TO OBSERVE GLOBAL FOREST BIOMASS
FOR A BETTER UNDERSTANDING OF THE CARBON CYCLE

Six Candidate Earth Explorer Core Missions – Report for Assessment 2
CANDIDATE EARTH EXPLORER CORE MISSION

biomass

Report for Assessment
November 2008
SP-1313/2
# Table of Contents

Chapter 1  Introduction .................................................. 1
1.1 Mission Summary .................................................. 3

Chapter 2  Background and Scientific Justification .................. 7
2.1 Introduction ....................................................... 7
2.2 The global carbon cycle ........................................... 9
2.2 The need for improved observations of forest biomass ............. 12
   2.2.2 The need for improved knowledge of the terrestrial carbon pools ................................................ 13
   2.2.3 The need for improved estimation of terrestrial carbon fluxes ...................................................... 18
   2.2.4 Using biomass to improve process model calculations ............. 21
   2.2.5 Additional benefits of forest biomass information for climate and management of the Earth’s resources ...... 26
2.3 The contribution of the BIOMASS mission ......................... 29
   2.3.1 Introduction ................................................ 29
   2.3.2 Forest biomass retrieval using P-band SAR .................... 29
   2.3.3 Measuring forest biomass change with time ................. 37
   2.3.4 Mapping forest disturbance area ............................ 39
   2.3.5 New information on forests through SAR tomography ......... 39
2.4 Secondary mission objectives .................................... 40
   2.4.1 Subsurface geomorphology ................................... 40
   2.4.2 Ice structure and interferometric ice flow measurements .... 41
   2.4.3 Forest inundation .......................................... 42
2.5 Conclusions ....................................................... 42

Chapter 3  Research Objectives ............................................ 45
3.1 Primary mission objectives ....................................... 45
3.2 Secondary mission objectives .................................... 47
3.2 Related planned missions ......................................... 48

Chapter 4  Observation Requirements ................................... 51
4.1 Introduction ....................................................... 51
4.2 Observational approach ......................................... 52
4.3 Geophysical product definition .................................. 54
4.4 Retrieval performance ............................................. 55
   4.4.1 Introduction ................................................ 55
   4.4.2 Forest biomass using radar intensity information ............. 55
   4.4.3 Forest height using polarimetric interferometry .............. 57
   4.4.4 Forest biomass using radar intensity and radar-derived height .................................................. 58
   4.4.5 Forest biomass temporal change ......................... 59
6.7.3 BIOMASS system performance ................................. 98

Chapter 7 Programmatics .............................................. 99
7.1 Introduction ...................................................... 99
7.2 Technical maturity, critical areas and risk .................... 99
  7.2.1 Satellite development ...................................... 99
  7.2.2 Antenna and accommodation ............................. 100
  7.2.3 Radar electronics .......................................... 100
  7.2.4 End-to-end calibration .................................... 101
7.3 Development approach and schedule ......................... 101

References .............................................................. 103

Acronyms ............................................................... 119
Chapter 1 Introduction

Earth Explorer missions focus on the science and research elements of ESA’s Living Planet Programme. Encompassing a new approach to observing the Earth from space, Earth Explorers are developed in direct response to scientific challenges identified by the scientific community. The fundamental principle of defining, developing and operating missions in close cooperation with the scientific community provides an efficient tool to address pressing Earth-science questions as effectively as possible.

Since the science and research elements of ESA’s Living Planet Programme were established in the mid-1990s, this on-going user-driven strategy has, so far, resulted in six Explorer missions selected for implementation. Together, they cover a broad range of issues to further our understanding of the Earth system and the impact of human activity. In addition, the scientific questions addressed also form the basis for the development of new applications for Earth observation data.

Earth Explorer missions are split into two categories – ‘Core’ and ‘Opportunity’. Core Earth Explorers are large missions addressing complex issues of scientific interest whilst Opportunity missions are smaller and supported scientifically by the proposing team. Through a process of selection, Core and Opportunity missions are implemented in separate cycles to ensure a steady flow of missions to address key Earth-science questions.

The first cycle for Core missions resulted in the Gravity field and steady-state Ocean Circulation Explorer (GOCE) launching in 2009, and the Atmospheric Dynamics Mission ADM-Aeolus (due for launch in 2010). The second cycle, initiated in 2000, resulted in the Earth Clouds Aerosols and Radiation Explorer (EarthCARE), due for launch in 2013. The first cycle for Opportunity missions resulted in the ice mission CryoSat, which is currently being rebuilt following a launch failure in 2005 and scheduled for launch in 2009, and the Soil Moisture and Ocean Salinity (SMOS) mission, also scheduled for launch in 2009. The second cycle resulted in the magnetic field mission Swarm, which is due for launch in 2010.

A third cycle of Earth Explorer Core missions was initiated by a Call for Ideas released in March 2005. In May 2006, six of the candidate missions were selected for Assessment Study (Phase 0) following a peer review of 24 proposed mission ideas. Prior to the next stage – the selection of missions for Feasibility Study (Phase A) – a Report for Assessment has been prepared for each of the six Candidate Earth Explorer Core Missions.

The following Reports for Assessment for each of the Candidate Earth Explorer Core Missions are provided to the Earth observation research community prior to the User Consultation Meeting held in January 2009 in Lisbon, Portugal:

- A-SCOPE – to observe atmospheric carbon dioxide for a better understanding of the carbon cycle,
• BIOMASS – to observe global forest biomass for a better understanding of the carbon cycle,
• CoReH₂O – to observe snow and ice for a better understanding of the water cycle,
• FLEX – to observe photosynthesis for a better understanding of the carbon cycle,
• PREMIER – to observe atmospheric composition for a better understanding of chemistry–climate interactions,
• TRAQ – to observe tropospheric composition for a better understanding of air quality.

