Additional modules of mosaicking and time-series processing for statistical analysis and physical feature extraction are also developed and a complete automatic processing chain to process mosaics over large areas and use dense time-series for establishing seasonal reference data sets has been established.
Norut has been already strongly involved in tropical forest monitoring through the EU FP7 project ReCover [Häme & Lönnqvist, 2011; Haarpaintner et al., 2012; Haarpaintner, 2013], a PhD grant from the Norwegian Research Council and through a Tanzanian-Norwegian bilateral cooperation project [Haarpaintner et al, 2012] developed as part of the GEO FCT efforts. Inside the "ReCover" project (2010-2013), Norut was the responsible service provider and coordinated a service team, including the University of Freiburg (Germany) and GMV (Spain), for the delivery of optical and SAR remotes sensing forest products (image mosaics, forest/non-forest (FNF), biomass and forest change maps) to OSFAC representing the case of DRC and IDEAM for Colombia. An example of delivered SAR product to OSFAC are presented in Figure 2.
Adapting Norut's operational SAR pre-processing system to these countries' requirements and providing it for implementation into their MRV systems with additional tools for mosaicking, time series analysis, and physical data extraction has therefore proven to be feasible and would be an important contribution for their REDD MRV activities.

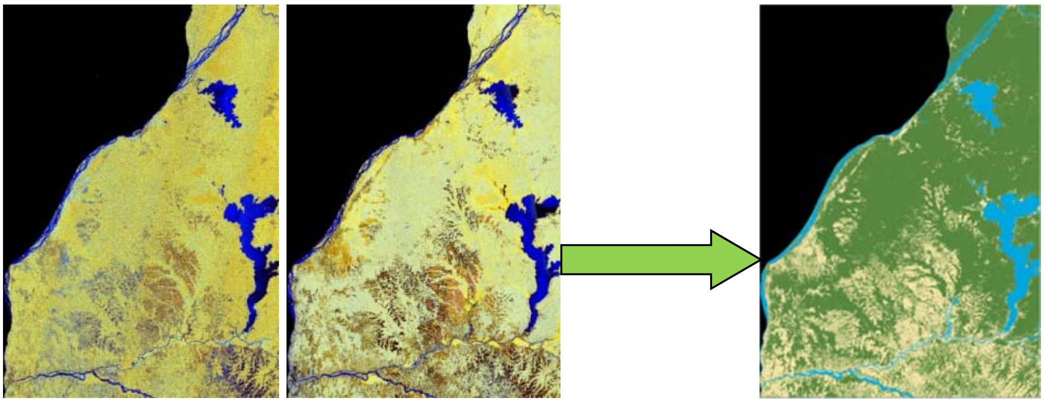

Figure 2. Example of the service delivery of the EU FP7 project ReCover: SAR image mosaics from the service area in DRC based on (a) ENVISAT ASAR AP (RGB = VV, VH, VV/VH) and (b) ALOS PALSAR FBD (RGB = HH, HV, HH/HV) and (c) the resulting forest/non-forest map for year 2010.

3 Project Team Composition

This project is managed by Norut (Northern Research Institute Tromsø AS, Tromsø, Norway), with the Observatoire Satellital des Forêts d'Afrique Centrale (OSFAC) as end-user. Both institutions are described in the following:

3.1 Norut - Northern Research Institute Tromsø, Norway,

Norut (Northern Research Institute Tromsø AS) is an independent, nonprofit, multidisciplinary research institute majority owned by the University of Tromsø, focusing on technology (earth observation, information and communication technology, biotechnology), social science research and innovation. Norut has about 130 employees, of which 20 scientists work in the Earth Observation group, and had an annual turnover of 132 million NOK (ca € 16.5 million) in 2013. Norut carries out research commissions for industry, business, and the public sector. Its mission is to be a tool for refinement and further development of innovative ideas coming from the University, from our own researchers and from our contract partners. As one of Norway's leading research institutes for both ICT and Earth Observation we have built a unique expertise in the cross-section between these two disciplines. The main focus of the Earth Observation group is on synthetic aperture radar processing and applications. Norut is a leading institute in developing prototype operational SAR monitoring systems for snow cover, flood, sea ice, ocean and geohazard monitoring. Our results have made Norut attractive as a partner in international EU and ESA projects.

In 2001, Norut was appointed as an ESA Expert Support Laboratory for the ENVISAT mission by the European Space Agency, and is currently a contracted partner in the Sentinel-1 Mission Performance Centre - Expert Support Laboratory programme.

Norut has participated in many large-scale application oriented projects. During the last decade, the institute has developed an extensive general purpose prototyping framework for SAR processing, called GSAR. Part of this framework is used within the official Sentinel-1 Level-2 ocean product processing chain. Norut has long experience in fundamental SAR signal processing algorithm development, including SAR processors, interferometry, precision geocoding, SAR data simulation, as well as many value added product prototypes, including InSAR based deformation time series analysis. A precision geocoding module is deployed at Kongsberg Satellite Services for operational delivery of calibrated, map projected RADARSAT-2 data An SBAS based deformation analysis system, with an intuitive easy-to use GUI and support for multicore processing nodes, has been in semi-operational use at Geological Survey of Norway since 2007.

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3.2 Observatoire Satellital des Forêts d'Afrique Centrale (OSFAC)

OSFAC was launched as the GOFC-GOLD network for Central Africa under the Global Terrestrial Observing System (GTOS) and was legally established as a Congolese NGO in 2005 dedicated to raising awareness about satellite data and their potential applications. Its primary objective is to support the management of natural resources and promote sustainable development by producing reliable land cover products, distributing satellite data, building capacity and providing technical assistance to implementing partners.

OSFAC operates out of a head office in Kinshasa and maintains a GIS/RS lab within the School of Agronomy at the University of Kinshasa. It serves as Central Africa's only satellite data clearing house and works in close partnership with academic and research institutions in the region, as well as, international academic and research institutions such as: the University of Maryland, South Dakota State University, the Université Catholique de Louvain and the Joint Research Center. It is committed to building regional capacity in GIS and remote sensing and offers a series of technical trainings through its lab at the University of Kinshasa and ex situ at sites across the Basin. To date OSFAC has trained over 500 individuals from over 30 different agencies in Central Africa.

OSFAC's forest monitoring activities contribute to the objectives of the Congo Basin Forest Partnership and multiple strategic areas within COMIFAC's Convergence Plan. It receives support through USAID as part of the Central African Regional Program for the Environment (CARPE) and is also an active collaborator of the FORAF/OFAC project to establish a regional observatory that will supply decision-makers and managers reliable information on environmental and socio-economic indicators and produce regular State of the Forest reports. Through its activities, OSFAC has collaborated with many national government agencies as well as non-governmental organizations and projects, including: FORAF, WRI, ERAIFT, UN/OCHA, IUCN, WWF, WCS, CI, AWF, UNICEF, UNESCO, MAFA, and Nature+.

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4 Project Organization

4.1 Work Breakdown Structure (WBS)

The overall project schedule follows two consecutive one-year phases:
Phase 1 (WP1, WP2): Requirement, engineering, technical specifications and product development,
Phase 2 (WP3, WP4): Product validation, pilot service demonstration and roll-out analysis.

The project is composed of five work packages (WP), two for each phase 1 and 2, and one overall management work package. The work packages are:
WP1 User Requirements
WP2 Technical Development
WP3 Service and Product delivery
WP4 Validation and Assessment
WP5 Project Management and Dissemination

Figure 3 shows the organization of the work packages. During phase 1, WP1 defines the service and products that are requested by the user in more detail and WP2 proposes a technical solution to deliver the requested service and products. The service and products are produced and delivered in WP3 and validated and assessed in WP4 by both the service provider and the user. In order to validate the products, a field campaign with participation of both the contractor and the user was organized.
A work flow chart below shows the logic of the study plan:

- WP1 user requirements define WP2 technical development.
- The WP2 technical development will specify the service and the products to be delivered as well as the validation procedures (WP3 and WP4)
- WP2 user requirements need to be satisfied by the user's validation of the products and the user's assessment of the service (WP4),
- WP5 oversees the whole project.

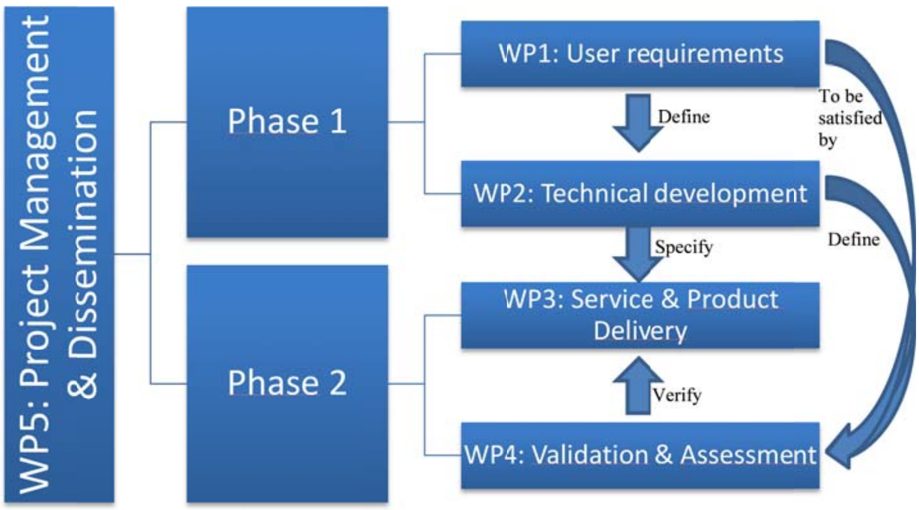


Figure 3. SAR for REDD work package organization

4.2 Data Procurement

The project mainly makes use of freely available ESA data from Sentinel-1 and for historical comparison also from ENVISAT ASAR.
A data acquisition plan has been established by GFOI over the REDD countries and the Congo Basin has been fully covered by Sentinel-1 data. In addition to the freely available ESA Sentinel-1 data. Norut is also PI for an ALOS-2 RA4 project and has acquired yearly coverages of the region with dual polarized L-band ALOS-2 PALSAR-2 data for comparison.
The project also uses freely available optical sets for validation from Landsat-8, readily analyzed forest products from Global Forest Watch (globalforestwatch.org) and on-line libraries of Google Earth and others. The project also profits from Spot5 data through the Spot5/Take5 program.

5 Area of interest and service demonstration area

The area of interest in general is the tropical forest area with persistent cloud cover and for the current user specifically the Congo Basin (Figure 4). The end-products however are demonstrated only on a limited demonstration area, which is the Mai-Ndombe District in Bandundu Province in DRC (Figure 5). However, the tools that are provided are able to process any data set over the user's area of interest and countries of involvement, which for OSFAC are DRC, Republic of Congo, Angola, Equatorial Guinea, the Central African Republic, Cameroun and Gabon. Forest and forest change mapping methods are tuned for the specified demonstration area. Geographical details of the size of the area of interest and demonstration area and a description are given in
Table 1.

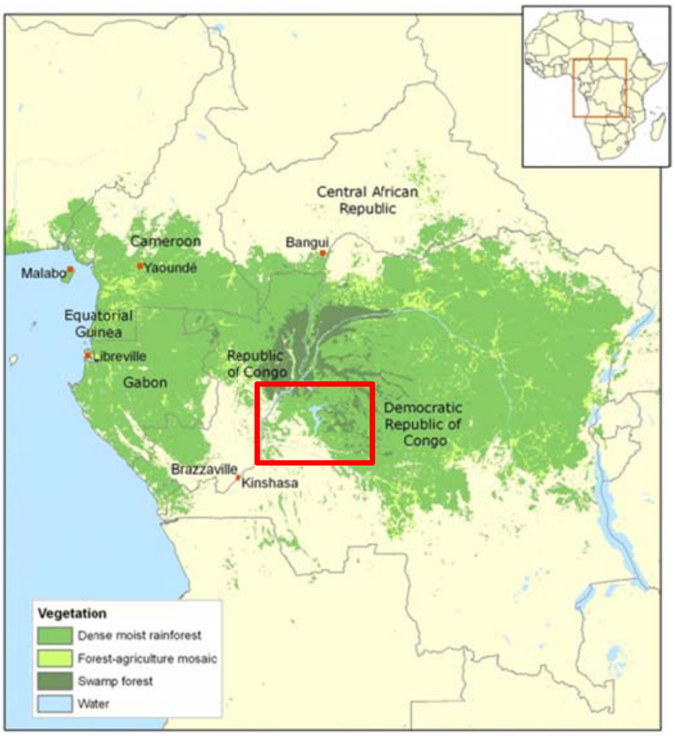


Figure 4. Tropical forest in the Congo Basin (from http://forestindustries.eu/)

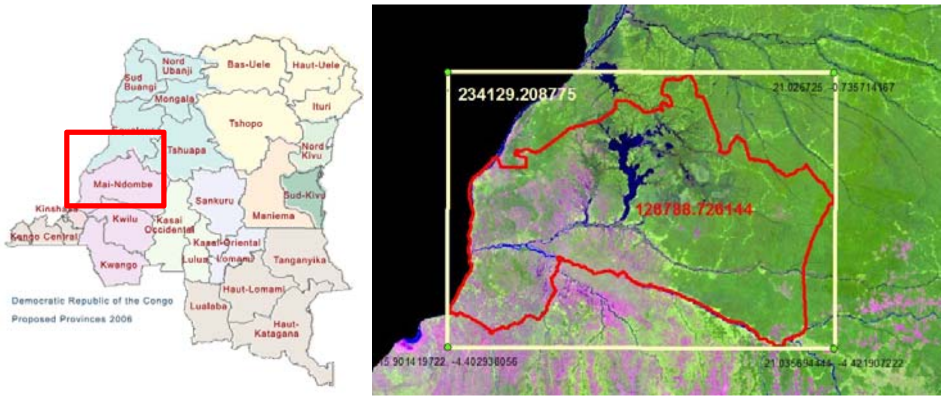


Figure 5. Demonstration area in DRC, the Mai-Ndombe District in Bandundu province. Landsat mosaic from GFC (Hansen et al. 2013) as background.

Table 1. Area of interest and demonstration area specifics

Area of Interest	
Name:	Congo Basin
Type:	Wet tropics, river basin and coastal area with tropical forest with persistent cloud cover
Geographical coordinates and size of area of interest:	**Congo Basin**: DRC, Republic of Congo, Angola, Equatorial Guinea, the Central African Republic, Cameroun and Gabon. Size: about 3.7 million km^2
Geographical coordinates and size of service demonstration area:	**Mai-Ndombe District**: Center geographical coordinates: Lon: 18°31'26.144"E Let: 2°42'0.999"S Red boundary area enclosed in UL: Lon: 15°54'3.004"E Let: 0°43'27.616"S UR: Lon: 21°1'36.21"E Let: 0°44'8.571"S LL: Lon: 15°54'5.111"E Let: 4°24'10.577"S LR: Lon: 21°2'8.5"E Let: 4°25'18.866"S Size: 128789 km^2 (12878873 ha)
Description:	Mai-Ndombe, the area of study is located in the Bandundu Province in the Democratic Republic of Congo (DRC). The area of Mai-Ndombe is very rich in biodiversity and endemic species (Bonobo). However, for many years this area is facing deforestation and forest degradation. The main causes of this loss of forests are charcoal production for cities, slash and burn agriculture and industrial logging. For sustainable forest management of Mai Ndombe and reduce emissions of greenhouse gases (GHGs) from deforestation and forest degradation, it is important to have reliable information on the extent and trends of these forests. This information is necessary in the implementation of the MRV/REDD + process in which DRC is engaged.
Problems/Issues:	Persistent cloud cover in the tropics often prevent optical remote sensing and synthetic aperture radar can overcome this problem

6 Processing Tools and Method Development

6.1 Processing System GSAR - Background

Since the 1990s, Norut has developed its in-house Generic SAR processing system, called GSAR (Larsen et al., 2005). GSAR is an extensive suite of modules for SAR processing. In a scientific setting, where data from a multitude of SAR instruments must be handled, the need for flexible processing software is imminent. Since most of the actual data processing is the same regardless of the SAR sensor, there is great potential for designing generic processing lines. The high flexibility and modularity of GSAR provides a flexible environment for rapid prototyping and an algorithm portfolio for testing of new ideas. GSAR is based on IDL (Interactive Data Language) and runs under the ENVI/IDL environment. GSAR has been developed to be applied in both, research and operational environments for automatic near-real time processing. Such automatic operation systems have been deployed for example at Kongsberg Satellite Service for specific monitoring purposes.

In this project, Norut provides the user with a compiled easy-to-use version of the necessary components in specific modules of GSAR that will allow the users to preprocess, i.e. precisely geocode, current and historical SAR data from the main used SAR satellites into georeferenced and radiometric calibrated SAR backscatter images, as well as provide tools for efficient further data stack analyses like mosaicking, statistical parameter extraction in order to be able to classify the SAR data into higher level products and detect changes.

The software package is divided in three individual modules: GEOCODING, MOSAICKING, and STATISTICS. All outputs are image files for ENVI software or alternatively as geotif. Once these products are produced, they can be further processed into classification products or change products. As these further processing needs individual consideration on case-by-case, further processing is better done in the user's favorite image processing software, ENVI/IDL, ERDAS imagine etc. Simple classification algorithm can also be provided with the GSAR software as well as change detection modules if necessary but make little sense without the necessary visualization software.

As an initial classification output a forest mask is calculated from the outputs of the MOSAICKING and STATISTICS modules.

Below we describe therefore the software delivery of the modules GEOCODING, MOSAICKING, STATISTICS.

All modules come as compiled *sav packages with a READ-ME file and a configuration file that can be edited for parametrization. All modules can be run under the license-free run-time (RT), or virtual machine (VM) version of IDL that can be downloaded for free when registered at http://www.exelisvis.com/IntelliEarthSolutions/GeospatialProducts/IDL.aspx .

6.2 GEOCODING: Pre-processing Tool

6.2.1 Supported SAR satellite sensors (Input data)

The GSAR geocoding module has readers for and supports the main satellite sensor and modes that are listed in Table 2. The main processing level to be used is level 1 or single look complex (SLC) data for best geocoding results.

Table 2: Supported SAR satellite sensors for precise geocoding

Satellite	SAR sensor	Operation Period	Acquisition Mode	Processing level
ERS-1	SAR (C-band)	1991-2000	IMS Image mode	Level 1: SLC (CEOS and ENVISAT format)
ERS-2	SAR (C-band)	1995-2011	IMS Image mode	Level 1: SLC (CEOS and ENVISAT format)
ENVISAT	ASAR (C-band)	2002-2012	IMS: image mode APS: alternating polarization WSM: wide swath mode	SLC SLC Medium resolution.
RADARSAT-2	SAR (C-band)	2007 - present	All modes except spotlight and restricted modes	SLC
ALOS	PALSAR (L-band)	2006-2011	FBD (Fine Beam Dual) FBS (Fine Beam Single)	Level 1.1 (SLC) Level 1.1 (SLC)
ALOS-2	PALSAR-2 (L-band)	2014 - present	FBD (Fine Beam Dual) FBS (Fine Beam Single)	Level 1.1 (SLC) Level 1.1 (SLC)
SENTINEL-1	CSAR (C-band)	2014 - present	All modes	Level L0, L1, L2

6.2.2 Auxiliary data

In addition to the level 1 SAR satellite data, precise geocoding needs addition auxiliary data. To calculate the correct pixel position, it is necessary to know the correct satellite position, i.e. the precise orbit parameters at the time of acquisition as well as the topography of the observed region. Precise orbit parameters for newer satellite are included in the SAR data. For ERS-1&2 as well as for ENVISAT ASAR data, this data is available from ESA as a data set and are provided with the GSAR software. Topography is described using digital surface models (DSM). The main available DSM used is the DSM provided by NASA's Shuttle Radar Topography Mission (SRTM). This DSM data is freely available at http://www2.jpl.nasa.gov/srtm/ . If the user has a more precise DSM of the region of interest (ROI), the software allows changing this input parameter. At the current version of GSAR, this DSM should be in envi-format and in lat-lon projection.

6.2.3 Running the GEOCODING module.

The precise geocoding module contains:

- A ***README.txt*** file that explains how to run the software
- the compiled IDL software binary file for geocoding "***gsar_geocoding.sav***",
- IDL savefile with necessary auxiliary data: ***gsar_geocoding_data.sav***
- Three folder with auxiliary files and precision orbits for ASAR for some sensors:
    - ***asar_aux*** for ENVISAT ASAR
    - ***s1_aux*** for Sentinel-1
    - ***PrecisionOrbits*** for precision orbits for ASAR
- And an example configuration file ***config_gsar_geocoding.txt.example,*** that specifies the necessary parameters to process the SAR data:
    - Sensor-type: ERS-1/2, ASAR, ALOS, ALOS-2, RS2, S1A, S1B
    - Path of input data
    - Path of output data
    - Path and file of the digital elevation model to be used
    - The output pixel size
    - The map-projection of the processed data
    - The path for log directory
    - The geographical coordinates of the area to be processed
    - Optional remove of pixels at near and far range, and
    - The out-put format of the processed data, in either ENVI image format or as geotif.

6.2.4 Software call sequence

The call sequence to run the geocoding process is:
idl -rt=/path/to/gsar_dir/gsar_geocoding.sav [-args [-config configfile]]

6.2.5 Pre-processing Output

The main output data of the geocoding module are the sigma backscatter images in dB for each polarization of the provided input SAR data. Polarization is defined by the two letters H and V, i.e. HH, HV, VH, VV, where the first letter is the emitted and the second letter the received polarization. H stands for horizontal polarization and V for vertical polarization. Dual polarization means in general an emitted SAR signal in either horizontal (or vertical polarization) and the reception in both horizontal and vertical polarization, (HH, HV) or (VV, VH). HH and VV are called co-polarization. HV and VH are cross-polarization. Single polarized images are emitted and receive in the same polarization, i.e. HH or VV.
The reflection or backscatter of the SAR signal is dependent on the local projection angle, which is dependent on the topography as well as the distance in range direction from the satellite. GSAR therefore also provides a so-called slope corrected backscatter image for each polarization following the slope correction by Ulander (1996).
Additional output data from the geocoding process are the ellipsoidal incidence angle image and a mask image for areas of SAR layover, shadow and no data areas. In addition, a projection angle image, which is used in the slope correction, is created.
Table 3 summarizes the output products from the geocoding process and its units. All output images are in the same map projection, image size and resolution that the user can define in the configuration file. Figure 6 shows an example of the pre-processing output from a Sentinel-1A scene.