The six Reports for Assessment all follow a common structure comprising this introductory first chapter and six subsequent chapters as follows:

• Chapter 2 – identifies the issues of concern to be addressed by the mission, considers related past and present activities, justifies the mission set within the post 2015 time frame and includes a review of the current scientific understanding of the issue in question while identifying the potential ‘delta’ that the mission could provide,
• Chapter 3 – drawing on arguments presented in Chapter 2 this chapter summarises the specific research objectives of the mission,
• Chapter 4 – specifies the observational requirements within the context of the scientific objectives including geophysical parameters and associated data products, space/time sampling requirements, timing of the mission etc.,
• Chapter 5 – provides an overview of the mission elements, including the space segment, ground segments and products that are required to fulfil the observational requirements,
• Chapter 6 – details the complete system concept and reviews the technological challenges and levels of technical maturity,
• Chapter 7 – outlines a programme of implementation. Drawing on previous chapters, this chapter also addresses technical maturity, the development status of key technologies, risks, logistics and schedules.
This Report for Assessment covers the BIOMASS mission and is based on contributions from the following members of the Mission Assessment Group (MAG):

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1.1 Mission Summary

Objectives

The scientific objective of BIOMASS is to determine for the first time, in a consistent manner, the global distribution of forest biomass, to reduce uncertainties in the calculations of carbon stocks and fluxes associated with the terrestrial biosphere.

BIOMASS will be used to improve quantification of:

- the terrestrial carbon stocks and fluxes in forests,
- terrestrial carbon sources and sinks, by monitoring and quantifying disturbances and recovery in forests.
The main outcome of the mission will be greatly improved knowledge of the size and distribution of the terrestrial carbon pool, and much improved estimates of terrestrial carbon fluxes.

**Science**

The release of carbon dioxide (CO₂) into the atmosphere by human activities has been recognised as a major driver of climate change. Terrestrial ecosystems play an important role, both in the release of carbon through land use change and deforestation, and in the sequestration of carbon through vegetation growth processes. Over the last 25 years, there is strong evidence that the terrestrial biosphere has acted as a net carbon sink, removing from the atmosphere approximately one third of the CO₂ emitted from fossil fuel combustion. However, terrestrial ecosystems are the largest single source of uncertainty in the global carbon budget (Intergovernmental Panel on Climate Change (IPCC), 2007). The uncertainties lie in the spatial distribution of carbon stocks and carbon exchange, and in the estimates of carbon emissions due to human induced or natural disturbances.

A central parameter in the terrestrial carbon budget is forest biomass, which represents a proxy for carbon. Despite its crucial role in the terrestrial carbon budget, forest biomass is poorly quantified across most parts of the planet due to the great difficulties in measuring biomass on the ground and consistently aggregating measurements across scales.

**Mission**

BIOMASS will be implemented as of a P-band Synthetic Aperture Radar (SAR) mission which will provide first observations of the global distribution of forest biomass.
biomass at a resolution and accuracy compatible with the needs of international reporting on carbon stocks and terrestrial carbon models. The mission will exploit the unique sensitivity of P-band SAR to forest biomass and employ advanced retrieval methods to map forest biomass globally across the whole biomass range encountered in tropical, temperate and boreal forests. BIOMASS will also provide the first opportunity of exploring the Earth’s surface at the P-band wavelength.
Chapter 2  Background and Scientific Justification

2.1  Introduction

The primary environmental science challenge in the early 21st century is to improve our understanding of how global change will affect the Earth system and the feedbacks in this system, in order that human societies can foresee their likely impacts and adopt ways to mitigate and adapt to these impacts.

Deeply embedded in the functioning of the Earth system is the carbon cycle, which consists of the intermeshed set of processes by which carbon is exchanged between the atmosphere, land and ocean. Quantifying this global-scale cycle is fundamental to understanding many of the dramatic changes taking place on Earth.

Terrestrial processes play a crucial role in the carbon cycle through processes of carbon uptake and respiration associated with vegetation growth, and emissions due to disturbance from both natural processes (for example, wildfires) and anthropogenic land-use change. There is strong evidence that over the last 50 years the terrestrial biosphere has acted as a net carbon sink, removing from the atmosphere approximately one third of the CO₂ emitted by fossil fuel combustion (Canadell et al., 2007). However, the status, dynamics and evolution of the terrestrial biosphere are the least understood and most uncertain elements in the carbon cycle.

This uncertainty spans a wide range of temporal scales: the inter-annual variability of atmospheric CO₂ is mainly controlled by the terrestrial biosphere, while the International Panel on Climate Change (IPCC, 2007) has identified the effects of coupling between the terrestrial carbon cycle and climate as one of the major areas of uncertainty in climate change over decadal to century timescales. Spatially, there are major uncertainties in the distribution of carbon stocks and carbon exchange, in the estimates of carbon emissions due to forest disturbances, and in the uptake of carbon due to forest regrowth.

A fundamental parameter characterising the spatial distribution of carbon in the biosphere is biomass, which is the quantity of living organic matter in a given space, usually measured as mass or mass per unit area. Half of biomass is carbon, so it represents a basic accounting unit for carbon. Forests contain 84% of the terrestrial above-ground biomass.

Biomass is identified by the United Nations Framework Convention on Climate Change (UNFCCC) as an Essential Climate Variable (ECV), needed to reduce uncertainties in our knowledge of the climate system (GCOS, 2003, 2004). While global observation programmes for most of the terrestrial ECVs are advanced or evolving, there is currently no such effort for biomass (Herold et al., 2006, 2007). In addition, sequestration of carbon in forest biomass is the only mechanism for mitigating climate change recognised under the Kyoto Protocol, other than reduced emissions. Obtaining global, spatially-explicit and consistent knowledge on biomass
is therefore a basic requirement for understanding and managing the processes involved in the carbon cycle, and supporting international policies for climate change mitigation and adaptation.

The importance of improved quantitative knowledge about the terrestrial carbon cycle is stressed in *The Changing Earth* (ESA SP-1304, 2006). Attention is drawn in SP-1304 to the need for better estimates of biomass stocks, fluxes and processes in order to quantify terrestrial carbon exchange. Measurement of biomass structure, status and dynamics is specifically recognised as a future observational priority. Furthermore, SP-1304 recognises that data have to be effectively linked to models in order to understand linkages and interactions between components of the Earth system, and to improve the predictive power of models. The BIOMASS mission concept has been developed to be entirely consistent with these principles, as this document demonstrates. Also demonstrated, is that BIOMASS will make significant contributions to several other areas identified in SP-1304, notably the water cycle, ecosystem characteristics and disturbances, land-use change, exploitation of natural resources and, potentially, ice-mass structure.

The BIOMASS mission will provide:

- global maps of forest biomass stocks at spatial resolution in the order of 100 m. These will improve forest inventories, such as the global Forest Resource Assessments (FRA) produced by the Food and Agriculture Organization of the United Nations (FAO) every five years, and give vastly improved information for managing the Earth’s forest resources. Because forest biomass changes only slowly, these maps will have value long past the end of the BIOMASS mission,
- global maps of forest biomass lost due to forest disturbances that can be directly used in models of carbon emissions. The same maps can be used to correct and calibrate the internally generated estimates of disturbance used by Dynamic Vegetation Models (DVM) and Earth System Models (ESM),
- global maps of increment in biomass due to forest growth for the tropical and temperate zones, giving much greater understanding of the location and strength of this carbon sink, and providing important constraints on land carbon models.

Basic facts about biomass:

- About 5% of incident solar radiation is fixed in biomass by plants (Gross Primary Production or GPP).
- 50% of forest biomass is carbon (IPCC Good Practice Guide, 2003).
- Biomass and its associated soil organic matter contain about three times more carbon than the CO₂ in the atmosphere.
- Land vegetation contains approximately 99% of the world’s biomass.
- Forests account for around 84% of the Earth’s above-ground biomass.
2.2 The global carbon cycle

Fundamental to our understanding of the global carbon cycle is accurate knowledge of where carbon is stored within the atmosphere, ocean and terrestrial biosphere, i.e. the carbon pools, and the rate of carbon flow between the different pools, usually referred to as fluxes. Fluxes are often further subdivided into sources (emissions to the atmosphere) and sinks (uptake from the atmosphere) and the net flux for a given component of the cycle is the difference between its source and sink strengths. Figure 2.1 shows our current knowledge about the size of the atmospheric, ocean and terrestrial biosphere pools of carbon and the net fluxes between them for the 1990s. The pools and fluxes are derived from IPCC 2007 and clearly bring out the role of the terrestrial biosphere within the carbon cycle.

The net flux to the atmosphere is the sum of the other four fluxes but is measured independently and is well-constrained, with uncertainty roughly 3% of its mean value (Marland et al., 2006). The net ocean-atmosphere flux estimated is derived from models, but the same value is derived for the 1990s using the O₂:N₂ ratio (IPCC, 2007), and thus it has well-defined error bars and an uncertainty of roughly 20% of its mean value. Emissions from fossil fuel burning are also well-known, with uncertainties roughly 6% of their mean value. The net terrestrial land-atmosphere flux is not measured directly, but is inferred by closing the mean and error budget of the other three terms. This inevitably causes it to have the largest uncertainty amongst all the net fluxes. It is estimated to be a net carbon sink, with uncertainty of the order of the net flux. Although the land sink is the smallest net flux in Figure 2.1, it is made up of source and sink terms that are comparable with the net flux to the atmosphere, and are very significant in the whole carbon balance, as will be seen below.
The terrestrial carbon pool

From Figure 2.1 we see that the terrestrial biospheric carbon pool in its entirety is roughly three times larger than that of the atmosphere (2300 Gigatons Carbon (GtC) versus 762 GtC) and the carbon in vegetation, mainly in forest biomass, is roughly equivalent to that of the atmosphere (600 GtC versus 762 GtC). The uncertainty in total biomass is, however, very large, with estimates ranging from 486 to 827 GtC in 18 studies published since 1975 (Smil, 2002). As we will see in Section 2.3, consistent and accurate forest biomass estimates at global scale would greatly reduce these uncertainties.

The terrestrial carbon fluxes

There are very large uncertainties in our knowledge of the carbon fluxes between land and atmosphere within the global carbon cycle. This is in strong contrast with the other components of the cycle, as can be seen in Figure 2.2. The land flux has two components, a source term thought to be mainly due to land use change (deforestation) in the tropics, and a very poorly understood sink term. Only the source term can be estimated from current observations, and reported estimates have an average value of 1.6 GtC y\(^{-1}\) for the 1990s (see Table 2.1, which also contains estimates for the 1980s and 2000–2005). The uncertainty about this value is indicated as a range, which arises from uncertainties both in the area deforested and in the biomass in the disturbed regions (DeFries et al., 2002). Taking the extremes of the range means that land use change contributed between 7% and 30% to the total anthropogenic flux to the atmosphere in the 1990s. In order to balance the carbon budget, the land therefore must have absorbed around 2.6 GtC y\(^{-1}\) in the 1990s if we adopt the mean value for the land emissions. However, this land sink is calculated purely as the difference between the net land sink (which is itself inferred) and the estimated emissions from land-use change, so is known as the residual land sink or missing sink. Errors in estimating emissions therefore translate directly into errors in estimating the residual land sink. It has uncertainty of roughly 70% of its mean value, and its location and the processes underlying it are the source of hot debate.

<table>
<thead>
<tr>
<th></th>
<th>1980s</th>
<th>1990s</th>
<th>2000–2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric increase</td>
<td>3.3 ± 0.1</td>
<td>3.2 ± 0.1</td>
<td>4.1 ± 0.1</td>
</tr>
<tr>
<td>Emissions (fossil fuel + cement)</td>
<td>5.4 ± 0.3</td>
<td>6.4 ± 0.4</td>
<td>7.2 ± 0.3</td>
</tr>
<tr>
<td>Net ocean to atmosphere flux</td>
<td>−1.8 ± 0.8</td>
<td>−2.2 ± 0.4</td>
<td>−2.2 ± 0.5</td>
</tr>
<tr>
<td>Net land to atmosphere flux</td>
<td>−0.3 ± 0.9</td>
<td>−1.0 ± 0.6</td>
<td>−0.9 ± 0.6</td>
</tr>
</tbody>
</table>

The net land flux is partitioned as follows:

<table>
<thead>
<tr>
<th></th>
<th>1980s</th>
<th>1990s</th>
<th>2000–2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use change flux</td>
<td>1.4 (0.4 to 2.3)</td>
<td>1.6 (0.5 to 2.7)</td>
<td>n.a.</td>
</tr>
<tr>
<td>Residual terrestrial sink</td>
<td>−1.7 (−3.4 to 0.2)</td>
<td>−2.6 (−4.3 to −0.9)</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Table 2.1: The global carbon budget in GtC y\(^{-1}\). The errors represent standard deviation estimates and not inter-annual variability, which is larger. The mean fluxes for the 1990s are as in Fig. 2.1. Positive fluxes are emissions to the atmosphere, negative fluxes are losses from the atmosphere. The uncertainties in the source and sink terms making up the net land to atmosphere flux are large and indicated only as ranges. These ranges arise from the methods used to assign uncertainty to the biomass and disturbed area estimates on which current methods to estimate the land use change flux are based (IPCC, 2007).
Nonetheless, the residual land sink is clearly important as a control on climate warming. Adding a land use change flux of 1.6 GtC y\(^{-1}\) to fossil fuel emissions implies a total anthropogenic flux of 8 GtC y\(^{-1}\) to the atmosphere in the 1990s. Of this, 40% has remained there, contributing to the ever-increasing level of CO\(_2\) in the atmosphere, while 27.5% was absorbed by the oceans. Hence, the land absorbed around 32.5% of the total carbon emissions, but with very large uncertainties arising as described above. Terrestrial carbon uptake is also highly variable around these average values, ranging from almost zero in some years to more than the entire total fossil fuel input in others, for reasons that are poorly understood. Similar trends have been seen since 2000 (Canadell et al., 2007). A key question, therefore, is how much of this missing sink is due to fixing of carbon in forest biomass.