Table 3: Output image from geocoding process

Output image	Number of images	Unit
Backscatter sigma naught: $\sigma_0(HH)$, $\sigma_0(HV)$, $\sigma_0(VV)$, $\sigma_0(VH)$	1 for each available polarization: HH, HV, VV, VH	dB (16 BITS)
Slope corrected backscatter image: $\sigma_0(HH_{sc})$, $\sigma_0(HV_{sc})$, $\sigma_0(VV_{sc})$, $\sigma_0(VH_{sc})$	1 for each available polarization: HH, HV, VV, VH	dB (16 BITS)
Local radar projection angle	1 image	Degrees (16 BITS)
Ellipsoidal incidence angle:	1 image	Degrees (16 BITS)
Mask for SAR layover, shadow and no data areas	1 image	8 BIT (layover =200, shadow = 128, no_data = 32)

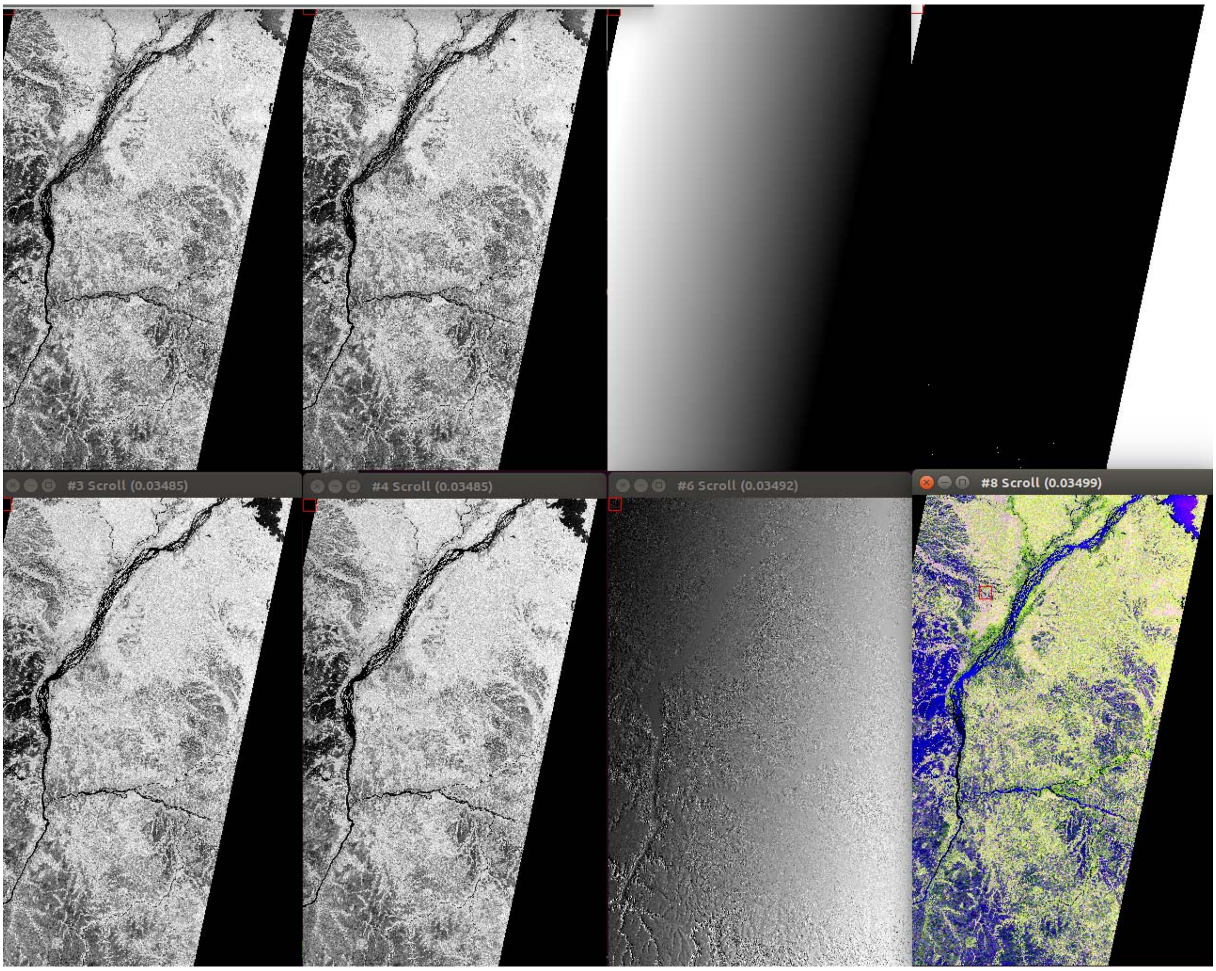


Figure 6. Example of pre-processing output for a Sentinel-1A path nr. 109 from 16 July 2015. (a) σ_0(VV), (b) σ_0(VV_{sc}), (c) σ_0(VH), (d) σ_0(VH_{sc}) , (e) ellipsoidal incidence angle, (f) mask image, (g), projection incidence angle, and (h) [RGB] = [σ_0(VV_{sc}), σ_0(VH_{sc}), NDI]

Figure 6h is not part of the pre-processing output, but an RGB composite with co-polarization backscatter, cross-polarization backscatter and NDI as the red, green and blue channel, respectively. This is a much used way to present dual-polarization images. NDI is the normalized difference index defined by NDI = (VV-VH)/(VV+VH). Forest areas appear light green-yellowish, non-forested areas in dark purple and water areas in blue/purple.
The default set up by Norut for pre-processed georeferenced, radiometrically corrected SAR backscatter images is a pixel resolution of 30m and automatically selected UTM projection. The UTM zone used for the demonstration site, the Mai-Ndombe district, is UTM zone 34S.

6.2.6 File naming:

The file naming for the pre-processed SAR data is as follows:
SSS_MMM_yyyymmdd_hhmmss_DES/ASC_ttt_type_,
Here,

SSS = SAR sensor	**MMM = acquisition mode**
ASAR: ENVISAT ASAR	APS, IMS, WSM
ERS-1: ERS-1 SAR	IMS
ERS-2: ERS-2 SAR	IMS
ALOS: ALOS PALSAR	FBD/FBS
ALOS-2: ALOS-2 PALSAR-2	FBD/FBS
S1A: SENTINEL-1 CSAR	IWH, EWH
RS2: RADARSAT-2 CSAR	SLC

yyyymmdd = date
hhmmss = time
DES/ASC = descending or ascending orbit
ttt = track number of scene

and

type = einc – ellipsoidal incidence angle
mask – shadow and layover mask
pang – projection angle
VH_sigma – VH backscatter (similar for HH, VV, HV)
VH_sigma_sc – slope corrected VH backscatter
VH_gamma – VH gamma backscatter.

For instance, a resulting VV backscatter image from Sentinel-1 will be called
S1A_IWH_ 20160303_075656 _DES_007_VV_sigma
All output files from one SAR scenes are collected into a folder named ***SSS_MMM_yyyymmdd_hhmmss_DES/ASC_ttt.***

6.3 Higher level GSAR processing

As stated in Delivery 1.1 Requirement Baseline, the project will also deliver software tools to produce higher-level satellite SAR products. In addition to the pre-processed, georeferenced and radiometrically corrected individual SAR data presented in section 6.2, SAR for REDD provides higher-level example products on the demonstration site, the Mai Ndombe district in DRC. All products will be based on synthetic aperture radar (SAR) imagery and the demonstration is based on C-band ENVISAT ASAR, Sentinel-1A and L-band ALOS PALSAR and ALOS-2 PALSAR-2 data. The provided software tools provide mosaicking and statistical analysis of time series that can then easily be used for classification and change detection.
So the provide software includes two additional modules: SAR mosaicking and SAR Statistical Analysis.

6.4 MOSAICKING - SAR data mosaics (MOS)

The MOSAIC module automatically makes a mosaic of the available data over a certain area. This module does not perform any statistical analysis but combines the data into one mosaic. This is especially the case if only one observation per pixel exists. If a time series or dense data set exists over a certain area, running the statistical analysis over the whole data might be more beneficial for further processing.
Here, SAR mosaics are defined as single acquisitions per pixel. This means that a data stack of individual SAR scenes is used to cover a certain area of interest by choosing only one measurement of the multiple acquisitions from the data stack per pixel. The input data would generally be the output data of the GEOCODING module. This GEOCODING output includes also the necessary auxiliary data like the mask image from the pre-processing, which defines the no-data areas for each individual pre-processed image as well as the ellipsoidal incidence angle image.
The user has to define an area of interest ("map_area") over which he/she wants to mosaic the data

The MOSAICKING module contains three files:

- A ***README.txt*** file that explains how to run the module
- the compiled IDL software binary file for geocoding "***gsar_mosaics.sav***",
- and an example configuration files **config_gsar_mosaics.txt.example.**

After making the mosaics for each polarization the module combines the dual-polarization channels into one RGB image where RGB = [copol., crosspol., NDI] , i.e. [HH,HV,NDI] or [VV, VH, NDI], with NDI = (HH-HV)/(HH+HV) or NDI = (VV-VH)/(VV+VH), respectively.
The module also classifies the final product into a forest/non-forest map that can be used as a first forest map approach. This forest/non-forest classification is based on a k-means classifier with average backscatter values given for the classes: forest, inundated forest, savannah, dry grassland and wet grassland, which are then aggregated into forest (forest, inundated forest) and non-forest (savannah, dry grassland and wet grassland). The average backscatter values for the sensors ALOS PALSAR, ALOS-2 PALSAR-2 and SENTINEL-1 are given in the configuration file and can be edited by the user. ALOS-2 PALSAR-2 values are the values without the -26 dB correction from the level1.1 data, so they are about 26 dB higher than ALOS PALSAR values.

6.4.1 Options

The user has several options which measurement he wants to choose in the overlay areas of the data stack. The possible options defined in the parameter called "*overlap_method*" are

- "*first*", which uses the first image (or lowest channel number if multi-channel image) in the image stack that covers the pixel. The naming convention of the pre-processing output is therefore important so that the first image corresponds to the first image in time. If dates are given, the images are sorted by earliest to latest instead of by channel number.
- "*last*", which uses the last image (or highest channel number if multi-channel image) in the image stack that covers the pixel. If dates are given, the images are sorted by latest to earliest instead of by channel number.
- "*date*", which for each pixel, use the image whose acquisition date is closest in time to "*master_date*" and that covers the pixel. Requires a vector "dates" with the Julian day for all images in the data stack and a defined "*master_date*" (also in Julian day).
- "*nearest*", which this method requires an auxiliary image stack, e.g., the ellipsoidal incidence angle images for all images in the data stack, defined as "*sortobj*" as well as a value ("*sortval*") or value range ("*sortrange*") to be specified. Which image to use for each pixel is determined as described in the following. If *sortval* is set, e.g., sortval=30 degrees for the ellipsoidal incidence angle, use the backscatter image whose corresponding ellipsoidal incidence angle (*sortobj*) is closest to *sorval* out of all the images that cover the pixel under consideration. If *sortrange* is set, use the first image whose corresponding value in *sortobj* is inside the interval specified by *sortrange*.

In addition the user can choose additional options to improve the data:

- *threshold*: pixel with lower backscatter than this threshold will be ignored.
- *filter_length*: to erode the individual scenes prior to mosaicking by the number of defined pixels. This option can be used to eliminate boarder effects of SAR images in near or far range.
- *Output_file_name* of the mosaic

6.4.2 Software call sequence

The call sequence to run the mosaicking module is:
idl -rt=/path/to/gsar_dir/gsar_mosaics.sav [-args [-config configfile]]

6.4.3 Output

The output of the mosaic procedure are 2-band images for each polarization where band 1 is the mosaic image over the area of interest of the σ_0 backscatter and band 2 indicates which pixel corresponds to which individual input file considering the method chose for the overlap areas. The order of input files are listed in the header file. The input and output files have to be in the same map projection. A prior choice of the individual scenes is advised to eliminate possible ambiguities. As an addition output, the software provides a 3-band image with RGB=[$\sigma_{0(copol)}$; $\sigma_{0(crosspol)}$; NDI] and a calculated forest mask. The forest mask is based on a k-means classier with provided mean σ_0 backscatter signatures for the classes “forest”, “inundated forest”, “savannah”, “dry grassland” and “wet grassland”, which are then aggregated into a forest (“forest”, “inundated forest”) / non-forest (savannah”, “dry grassland” and “wet grassland”) product.
The demonstration products produced by Norut are mosaics over the demonstration area Mai Ndombe district at UTM zone 34S projection in 30m resolution. The single measurements are the closest to a date inside the dry period and the overlay option will be “*nearest*” to the central ellipsoidal incidence angle of the specific SAR mode. All delivered products are in IDL/ENVI or geotif format.

6.5 STATISTICS: Averaged mosaics and statistical data stack analysis

The average and statistical data stack or time series analysis STATISTICS module is a GSAR tool to extract statistical parameters for each pixel in a define "*map_area*" from a SAR data stack. The output parameters extracted are:

- the averaged value of each pixel
- the variance in each pixel
- the number of values used to create the average/variance in each pixel
- the minimum value across the stack for each pixel
- the maximum value across the stack for each pixel
- a mask image indicating pixels that are in SAR layover or shadow for at least one image in the stack

One of the main purposes of this method is to temporally filter the data stack by averaging it to produce a "smoother" average backscatter mosaic. Averaging also eliminates humidity or other backscattering effect due to seasonality on the ground. The min, max and variance of especially non-forest areas give a good indication of the backscatter variability, which can help to divide between forest and non-forest areas.
A large time series can efficiently eliminate the speckle effect and will allow for generally better classification results thereafter.
After making the statistical analysis for each polarization the module combines the mean backscatter values into one RGB image where RGB = [copol., crosspol., NDI] , i.e. [HH,HV,NDI] or [VV, VH, NDI], with NDI = (HH-HV)/(HH+HV) or NDI = (VV-VH)/(VV+VH), respectively.
The module also classifies the final RGB product into a forest/non-forest map that can be used as a first forest map approach. This forest/non-forest classification is based on a k-means classifier with average backscatter values given for the classes forest, inundated forest, savannah, dry grassland and wet grassland, which are then aggregated into forest (forest, inundated forest) and non-forest (savannah, dry grassland and wet grassland). The average backscatter values for the sensors ALOS PALSAR, ALOS-2 PALSAR-2 and SENTINEL-1 are given in the config file and can be edited by the user. ALOS-2 PALSAR-2 values are the values without the -26 dB correction from the level1.1 data, so they are about 26 dB higher than ALOS PALSAR values.

The *inpath* would generally be the *outpath* of the GEOCODING module.
The module contains three files:

- A ***README.txt*** file that explains how to run the module
- the compiled IDL software binary file for geocoding **gsar_statistics.sav**,
- and an example configuration files **config_gsar_statistics.txt.example.**

6.5.1 Software call sequence

The call sequence to run the statistical analysis module is:
idl -rt=/path/to/gsar_dir/gsar_statistics.sav [-args [-config configfile]]

6.5.2 Input

The input is a data stack of SAR scenes with the same map projection, but not necessarily the same area coverage, in a defined input folder. For example the output folder from the individual per-processed SAR data can be used directly. This folder includes also the necessary auxiliary mask files, which define the no-data areas for each individual pre-processed image.
The user has to define an area of interest ("map_area") over which he wants to statistical analyze the data stack or time series.

map_area=[east_min,east_max,north_min,north_max] in UTM or
map_area=[lon_min,lon_max,lat_min,lat_max] in lat/lon .

6.5.3 Options

The user has only a few options to consider.

- "threshold" and "upper_threshold" ignores pixel values below "threshold" and values above "upper_threshold" when calculating the statistics.
- "filter_length", which will erode the individual scenes prior to averaging by the number of defined pixels. This option can be used to eliminate boarder effect of SAR images in near or far range.

6.5.4 Output

The output of the statistical analysis procedure is a file with six images (a 6 channel image) where the channels represent the following values per pixel in the defined map_area.
Channel 0 contains the averaged value of each pixel; channel 1 contains the variance in each pixel. Channel 2 has the number of values used to create the average/variance in each pixel. Channel 3 and 4 have the minimum and maximum value, respectively, in the image stack for each pixel. Finally, in channel 5 all pixels that have been masked out in at least one image of the stack are flagged.

The average backscatter mosaics provided through this tool are not single time mosaics, but integrated over longer time series. However, if little land cover changes occur, these averaged smoother mosaics are generally better suite for forest land cover classification.
As an addition output, the module also provides a 3-band image using the mean backscatter values with RGB=[$\sigma_{0(copol)}$; $\sigma_{0(crosspol)}$; NDI] and a calculated forest mask. The forest mask is based on a k-means classier with provided mean σ_0 backscatter signatures for the classes "forest", "inundated forest", "savannah", "dry grassland" and "wet grassland", which are then aggregated into a forest ("forest", "inundated forest") / non-forest (savannah", "dry grassland" and "wet grassland") product.

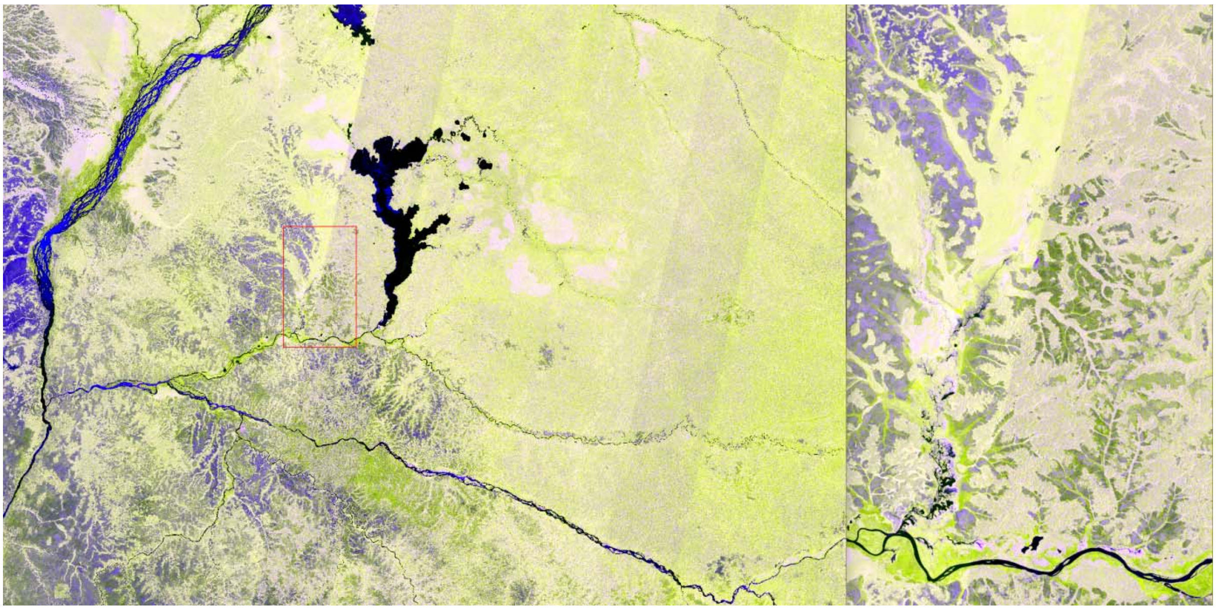


Figure 7. Sentinel-1A averaged mosaic over Mai-Ndombe district for the year 2015. [RGB] = [σ_0(VV_{sc}), σ_0(VH_{sc}), NDI]. Right panel shows the zoom of the red rectangle.

6.6 Forest/Land cover classification (FLC)

The GSAR software also includes classification components. A k-means (KM) classification is included in the MOSAIC and STATISTICAL ANALYSIS modules that are provided to the user in order to provide a first attempt of forest/non-forest map based on pre-set mean SAR signatures for the different sensors. The user is however advised to proceed with a more individual classification method using their in-house processing software and knowledge. The MOSAIC or STATISTICAL ANALYSIS outputs are supposed to serve as a basis, i.e. features in those classifications.
The method used for the demonstration products is a supervised Maximum Likelihood Classification (MLC) inside ENVI using seasonal (dry and wet season), yearly or multi-yearly means of the dual polarizations as features. Other statistical features (backscatter variance, minimum or maximum backscatter) have specifically been used for single polarized data sets like ENVISAT ASAR wide-swath.

The classification results are highly dependent on the original image quality and the separability of the classes inside this image. Because of speckle effects and the strong dependency of the SAR backscatter on ground humidity, automatic classification of individual SAR images can be tricky and ambiguous. However, speckle filtering or temporal filtering over longer time period depending on the satellite coverage will in general improve the classification results (Haarpaintner et al., 2015). The forest land cover classification results produced on the demonstration site therefore follow this approach by integrating over a time period of at least one year. As satellite acquisitions have not been uniform in the past, the classification is highly dependent on the satellite coverage, and mosaics to be classified have to be wisely chosen in regard to the satellite cover.

6.6.1 Input

Input data for the forest land cover classification are in general averaged, temporarily filtered, speckle reduced mosaics of the available polarizations. If more than one satellite sensor is available for the considered time period, a multivariate multi-sensor classification can also be run by using the different satellite sensors and polarizations. For long or dense time series the statistical parameters extracted can also be used as classification features.

6.6.2 Output

The delivered forest land cover products follow the pixel coding established under the EU FP7 project “ReCover”. The 8bit pixel coding is specified in Annex2.

6.7 Forest Change Detection (FCD)

Forest change detection is mainly based on thresholding a backscatter decrease for forest loss or backscatter increase for forest gain/revegetation over a certain time period. A decrease of -3 dB in backscatter has proven to be a balanced choice between significant changes and false change detection. No automatic module is provided for the change detection as this is highly dependent on the data quality and the users' purpose of change detection and method of quality insurance. For yearly change detection a -3dB decrease between yearly averaged cross-polarized backscatter mosaics would be the original choice masked with the maximum forest extension between those dates extracted from the forest/non-forest mapping

6.7.1 Input

Input data for the forest change detection are two backscatter images/mosaics for either two defined times or integrating time period. Seasonal effect should be eliminated as much as possible.
For yearly forest changes, the input data can be yearly or monthly averaged mosaics that can be subtracted from each other. The average period will depend on the time density of the data acquisition.
Input can for example be the averaged mosaics. If available cross-polarized backscatter images are better suited as the detected volume scatter in the cross-polarized image is better correlated with vegetation as the co-polarized backscatter images.

6.7.2 Output

The output data will be a mask image masking the areas that are higher or lower the change detection threshold.

The delivered forest land cover change products will follow the pixel coding established under the EU FP7 project "ReCover". The 8bit pixel coding is specified in Table 14.