It is a remarkable fact that the accelerating growth in emissions has been accompanied by increasing take-up of atmospheric CO\(_2\) by the land and oceans (Sarmiento and Gruber, 2002). This is insufficient to stop the ever-increasing rise of CO\(_2\) in the atmosphere, but slows it down. However, recent evidence suggests that the effectiveness of the terrestrial control on atmospheric build-up of CO\(_2\) may have decreased by 0.25 ± 0.21% y\(^{-1}\) since Keeling began his systematic measurements of atmospheric CO\(_2\) in 1958 (Canadell et al., 2007). If this decrease continues (as models predict, with some even predicting that the land becomes a carbon source in the latter part of the 21st century; Cox et al., 2000, Friedlingstein et al., 2006), the build-up of atmospheric CO\(_2\) will accelerate and drive faster climate warming. Increased emissions from deforestation would further exacerbate this rise, while an increase in land take-up would mitigate it. Hence, knowledge about these land processes is crucial both to understand their contribution and also for attempts to manage the carbon cycle in order to mitigate climate change.
In addition to the global estimates of net land-carbon fluxes reported above, coarse spatial detail has been added by use of atmospheric inversion. This technique exploits the differences between CO₂ concentrations measured with a worldwide set of flasks, together with atmospheric transport models, to infer sources and sinks at sub-continental scale (Gurney et al., 2002; Jacobson et al., 2007; Rödenbeck et al., 2003; Baker et al., 2006; Stephens et al., 2007). Table 2.2 collates a set of recent results from this approach, aggregated into broad latitudinal bands. The estimated total net land fluxes range from −2.3 to −1.1 GtC y⁻¹, and the variation in the fluxes estimated by latitude is even larger. Northern latitudes are consistently found to be a carbon sink, though of widely varying magnitude, but even the sign of the tropical flux is unknown. Hence current atmospheric inversion results provide only weak constraints on the land carbon cycle, and only at sub-continental scales.

Table 2.2. Estimates of net land surface CO₂ fluxes for 1992–1996 in broad latitudinal bands calculated in a range of studies. Compiled values are taken from Emanuel Gloor (private communication). Positive values indicate a carbon source to the atmosphere. Units are GtC y⁻¹.

<table>
<thead>
<tr>
<th></th>
<th>Gurney et al., 2002</th>
<th>Jacobson et al., 2007</th>
<th>Rodenbeck et al., 2003</th>
<th>Baker et al., 2006</th>
<th>Stephens et al., 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>S Hem (&lt; 20S)</td>
<td>−0.2 ± 1.1 (0.2)</td>
<td>−2.4 ± 2.0</td>
<td>0.0 ± 0.2</td>
<td>−1.2</td>
<td>0.1 ± 1.1</td>
</tr>
<tr>
<td>Tropics</td>
<td>1.1 ± 1.3 (1.5)</td>
<td>4.2 ± 2.7</td>
<td>−1.0 ± 0.4</td>
<td>1.6</td>
<td>0.7 ± 1.4</td>
</tr>
<tr>
<td>N Hem (&gt; 20N)</td>
<td>−2.3 ± 0.6 (−0.7)</td>
<td>−2.9 ± 1.0</td>
<td>−0.7 ± 0.2</td>
<td>−2.7</td>
<td>−2.2 ± 0.6</td>
</tr>
<tr>
<td>Total net flux</td>
<td>−1.4</td>
<td>−1.1</td>
<td>−1.8</td>
<td>−2.3</td>
<td>−1.4</td>
</tr>
</tbody>
</table>

In summary, the uncertainties in current estimates of the global carbon budget are dominated by uncertainties about the size and location of the terrestrial sources and sinks. The main land source is thought to be principally due to deforestation in the tropics, but its magnitude has uncertainty around 20% of the total net annual anthropogenic CO₂ flux to the atmosphere. A land sink is needed to close the global carbon budget but its nature, size and location are highly uncertain, though atmospheric inversion indicates a net carbon sink somewhere in the northern mid-latitudes. Estimates of both the land emissions and land uptake would be significantly improved if reliable estimates of global biomass and biomass changes were available.

2.2 The need for improved observations of forest biomass

The previous section summarised our knowledge of the global carbon cycle and highlighted the large uncertainties in the terrestrial elements of this cycle. The key role of forest biomass as the main repository of vegetation carbon and the importance of biomass in carbon emission and uptake fluxes was stressed. In this section we document the need for improved observations of forest biomass, its spatial distribution and its change with time. As indicated in Figure 2.3, worldwide knowledge of forest biomass is expected to contribute in four distinct ways:

- improved knowledge of the terrestrial carbon pools through the direct conversion of forest biomass estimates into equivalent carbon stocks and through improved vegetation modelling,
- improved estimates of carbon emissions due to land-use change,
• improved estimation of land carbon uptake from forest regrowth over time,
• improved vegetation modelling and long-term climate predictions through data assimilation, model calibration and verification of vegetation models.

Subsequent sections deal with each of these four ways to exploit biomass; descriptions of the terms used in Figure 2.3 are deferred to these sections.

2.2.2 The need for improved knowledge of the terrestrial carbon pools

2.2.2.1 The need for improved international reporting on biomass

Maps of biomass stocks are the basis for calculating emissions based on land-use change. In addition, biomass maps are of enormous value in themselves: they tell us about the world’s forest resources. This is crucial because of the role of forests for renewable raw materials and energy, mitigating climate change, maintaining biological diversity, protecting land and water resources, providing recreation and improving air quality.

The importance of knowing about forests and the very wide range of ecosystem services they provide underlies the provision of the Forest Resource Assessments (FRA) by the United Nations Food and Agriculture Organization (FAO) every five to ten years since 1946. These are the main sources of information on worldwide forest biomass stocks and provide, *inter alia*, forest area and average values of biomass at country level. Country statistics are based on data from national forest inventories, which are themselves based on sample plots and direct measurement of tree characteristics such as growing stock at ground level.