6.8 Product File Naming

The following file naming is finally applied on the remote sensing products that have been delivered:
Country_ROI_ProductType _Date_MapProjection_Resolution_format_optionalInfo_format

- Country: DRC
- ROI or project: “S4R” stands for SAR for REDD)
- Product Type:
  - MOS → Mosaic
  - STAT → Statistical analysis output
  - FLC → Forest/land cover classification
  - FNF → Forest/Non-Forest classification
  - FCD → Forest change detection
- Sensor:
  - ERS-1 → ERS-1 SAR
  - ERS-2 → ERS-2 SAR
  - ASA → ENVISAT ASAR (ASAWS or ASA-IS4 for APS)
  - PAL → ALOS PALSAR
  - PAL2 → ALOS-2 PALSAR-2
  - S1A → Sentinel-1A CSAR
  - RS2 → Radarsat-2 SAR
- Date: yyyy, yyyymm or yyyy-yyyy if time period
- Map projection: default: UTM34S
- Resolution: Default 30m
- optionalInfo: can include information on the previous processing steps or bands that have been used, version number, processing date, number of single images used to make mosaics)
- Format: All products in standard or classified envi-format. 300m resolution quicklooks in envi and as *png for visualization

Each parameter can include addition information, like f.e. sensor mode used (FBD, IS4, etc.) or specific bands of statistical parameters that have been used in the classification process.

All data have been delivered in envi format with a header file *.hdr. Table 13 lists all the remote sensing end products that have been delivered. Only versions in 30m resolution are stated here. 300m resolution browse images have also been delivered for the use in presentations.

Table 14 specifies the pixel coding of the classified images FLC, FNF and FCD.

6.9 General Software Specification and Summary

Table 4 summarizes the general software specification.
The overall aim is that the user can reproduce those demonstration products and apply the methods on other historical or future data.

Table 4. Description of Processing Tools

SAR Processing Tools	
General description	
General service/product description:	Software will be provided to the user in order to assure in-house processing capability of the satellite end-products presented. This software/processing package is based on Norut's SAR processing software GSAR written in IDL and includes 3 modules 1) GEOCODING that pre-processes Level-1 SAR data readers into georeferenced, radiometrically corrected sigma0 backscatter image. 2) MOSAICKING that combine several individual SAR scenes over one region into one product where each pixel is a specific measurement dependent on the user's priority and applies a k-mean based forest/non-forest classification. 3) STATISTICS, that provides statistical analysis over a large data set over a specified region and time-period , giving, mean, variance, minimum, maximum backscatters, a combined SAR shadow/layover mask and number of observations per pixel. This module has also a FNF map as output by k-mean classification based on averaged backscatters
Uses and benefits:	Build in-house capacity for SAR processing
General Software Specifications	
Working platform	LINUX
Software platform	IDL/ENVI
Pre-requisite	Tools should work under free IDL Run-Time or Virtual Machine, but easier operational handling with IDL license.
Software format:	Compiled software package (.sav), configuration files, (.cfg), or IDL scripts (.pro)
Min. sensor processing capability	ERS-1/2Sentinel-1A/B, ENVISAT ASAR, ALOS PALSAR, ALOS-2 PALSAR-2, Radarsat-2

7 Demonstration - SAR-based End Products

7.1 SAR mosaics

Generally, the SAR mosaics over the demonstration area are mosaics based on a statistical analysis of the complete data set. The statistical analysis extracts the average, the variance, the number of measurements, and the minimum and maximum backscatter for each pixel for a give data set. It also gives the accumulated mask for layover and SAR shadow pixels. For single polarization data like ENVISAT ASAR wide-swath data, the RGB mosaic is then based on the average, minimum and maximum backscatter for each pixel. For dual-polarization data, the RGB mosaic is based on the co-polarized backscatter, the cross-polarized backscatter and the normalized difference index defined by NDI = (VV-VH)/(VV+VH). All SAR data have been pre-processed, geocoded, radiometrically and slope-corrected with Norut's in-house GSAR processor (Larsen et al., 2005) on the UTM 34S projection in 30m resolution. All mosaics are 3 channels, each in 16 bits, in 30m resolution and on UTM34S.

7.1.1 ENVISAT ASAR wide-swath (ASAR-WS), 2002-2010

ASAR-WS data are single polarized SAR data and have a normal resolution of only 150 m. The data were however pre-processed in 30m resolution, in order to be directly compared to the other SAR data. It is therefore an up-sampling of the SAR signal and as such an interpolated enhanced resolution.
Ascending (ASC) paths were nr. 071, 114, 157, 257, 300, 343, 386, 429.
Descending (DES) paths were nr. 021, 064, 107, 150, 250, 293, 336,379, 479.
Table 5 shows the yearly number of ASAR-WS acquisition in regard to the polarization, ASC/DES.
Because of the bigger occurrence of VV polarized data compared to HH, the final ENVISAT ASAR WS SAR mosaic was based on VV polarized data only, from both ascending and descending paths with the majority of the acquisition from 2003 to 2006.
Figure 8 shows the delivered ENVISAT ASAR-WS mosaic based on the statistical parameters average, minimum and maximum backscatter in RGB.

Table 5. Number of ENVISAT ASAR-WS acquisitions over the period 2002-2012.

Acquisition year	ASC VV	DES VV	Total VV	ASC HH	DES HH	Total HH
2002		7	**7**		1	1
2003	2	8	**10**			
2004	10	7	**17**			
2005	17	6	**23**	1		1
2006	3	12	**15**			
2007	1	6	**7**			
2008		4	**4**			
2009	1	3	**4**			
2010	2	1	**3**			
2011				6	1	7
2012				10		10
Total 2002-2012	**36**	**54**	**90**	17	2	19

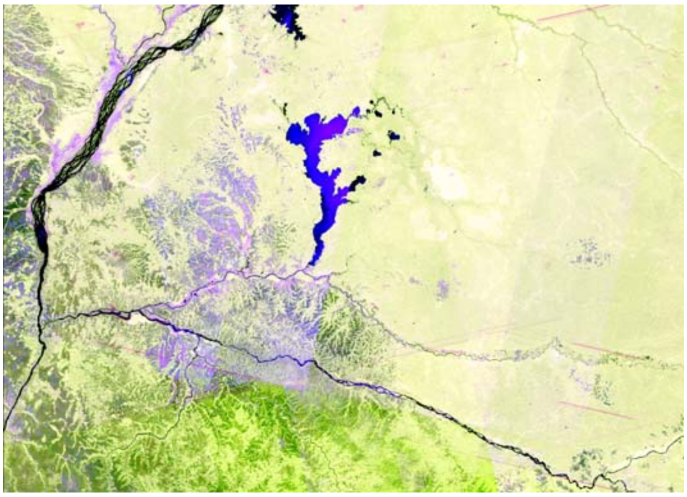


Figure 8. ENVISAT ASAR-WS mosaic based on 90 scenes in VV-polarization from 2002-2010. RGB are average, minimum and maximum backscatter.

7.1.2 ENVISAT ASAR alternate polarization (ASAR-APS) 2010-2011

ASAR-APS is dual polarized data in HH/HV or VV/VH polarization combination. Only 3 scenes exist in HH/HV over our ROI from mode IS2 and were disregarded. In autumn 2011 the satellite orbit was lowered and the incidence angle mode was switched from APS-IS4 to APS-IS1 in order to have overlapping scenes (lower incidence angles). 17 scenes only exist in mode IS1 from 2011 to 2012 and do not cover the whole area, whereas 89 APS-IS4 scenes exist from February 2010 to October 2011 covering the ROI only once completely. The final ASAR APS mosaic is therefore based on mode IS4 only. All acquisitions are taken in DES orbits from path nr. 064, 093, 107, 208, 250, 251, 294, 336, 409, 479 with 66 acquisition in 2010 and 23 acquisitions in 2011
Table 6 shows the number of ASAR-APS acquisitions in the different modes from 2010-2012.
Figure 9 shows the delivered ENVISAT ASAR-APS mosaic with RGB = [VV, VH, NDI].

Table 6. Number of ENVISAT ASAR-APS IS1, IS2 and IS4 acquisitions over the period 2010-2011.

Acquisition year	IS1 (VVVH)	IS2 (HHHV)	IS4 (VVVH)
2010		3	66
2011	4		23
2012	13		
Total 2010-2012	27	3	89

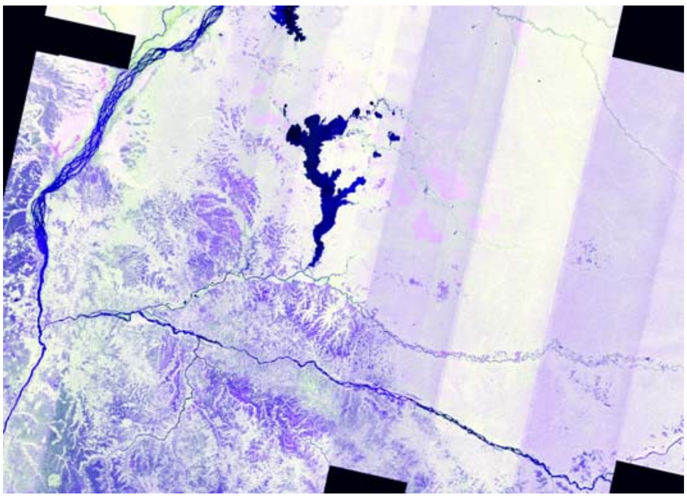


Figure 9. ENVISAT ASAR-APS mosaic based on 89 scenes from 2010-2011. RGB = [VV, VH, NDI].

7.1.3 ALOS PALSAR 2006-2010

ALOS PALSAR data has been acquired from both fine beam single (FBS) and fine beam dual (FBD) polarization modes, HH and HH/HV, respectively. Volume scattering from HV cross-polarized data gives more information on forest cover and biomass, so data ordering has been concentrated on FBD data. FBS data was available from a former EU FP7 project ReCover in the west of Mai Ndombe only. ALOS has been mainly programmed in order to acquire FBD data specifically during the dry season and FBS data during the wet season over the tropics. However, there is full cover in both polarization HH and HV for both the wet and the dry season. The dry season has been defined from June to September and the rest of the year as wet season. The combination of those two has been used in the forest land cover classification. However, for the construction of RGB mosaics, HH, HV and NDI from the FBD data have only been used. Yearly averaged ALOS PALSAR FBD mosaics for the years 2007 to 2010 have been delivered, as well as a an average mosaics for the whole ALOS FBD mission period from 2007-2010, shown in Figure 10.
All single scene data over the ROI have been acquired in ascending orbits with path numbers 596 to 605.
Table 7 shows the number of ALOS PALSAR FBS and FBD acquisition for each year over the ROI from 2006 to 2010.

Table 7. Number of ALOS PALSAR acquisitions from 2006-2010 in FBS and FBD mode.

Acquisition year	FBS (HH)	FBD (HH,HV)	Total
2006	8		8
2007	28	93	121
2008	42	50	92
2009	18	102	120
2010	57	118	175
Total 2006-2010	153	363	516

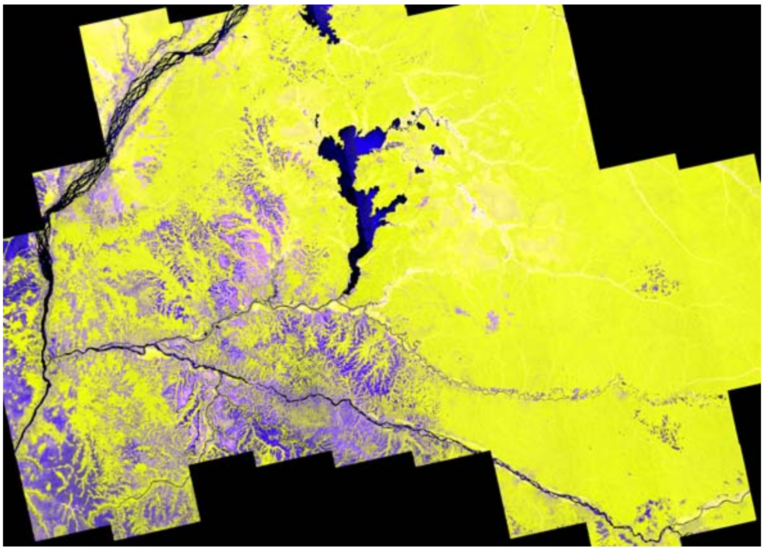


Figure 10. Averaged ALOS PALSAR FBD mosaic based on 363 singles scenes over the period 2007-2010. RGB = [HH, HV, NDI].

7.1.4 ALOS-2 PALSAR-2 2014 - present

ALOS-2 PALSAR-2 data has been mainly acquired through the ALOS-2 RA4 (Research Announcement 4) from JAXA and some through GFOI.
ALOS-2 PALSAR-2 is the successor of ALOS PALSAR, both in L-band. Only FBD from the 70km swath width were acquired over the region with a nominal resolution of 10m. Still, considering the size of the ROI and the thematic of forest region, all data was processed on the 30m grid, also in order to reduce SAR speckle. All together 159 single scenes in ascending orbits have been acquired until today, but only 108 before the delivery to OSFAC in November 2016, covering the ROI completely 3 times. Path numbers are 184 to 187 and polarization is again HH and HV.
Yearly averaged ALOS-2 PALSAR-2 FBD mosaics for the years 2015 and 2016 have been delivered, as well as a an average mosaics for the whole ALOS FBD mission period from 2014-2016, shown in Figure 11, as well as a two-year average for 2015-2016. The new version includes the new correction for the different beams F2-5, F2-6-, and F2-6 according to http://www.eorc.jaxa.jp/ALOS-2/en/calval/PALSAR2_CalVal_Result_JAXA_20170323_En.pdf . Probably the radiometric correction will be readjusted by JAXA in the future.
It should also be noted that the radiometric calibration with the input data given in the ALOS-2 level 1.1 header files results in sigma-0 values about 26 dB high compared to ALOS-1. So an additional absolute corrections needs to be considered.
All single scene data over the ROI have been acquired in ascending orbits with path numbers 184 to 187.
Table 8 shows the number of ALOS-2 PALSAR-2 FBD acquisition for each year and in total over the ROI from 2014 to 2016.

Table 8. Number of ALOS-2 PALSAR-2 acquisitions from 2014-2016 in FBD mode.

Acquisition year	FBD
2014	17
2015	68
2016	74
Total 2010-2012	159

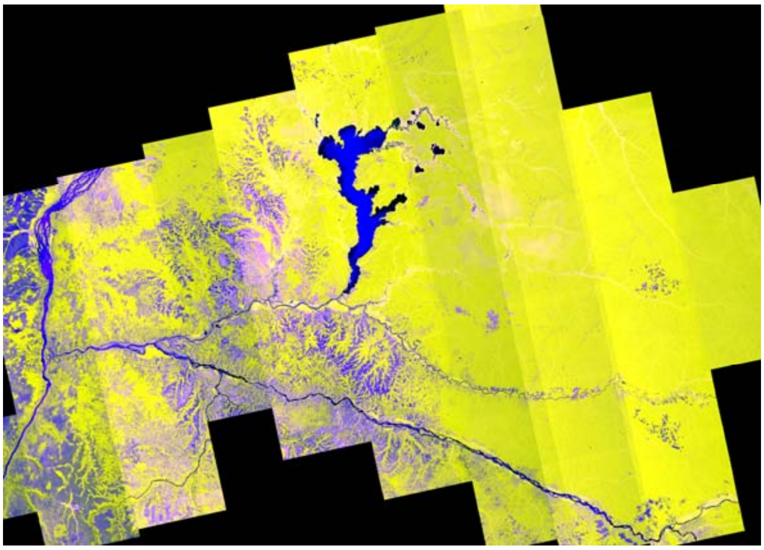


Figure 11. Averaged ALOS-2 PALSAR-2 FBD mosaic based on 159 singles scenes over the period 2014-2016. RGB = [HH, HV, NDI].

7.1.5 Sentinel-1A 2015 - present

Sentinel-1A (S1A) acquisition over the ROI started in April 2015. The ROI is covered by three S1A paths 109, 036 and 138 from west to east. DRC was not a focus area in the ESA Sentinel-1 acquisitions plan and was not well periodically covered until S1B was launched. Only the most western path has been acquired as a relatively dense times series with about bi-weekly observations. Only a few observation exist from path 036 and 138 (Figure 12). The situation changed with the launch of Sentinel-1b and since November 2016 all three paths are acquired on a 12 day revisiting time after the products already have been delivered.

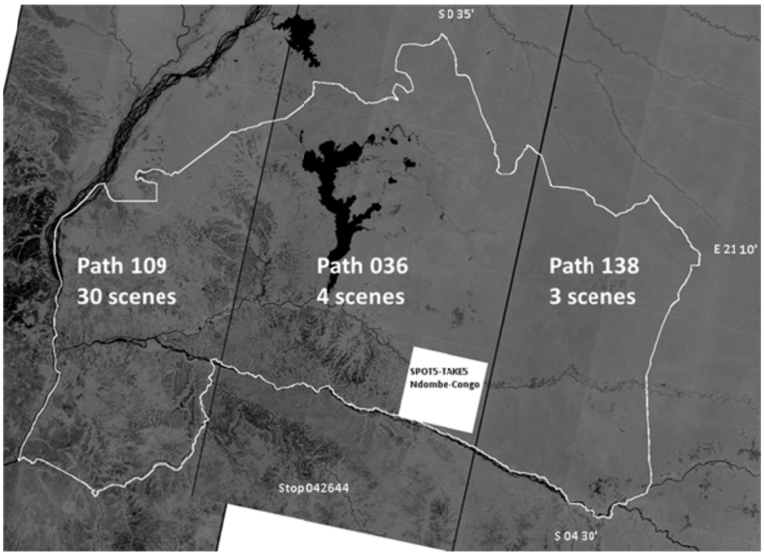


Figure 12. S1A paths numbers and number of acquisition over the ROI from April 2015 to October 2016.

Generally each path over the area acquires 2-3 single scenes which are then put together. Until 16 October 2016, 37 orbits of the 3 path were made. All acquisitions over the ROI are in interferometric wide-swath mode in dual polarization VV and VH from descending orbits

Yearly averaged S1A mosaics for the years 2015 and 2016 have been delivered, as well as an average mosaics for the whole period April 2015 – October 2016.6, shown in Figure 13.

Table 9 shows the number of Sentinel-1A acquisition for each year and in total over the ROI from 2015 to 2016.

Table 9. S1A acquisitions in the period Apr 2015 – Oct 2016 in IWH mode over the ROI.

Acquisition year	109	036	138	Yearly Total
2015 (Apr-Dec)	14	2	2	18
2016 (Jan –Oct)	16	2	1	19
Total 2015-2016	30	4	3	37

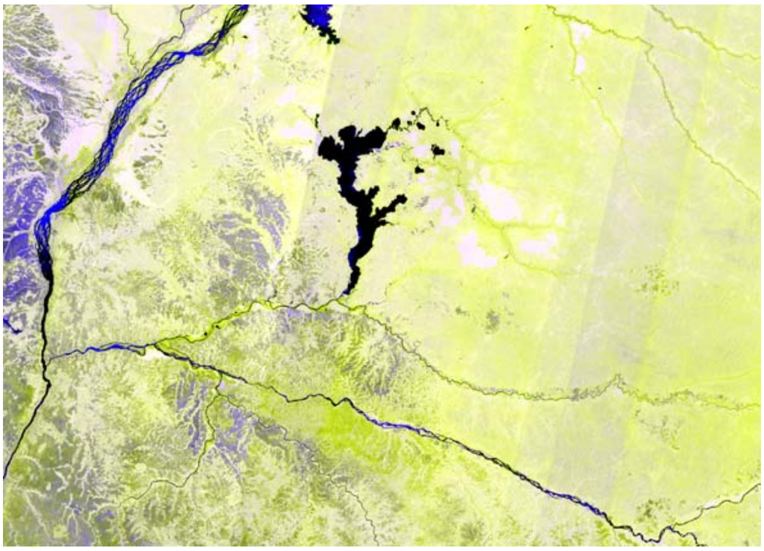


Figure 13. Averaged Sentinel-1A IWH mosaic based on 37 orbit acquisitions from Apr 2015 to Oct 2016. RGB = [VV, VH, NDI].

7.2 Forest Land Cover and Forest/Non-Forest Maps

The forest land cover (FLC) and forest/non-forest (FNF) classifications are based on a supervised maximum likelihood classifier (MLC). Training polygons were manually extracted from a visual interpretation of both optical and SAR data over the ROI, as well as using the knowledge collected during field work in March 2013 and VHR optical data from Google Maps and RapidEye data from 2012. The land covers that could be distinguished in some areas of these data for training the MLC are: forest, inundated forest, savannah, dominantly wet or dry grassland areas and river swamps. The legends used for theses classes in the FLC and FNF products are shown in Table 10 and Table 11, respectively.

A new water mask was constructed by using existing water masks shapefiles of lakes and rivers, the water mask extracted from the Facet Atlas (OSFAC, 2010) and by thresholding the cross-polarized SAR data.

The features used for the MLC are dependent on the availability of the different SAR data sets. The general idea was to use temporally averaged SAR backscatter data to reduce SAR speckle in the data without losing spatial resolution. If dense time series or all year data were available, wet and dry seasonal averages or in the case of single polarized data, minimum and maximum backscatters were used as different parameters as explained in the following.

The classifications were then filtered with a 3x3 majority filter to take the forest definition of 0.5 ha into account. All products are in 30m resolution on a UTM34S projection.

Table 10. FLC Legend

LEGEND	Color	Pixel Value
Forest		10
Inundated Forest		19
Savannah		30
Dry Grassland		40
Wet Grassland		45
River Swamp		50
Water		60
No data		250
Outside of AOI		255

Table 11. FNF Legend

LEGEND	Color	Pixel Value
Forest		10
Non-Forest		30
Water		60
No data		250
Outside of AOI		255

7.2.1 FLC and FNF from ENVISAT ASAR wide-swath (ASAR-WS), 2002-2010

The MLC classification is based on the ASAR-WS mosaic shown in Figure 8 representing the features average, minimum and maximum backscatter over the period 2020-2010 in RGB.
The FLC and FNF results are shown in Figure 14 and Figure 15, respectively.

LEGEND	Color	Pixel Value
Forest		10
Inundated Forest		19
Savannah		30
Dry Grassland		40
Wet Grassland		45
River Swamp		50
Water		60
No data		250
Outside of AOI		255

Figure 14. FLC based on ENVISAT ASAR-WS mosaic 2002-2010.

LEGEND	Color	Pixel Value
Forest		10
Non-Forest		30
Water		60
No data		250
Outside of AOI		255

Figure 15. FNF based on ENVISAT ASAR-WS mosaic 2002-2010.