While the FRA provide unique data on worldwide forest biomass stocks, they suffer from a number of shortcomings that limit their usefulness. In particular:

• The FRA are incomplete. In the most recent report (FAO, 2006), estimates
were provided by 150 out of 229 countries and territories, comprising 88% of the global forest area but with several countries (for example, Australia) not providing information. This compromises global estimates of biomass based on summing the data reported by the individual countries.

- The FRA are inconsistent. Many countries lack the quality and amount of inventory data required to support reliable national estimates of growing stock. Hence the estimates have unknown errors and biases, which are likely to vary greatly from country to country. There are also inconsistencies in the forest definitions adopted by different countries (Matthews, 2001; FAO, 2006; Noble et al., 2000; Houghton, 2005; Mather, 2005) affecting not only estimates of forest growing stock but also total forest area (Grainger, 2008). In addition, the methods to convert volume estimates to biomass or carbon units are not harmonised and represent an important source of uncertainty (Köhl et al., 2000; Löwe et al., 2000).

- The FRA are not spatially explicit. Data compiled at the national level are reported through a single value for forest growing stock. The geographical distribution of growing stock, required by vegetation models, is not reported.

- The national values of average biomass per unit area (biomass density) reported in the FRA are likely to be overestimated, since the forest inventories on which they are based were originally developed to satisfy the needs of forest management and hence limited themselves to considerations of marketable timber. As a result, national inventories tend to focus on managed forests or mature forests having the greatest commercial value (Shvidenko and Nilsson, 2002), and in which the biomass density is likely to be higher than the country average.

### 2.2.2.2 The need for improved mapping of biomass

There is no current source of global gridded biomass data except at very coarse spatial resolutions. Indeed, only a few sources of gridded data exist. A map at a spatial resolution of $1^\circ \times 1^\circ$ was produced by Olson et al. (1983) from patterns of pre-agricultural vegetation, aerial surveys and biomass measured at research sites. This was subsequently refined using land cover information derived from satellite data (World Resources Institute, 2000) and updated by Olson et al. (2001), but is still based on relatively old data, is available only in the form of a general ecosystems map (for example, only two values of biomass are depicted in the whole of the Amazon), and is of unknown accuracy. A recent biomass map by Kindermann et al. (2008) downscales the FRA country map to a $\frac{1}{2}^\circ$ grid using relations between biomass and both Net Primary Production (NPP), the net uptake of carbon by plants after allowing for respiration, and human activity. However, this spatial resolution is too coarse for accurate carbon flux calculations and the accuracy of the map still relies on the highly variable quality of the FRA-2005 country data, as well as the assumptions implicit in the downscaling procedure.

Biomass maps have also been produced at regional scale, most notably for the Amazon. Seven such maps are compared in Houghton et al. (2001) and shown in Figure 2.4. The figure shows that different methodologies predict very different biomass levels and biomass spatial distribution patterns. Estimates of the total
amount of carbon in the Brazilian Amazon forests vary by more than a factor of two, from 39–93 GtC. In addition, there is little agreement about the distribution of biomass between different methods. Indeed, Houghton et al., (2001) noted that the level of agreement was only slightly better than would be expected by chance. This is true even for methods that produce similar total carbon estimates for the Amazon; for example, the maps by Brown and Potter (Figure 2.4) are almost the reverse of each other as regards the location of high- and low-biomass forests.

Two other biomass maps of the Amazon basin have also been produced recently. Saatchi et al., (2007) combined data from over 500 ground plots with remote sensing measures of structure and environmental variables, and estimated the total biomass
Biomass (including below-ground and dead wood) to be 86 GtC, with an error of 20%. Malhi et al. (2006) mapped the geographical distribution of biomass in old-growth Amazon forests on the basis of data from 227 forest plots. Their estimate for the total above-ground biomass of 93 ± 23 GtC takes no account of disturbed forests.

Global maps of biomass can also be produced by process-based vegetation models, both those which are climate-driven (for example, see Friedlingstein et al., 2006) and those which include absorbed radiation measurements derived from remote sensing data (for example, Potter, 1999). Large differences are seen between the predictions of biomass in these models and they are not extensively validated (see Section 2.2.4.2), so there is little confidence in their accuracy. In fact, a major gain from the BIOMASS mission is to help test these models, as discussed in Section 2.2.4.2.

Remote sensing has also been used to produce biomass maps, but with strong limitations. Optical data are not physically related to biomass, although relationships between biomass and optical greenness indices such as Leaf Area Index (LAI) have been derived. These are neither robust nor meaningful above a low value of LAI. For example, Myneni et al. (2001) used optical data from the Advanced Very High Resolution Radiometer (AVHRR) sensors to infer biomass changes in northern forests over the period 1981–1999, and concluded that Eurasia was a large sink. However, both field data and vegetation models indicate that the Eurasian sink is much weaker (Beer et al., 2006). C-band radar data from ERS, Radarsat and Envisat Advanced Synthetic Aperture Radar (ASAR) are not well adapted to biomass retrieval, since the difference in backscatter values at C-band between clear-cuts and mature forests is highly variable and at best of the order of a few dB. In the best case, ERS Tandem data were combined with Japanese Earth Resource Satellite (JERS) data to generate a map of biomass up to 40–50 t ha⁻¹ with 50 m pixels covering 800 000 km² of central Siberia (the SIBERIA-I project; Schmullius et al., 2001). However, the lack of consistent regional and global coverage from the existing Synthetic Aperture Radar (SAR) satellites prevents the production of maps, even over this restricted biomass range. Despite intensive dedicated data acquisitions for the SIBERIA-II project, only two disconnected regions of 0.6 and 0.7 Mkm², out of the planned 3 Mkm², could be mapped from ASAR data acquired since 2003.