7.2.2 FLC and FNF from ENVISAT ASAR alternate polarization (ASAR-APS) 2010-2011

The MLC classification is based on the ASAR-APS mosaic shown in Figure 9. The features used for this classification are averaged backscatter VV, VH and the NDI.
The FLC and FNF results are shown in Figure 16 and Figure 17, respectively.

LEGEND	Color	Pixel Value
Forest		10
Inundated Forest		19
Savannah		30
Dry Grassland		40
Wet Grassland		45
River Swamp		50
Water		60
No data		250
Outside of AOI		255

Figure 16. FLC based on ENVISAT ASAR-APS mosaic 2010-2011.

LEGEND	Color	Pixel Value
Forest		10
Non-Forest		30
Water		60
No data		250
Outside of AOI		255

Figure 17. FNF based on ENVISAT ASAR-APS mosaic 2010-2011.

7.2.3 FLC and FNF from ALOS PALSAR 2006-2010

The MLC classification is based on the features from the statistical analysis of the whole ALOS PALSAR FBD and FBS 2007-2010 data set acquired. Attempts with several feature combinations were done. The most promising feature combination was to use the average backscatter in HH and HV polarization and their variance over the whole period 2007-2010, i.e. 4 features in the MLC. Just using the mosaic of averaged backscatter also gives good FNF results as ALOS-2 PALSAR-2 shows. The variance as additional feature however seems to clearly improve the accuracy of the sub-classification into different non-forest classes (see Deliverable 2.2 – Product Validation Report).
The FLC and FNF results are shown in Figure 18 and Figure 19, respectively.

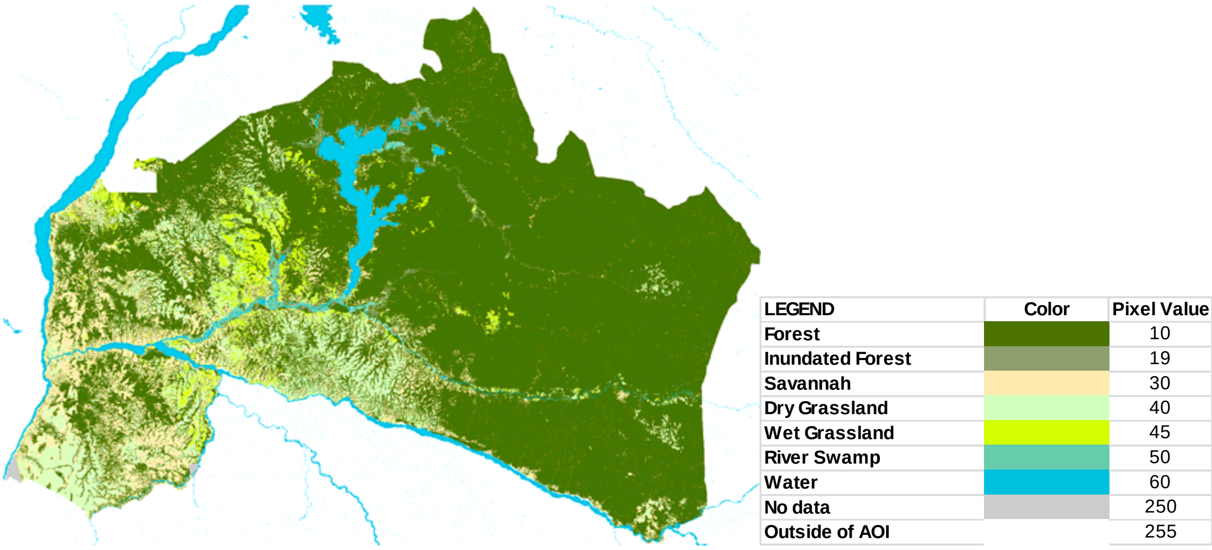


Figure 18. FLC based on 4 ALOS PALSAR features HH_{mean}, HV_{mean}, HH_{var} and HV_{var} over the period 2007-2010.

Figure 19. FNF based on 4 ALOS PALSAR features HH_{mean}, HV_{mean}, HH_{var} and HV_{var} over the period 2007-2010.

7.2.4 FLC and FNF from ALOS-2 PALSAR-2 2014 - present

The MLC classification is based on the backscatter averaged ALOS-2 PALSAR-2 mosaic over the period 2014-2016. Not enough data was available to perform the same approach as with ALOS PALSAR. Clearly, the FLC classification differs quite a lot with the ALOS PALSAR FLC map. This indicates that the seasonal variation especially over non-forest areas can be quite significant. Filtering such seasonal variations out through temporal filtering seems to be a promising approach if the data is available.
The FLC and FNF results are shown in Figure 20 and Figure 21, respectively.

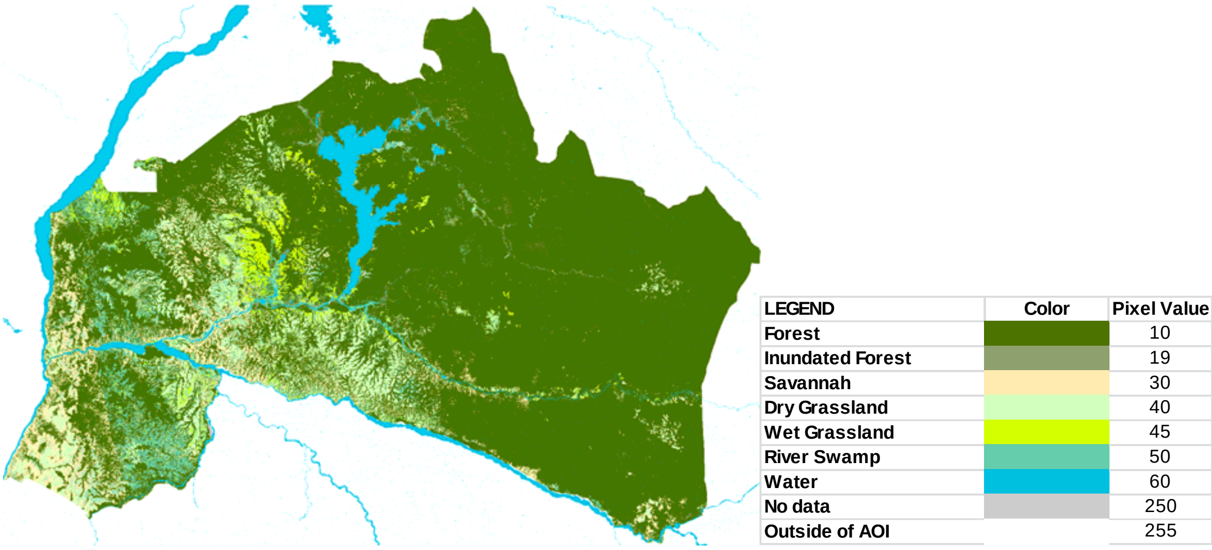


Figure 20. FLC based on ALOS-2 PALSAR-2 2014-2016 mosaic (HH, HV, NDI).

Figure 21. FNF based on ALOS-2 PALSAR-2 2014-2016 mosaic (HH, HV, NDI).

7.2.5 FLC and FNF from Sentinel-1A 2015 - present

The MLC classification is based on the averaged Sentinel-1A mosaic over the period Apr 2015 to Oct 2016. The features are therefore VV_{mean}, VH_{mean} and NDI. As the eastern satellite paths have only been covered 3 times, there is still a strong speckle or seasonal effect in the data. The results show that averaging the backscatter over a certain time period if dense time series exist, will make the results more homogeneous and less noisy.

The FLC and FNF results are shown in Figure 22 and Figure 23, respectively.

LEGEND	Color	Pixel Value
Forest		10
Inundated Forest		19
Savannah		30
Dry Grassland		40
Wet Grassland		45
River Swamp		50
Water		60
No data		250
Outside of AOI		255

Figure 22. FLC based on Sentinel-1A 2015-2016 mosaic (VV,VH,NDI].

LEGEND	Color	Pixel Value
Forest		10
Non-Forest		30
Water		60
No data		250
Outside of AOI		255

Figure 23. FNF based on Sentinel-1A 2015-2016 mosaic (VV,VH,NDI].

7.2.6 FLC and FNF from combined ALOS-2 PALSAR-2 2014–present and Sentinel-1A 2015-present

The MLC classification is based on combining the averaged backscatters from both the ALOS-2 PALSAR-2 and the Sentinel-1A mosaics as features, i.e. HH_{mean}, HV_{mean}, VV_{mean} and VH_{mean}. As L-band SAR and C-band SAR have different penetration depth in the forest canopy and vegetation, their signal will reflect the land cover types quite differently.
The FLC and FNF results are shown in Figure 24 and Figure 25, respectively.

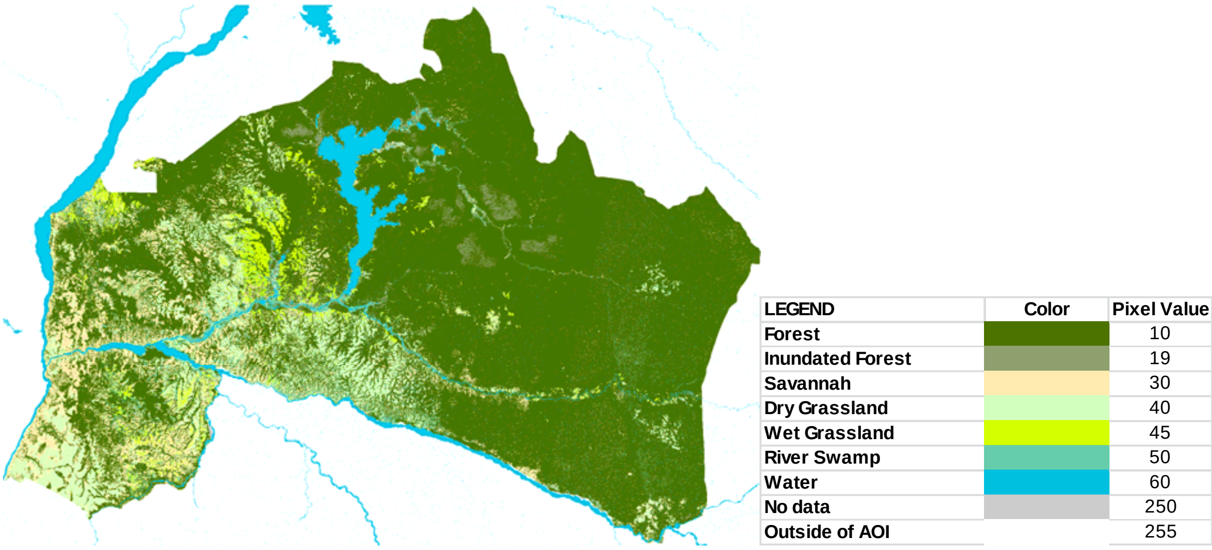


Figure 24. FLC using the four averaged backscatters features from ALOS-2 PALSAR-2 2014-2016 (HHmean, HVmean) and Sentinel-1A 2015-2016 (VVmean and VHmean).

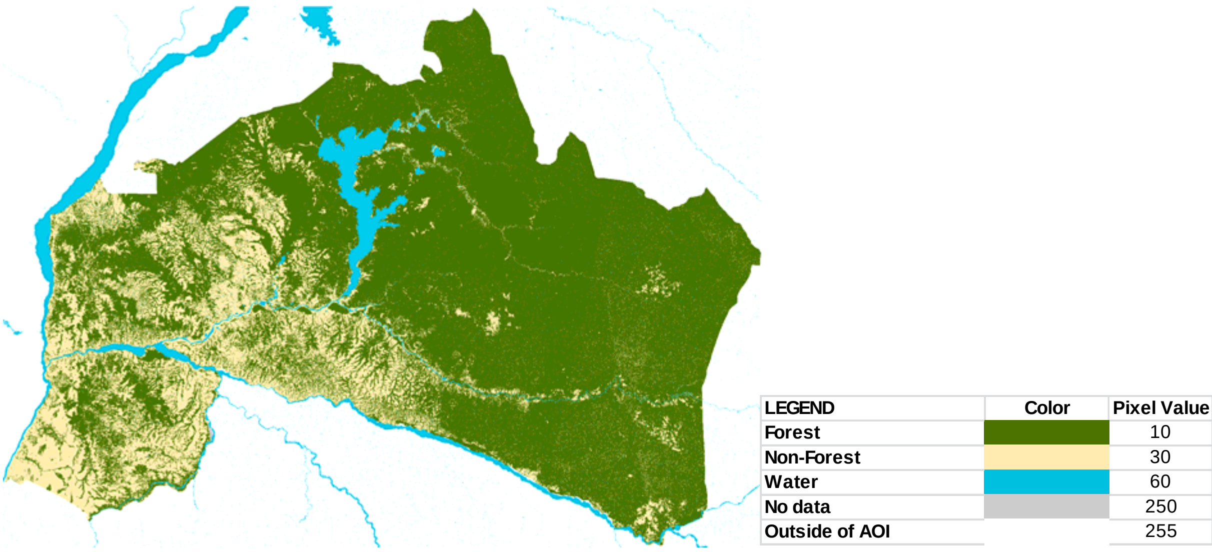


Figure 25. FNF using the four averaged backscatters features from ALOS-2 PALSAR-2 2014-2016 (HHmean, HVmean) and Sentinel-1A 2015-2016 (VVmean and VHmean).

7.3 Forest Change Detection (FCD) Maps

Several forest change maps have been produced. The general approach is to threshold a decrease in cross-polarized backscatter in forest areas that have been previously mapped. It is therefore important that the original forest map has a high accuracy. A typical threshold value would be a decrease of 3dB. The lower the decrease threshold, the more false forest changes will be detected, the higher the decrease threshold, the less forest changes will be detected. Dependent on the time scale of the forest change and abundance of time series available, a temporal filtering to reduce speckle or seasonal variability might be necessary and should be considered case by case. Regrowth of vegetation can be a significant obstacle to detect forest loss over long time periods, especially with C-band SAR, i.e. ENVISAT ASAR and Sentinel-1. L-band does not react as fast on new vegetation and is generally better suited for longer time periods. Sentinel-1 however has high revisit times and can as such also detect forest changes or slash & burn activities in low vegetated areas. Combination of L-band and C-band SAR can also be an advantage in order to filter false forest change detections.
Two forest change products have been delivered to OSFAC in November 2016: A three year forest change detected over 3 years based ALOS PALSAR and a 5-year forest change detection between the ALOS PALSAR and ALOS-2 PALSAR-2 era, approximately 2010-2015. In additional yearly forest change from 2015 to 2016 has been detected based on Sentinel-1 and ALOS-2 PALSAR-2 individually, and using a combination of both Sentinel-1 and ALOS-2 PALSAR-2. Time-series of Sentinel-1 data also clearly shows a possibility to detect slash & burn areas on a short time scale that could be used as an alert system.
Forest gain has been tried to be detected with a backscatter increase, also using 3dB as a threshold. As backscatter variations can be quite strong in non-forest areas however, forest gain is still a challenge if the original conditions are not known. But vegetation growth is general visible in the data especially in non-forest areas.
As the 2007-2010 FNF product based on ALOS PALSAR had the highest accuracies and is prior to the forest change period, this FNF product has been used to provide a forest mask for all FCD maps. All products are in 30m resolution on a UTM34S projection. Table 12 shows the legend of the FCD products.
For visualization below, the forest change products have been reduced to a 300m resolution and each 300m x 300m red pixel represent a forest loss of at least 0.5 ha in this pixel.

Table 12. FCD Legend

LEGEND	Color	Pixel Value
Forest		10
Non-Forest		30
Water		60
Forest Loss		210
Forest Gain		220
No data		250
Outside of AOI		255

7.3.1 FCD 2007-2010 with ALOS PALSAR

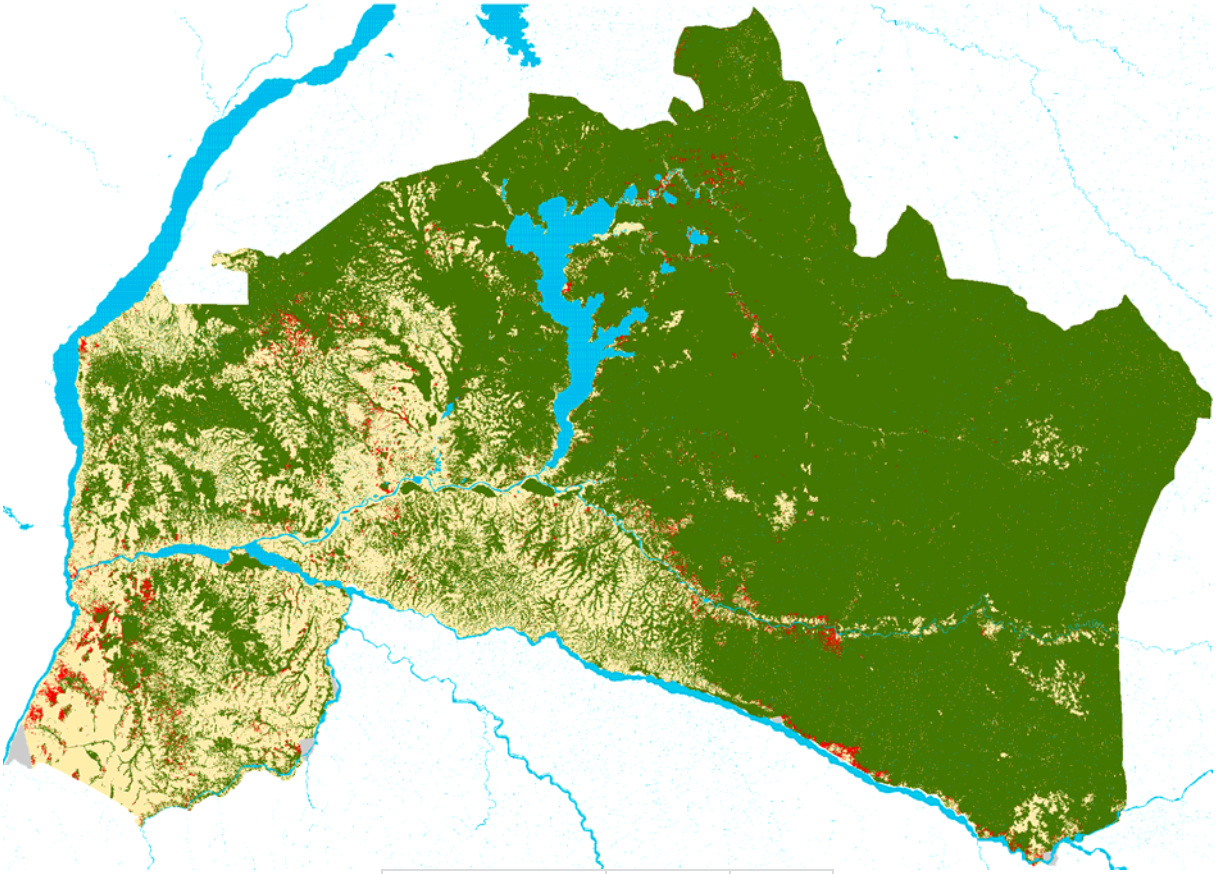
Figure 26 shows the forest loss from the forest change product based on ALOS PALSAR data from 2007-2010. Forest loss has been detected by a 3dB decrease from the 2007 to 2010 averaged HV backscatter. The detected area has then been masked with using a forest mask based on the maximum forest extension in the period 2007-2010.
For visualization below, the forest change products have been reduced to a 300m resolution and each 300m x 300m red pixel represent a forest loss of at least 0.5 ha in this pixel.

LEGEND	Color	Pixel Value
Forest		10
Non-Forest		30
Water		60
Forest Loss		210
Forest Gain		220
No data		250
Outside of AOI		255

Figure 26. 2007-2010 Forest loss based on ALOS PALSAR data from 2007 and 2010.

7.3.2 FCD from 2007-2010 ALOS PALSAR to 2014-2016 ALOS-2 PALSAR-2

Figure 27 shows the forest loss from the forest change product based on a 3dB decrease in averaged HV backscatter from 2007-2010 ALOS PALSAR data to 2014-2016 ALOS-2 PALSAR2- data. Forest loss has then been masked using a FNF products based on the 2007-2010 ALOS PALSAR data (Figure 19). The 3dB change detection threshold has been applied after correcting the ALOS-2 mosaics for the absolute correction of -26 dB. The individual beam correction as mentioned in 7.1.4. (http://www.eorc.jaxa.jp/ALOS-2/en/calval/PALSAR2_CalVal_Result_JAXA_20170323_En.pdf) had not yet been applied on the data before producing this forest change product.
For visualization below, the forest change products have been reduced to a 300m resolution and each 300m x 300m red pixel represent a forest loss of at least 0.5 ha in this pixel.



LEGEND	Color	Pixel Value
Forest		10
Non-Forest		30
Water		60
Forest Loss		210
Forest Gain		220
No data		250
Outside of AOI		255

Figure 27. 2010-2015 Forest loss based ALOS PALSAR 2000-2010 and ALOS-2 PALSAR-2 2014-2016

7.3.3 FCD 2015-2016 with Sentinel-1A and ALOS-2 PALSAR-2

Figure 28 shows the forest loss from year 2015 to year 2016. It is based on the combined use of Sentinel-1 and ALOS-2 PALSAR-2 data. Yearly averaged cross-polarized backscatter mosaics where produced for both Sentinel-1 VH and ALOS-2 PALSAR-2 HV backscatter for the years 2015 and 2016.