L-band SAR measurements give good contrast between the backscatter of forest and cleared areas. However, although detection of deforestation has been demonstrated with JERS-1, biomass retrieval was found to be restricted to values only up to around 50 t ha⁻¹ (for example, Luckman et al., 2000). Moreover the lack of consistent coverage prevented the production of global forest maps. For the more recent Advanced Land Observing Satellite (ALOS) mission, launched by the Japan Aerospace Exploration Agency (JAXA) in 2006, Phased Array type L-band Synthetic Aperture Radar (PALSAR) data are being systematically collected to cover the major forest biomes. Initial results (http://www.ies.aber.ac.uk/en/subsites/the-alos-kyoto-amp-carbon-initiative) have shown potential to map deforestation (for example, in Amazonia and Siberia). However, forest biomass retrieval results are still limited to low biomass values, typically less than 50 t ha⁻¹, which excludes most temperate
and tropical forests. The low temporal coherence at L-band also prevents the use of interferometry for forest height retrieval, and hence extension of the range of retrievable biomass.

Another relevant remote sensing technique is lidar, since airborne lidars have proved effective in measuring vertical structure and height in forest canopies (for example, Drake et al., 2002; Anderson et al., 2006). A Geoscience Laser Altimeter System (GLAS) was launched in 2003 on the National Aeronautics and Space Administration (NASA) ICESat satellite. The main concerns of this mission are the cryosphere, clouds and aerosols, but recovery of topography and canopy height over land are secondary objectives. However, the processing of ICESat data to estimate forest height is complicated by the pulse broadening associated with large-footprint, waveform-sampling lidar, and only a few results on canopy measurements have been published. For example, Lefsky et al., (2005) used GLAS waveforms to explain about 60% of the variance in field-measured forest height at three study sites, while Sun et al., (2008) found reasonable correlation between GLAS and airborne and lidar waveforms, but the heights showed several metres of bias. Better results would be expected from a lidar optimised for vegetation canopies, but with two important limitations: (1) it would not provide contiguous coverage, only point samples that require interpolation to generate a map and (2) it would be affected by cloud. Nonetheless, the potential of lidar to measure forest vertical structure makes it an attractive companion to a dedicated biomass mission. This opportunity may arise from NASA's proposed Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI) mission (DESDynI mission concept report 2008), which combines a spaceborne lidar for height retrieval with an L-band SAR, but the mission design is not yet agreed or approved.

2.2.2.3 Summary

Knowledge about forest biomass levels and their distribution is fundamentally important in assessing the size of the land carbon pool, managing the Earth’s resources and in current methods for estimating emissions from land-use change. However, the above discussion shows that present methods for assessing the magnitude and spatial distribution of the terrestrial biomass pool are inadequate. Information derived from international reporting on forest growing stock is not spatially explicit and contains unknown errors and bias. Explicit biomass maps exist for some parts of the world but these are mostly at coarse resolution, contain unknown, spatially-varying biases and, in regions critical for the carbon balance, are too uncertain to support accurate calculations of carbon fluxes. Existing or currently planned satellite missions have limited capability to measure forest biomass.

A dedicated satellite mission providing global, consistent, frequently updated maps of forest biomass at scales consistent with changes due to deforestation would greatly improve our knowledge about the current magnitude of biomass stocks and their geographical distribution. Since forest biomass changes slowly, the dataset would have long-lasting value for post-mission emissions estimates derived from land-use change.
2.2.3 The need for improved estimation of terrestrial carbon fluxes

Clearing of tropical forests destroys huge amounts of biomass and provides the major anthropogenic carbon flux from the land to the atmosphere (Houghton, 2005; DeFries et al., 2002; Achard et al., 2004), particularly when associated carbon losses from soils are included (Page et al., 2002). In the tropics, forest degradation due to selective removal of timber and localised forest clearing is also a major source of emissions (Asner et al., 2005). Conversely, forest regrowth after disturbances such as harvest, infestations and fire can give rise to large carbon sinks (Myneni et al., 2001; Caspersen et al., 2000). Indeed, regrowth fluxes may be large enough to account for the carbon sink in the northern hemisphere inferred from atmospheric inversion studies (Schimel et al., 2001; Sedjo, 1992).

Accurate information on both forest area and biomass are fundamental in quantifying either of these fluxes.

2.2.3.1 The need for improved estimates of terrestrial carbon emissions

Most current estimates of carbon emissions, $C_{em}$, from deforestation (for example, those recommended in the UNFCCC Good Practice Guide, IPCC, 2003) are based on the expression

\[ C_{em} = \sum_{i=1}^{m} \Delta A_i \times B_i \times E_i \]

where $\Delta A_i$ is the change in area of forest type $i$, which has mean biomass $B_i$ (in carbon units) and a burning efficiency $E_i$ that quantifies the fraction of biomass converted to carbon dioxide. Calculating the subsequent temporal behaviour of carbon fluxes requires accounting for associated temporal changes in other components of the ecosystem (dead biomass, below-ground biomass, coarse woody debris and soil organic carbon), removal of wood products and possible regrowth. On the basis of idealised curves representing the time-history of each of these changes, Houghton (2003, 2005) developed a book-keeping approach that allows the temporal trajectory of carbon balance to be calculated at regional scale, given estimates of the rate of disturbance. A similar approach has been adopted by other authors (for example, DeFries et al., 2002). On this basis, Houghton (2005) calculated the annual carbon emissions due to land-use change in the tropics using three different values of mean deforestation rate: those reported by FAO (2001), Achard et al., (2004) and DeFries et al., (2002). Three different mean biomass values were also used: from Houghton (2003), also used by DeFries et al., (2002); FAO (2001); and FAO/UNEP (1981). The combined effect of differences in mean biomass and mean deforestation rate leads to the large differences in estimated carbon emissions shown in Figure 2.5.

The following key points emerge from the analysis in Houghton (2005):

- The uncertainty in carbon emissions due to uncertainty in biomass is comparable to that from uncertaini in the rate of land-use change. Differences
just in the rate of land-use change gave rise to emission estimates in the range of 0.84–2.15 GtC y\(^{-1}\) for the 1990s, while differences in mean biomass led to a range of 1.20–2.15 GtC y\(^{-1}\). In addition, the use of average values of biomass rather than the biomass of the areas actually deforested means that the effects of biomass uncertainty are probably underestimated,

- the uncertainty in the land source term becomes comparable to that in the ocean term (see Figure 2.2) if the uncertainty in the associated biomass change can be reduced to approximately 20%
- measuring biomass at a scale comparable to disturbances (100–200 m) is important for accurate emission calculations.

2.2.3.2 Improved estimates of terrestrial carbon uptake

While forest disturbance is a large carbon source, forest growth is a major contribution to the terrestrial sink of 2–3 GtC y\(^{-1}\) through the 1990s, and can act as a sink over decades. Important mechanisms include:

- afforestation; for example, China is estimated to have increased carbon storage by 0.45 GtC through a large reforestation programme (Fang et al., 2001),
- woody encroachment in semi-arid regions and savannahs largely due to fire suppression and pasture management, a process accounting for 22–40% of the USA land carbon sink (Pacala et al., 2001),
- regrowth after disturbance from harvest, wildfire or abandonment of cropland.