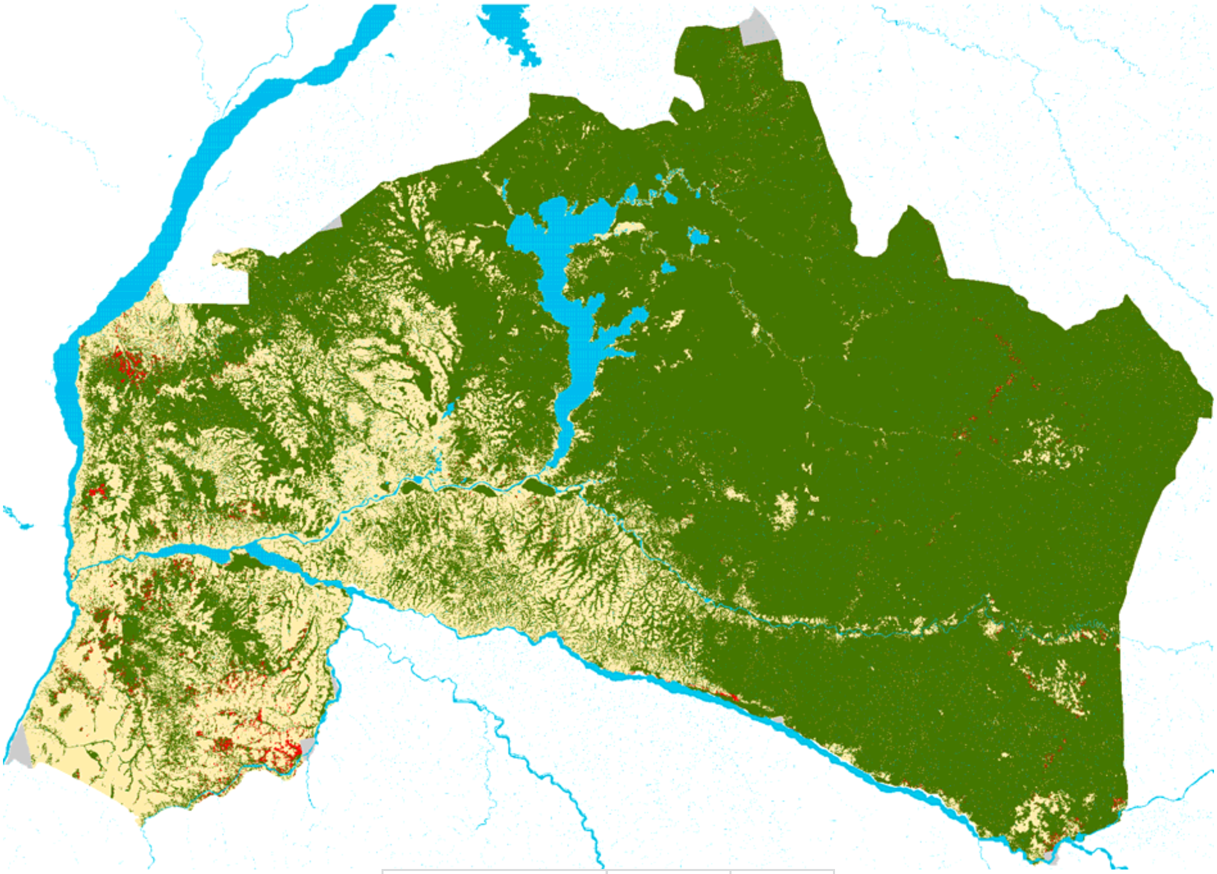
Forest change was then detected individually for each sensor with a 3dB decrease in VH and HV backscatter for Sentinel-1A and ALOS-2 PALSAR-2, respectively.

Those FCD products already detected quite well some forest loss, but since the data acquisition is not homogeneous over the whole area, some areas where more noisy than others. A combination of both sensors revealed a good method to detect forest loss that is well detectable in both data sets, Sentinel-1A and ALOS-2 PALSAR-2.

Forest loss pixel where therefore detected if the sum of the backscatter decrease of Sentinel-1A and ALOS-2 PALSAR-2 was greater than 5dB, i.e.: There is forest loss if

$$(\sigma_{VH}[2016] - \sigma_{VH}[2015]) + (\sigma_{HV}[2016] - \sigma_{HV}[2015]) < -5dB$$

Forest loss has then been masked using a FNF products based on the 2007-2010 ALOS PALSAR data (Figure 19). For visualization below, the forest change products have been reduced to a 300m resolution and each 300m x 300m red pixel represent a forest loss of at least 0.5 ha in this pixel.



LEGEND	Color	Pixel Value
Forest		10
Non-Forest		30
Water		60
Forest Loss		210
Forest Gain		220
No data		250
Outside of AOI		255

Figure 28. 2015-2016 Forest loss based on a combination of Sentinel-1A and ALOS-2 PALSAR-2.

Table 13. List of the final end-products delivered to the user (June 2017).

Product name	Sensor/s	Bands	Time-period	Proj.	Res.	Nr of scenes	File_Size
MOSAICS		3x16bits					
DRC_S4R_MOS_ASA-WS_VVavg-min-max_2002-2010_UTM34S_30m_v3 (*300m*)	ASA-WS	VV(avg-min-max)	2002-2010	UTM34S	30m	90	3.1 Gb
DRC_S4R_MOS_ASA-IS4_2010-2011_UTM34S_30m_v3 (*300m*)	ASA-IS4	VV-VH-NDI	2010-2011	UTM34S	30m	89	3.1 Gb
DRC_S4R_MOS_PAL-FBD_2007-2010_UTM34S_30m_v3 (*300m*)	PAL	HH-HV-NDI	2007-2010	UTM34S	30m	363	3.1 Gb
DRC_S4R_MOS_PAL-FBD_2007_UTM34S_30m_v3	PAL	HH-HV-NDI	2007	UTM34S	30m	93	3.1 Gb
DRC_S4R_MOS_PAL-FBD_2008_UTM34S_30m_v3	PAL	HH-HV-NDI	2008	UTM34S	30m	50	3.1 Gb
DRC_S4R_MOS_PAL-FBD_2009_UTM34S_30m_v3	PAL	HH-HV-NDI	2009	UTM34S	30m	102	3.1 Gb
DRC_S4R_MOS_PAL-FBD_2010_UTM34S_30m_v3	PAL	HH-HV-NDI	2010	UTM34S	30m	118	3.1 Gb
DRC_S4R_MOS_PAL2-FBD_2014-2016_BC-JAXA_UTM34S_30m_v3 (*300m*)	PAL2	HH-HV-NDI	2014-2016	UTM34S	30m	159	3.1 Gb
DRC_S4R_MOS_PAL2-FBD_2015-2016_BC-JAXA_UTM34S_30m_v3 (*300m*)	PAL2	HH-HV-NDI	2015-2016	UTM34S	30m	142	3.1 Gb
DRC_S4R_MOS_PAL2-FBD_2015_BC-JAXA_UTM34S_30m_v3	PAL2	HH-HV-NDI	2015	UTM34S	30m	68	3.1 Gb
DRC_S4R_MOS_PAL2-FBD_2016_BC-JAXA_UTM34S_30m_v3	PAL2	HH-HV-NDI	2016	UTM34S	30m	74	3.1 Gb
DRC_S4R_MOS_S1A-IW_2015-2016_UTM34S_30m_v3 (*300m*)	S1A	VV-VH-NDI	2015-2016	UTM34S	30m	73	3.1 Gb
DRC_S4R_MOS_S1A-IW_2015_UTM34S_30m_v3	S1A	VV-VH-NDI	2015	UTM34S	30m	24	3.1 Gb
DRC_S4R_MOS_S1A-IW_2016_UTM34S_30m_v3	S1A	VV-VH-NDI	2016	UTM34S	30m	49	3.1 Gb
FOREST LAND COVER & FOREST/NON-FOREST MAPS		8bits					
DRC_S4R_FLC_ASAWS-avgminmax_2002-2010_UTM34S_30m_v3 (*300m*)	ASA-WS	Class	2002-2010	UTM34S	30m		258.4 Mb
DRC_S4R_FNF_ASAWS-avgminmax_2002-2010_UTM34S_30m_v3 (*300m*)	ASA-WS	Class	2002-2010	UTM34S	30m		258.4 Mb
DRC_S4R_FLC_ASA-IS4-MOS_2010-2011_UTM34S_30m_v3 (*300m*)	ASA-IS4	Class	2010-2011	UTM34S	30m		258.4 Mb
DRC_S4R_FNF_ASA-IS4-MOS_2010-2011_UTM34S_30m_v3 (*300m*)	ASA-IS4	Class	2010-2011	UTM34S	30m		258.4 Mb
DRC_S4R_FLC_PAL-FBX-avg_var_2007-2010_UTM34S_30m_v3 (*300m*)	PAL	Class	2007-2010	UTM34S	30m		258.4 Mb
DRC_S4R_FNF_PAL-FBX-avg_var_2007-2010_UTM34S_30m_v3 (*300m*)	PAL	Class	2007-2010	UTM34S	30m		258.4 Mb
DRC_S4R_FLC_PAL2-FBD-HHHVNDI_2014-2016_108_UTM34S_30m_v3 (*300m*)	PAL2	Class	2014-2016	UTM34S	30m		258.4 Mb
DRC_S4R_FNF_PAL2-FBD-HHHVNDI_2014-2016_108_UTM34S_30m_v3 (*300m*)	PAL2	Class	2014-2016	UTM34S	30m		258.4 Mb
DRC_S4R_FLC_S1A-VVVHNDI_2015-201610_UTM34S_30m_v3 (*300m*)	S1A	Class	2015-2016	UTM34S	30m		258.4 Mb
DRC_S4R_FNF_S1A-VVVHNDI_2015-201610_UTM34S_30m_v3 (*300m*)	S1A	Class	2015-2016	UTM34S	30m		258.4 Mb
DRC_S4R_FLC_S1A-PAL2-VVVHHHHV_2014-201610_UTM34S_30m_v3 (*300m*)	S1A-PAL2	Class	2014-2016	UTM34S	30m		258.4 Mb
DRC_S4R_FNF_S1A-PAL2-VVVHHHHV_2014-201610_UTM34S_30m_v3 (*300m*)	S1A-PAL2	Class	2014-2016	UTM34S	30m		258.4 Mb
FOREST CHANGE MAPS		8bits					
DRC_S4R_FCD_PAL-PAL-HVdiff3_2007-2010_UTM34S_30m_v3 (*300m*)	PAL	Class	2007-2010	UTM34S	30m		258.4 Mb
DRC_S4R_FCD_PAL-PAL2-HVdiff3_2010-2015_UTM34S_30m_v3 (*300m*)	PAL-PAL2	Class	2010-2015	UTM34S	30m		258.4 Mb
DRC_S4R_FCD_S1A-PAL2_2015-2016_diff5_UTM34S_30m_v3 (*300m*)	S1A-PAL2	Class	2015-2016	UTM34S	30m		258.4 Mb

Table 14. 8 bit pixel coding for FLC, FNF and FCD classification images

Pixel value		Biomass (t/h)	Color code RGB
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
10	Forest		76/115/0
11		Sub-forest classes	
12		Sub-forest classes	
13		Sub-forest classes	
14		Sub-forest classes	
15		Sub-forest classes	
16		Sub-forest classes	
17		Sub-forest classes	
18		Sub-forest classes	
19		degraded forest	140/160/110
20	Shrubland	Sub-shrubland classes	90/170/0
21		Sub-shrubland classes	
22		Sub-shrubland classes	
23		Sub-shrubland classes	
24		Sub-shrubland classes	
25		Sub-shrubland classes	
26		Sub-shrubland classes	
27		Sub-shrubland classes	
28		Sub-shrubland classes	
29			
30	CropLand		255/235/175
31		Crop-land classes	
32		Crop-land classes	
33		Crop-land classes	
34		Crop-land classes	
35		Crop-land classes	
36		Crop-land classes	
37		Crop-land classes	
38		Crop-land classes	
39		Crop-land classes	
40	Grassland		211/255/190
41		Grassland classes	
42		Grassland classes	
43		Grassland classes	
44		Grassland classes	
45		Grassland classes	211/255/0
46		Grassland classes	
47		Grassland classes	
48		Grassland classes	
49		Grassland classes	

Pixel value		Biomass (t/h)	Color code RGB
50	Wetlands		102/205/171
51		Wetland classes	
52		Wetland classes	
53		Wetland classes	
54		Wetland classes	
55		Wetland classes	
56		Wetland classes	
57		Wetland classes	
58		Wetland classes	
59		Wetland classes	
60	Water bodies		0/192/224
61		Ocean	
62		Lakes	
63		Big Rivers	
64		Small rivers	
65		Water body classes	
66		Water body classes	
67		Water body classes	
68		Water body classes	
69		Water body classes	
70	Settlements		245/162/122
71		Capitals	
72		cities	
73		villages	
74		single houses	
75		Settlement classes	
76		Settlement classes	
77		Settlement classes	
78		Settlement classes	
79		Settlement classes	
80	other land		
81		roads	245/165/218
82		other land ?	
83		other land ?	
84		other land ?	
85		other land ?	
86		other land ?	
87		other land ?	
88		other land ?	
89		other land ?	
90			
91			
92			
93			
94			
95			
96			
97			
98			
99		m3/ha or t/ha	

Pixel value		Biomass (t/h)	Color code RGB
100	Biomass	0	255/235/175
101	Biomass	5	255/235/175
102	Biomass	10	
103	Biomass	15	234/241/221
104	Biomass	20	
105	Biomass	25	
106	Biomass	30	
107	Biomass	35	
108	Biomass	40	
109	Biomass	45	
110	Biomass	50	
111	Biomass	55	
112	Biomass	60	
113	Biomass	65	
114	Biomass	70	
115	Biomass	75	
116	Biomass	80	
117	Biomass	85	
118	Biomass	90	
119	Biomass	95	
120	Biomass	100	
121	Biomass	105	215/228/188
122	Biomass	110	
123	Biomass	115	
124	Biomass	120	
125	Biomass	125	
126	Biomass	130	
127	Biomass	135	
128	Biomass	140	
129	Biomass	145	
130	Biomass	150	
131	Biomass	155	
132	Biomass	160	
133	Biomass	165	
134	Biomass	170	
135	Biomass	175	
136	Biomass	180	
137	Biomass	185	
138	Biomass	190	
139	Biomass	195	
140	Biomass	200	194/214/154
141	Biomass	205	
142	Biomass	210	
143	Biomass	215	
144	Biomass	220	
145	Biomass	225	
146	Biomass	230	
147	Biomass	235	
148	Biomass	240	
149	Biomass	245	

Pixel value		Biomass (t/h)	Color code RGB
150	Biomass	250	
151	Biomass	255	
152	Biomass	260	
153	Biomass	265	
154	Biomass	270	
155	Biomass	275	
156	Biomass	280	
157	Biomass	285	
158	Biomass	290	
159	Biomass	295	
160	Biomass	300	
161	Biomass	305	117/146/60
162	Biomass	310	
163	Biomass	315	
164	Biomass	320	
165	Biomass	325	
166	Biomass	330	
167	Biomass	335	
168	Biomass	340	
169	Biomass	345	
170	Biomass	350	
171	Biomass	355	
172	Biomass	360	
173	Biomass	365	
174	Biomass	370	
175	Biomass	375	
176	Biomass	380	
177	Biomass	385	
178	Biomass	390	
179	Biomass	395	
180	Biomass	400	
181	Biomass	405	79/98/40
182	Biomass	410	
183	Biomass	415	
184	Biomass	420	
185	Biomass	425	
186	Biomass	430	
187	Biomass	435	
188	Biomass	440	
189	Biomass	445	
190	Biomass	450	
191	Biomass	455	
192	Biomass	460	
193	Biomass	465	
194	Biomass	470	
195	Biomass	475	
196	Biomass	480	
197	Biomass	485	
198	Biomass	490	
199	Biomass	495+	

Pixel value		Biomass (t/h)	Color code RGB
200	Land Cover change		
201		Land Cover change classes	
202		Land Cover change classes	
203		Land Cover change classes	
204		Land Cover change classes	
205		Land Cover change classes	
206		Land Cover change classes	
207		Land Cover change classes	
208		Land Cover change classes	
209		Land Cover change classes	
210	Decrease in Biomass		255/0/0
211		Forest-> Nonforest	255/0/0
212		Forest -> Degraded forest	255/192/0
213		Degraded Forest -> non-forest	255/255/0
214			255/0/0
215			255/0/0
216			255/0/0
217			255/0/0
218			255/0/0
219			255/0/0
220	Increase in biomass		
221		Non forest-> Forest	150/70/70
222		Degraded forest - Forest	120/50/60
223		Non-forest -> Growing forest	220/150/140
224			
225			
226			
227			
228			
229			
230	No data (Atmos. affects)		204/204/204
231		Clouds	
232		Haze	
233		Mist	
234		etc.	
235			
236			
237			
238			
239			
240	No data (Sensor affects)		
241		SAR shadow	
242		SAR folding	
243		interference	
244		etc.	
245			
246			
247			
248			
249			
250	No data		204/204/204
251		No satellite coverage	
252			
253			
254			
255	Outside of AOI		255/255/255

8 Validation

All products have been validated and assessed for accuracy and quality. The detailed validation is described in the delivery report "D2.2 – Product Validation Report (PVR)" (Haarpaintner & Singa, 2017). The report has been summarized below.

8.1 Mosaic – Georeferencing and Slope Correction

There are three parameters that play an important role in the production of homogeneous mosaics. These are:

- the radiometric calibration,
- the geocolocation, and
- the slope correction.

The single SAR scenes and SAR mosaic products have been visually assessed based on these parameters showing high accuracies in geolocation and stability in radiometric values.
Slope correction was significantly improved when using a 30m resolution DEM instead of the original 90m resolution DEM. Very few single SAR scenes need to be rejected because of obviously not correct orbit parameters. They were eliminated manually.

8.2 Forest Land Cover (FLC) and Forest/Non-Forest (FNF) Map Accuracies

8.2.1 Background, method and reference data

The general approach to estimate the accuracy and quantifying uncertainty of land cover and land cover change maps is done by comparing a reference data set with the produced maps via a confusion matrix. This has been outlined in several publications and a good practice guideline has been established and described in the Methods and Guidance Document from the Global Forest Observations Initiative (GFOI, 2014). It has also been described in detail in Olofsson et al. (2013) and Olofsson et al. (2014). We will follow this approach in validating the FLC and FNF remote sensing products.
The FLC maps include 6 land cover/vegetation classes. However, manual interpretation from optical satellite images did in general not allow a better classification than into forest, savannah, and grassland (FSG) as the other classes were not abundant in the VHR images. Only from Google earth data it was possible to distinguish also inundated forest and some kind of river swamps. The FLC maps are therefore sub-classified into these three classes. First validation results showed that especially the river swamp class in FLC from C-band SAR products showed a lot of inaccuracies. The sub-classification was done therefore in two possible ways: (1) with the river swamp class defined as grassland, called FSG1 and (2) with the river swamp class defined as forest, called FSG2. The FSG maps were then again sub-classified into FNF maps where FNF1 is the original FNF map and in FNF2, the "river swamp" class is defined as forest. Table 15 specifies the classification and sub-classification for the validation.

Table 15. FLC Classification and sub-classification into forest-savannah-grassland (FSG1 and FSG2) legend for the validation.

FLC Classification			Forest-Svannah-Grassland Classification (1)			Forest-Svannah-Grassland Classification (2)		
LEGEND	Color	Pixel Value	LEGEND	Color	Pixel Value	LEGEND	Color	Pixel Value
Forest		10	Forest		10	Forest		10
Inundated Forest		19	Forest		10	Forest		10
Savannah		30	Savannah		30	Savannah		30
Dry Grassland		40	Grassland		40	Grassland		40
Wet Grassland		45	Grassland		40	Grassland		40
River Swamp		50	Grassland		40	Forest		10
Water		60	Water		60	Water		60
No data		250	No data		250	No data		250
Outside of AOI		255	Outside of AOI		255	Outside of AOI		255

The FLC and FNF results to be validated are shown in Table 16 and have been presented in delivery “D2.1 – Product Delivery Report”.

Table 16. List of forest land cover and forest/non-forest products delivered to the user

FOREST LAND COVER & FOREST/NON-FOREST MAPS	Sensor	Time
DRC_S4R_FLC_ASAWS-avgminmax_2002-2010_UTM34S_30m_v2_Oct16_FNFFLC_RGB_maj3	ASA-WS	2002-2010
DRC_S4R_FNF_ASAWS-avgminmax_2002-2010_UTM34S_30m_v2_Oct16_FNFFLC_RGB	ASA-WS	2002-2010
DRC_S4R_FLC_ASA-IS4-MOS_2010-2011_UTM34S_30m_3x3_v2_Oct16_FNFFLC_RGB_maj3	ASA-IS4	2010-2011
DRC_S4R_FNF_ASA-IS4-MOS_2010-2011_UTM34S_30m_3x3_v2_Oct16_FNFFLC_RGB_maj3	ASA-IS4	2010-2011
DRC_S4R_FLC_PAL-FBX-avg_var_2007-2010_UTM34S_30m_v2_Oct16_FNFFLC_RGB_maj3	PAL	2007-2010
DRC_S4R_FNF_PAL-FBX-avg_var_2007-2010_UTM34S_30m_v2_Oct16_FNFFLC_RGB_maj3	PAL	2007-2010
DRC_S4R_FLC_PAL2-FBD-HHHVNDI_2014-2016_108_UTM34S_30m_v2_Oct16_FNFFLC_RGB_maj3	PAL2	2014-2016
DRC_S4R_FNF_PAL2-FBD-HHHVNDI_2014-2016_108_UTM34S_30m_v2_Oct16_FNFFLC_RGB_maj3	PAL2	2014-2016
DRC_S4R_FLC_S1A-VVVHNDI_2015-201610_UTM34S_30m_v2_Oct16_FNFFLC_RGB_maj3	S1A	2015-2016
DRC_S4R_FNF_S1A-VVVHNDI_2015-201610_UTM34S_30m_v2_Oct16_FNFFLC_RGB_maj3	S1A	2015-2016
DRC_S4R_FLC_S1A-PAL2-VVVHHHHV_2014-201610_UTM34S_30m_v2_Oct16_FNFFLC_RGB_maj3	S1A-PAL2	2014-2016
DRC_S4R_FNF_S1A-PAL2-VVVHHHHV_2014-201610_UTM34S_30m_v2_Oct16_FNFFLC_RGB_maj3	S1A-PAL2	2014-2016

The used reference data was:

- Very high resolution (VHR) optical satellite data based on SPOT5/TAKE5 and Pléiades satellites (Figure 29),
- Optical data extracted from Google Earth,
- Landsat interpretation,
- Landsat-based forest maps from Global Forest Change (GFC) (Hansen et al., 2013),
- Aerial mosaics from remotely piloted aerial system (RPAS), a DJI Phantom3 quadcopter from a field mission in September 2016 (Figure 30), and
- GPS position from forest boarders collected during the field mission in September 2016 (Figure 29).

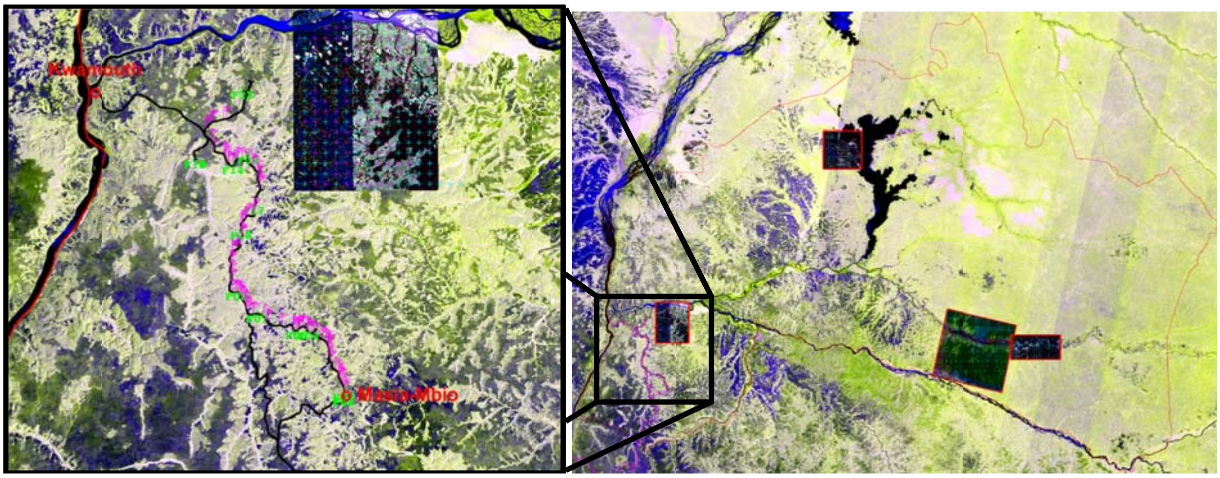


Figure 29. Position of the reference data in the Mai Ndombe district (right panel). The magenta line “–“ shows the road track during the field mission in September 2016 in the Kwamouth region (zoom, left panel), red rectangles show the VHR optical dada from Pléiades and SPOT5 (biggest rectangle).

The validation report also presents an alternative validation approach, which is to validate the position of forest border with GPS position collected during fieldwork.

8.2.2 Field mission in the Kwamouth region in September 2016.

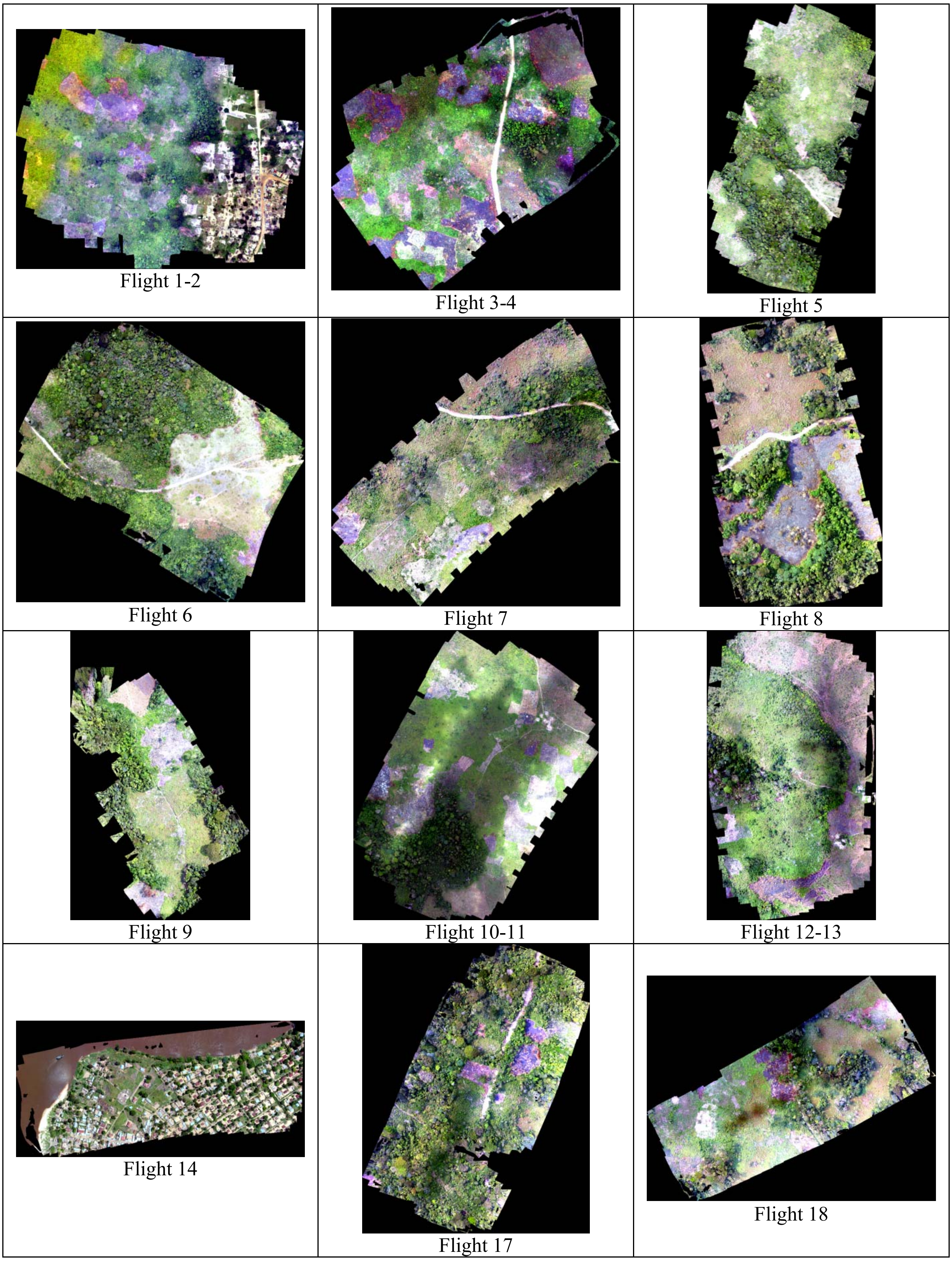


Figure 30. Aerial image mosaics acquired with DJI Phantom 3pro during fieldwork in Sep 2016 in the Kwamouth Region

A 6 day field mission was done from 6-11 September 2016 in the Kwamouth region in the south-west of Mai Ndombe in order to collect ground truth data for validation. Participants included Norut, OSFAC, WWF and the DRC Ministry of Environment.

The data collection consisted in

- visual observation made by GPS referenced ground photography, as well as
- Aerial observation from a remotely piloted aerial system (RPAS), a small quadcopter DJI Phantom 3 Pro.
- Collection of GPS position of land cover transitions, particularly forest/non-forest transitions, along the driven track, and
- Tree height and tree count measurements.

Figure 30 shows the 12 aerial image mosaics that were collected during the fieldwork. No images, but videos were acquired during flight 15 and 16.
The flight positions were chosen according to forest loss detected between ALOS PALSAR 2010 and ALOS-2 PALSAR-2 2015 along the road from Masia Mbio to Kwamouth. The field visit confirmed that all those observed areas underwent strong changes in the past years. Use of those image mosaics to validated forest maps from earlier years or from integration over longer time periods (f.e. 2 years) is therefore not really appropriate since they are biased on forest change. Nevertheless, every 90 m (every 3rd pixel in 30m resolution) was sampled for a validation with a confusion matrix for the FLC and FNF products from ALOS-PALSAR 2007-2010, ALOS-2 PALSAR2 2014-2016 and S1A 2015-2016. Accuracies are however very low since the regions have undergone strong changes. We note also that geolocation errors might have been introduced in the transformation from different map projection UTM to lat-lon.
The overall accuracies and kappa values are summarized in Table 17. The products based on ALOS-2 PALSAR-2 show the highest accuracies. Figure 31 shows the example of flight 9 with superposed FNF boarders from ALOS, ALOS-2 and Sentinel-1.

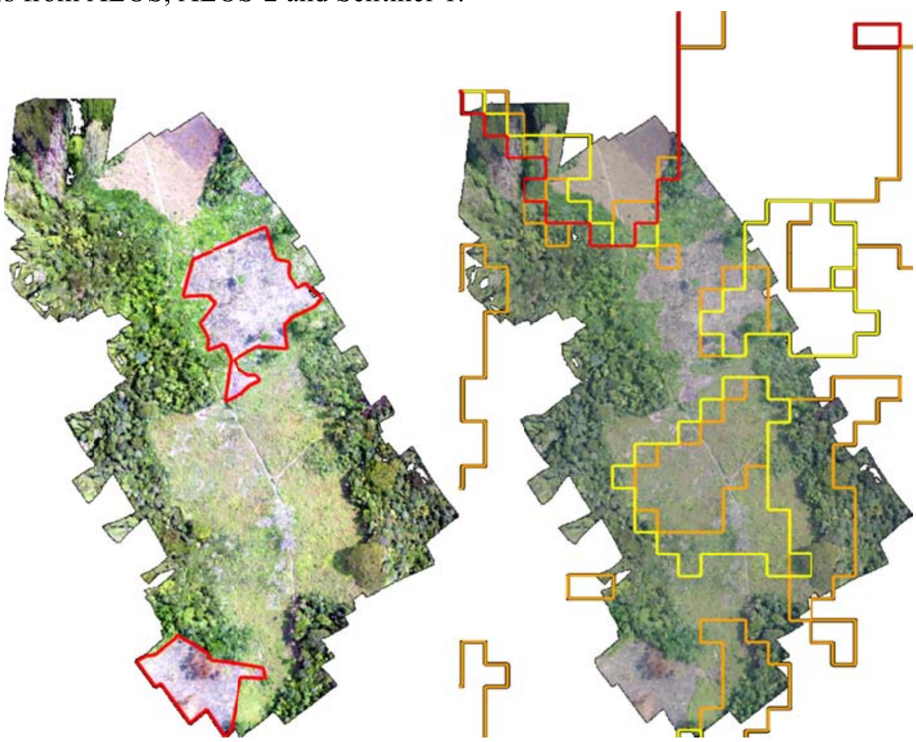


Figure 31. (Left) Flight 9 image mosaic with burned areas marked in red. (Right) FNF borders from ALOS PALSAR 2007-2010 (red), ALOS2 PALSAR-2 2014-2016 (yellow) and S1 (2015-2016) (orange) superposed over the aerial image mosaics from flight 9.

8.2.3 Summary the Forest Land Cover (FLC) and Forest/Non-Forest (FNF) Validation with Confusion Matrix

The validation report (Haarpaintner & Singa, 2017) presents the validation of all the products that have been delivered to OSFAC in detail. In addition to the general confusion matrix approach, alternative validation approaches have been presented, like the use of aerial images from RPAS or GPS positions of forest borders.
The report also includes a validation performed by the user, OSFAC, using the data and methods that they are most familiar with, i.e. Landsat imagery and the GFC data set.
Confusion matrixes, overall accuracies and kappa values from the validation with 5 land cover classes (Forest, inundated forest, savannah, grassland and river swamp), 3 land cover classes (forest, savannah and grassland) and a simple forest/non-forest validation with two classes have been produced.
Validation with different reference data sets give of course different results. However, in conclusion, it is quite obvious that L-band SAR data is better suited for forest land cover mapping than C-band SAR data. Nevertheless, the availability of dense time series to eliminate SAR speckle and seasonal variation is a quite important factor for the accuracies. Having a long time series of ALOS PALSAR data showed therefore the highest accuracies of up to 89 % and 95% when validating forest/savannah/grassland and forest/non-forest products, respectively, with Google Earth data.
The somewhat disappointing results from the Sentinel-1 data are probably due to the low availability of SAR data in the eastern part of the region that introduced a lot of noise in the results.
When validating with VHR SPOT-5 and Pleiades data, ALOS PALSAR still performed better than all the others, but Sentinel-1 clearly outperformed the ENVISAT data and showed even slightly higher accuracies than ALOS-2 PALSAR-2 results.
The alternative validation approach using GPS position from forest borders from fieldwork in an area with dense time series in the Kwamouth region actually showed that Sentinel-1 performed better than all other SAR sensors in the detection of the forest border (see next section).
Another factor might be that Sentinel-1 resolution is also better than older SAR data and single trees and inhomogeneous forest canopies can introduce shadow effect from the highest tress. Since L-band SAR signal penetrates deeper in the forest canopy such variable tree heights should therefore have a smaller effect in L-band than in C-band data.
Another obvious results from Table 17 is that accuracies are higher when C- and L-band data is combined.
In summary, all FNF validation show accuracies in the high 80s % until mid 90s %, which is comparable to accuracies of optical satellite sensors.

Table 17. Summary of the different FNF accuracy assessments with manually interpreted Google Earth, VHR (SPOT-5/Pleiades), Landsat data, UAV aerial photos and forest maps from GFC Global Forest Change project (Hansen et al., 2013)

Sensor	Year		Google Earth	SPOT-5 Pleiades	Landsat	UAV	GFC
ENVISAT ASAR -WS	**2002-2010**	**Accuracy**	**92.48**	**86.36**			
		Kappa	0.80	0.57			
ENVISAT ASAR -AP	**2010-2011**	**Accuracy**	**87.58**	**84.09**	**64,18**		**85,76**
		Kappa	0.67	0.48	0,18		0,55
ALOS PALSAR	**2007-2010**	**Accuracy**	**94.77**	**92.10**	**69,60**	**64,08**	**86,48**
		Kappa	0.87	0.76	0,30	0,32	0,59
ALOS-2 PALSAR-2	**2014-2016**	**Accuracy**	**89.87**	**85.61**	**92,43**	**67,58**	**90,13**
		Kappa	0.72	0.49	0,05	0,38	0,64
Sentinel-1	**2015-2016**	**Accuracy**	**84.31**	**87.12**	**88,81**	**57,23**	**84,97**
		Kappa	0.60	0.58	0,01	0,20	0,54
Sentinel-1/ALOS-2	**2014-2016**	**Accuracy**	**91.83**	**89.39**	**95,62**		
		Kappa	0.78	0.65	0,84		

8.2.4 Validation with GPS position from forest/non-forest borders taken during fieldwork in September 2016.

During the field mission in September 2016, 138 GPS positions of forest borders were taken along the road from Masia-Mbio to Kwamouth. As a different validation approach, these positions were then compared to the forest border pixels in the FNF products. The forest border pixels in the FNF products are defined as the either the forest pixel or the non-forest pixel along the 2 classes. By subsequent dilation of these border pixels, we define the pixel distance 1, pixel distance 2 etc.
Along the forest border, the maximum distance of the forest pixel to the measured GPS position is therefore the (pixel size) x (pixel distance+1).
This measured was applied to the unfiltered FNF products in 30m resolution (Table 18) the FNF products where a 3x3 majority filter was applied (Table 19)
With this validation methods the Sentinel-1 products are the most accurate, followed by the combine S1A and ALOS-2 PALSAR-2 based product and the ALOS PALSAR product.

Table 18. Pixel distance of FNF border pixels to forest border GPS positions (unfiltered FNF products)

Sensor	Year	30m-Pixel Distance to GPS Forest Border Position							
		0	1	2	3	4	5	>5	Mean
Sentinel-1	2015-2016	115	18	5					1.20
Sentinel-1/ALOS-2	2014-2016	108	23	7					1.27
ALOS-2 PALSAR-2	2014-2016	89	38	10	1				1.44
ENVISAT ASAR -AP	2010-2011	93	28	11	4	2			1.51
ALOS PALSAR	2007-2010	105	28	4	1				1.28
ENVISAT ASAR -WS	2002-2010	67	30	20	6	5	5	5	2.18

Table 19. Pixel distance of FNF border pixels to forest border GPS positions (FNF products filtered with a 3x3 majority filter)

Sensor	Year	30m-Pixel Distance to GPS Forest Border Position							
		0	1	2	3	4	5	>5	Mean
Sentinel-1	2015-2016	93	28	15	1	0	1	0	1.48
Sentinel-1/ALOS-2	2014-2016	89	24	17	7	1	0	0	1.60
ALOS-2 PALSAR-2	2014-2016	64	36	15	13	4	4	2	2.11
ENVISAT ASAR -AP	2010-2011	77	31	18	8	3	1	0	1.78
ALOS PALSAR	2007-2010	87	26	12	7	3	2	1	1.72
ENVISAT ASAR -WS	2002-2010	51	31	20	6	11	5	14	2.75

8.3 Validation of Forest Change Detection (FCD) Products

8.3.1 Assessment of the FCD products with Global Forest Cover.

Table 20. FCD products delivered to OSFAC

FOREST CHANGE MAPS		
DRC_S4R_FCD_ForestPALavgvar_maj3_PAL-PAL-HVdiff3_2007-2010_UTM34S_30m_v2	PAL	2007-2010
DRC_S4R_FCD_ForestPALavgvar_maj3_PAL-PAL2-HVdiff3_2010-2015_UTM34S_30m_v2	PAL-PAL2	2010-2015
DRC_S4R_FCD_S1A-PAL2_2015-2016_diff5_UTM34S_30m	S1A-PAL2	2015-2016

8.3.2 Assessment of the FCD products with Global Forest Cover.

Table 20 shows the forest change detection end products that have been developed during the project. FCD is mainly based on thresholding a difference in backscatter between two times or time periods. The level of threshold has to be smartly chosen in order to find a good balance between detecting real changes and false alarms. Most small scale changes are therefore more an indication of where changes occur rather than a precise delimitation of the area changed, especially if post filtering is applied to the FCD products.

Quantitative validation of such products is quite challenging for several reasons:

- VHR reference products are rarely available over large areas at the right times, just before time 0 and just after time1.
- Forest changes and forest loss over long time periods might not be clearly visible because of strong regrowth in the tropics. Especially C-band SAR data can saturate quickly in this regard.
- The validation of forest land cover products improve with the density of time series of data, hence with the integration of longer time periods of SAR data. This approach, which has mainly been used in this project since we try to observe a relatively large region will generally filter out strong abrupt small changes.

It should therefore be noted that the above results indicate more hotspots of forest changes than correct delimitations of those changes. Data availability, data timing needs then better to be controlled and change thresholds can then also be adapted to detect the changes in a more precise way at particular sites. A commonly accepted reference for forest change is based on the Global Forest Change data (GFC) from Hansen et al. (2013). Figure 32 shows the interannual variability of the annual forest loss for the Mai Ndombe region according to GFC. As it varies by a factor of 5 between 2003 and 2010 for example, it is still questionable if this data really is a reliable reference for validation.

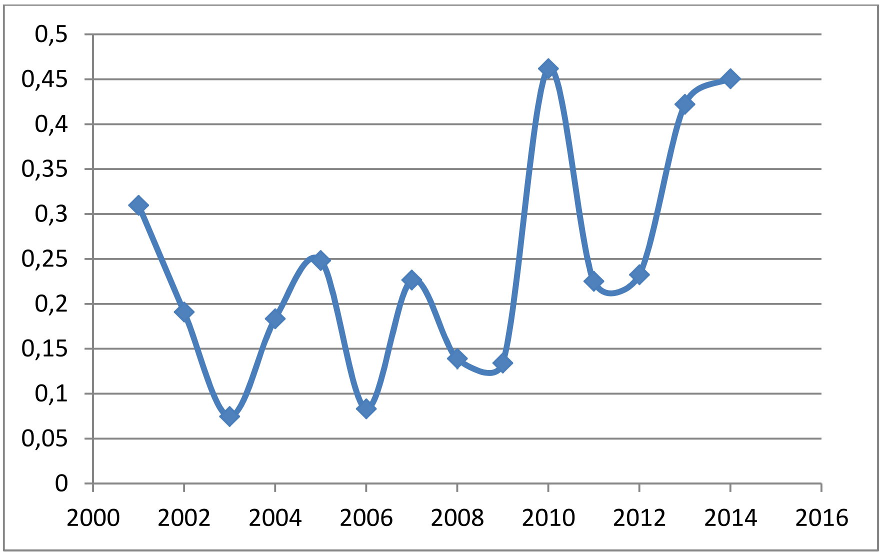


Figure 32. Forest loss in percent per year in the Mai Ndombe district according to GFC (Hansen et al., 2013)

Detected forest loss in the SAR data when compared to results from GFC show therefore high discrepancies. Still, there is strong agreement on hotspots of forest loss as indicated in Figure 33.

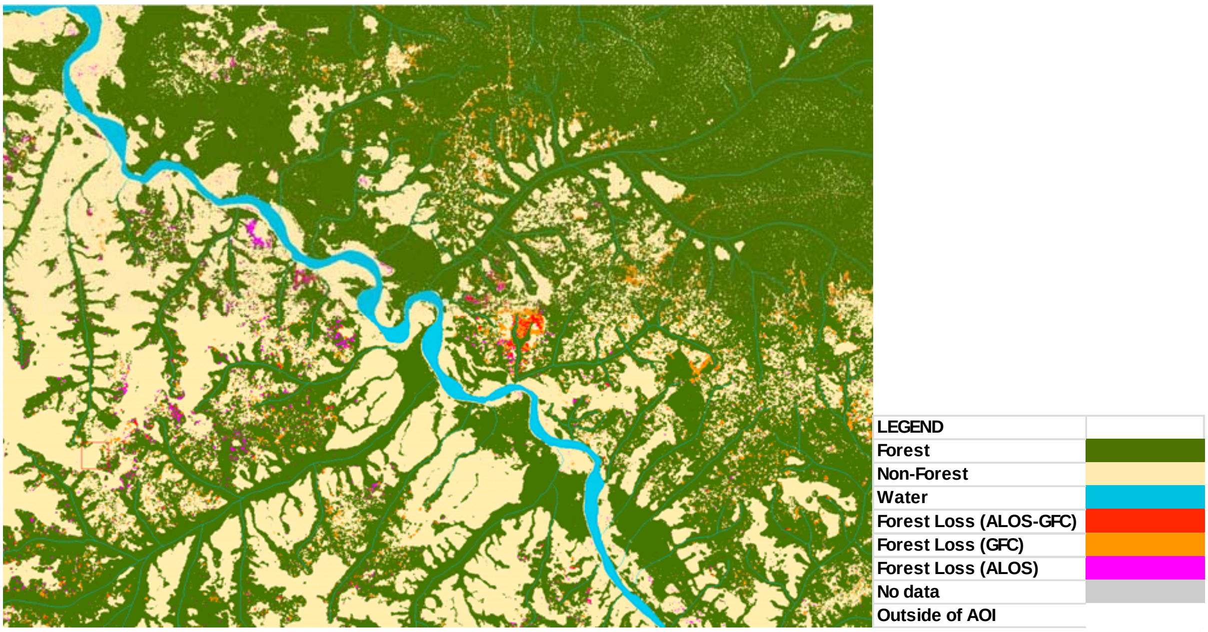


Figure 33. Detailed view if the comparison between forest loss of GFC and ALOS PALSAR FCD for the period 2007-2010.

8.3.3 Qualitative Assessment of the FCD products with Ground Truth and VHR data

On a more qualitative basis, comparing FCD results with aerial image mosaics from fieldwork (Figure 34) and VHR satellite data (Figure 35) showed good agreements also on a smaller scales. All visited sites during fieldwork that were chosen based on forest loss results from ALOS and ALOS-2 confirmed that all these regions had undergone strong forest changes in the past.