The size of the forest growth sink is poorly known, in part because the size of the overall residual land sink is so poorly known (see Figure 2.2). Houghton et al., (2000)
estimated that forest regrowth sequestered carbon equivalent to around 20% of emissions for Brazilian Amazon in the late 1990s. In contrast, DeFries et al., (2002) found a value of only 6% for tropical Latin America, and 5% for the pan-tropical belt. The latter calculations used satellite-based estimates of regrowing forest area and are subject to at least the same level of error as the emissions due to land-use change discussed above.

The role of biomass accumulation to explain the sink in northern mid-latitudes is still highly debatable, although it is identified as a major factor in the net carbon sink of the USA (Houghton and Hackler, 2000; Houghton et al., 2000) and Europe (Janssens et al., 2005). Since forests in northern mid-latitudes are by and large not changing in area, their role as carbon sinks therefore depends on whether their biomass is changing as they recover from earlier changes in land management.

The ability to quantify regrowth will depend on the mean annual increment in a given forest and the age of the forest (since the methods discussed in Section 2.3 tend to be less sensitive to changes in older forests with higher biomass). In the tropics, average biomass increments exceed 5.6 t ha\(^{-1}\) y\(^{-1}\) (equivalent to 2.8 tC ha\(^{-1}\) y\(^{-1}\)) and can reach 12 t ha\(^{-1}\) y\(^{-1}\) in specific regions and in forest plantations (Uhl et al., 1988; Achard et al., 2002). Temperate forests show a wide range of growth rates, but values exceeding 4 t ha\(^{-1}\) y\(^{-1}\) seem to be general, with many temperate forests showing much higher growth rates (Keeling and Phillips, 2007). Boreal forests grow much more slowly, particularly at higher latitudes. Because the relative annual changes in biomass are small, except in young forests, assessing the size of increment requires measurements taken over several years.

2.2.3.3 **Summary**

Present methods of estimating emissions due to land-use change are dependent on multiplying very uncertain estimates of deforested area by equally uncertain estimates of the mean biomass of this area. Even if the mean biomass was well-known (which it is not), this procedure would be biased if the deforested areas were consistently of high or low biomass relative to the mean. Better estimates require measurements of forest biomass change at resolutions comparable to the scale of land-use change. Direct measurements of biomass loss due to land-use change would preclude the need for separate estimates of deforested area and mean biomass; estimates of land-use change would arise as a subsidiary output.

Reducing the present large uncertainties in how much of the missing carbon sink arises from forest regrowth requires measurements of biomass increment across several years, with changes being more readily measurable for younger forests, particularly quickly regrowing forest in the tropics. Measuring these changes would also improve the estimates of carbon flux due to forest regrowth after disturbance in book-keeping methods for carbon balance.
2.2.4 Using biomass to improve process model calculations

Book-keeping models provide a very direct and powerful way to use biomass data directly as a model input to estimate the carbon fluxes arising from land-use change, and thus address a key uncertainty in the carbon cycle. However, they contain no representation of important processes that affect carbon fluxes, such as interannual variation and longer term variations in climate, spatial variation in soil properties or the effects of enhanced atmospheric CO₂ on plant growth. Accounting for these effects requires models that take a process-based approach.

At the heart of all such models are two basic equations, where the simplest forms are:

\[\Delta C = \Delta B_A + \Delta B_B + \Delta L + \Delta S\]

\[\Delta C = GPP - R_P - R_H - D\]

where \(\Delta\) indicates a change and the other symbols are defined as follows:

- \(\Delta C\): carbon sequestered by vegetation and soil with negative values implying loss to the atmosphere
- \(B\): biomass (\(A\): above and \(B\): below ground),
- \(L\): litter,
- \(S\): soil carbon,
- \(GPP\): Gross Primary Production (photosynthesis),
- \(R\): respiration (\(P\): plant and \(H\): heterotrophic),
- \(D\): carbon loss by disturbance (mainly fire).

These equations can be applied globally or locally, but in the latter case lateral flows of carbon (for example by carbon runoff in rivers or transport after harvest) may need to be accounted for.

Equation 2.2 is exploited in inventories and hence forms the basis of the FRA. Here the overall change in carbon within a given area is measured simply by measuring the changes in the vegetation and soil carbon pools. Above-ground biomass is not only an explicit term in Equation 2.2 but is also strongly related to below-ground biomass and litter production, and through litter to changes in soil carbon.

Equation 2.3 identifies the processes by which carbon change occurs, and process models involve coupling Equation 2.2 with Equation 2.3. This converts Equation 2.2 into an allocation equation, in which processes modify the carbon content in the different pools. Biomass has a direct impact on Equation 2.3 through the disturbance term, as discussed extensively in Section 2.3. However, biomass also has strong effects on the other terms. For example, a near-linear relationship between biomass and NPP is observed for lower productivity forests (Whittaker and Likens, 1973; O’Neill and de Angelis, 1981; Raich et al., 2006), although this
sensitivity weakens at higher productivities, and flattens out in very productive tropical forests (Keeling and Phillips, 2007).

Because biomass is so deeply embedded in these core equations, improved knowledge about its distribution and changes over time can be exploited to improve model calculations, as we now illustrate.

### 2.2.4.1 Assimilating biomass into simplified ecosystem models

The simplest ecosystem models are known as ‘box’ models, and are designed specifically to assimilate time-series of data. A schematic showing the structure of such a model (the Data Assimilation Land Ecosystem Carbon model or DALEC; Williams et al., 2005) is given as Figure 2.6. As shown, the model allocates a proportion of NPP to the leaf, root and woody biomass pools, each of which has a loss rate of carbon to litter, which further decays to produce soil carbon, which itself has a decay rate through soil respiration. Although greatly over-simplified (for example, typically there would be soil and litter pools with fast and slow decay rates), Figure 2.6 captures the essence of such models. Effectively they are resistor-capacitor models that can be represented by first order differential equations, in which the parameters of the models will usually be dependent on environmental conditions, such as temperature. Note that disturbance is omitted, since these models are normally used to gain knowledge about the functioning and parameters of undisturbed ecosystems. Woody biomass is a specific pool involved in the dynamics of the model.