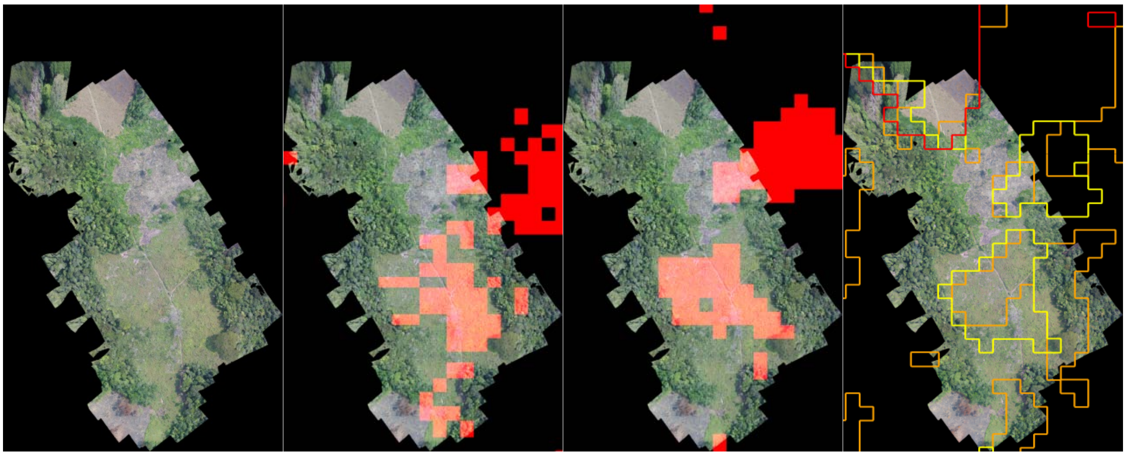


Figure 34. (a) Aerial mosaic from RPAS flight 9 in the Kwamouth region with: (b) GFC forest loss superimposed in red, (c) ALOS/ALOS-2 forest loss superimposed in red and (d) FNF borders from ALOS PALSAR 2007-2010 (red), ALOS2 PALSAR-2 2014-2016 (yellow) and S1 (2015-2016) (orange).

Figure 35 shows the 2015-2016 forest loss areas from combining Sentinel-1 and ALOS-2 data superimposed on a Pleiades image from 19 Nov 2016 over the Kwamouth region in the south-west of Mai-Ndombe district. It clearly detects quite well slash and burn areas visible in this VHR image.

Figure 36 shows also how visible such slash and burn areas are in single scene Sentinel-1 images taken just after the slash & burn activities. Such short term forest changes will not be visible in yearly averaged C-band SAR images because of rapid regrowth.

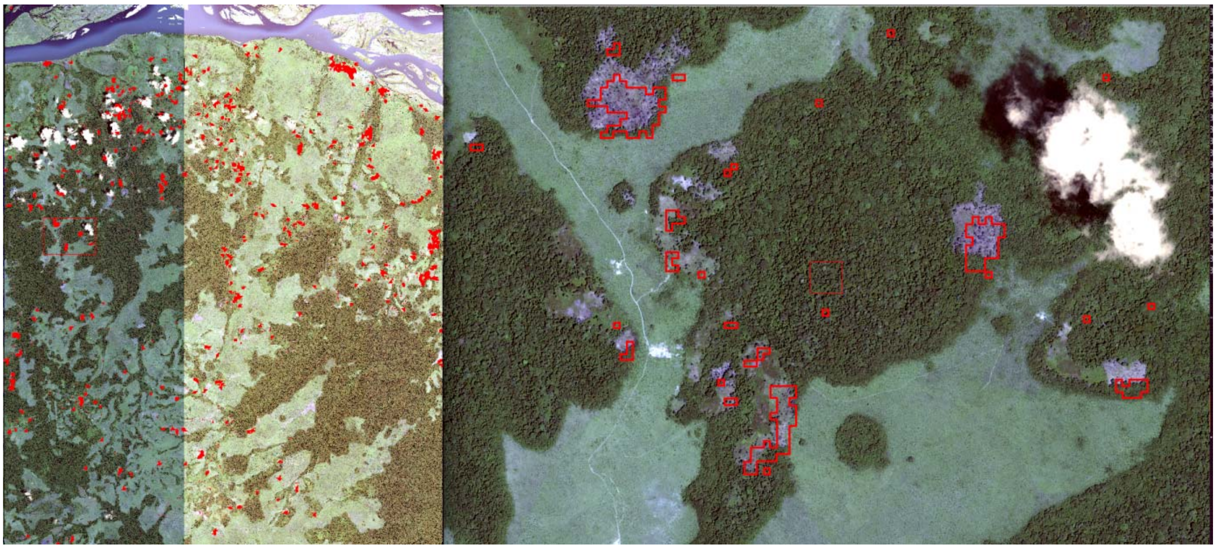


Figure 35. 2015-2016 forest loss areas from combining Sentinel-1 and ALOS-2 data superimposed on a Pleiades image from 19 Nov 2016 over the Kwamouth region. The right panel shows a detailed zoom of the red rectangle in the left.

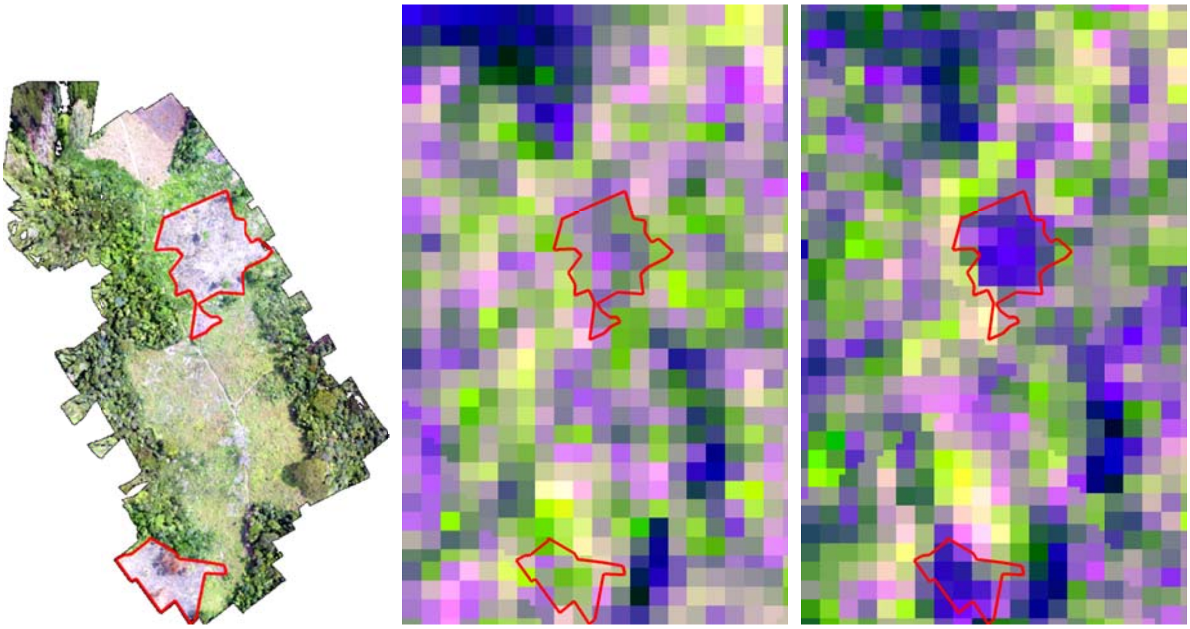


Figure 36. (a) Aerial image mosaic from RPAS flight 9 on 9 September 2016 with slash & burn areas contoured in red, and the S1 images from (b) 16 Jun 2016 and (c) 20 Sep 2016.

Such detailed comparison shows the high potential of using SAR data for annual, multi-annual forest change detection as well as for the detection of slash and burn scares. As a final note, the whole series of FLC, FNF and FCD products are demonstration products for a relatively large region. Forest changes and forest/land cover types might vary over the whole area, meaning that the approach could be optimizes for specific sites and would probably result in even higher accuracies than those presented in the validation report (Haarpaintner & Singa, 2017). The delivery of the SAR processing system should give the regional user the possibility to adapt such approaches to specific needs.

9 Capacity Building

Figure 37. Participants at the OSFAC-Norut SAR workshop

9.1 Background

Since the 1990s, Norut has developed its own in-house SAR (pre)-processing system, based on IDL, for both research as well as operational tasks. OSFAC has shown strong interest to implement such technology into their operations and satellite data portfolio and requested Norut's support for technical and human capacity building. Commercial software for SAR pre-processing is often very expensive and free software seems not so easy to be adapted for operation operations or requires quite a lot of prior knowledge to be used correctly.. The delivery of easy to use technical SAR processing capabilities as well as to build the necessary human capacity so that these tools can be used at the users premises is the aim of SAR for REDD. To achieve this, a short technical workshop on SAR background, pre-processing and application was originally planned at the end of the project. Instead, a one week workshop was held in the middle of the project and a follow up was proposed via skype with an updated version of the software tools. The first SAR workshop was therefore held at OSFAC's premises in Kinshasa from 25-29 April 2016.

9.2 OSFAC-Norut SAR workshop, Kinshasa, DRC, 25-29 April 2016

9.2.1 Aim of the SAR workshop

The aim of this first workshop was to give an introduction to SAR technology to present the general principles of satellite based radar remote sensing, including in regard to its differences to optical satellite monitoring, different radar frequencies, acquisition geometry and processing/application challenges. The workshop also provided a hands-on experience on pre-processing level-1 SAR data with Norut's software, analyzing the georeferenced data from a statistical point of view and further processing the data into forest and land cover products.

9.2.2 Agenda of the workshop

The agenda of the 5-day workshop was as follows:

Monday, 25 April 2016
Introduction
Generalities about Synthetic Aperture Radar
Different SAR satellite data, formats and ordering platforms

***Tuesday, 26 April 2016**:*
Pre-processing SAR data from level-1 to geo-referenced backscatter images
Exercise: Test of Norut's pre-processing system

Wednesday, 27 April 2016
Mosaicking, temporal averaging and statistical analysis of time series and big data sets
Exercise: Test Norut's tool for mosaicking and statistical analysis

Thursday, 28 April 2016
Forest and land cover mapping with SAR
Forest change detection with SAR

Friday, *29 April 2016*
Validation with optical data

9.2.3 Workshop material:

The presentations at the SAR workshop were in a large part based on presentations from the "SAR Remote Sensing Educational Initiative (SAR-EDU)" from the German Aerospace Center (DLR) that are freely available at https://saredu.dlr.de/ , and 6th ESA Training Course on Radar Remote Sensing (http://www.trisat.um.si/esaradar/). Additional slides were extracted from capacity building workshops organized by the Global Forest Observation Initiative (GFOI) and the SilvaCarbon technical workshops and personal presentations from Jörg Haarpaintner (Norut).
The processing software used during the workshop was the preliminary version of an easy-to-use compiled software toolbox of Norut's in-house developed SAR processing software GSAR. This software package has also been provided to OSFAC for further application and in-house processing capabilities. An up-dated version of this software has then been provided at the end of the project. See Section 6 of this report for technical details of this software package.
SAR satellite data used during the workshop was from the whole data set over the Mai-Ndombe district processed as demonstration products. The data was provided through ESA cat-1 proposal nr. 27689, the Sentinel Science Hub and JAXA ALOS-2 RA4 proposal nr PI-1205, covering the SAR for REDD study site, the Mai Ndombe district .

9.2.4 Workshop participants

The whole workshop, lectures and exercises were given by Jörg Haarpaintner, Norut.
The entire technical staff from OSFAC attended the 5-day workshop and participated in the exercises. The participants are shown in Figure 37.

9.3 Summary, Challenges & Outcome

The workshop was held in French with presenting material in English and followed quite closely the original agenda, starting with theoretical power-point presentations in the morning (ca. 0900-1200) and data analysis and processing exercises in the afternoon (1400-1700). Norut's software included three main tools that are run on Linux with free IDL runtime version and provides pre-processing, mosaicking and statistical analysis capabilities. No IDL license is needed to run these tools. One Linux computer with IDL installed was provided for this workshop. As the Linux version and IDL version were not compatible at the start, exercises were started from the second day of the workshop on. Level-1 data sets and time series from Sentinel-1, ALOS PALSAR and ALOS PALSAR-2 data were processed during the workshop in groups of 2-3 students. These georeferenced, radiometrically corrected SAR backscatter images were then mosaicked and statistically analyzed for land cover classifications by each group. Land cover classifications attempts were done individually on the students' preferred image processing software. During this workshop each student therefore had the opportunity and should theoretical be able to process level-1 SAR data to forest-land cover products. These products were then compared to GoogleEarth data and the FACET atlas.

The main challenges with this workshop were short power failure and slow internet connection, which made installing Linux or IDL updates challenging. Near-real time downloading of Sentinel-1 data for example was not possible. Data collected prior to this workshop by Jörg Haarpaintner, was handed on a 4GB external hard drive to OSFAC together with the presentations held at the workshop and Norut's software tools.

Both, Norut and OSFAC still considered this workshop a success and look forward to more cooperation in the future.

Norut is available for further question about the software via skype and email, especially concerning the updated version of the software. A demonstration of the software to other local stakeholder is also still considered as soon as OSFAC has acquired more experience with it.

10 Service Assessment and Future Outlook

The service has been assessed by both, the provider (Norut) and the user (OSFAC) with some comments about the future outlook. The complete service assessments are attached in the Annex B1 and B2, respectively.

10.1 Norut' Service Assessment

Norut's considers the overall service provision as successful.
All SAR based satellite products have been delivered as well as necessary SAR processing tools that should provide the user with the technical capacity to reproduce the results. One technical workshop has taken place in order that OSFAC has also the human capacity to run the provided tools and further develop methodologies using SAR data. The demonstration products and their method description should serve as references for monitoring other regions.
The products provided and specifically the forest/non-forest classification products have accuracies in the range of 85%-95% comparable with optical products.
With the launch of Sentinel-1B, denser time series will be available and will further increase the accuracies as well as the detection of forest change on smaller time scales, such as burn scars.
The service and processing tools should enable the user to handle SAR data and implement such data in the daily operations. It should also allow the user of more contribution to other remote sensing projects and strengthen their position as consultant to the Ministry of Environment.
Since autumn 2016, the political situation in DRC has been quite challenging which affected the final dissemination plan of the project and organized a final public workshop for other stakeholders.
We hope that a final dissemination workshop can still be done to promote the project. The next AFRIGEOSS symposium in 2018 could be an alternative opportunity and would also reach out to other countries.
A main issue for institutions in DRC and bottle neck for the use of the capacity is still the data transfer of high volume satellite data. In order to provide near-real time data processing, either the data transfer has to be improved or it would be necessary to offer the whole SAR processing system via cloud processing with easy access.
A political issue is that the most important REDD stakeholders and funding providers have their main focus on optical monitoring and seem to be quite skeptical to monitoring results based on SAR data. We hope that this project and hopefully the continuous use of the capacity by the user show the high potential of SAR monitoring for REDD.

10.2 OSFAC's Service Assessment

Also OSFAC considered the overall service provision as a success.
The demonstration products were assessed and validated in detail and are considered useful, of high quality and accuracy by the user.
The provided software tools enable OSFAC to analyze and process SAR data themselves in the future.
It will enable OSFAC and its partners, in particular the Ministry of the Environment, to diversify their sources of data on forest monitoring.
OSFAC plans to fully integrate the system into their current operation shortly in order to improve their monitoring capabilities in regard to the national process to implement REDD, and an adequate forest monitoring system to ensure reliable and efficient Monitoring Reporting and Verification (MRV).
OSFAC wishes to further strengthen its technical staff on the processing of SAR data to better appropriate the service they have received.
An important prerequisite and requirement from OSFAC is that a complete and regular supply of data is ensured in the future for regular monitoring of Congo Basin forests. It would therefore be desirable that the collaboration between ESA and End Users be formalized in order to facilitate good communication on some key points such as opportunities and challenges on the practical use of Earth observation data in sustainable forest management.

11 Dissemination of results.

The project has been disseminated through eight oral and three poster presentation at international conferences, workshops and meeting, and further publication of the results in scientific journals is also planned.

A leaflet with an executive summary has been produced.

The project and results have been presented at several occasions:

- the BMZ-DLR international conference on MRV of REDD, Bad Godesberg, Germany, 21-22 September 2015.
- ESA's 6th International Workshop on Retrieval of Bio- & Geo-physical Parameters from SAR Data for Land Applications, ECSAT, Harwell, UK, 17-19 November 2015,
- GFOI Plenary Meetings, Frascati, Italy, 22-26 February 2016,
- SAR workshop, OSFAC, Kinshasa, DRC, 25-29 April 2016,
- ESA Living Planet Symposium 2016, Prague, Czech Republic. 9-13 May 2016,
- GEO European Project workshop, Berlin, Germany, 31 May -2 June 2016,
- GFOI Science Meeting in Den Haag, The Netherlands, 31 Oct – 3 Nov 2016.
- Worldcover2017 ESA conference, Frascati, 14-16 March 2017,
- ISRSE-37, Tshwane, Pretoria, South Africa, 7 - 12 May 2017.
- 3rd PI Workshop of the Advanced Land Observing Satellite-2 (ALOS-2) Research Announcement (RA), Tokyo, Japan, 22-25 January 2018

11.1 List of Published Articles/papers

Haarpaintner, J. (2016). SAR for REDD+ in the Mai Ndombe District (DRC). Proc. 'Living Planet Symposium 2016', Prague, Czech Republic, 9–13 May 2016 (ESA SP-740, August 2016, ISBN 978-92-9221-305-3, ISSN 1609-042X).

Reiche, J., R. Lucas, A.L. Mitchell, J. Verbesselt, D.H. Hoekman, J. Haarpaintner, J.M. Kellndorfer, A. Rosenqvist, E.A. Lehmann, C.E. Woodcock, F.M. Seifert and M. Herold. (2016). Combining satellite data for better tropical forest monitoring. *Nature Climate Change 6(2),120-122, DOI: 10.1038/nclimate2919.*

11.2 List of Promotional Events

- 21-22 September 2015. Poster presentation at the BMZ-DLR international conference on MRV of REDD, Bad Godesberg, Germany.
  - Haarpaintner, J. " SAR for REDD+ - Providing Synthetic Aperture Radar Processing Capabilities to REDD Countries."

- 17-19 November 2015. Oral presentation at ESA's 6th International Workshop on Retrieval of Bio- & Geo-physical Parameters from SAR Data for Land Applications (ECSAT, UK).
  - Haarpaintner, J. "SAR for REDD+."

- 22-26 February 2016. Oral presentation at GFOI Plenary Meetings, Frascati, Italy.
  - Haarpaintner, J. "SAR for REDD. "

- 25-29 April 2016. SAR workshop held for OSFAC staff, OSFAC, Kinshasa, DRC, by J.Haarpaintner

- 9-13 May 2016. Poster presentation at 2016 ESA Living Planet Symposium 2016, Prague, Czech Republic.

- Haarpaintner, J. (2016). SAR for REDD+ in the Mai Ndombe District (DRC). *Proc. 'Living Planet Symposium 2016', Prague, Czech Republic, 9–13 May 2016 (ESA SP-740, August 2016, ISBN 978-92-9221-305-3, ISSN 1609-042X).*

- 31 May 2016. Oral presentation at GEO European Project workshop, Berlin, Germany.
  - Haarpaintner, J. "SAR FOR REDD+: Supporting GFOI R&D priorities using Synthetic Aperture Radar - SAR for REDD."

- 31 Oct – 3 Nov 2016. Oral presentation at the GFOI Science Meeting in Den Haag, The Netherlands, 31 Oct – 3 Nov 2016.
  - Haarpaintner, J. "Forest, Landcover and Forest Change mapping with SAR from ENVISAT/ALOS to Sentinel-1/ALOS-2 in the Mai-Ndombe District, DRC."

- 14-16 March 2017. Poster at Worldcover2017 ESA conference, Frascati, Italy.
  - Haarpaintner, J., A. Mazinga, and L. Mane. "Sentinel-1 Forest Land Cover Classification and Forest Change of the Mai-Ndombe District, D.R. Congo."

- 7 - 12 May 2017. 2 oral presentations at the ISRSE-37, Tshwane, Pretoria, South Africa.
  - Haarpaintner, J. "Forest and Forest Loss Mapping with SAR from the ENVISAT/ALOS era to the Sentinel-1/ALOS-2 present in the Mai-Ndombe District, DRC. "
  - Haarpaintner, J. "Validation of SAR-based forest land cover and forest change maps and detectability of slash-and-burn activities in the Kwamouth region, Mai-Ndombe District, DRC. "

- 22 – 25 May 2018. Oral presentation at the 3rd PI Workshop of the Advanced Land Observing Satellite-2 (ALOS-2) Research Announcement (RA), TKP Garden City Takebashi, Tokyo, Japan.
  - Haarpaintner, J. "Forest and forest loss mapping from ALOS to ALOS-2 in the Mai-Ndombe District, DRC."

12 References

Almeida-Filho, R., Shimabukuro, Y. E., Rosenqvist, A. and G.A. Sánchez, "Using dual-polarized ALOS PALSAR data for detecting new fronts of deforestation in the Brazilian Amazônia", International Journal of Remote Sensing, vol. 30, no. 14, pp. 3735–3743, Jan. 2009.

ESA (2016). http://www.esa.int/spaceinimages/Images/2016/05/African_mosaic

GEO (2012), AfriGEOSS, an initiative to reinforce GEO in Africa, GEO Executive Committee, March 2012. ftp://ftp.earthobservations.org/GEO-X/GEO-X_11_AfriGEOSS%20-%20Approach,%20Progress%20and%20Way%20Forward.pdf

GFOI (2013) Integrating remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests: Methods and Guidance from the Global Forest Observations Initiative: Pub: Group on Earth Observations, Geneva, Switzerland, 2014, ISBN 978-92-990047-4-6.

GFOI (2013), Review of Priority Research & Development Topics: R&D related to the use of Remote Sensing in National Forest Monitoring, Pub. GEO, Switzerland, 2013 ISBN 978-92-990047-5-3. http://www.gfoi.org/sites/default/files/GFOI_ReviewPrioityRDTopics_V1.pdf

Gullison, R.E., P.C. Frumhoff, J.G. Canadell, C.B. Field, D.C. Nepstad, K. Hayhoe, R. Avissar, L.M. Curran, P. Friedlingstein, C.D. Jones, and C.Nobre, "Tropical Forests and Climate Policy," Science, vol. 316, no. 5827, pp. 985-986, 2007.

Haarpaintner, J. (2016). D1.1 - Requirement Baseline (RB), Delivery 1.1 for ESA DUE – Innovator III project "SAR for REDD", 3 Nov 2015.

Haarpaintner, J. (2016). D1.2 – Technical Specifications (TS), Delivery 1.2 for ESA DUE – Innovator III project "SAR for REDD", 31 Mar 2016.

Haarpaintner, J. (2016). D1.3 – Product Validation Plan (PVP), Delivery 1.3 for ESA DUE – Innovator III project "SAR for REDD", 31 May 2016.

Haarpaintner, J., & H. Hindberg (2017). D2.1 – Product Delivery Report (PDR), Delivery 2.1 for ESA DUE – Innovator III project "SAR for REDD", 4 Apr 2017.

Haarpaintner, J. & C. Singa (2017). D2.2 – Product Validation Report (PVR), Delivery 2.2 for ESA DUE – Innovator III project "SAR for REDD", 18 Apr 2017.

Haarpaintner, J. (2015). SAR for REDD+ - Providing Synthetic Aperture Radar Processing Capabilities to REDD Countries. Oral presentation at BMZ-DLR International Conference on MRV of REDD, Bonn, Germany, 21-22 Sep 2015.

Haarpaintner, J. (2015). SAR for REDD+. Oral presentation at 6th International Workshop on Retrieval of Bio- & Geo-physical Parameters from SAR Data for Land Applications, ESA/ECSAT, Harwell, Oxfordshire, UK, 17-19 November 2015.

Haarpaintner, J. (2016). SAR for REDD+ in the Mai Ndombe District (DRC). Proc. 'Living Planet Symposium 2016', Prague, Czech Republic, 9–13 May 2016 (ESA SP-740, August 2016, ISBN 978-92-9221-305-3, ISSN 1609-042X).

Haarpaintner, J., (2016). SAR for REDD. Oral presentation at GFOI Plenary Meetings, Frascati, Italy, 22-26 February 2016.

Haarpaintner, J., (2016). SAR FOR REDD+: Supporting GFOI R&D priorities using Synthetic Aperture Radar - SAR for REDD. Oral presentation at GEO European projects' workshop, Berlin, Germany, 31 May – 2 Jun 2016.

Haarpaintner, J., R. Almeida-Filho, Y.E. Shimabukuro, E. Malnes, and I. Lauknes, "Comparison of ENVISAT ASAR deforestation monitoring in Amazônia with Landsat-TM and ALOS PALSAR images". Anais XIV Simpósio Brasileiro de Sensoriamento Remoto, Natal, Brasil, 25-30 Apr 2009, INPE, 5857-5864, 2009.

Haarpaintner, J, C. Davids, H. Hindberg, E. Zahabu, and R.E. Malimbwi, 2015. Forest and Forest Change Mapping with C- and L-band SAR in Liwale, Tanzania. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XL-7/W3, 391-395, doi:10.5194/isprsarchives-XL-7-W3-391-2015, 2015.*

Haarpaintner, J., Ø. Due Trier, and J. Otieno, "GEO FCT Product Development Team Report – Tanzania", Presentation at the GEO-FCT Science & Data Summit #3, Arusha, Tanzania, February 6-10, 2012.

Haarpaintner, J., K. Einzmann, Y. Larsen, D. Pedrazzani, M.T. Mateos San Juan, M. Gómez Giménez, F. Enβle, J. Heinzel, and L. Mane, "Tropical forest remote sensing services for the Democratic Republic of Congo case inside the EU FP7 ReCover project (1st iteration)", Proceedings of IEEE International Geoscience and Remote Sensing Symposium 22-27 July 2012, Munich, Germany, IEEE Catalog Number CFP12IGA-USB, ISBN: 978-1-4673-1158-8, pp. 6392-6395, 2012.

Haarpaintner, J., M. Kohling, D. Pedrazzani, F. Enßle, and L. Mane, "Improving the Tropical Forest Remote Sensing Services for the Dem. Rep. of Congo inside the EU FP7 "RECOVER" Project", Oral presentation at the ESA Living Planet Symposium 2013, Edinburgh, UK, 09-13 Sep. 2013.

Haarpaintner, J., A. Mazinga, and L. Mane (2017). Sentinel-1 Forest Land Cover Classification and Forest Change of the Mai-Ndombe District, D.R. Congo. Poster at the Worldcover 2017 Conference, ESA/ESRIN, Frascati, Italy, 14-16 March 2017.

Häme, T. and A. Lönnqvist, "Science-based remote sensing services to support REDD and sustainable Forest management in the tropical region", Proceedings of Hungarian Space Conference, Budapest, Hungary, May 2011.

Hansen M.C., Potapov P. V., Moore R., Hancher M., Turubanova S. A., Tyukavina A., Thau D., Stehman S.V., Goetz S.J., Loveland T.R., Kommareddy A., Egorov A., Chini L., Justice C.O., Townshend J.R.G. (2013) High-resolution global maps of 21-st-century forest cover change. Science, 342, 850-853. Data available on-line from: http://earthenginepartners.appspot.com/science-2013-global-forest.

Herold, M. and M. Skutsch, "Measurement, reporting and verification for REDD+: Objectives, capacities and institutions," in Measurement, reporting and verification in a post-2012 climate agreement, CIFOR, pp. 85-100, 2009.

Hoekman, D.H., Vissers, M.A.M. and N. Wielaard, "PALSAR Wide-Area Mapping of Borneo: Methodology and Map Validation", IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 3, no. 4, pp. 605-617, Dec. 2010.

Larsen, Y., G. Engen, T. R. Lauknes, E. Malnes, and K. A. Høgda, 2005.A generic differential InSAR processing system, with applications to land subsidence and SWE retrieval, *FRINGE 2005, ESA ESRIN, Frascati, Italy, Nov 28-Dec 2, 2005.*

Mitchard. E.T.A., S.S. Saatchi, I.H. Woodhouse, G. Nangendo, N.S. Ribeiro, M. Williams, C.M. Ryan, S.L. Lewis, T.R. Feldpausch, and P. Meir, "Using satellite radar backscatter to predict above-ground woody biomass: A consistent relationship across four different African landscapes". Geophys. Res. Letters, vol. 36, L23401, 2009.

Olofsson, P., Foody, G.M., Stehman, S.V., & Woodcock, C.E. (2013). Making better use of accuracy data in land change studies: estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sensing of Environment 129:122-131.

Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E. & Wulder, M.A. (2014). Good practice for estimating area and assessing accuracy of land change. Remote Sensing of Environment 148:42-57.

OSFAC (2010). Monitoring the forests of Central Africa using remotely sensed data sets (FACET), 2010. Forest cover and forest cover loss in the Democratic Republic of Congo from 2000 to 2010. Published by South Dakota State University, Brookings, South Dakota, US, ISBN: 978-0-9797182-5-0, © Observatoire Satellital des forêts d'Afrique centrale, 2010.

Reiche, J., R. Lucas, A.L. Mitchell, J. Verbesselt, D.H. Hoekman, J. Haarpaintner, J.M. Kellndorfer, A. Rosenqvist, E.A. Lehmann, C.E. Woodcock, F.M. Seifert and M. Herold. (2016). Combining satellite data for better tropical forest monitoring. Nature Climate Change 6(2),120-122, DOI: 10.1038/nclimate2919.

Sukhdevb, P., R. Prabhua, P. Kumara, A. Bassic, W. Patwa-Shaha, T. Entersa, G. Labbatea, and J. Greenwalta, "REDD+ and a Green Economy: Opportunities for a mutually supportive relationship", UN-REDD Programme Policy Brief, Issue #01, http://www.un-redd.org, 2012.

Ulander, L., 1996. Radiometric slope correction of synthetic aperture radar images. *IEEE Transactions on Geoscience and Remote Sensing,34(5), pp.1115-1122.*

Van der Werf, G.R., D. C. Morton, R. S. DeFries, J. G. J. Olivier, P. S. Kasibhatla, R. B. Jackson, G. J. Collatz and J. T. Randerson, "CO2 emissions from forest loss," Nature Geoscience, vol. 2, no. 11, pp. 737-738, Nov. 2009.

13 ANNEX A: User Requirement Document (URD) from OSFAC

A.1 End-User organisation presentation and expectations

A.1.1 End-user organisation

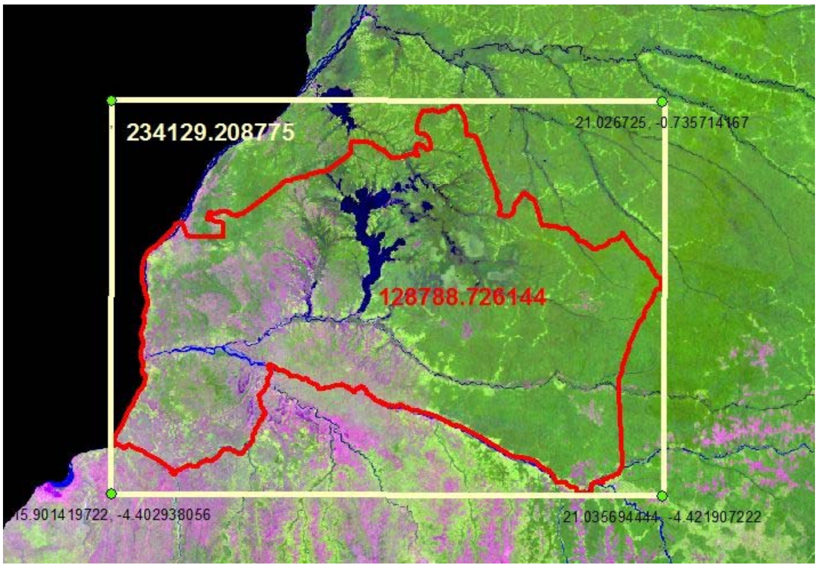
1. End-User Organisation	
Name:	Observatoire Satellital des Forêts d'Afrique Centrale (OSFAC)
Type of organisation:	Non-Governmental Organisation (NGO)
Description:	OSFAC was launched as the GOFC-GOLD network for Central Africa under the Global Terrestrial Observing System (GTOS). Its primary objective is to support the management of natural resources and promote sustainable development by producing reliable land cover products, distributing satellite data, building capacity and providing technical assistance to implementing partners.
Department/Division/Section/Unit:	Technical Department at OSFAC head office in Kinshasa (DRC)
Website:	http://www.osfac.net/
Contact person:	Dr Landing Mane (Director) Email: lmane@osfac.net Tel.: 243992783035

A.1.2 Requirements overview

2. Requirements overview	
Description of the requested services:	OSFAC requests tools for pre-processing and analysis of up-coming SAR data specifically from Sentinel-1 and ALOS2
Current practice:	Optical remote sensing
Motivation and expectation:	Complement optical remote sensing with synthetic aperture radar for monitoring tropical forest for monitoring, reporting and verification of REDD+ activities.

A.2 Service and product requirements

A.2.1 Areas of interest and service demonstration areas

3. Area of Interest	
Name:	Congo Basin
Type:	Wet tropics, river basin and coastal area with persistent cloud cover
Geographical coordinates and size of area of interest:	Congo Basin
Geographical coordinates and size of service demonstration area:	ER-PIN area :  - Center geographical coordinates: Lon: 18°31'26.144"E Lat: 2°42'0.999"S Red boundary area enclosed in UL: Lon: 15°54'3.004"E Lat: 0°43'27.616"S UR: Lon: 21°1'36.21"E Lat: 0°44'8.571"S LL: Lon: 15°54'5.111"E Lat: 4°24'10.577"S LR: Lon: 21°2'8.5"E Lat: 4°25'18.866"S Size: 128788.726144 km2 (12878872.6144 ha)
Description:	Mai-Ndombe the area of study is located in the Bandundu Province in the Democratic Republic of Congo (DRC). The area of Mai-Ndombe is very rich in biodiversity and endemic species (Bonobo). However, for many years this area is facing deforestation and forest degradation. The main causes of this

	loss of forests are charcoal production for cities, slash and burn agriculture and industrial logging. For sustainable forest management of Mai Ndombe and reduce emissions of greenhouse gases (GHGs) from deforestation and forest degradation, it is important to have reliable information on the extent and trends of these forests. This information is necessary in the implementation of the MRV/REDD + process in which DRC is engaged.
Problems/Issues:	Persistent cloud cover in the tropics often prevent optical remote sensing and synthetic aperture radar can overcome this problem
User organisation:	OSFAC

A.2.2 Description of the required service and products

4. Description of service/product	
General description	
General service/product description:	All products should be based on synthetic aperture radar (SAR) imagery to complement optical remote sensing products : Operational near- real time pre-processing (georeferencing, radiometric correction and slope correction) of SAR imagery from ESA's Sentinel-1, Radarsat-2 and ALOS-2 in all available polarizations. Provision of wet and dry seasonal mosaics, time series and temporal-average, speckle-reduce composites Derived yearly forest-non forest maps from SAR imagery Yearly change products Hot-spot alert system for deforestation
Uses and benefits:	Interoperability and complementarity with optical data sets
Product specifications	
Spatial scale:	30m
Minimum cell size (or mapping unit):	30m x 30m
Information layers:	Sigma0 Backscatter image

	Forest/non-forest Forest change
Product format:	Raster files in geotiff and/or ENVI format
Software platform compatibility:	Compatibility with most GIS and image processing software (specifically ArcGIS, ENVI)
Product accuracy:	
Service Specifications	
Years of interest:	Up-coming years of ESA's Sentinel-1 operation, ALOS-2 and Radarsat-2
Temporal range:	2015-2017
Updating frequency:	Near-real time up-dating with all available data from Sentinel-1 , ALOS-2 and Radarsat-2
Temporal baseline:	2015
Ordering:	In-house processing
Delivery time required:	In-house processing (Near-real time for pre-processed single scene, monthly/bi-annual for mosaics and temporal averaged products average and yearly for forest/non-forest products and yearly change near-real time hot spots of deforestation
Delivery format:	Web-based if possible depending on internet accessibility or DVD/hard drives
Validation data	
Available at the end-user's premises:	- Mai-Ndombe field data. - Draft of Carbon map provided by WWF and UCLA - Forest maps of EO4REDD project (west area)
Available elsewhere:	Landsat-8, SPOT5/TAKE5
Planned collection and when:	Field campaign in 2016 to collect land cover descriptions if possible with aerial photos from remotely piloted aerial system Data on forest inventory for biomass and GHGs quantification.

14 ANNEX B1: Service Assessment Sheet by Norut

ANNEX B. SERVICE ASSESSMENT SHEET

By Norut

The following Service Assessment Sheets shall be separately completed by each end-user and by the Contractor, at the Mid Term Review and at the Final Review.

B.1 Assessment of the user requirements

Adequacy of the User Requirements Document (URD) requirements (including accuracy)	Evaluation*		
	L	M	H
		X	

Comments:

The URD is set up for the provision of satellite products. However, the main goal of this project was to provide SAR pre-processing and analysis software in order to build human and technical capacity at the user's premises.
The products defined are therefore more products the user aims to be able to produce in-house.
D1.1-Requirement Baseline defines in more detail the products that had to be delivered during the project.

* Low; Medium; High

B.2 Product compliance

Overall product compliance to the user requirements	Evaluation*		
	L	M	H
			X

Comments:

All yearly products were delivered as required.
In addition pre-processed single scenes were provided as well as the software to reprocess the data and reproduce the results as well as produce additional results, like seasonal (wet and dry) mosaics.
The provided processing software also produces an automatic forest/non-forest products. However, in order to result in high accuracies, manual selection of input data and which seasonal mosaics to consider is advised, especially considering forest change.

* Low; Medium; High

Product accuracy compliance to the user requirements	Evaluation*		
	L	M	H
			X

Comments:

The forest and forest land cover products show high accuracies (in the range of 85-95 %) comparable to optical Landsat-like data. The accuracy requirement was 80% and the delivered products fulfilled therefore clearly the requirements.
Forest change maps provided hotspots of forest loss also at a yearly time scale and detected forest loss areas that have been visited during fieldwork were confirmed on site.
The geolocation of SAR products is only dependent on the digital elevation model and provision of satellite orbit parameters. Both auxiliary data showed to be of high accuracies and therefore also the inter-comparison of the geolocation/colocation of the product

* Low; Medium; High

Confidence in the product quality (including accuracy)	Evaluation*		
	L	M	H
			X

Comments:

Confidence in the products' quality is very high. In addition to the forest-non-forest map, also land cover types have been validated and confirmed during fieldwork. Especially the ALOS PALSAR L-band based forest land cover products showed very high correspondence in-situ. It is clear that denser time series will additionally improve the temporal filtering and such the accuracies of the products.

* Low; Medium; High

B.3 Utility assessment

Benefits of the demonstrated service and products	Evaluation*		
	L	M	H
			X

Comments:

The main purpose of the provided products is to demonstrate the contribution of SAR data for operational national forest monitoring systems for REDD and that even relatively simple methods, like maximum likelihood classification, which are part of most image processing software are quite robust. The overall aim for the project is to enable the user to overcome the technical hurdles of pre-processing and temporal filtering of SAR data with automatic, easy-to-use tools.

* Low; Medium; High

Impact of the service and products on current end-user practices	Evaluation*		
	L	M	H
			X

Comments:

The service and processing tools should enable the user to handle SAR data and implement such data in the daily operations. It should also allow the user of more contribution to other remote sensing projects and strengthen their position as consultant to the Ministry of Environment.

* Low; Medium; High

B.4 Future outlook

Probability of service integration into existing practices	Evaluation*		
	L	M	H
			X

Comments:

The user has already participated in a proposal where SAR data processing and analysis is part of the contribution. So the probability to integrate the service in their existing practices should be high.

* Low; Medium; High

Desired service and/or product(s) improvements	Evaluation*		
	L	M	H
			X

Comments:

Norut would be happy to further contribute to further method development and to implement SAR data into national forest monitoring systems for REDD/MRV. In addition, the era of dense time series of SAR data has just begun and it opens a wide range of further potential use especially considering short time scale forest changes, detection of forest burn scares etc. Also, longer time series could open for more applications and higher accuracies in the results. A next step would also be cloud processing of the data which would allow very large scale applications.

* Low; Medium; High

Needs for a large-scale service/product demonstration	Evaluation*		
	L	M	H
			X

Comments:

The service has already been demonstrated on a quite large scale of more than 128 000 km^2. A further extension in space would be possible and with the high availability of the data, it would be necessary to overcome the data transfer, by cloud processing. Norut is working in this direction.

* Low; Medium; High

B.5 Overall evaluation

Overall service and products evaluation	Evaluation*		
	L	M	H
			X

Comments:

The overall service and the delivered products are considered quite important. Political instability in the Democratic Republic of Congo has made the last part of the project more difficult in regard to a possible final workshop to present the results to stakeholders and among them the ministry of environment. We hope that this can be done in the future.
It also seems that this situation effected also the daily operation of the user as the response time was slower as before. Communication via internet or phone is already technical challenging with DRC.

* Low; Medium; High

Recommendations to the European Space Agency

Comments:

The important issues that appeared during this project is the transfer and internet access for the user as well as the high volume of data that had to be downloaded and processed. A focus for future projects should be cloud processing, which also requires the timely data availability.
Another recommendation could also be that ESA can support a stronger integration of such projects in other ESA or international project/programs.

15 ANNEX B2: Service Assessment Sheet by OSFAC

ANNEX B. SERVICE ASSESSMENT SHEET

BY OSFAC

The following Service Assessment Sheets shall be separately completed by each end-user and by the Contractor, at the Mid Term Review and at the Final Review.

B.1 Assessment of the user requirements

Adequacy of the User Requirements Document (URD) requirements (including accuracy)	Evaluation*		
	L	M	H
			X

Comments:

As users, the Satellite Observatory for Central African Forests (OSFAC) received the system and the products generated during the realization of this Project.

* Low; Medium; High

B.2 Product compliance

Overall product compliance to the user requirements	Evaluation*		
	L	M	H
			X

Comments:

With the software and programs provided by NORUT, OSFAC was able to analyze and process SAR data. The technical staff of OSFAC is now able to use the service provided to perform certain analyzes and produce interesting results.

* Low; Medium; High

Product accuracy compliance to the user requirements	Evaluation*		
	L	M	H
			X

Comments:

OSFAC made an accurate assessment of the products received and wrote a report. This evaluation showed that the results of the Forest cover Analysis and Change detection realized by the Project are very accurate.

* Low; Medium; High

Confidence in the product quality (including accuracy)	Evaluation*		
	L	M	H
			X

Comments:

The products received by OSFAC are very good qualities. Indeed the service and the products seem very suitable for the area studied by the Project.

* Low; Medium; High

B.3 Utility assessment

Benefits of the demonstrated service and products	Evaluation* L	M	H
			X

Comments:

The system and products provided by the project are beneficial. The countries of Congo Basin and particularly the DRC are in the process of implementing REDD. A requirement of this process is the implementation of an adequate forest monitoring system to ensure reliable and efficient Monitoring Reporting and Verification (MRV).

* Low; Medium; High

Impact of the service and products on current end-user practices	Evaluation* L	M	H
			X

Comments:

The service and products will enable OSFAC and its partners, in particular the Ministry of the Environment, to diversify their sources of data on forest monitoring.

* Low; Medium; High

B.4 Future outlook

Probability of service integration into existing practices	Evaluation*		
	L	M	H
			X

Comments:

Full integration of this service into the current OSFAC system will be finalized shortly. The service and products will significantly improve current practices in the field of forest monitoring in the DRC.

* Low; Medium; High

Desired service and/or product(s) improvements	Evaluation*		
	L	M	H
			X

Comments:

OSFAC as End User wants that capabilities of its technical staff on the processing of SAR data to be further strengthened to enable them to better appropriate the service they have received.

* Low; Medium; High

Needs for a large-scale service/product demonstration	Evaluation*		
	L	M	H
			X

Comments:

The area chosen in DRC for these initial analyzes is interesting because it allowed to show the opportunities and the constraints for the implementation of the System. The transition to a larger (national) scale should be easy. However, the challenges will not be missed, especially on the one related to the complete and regular availability of satellite data.

* Low; Medium; High

B.5 Overall evaluation

Overall service and products evaluation	Evaluation*		
	L	M	H
			X

Comments:

Overall the service and the products provided are very interesting for the actors of the region and particularly the institutions in charge of forest management. Instability and governance issues in the DRC often have hard-to-predict impacts in the implementation of planned activities. Let's hope that the country's political situation will improve in the years to come.

* Low; Medium; High

Recommendations to the European Space Agency

Comments:

OSFAC recommends that ESA be able to ensure a complete and regular supply of the data needed for regular monitoring of Congo Basin forests. It is also desirable that the collaboration between ESA and End Users be formalized in order to facilitate good communication on some key points such as opportunities and challenges on the practical use of Earth observation data in sustainable forest management.