![Figure 2.6: Simplified version of the DALEC model showing how atmospheric carbon fixed by photosynthesis flows through the plant-soil system and back to the atmosphere. The diagram is related to Eqs. 2.2 and 2.3. Note the importance of the root and woody biomass pools (with soils) as cumulative long-term stores of carbon. [Credits: Visio].](image)

Figure 2.7 shows initial results from two assimilation experiments conducted with DALEC. In the first, based on Quaife et al., (2008), a Kalman filter has been used with simulated biomass measurements to adjust the state of the model during forward integration. In the second, simulated biomass and Leaf Area Index (LAI) measurements have been assimilated to estimate DALEC model parameters and hence improve model outputs.

The calculations used to generate Figure 2.7 (a) are for an initial biomass of 200 t ha$^{-1}$, with all model parameters taken to be correct except for an imposed
bias of $-100 \text{ t ha}^{-1}$ on the initial biomass. The model was run for 5 years, assimilating biomass observations every 6 months with observation errors generated from a Gaussian distribution with 10% relative error for biomass of less than 200 t ha$^{-1}$ and 20% relative error for higher biomass. The dark and light grey regions are the estimated uncertainty bounds for the calculations with and without data assimilation respectively. Assimilating biomass data fairly quickly corrects the model to true values of biomass.

In addition, assimilating biomass also improves the estimation of net carbon uptake, or Net Ecosystem Production (NEP). This is indicated by Figure 2.7 (b). In this case, the model parameters were assumed to be unknown and were calibrated against simulated Leaf Area Index (LAI) and BIOMASS-type observations. The results show the probability density function for NEP based on assimilating LAI alone (in black) and assimilating LAI and biomass (in light grey). Including biomass in the assimilation increases the probability of estimating the correct NEP within $\pm 25\%$ from 39.8% to 46.7%.

Hence, assimilating a time-series of biomass data into ecosystem models provides access to information about ecosystem functioning and the parameters controlling ecosystem processes. This forms part of a wider development of carbon-cycle data assimilation (Ciais et al., 2003), in which major steps forward can be expected in the next few years.

2.2.4.2 Exploiting biomass data in dynamic vegetation models and Earth system models

Book-keeping models are specifically tailored to calculating emissions and uptake arising from disturbance, while box models are concerned with ecosystem
functioning. Both types of model involve simplified representations of terrestrial processes, in which simplicity is the price paid to allow effective exploitation of data. However, recent years have seen substantial development of numerical process-based models (DVMs) of the terrestrial biosphere. These models attempt to capture the best representations of ecosystem processes together with the longer term dynamics of vegetation populations as a result of disturbance and climate variation (for example, see Cramer et al., 2001; Friedlingstein et al., 2006 and Sitch et al., 2008 for description and comparison of a range of DVMs operating in both stand-alone mode, driven by climate, and coupled to climate models). DVMs can also estimate the global spatial distribution of carbon fluxes at the resolution of the climate models, how these distributions vary with time, partition the net fluxes amongst their components, attribute them to processes and, when coupled to a climate model, predict current and future carbon and water fluxes. They are also fundamentally important in climate calculations since they form major components of the Land Surface Models that are embedded in Global Circulation Models and Earth System Models. Improvements in DVMs by exploiting biomass therefore have direct impacts on climate models and Earth System Models. The need for such improvements is brought strikingly home by Friedlingstein et al., (2006), where comparison of 11 climate models fully coupled to the land carbon cycle showed vastly different estimates of the rate of climate warming due to feedbacks between the terrestrial carbon cycle and climate. These feedbacks were recognised by the IPCC (2007) as a major source of uncertainty in climate predictions.

DVMs were originally designed to be almost data-independent, and derive most processes internally (for example, disturbance or absorption of radiation) from climate data. This was because few global datasets were available, but also to give them predictive power. Hence, it has not proved easy to interface such models to data, and current DVMs are poorly constrained by measurements, in particular the global datasets available from satellites. The need to improve this situation has led the carbon cycle and climate community to pay increasing attention to making better use of global satellite data. For example, the fraction of photosynthetically absorbed radiation measured by satellites has been assimilated into DVM calculations (Rayner et al., 2005; Knorr and Lakshmi, 2001) and satellite data have also been used to calibrate the parameters controlling the day of budburst (and hence carbon uptake) in boreal forests (Picard et al., 2005). The need for biomass information in a global carbon cycle data assimilation scheme is well-documented (Ciais et al., 2003). It will provide powerful constraints on models, particularly for the slow processes of carbon accumulation that determine the long-term dynamics of forest ecosystems and are currently hard to estimate.

We can illustrate this by comparing model calculations with the Siberian biomass map described in Section 2.2.2.2. Le Toan et al., (2005) attributed large differences found between the observed biomass and that modelled by the Sheffield Dynamic Global Vegetation Model (SDGVM) (Woodward and Lomas, 2004) to land cover errors and failure to account for disturbances. An update of the Le Toan et al., (2005) comparison is given as Figure 2.8, with a degradation of the original satellite-derived Siberia map to a ½° grid on top, and the SDGVM calculation below this. The
Chapter 2

Six Candidate Earth Explorer Core Missions

The model and measurements show differences both in the range and spatial distribution of biomass. The saturation of SDGVM values of biomass seen in the scatterplot is probably a result of incorrect model assumptions about the age of forest mortality. The reasons for the differences in spatial distribution are not yet known, but in part will arise from forest disturbance being generated solely from climate data in the model, thus not corresponding to the reality contained in the data. What is abundantly clear, however, is that biomass maps that are global and cover a much wider range of biomass than the SIBERIA-I data will be invaluable in testing models across all biomes.

There is much more information in the original SIBERIA-I biomass map than in its degradation to ½° grid-size. It is important to realise that such higher-resolution data can be exploited to refine the land cover description used in DVMs. This is because DVMs represent the contents of a grid-cell as proportions of different plant functional types, with forest being further divided into age (and hence biomass) classes. If the biomass classes in a grid-cell are measured, the proportions can be modified accordingly. This is a major advantage, since forest age structure, together with assumptions about future forest replacement and disturbance, are primary factors in predicting the future of a forest as a carbon source or sink (Nabuurs 2004). Large errors in model estimates of carbon flux arise both from incorrect description of land cover (Quaife et al., 2008), for example due to deforestation, and from failure to account for the age structure imposed on forests by management practices (Drezet and Quegan, 2007).

Global biomass maps will also allow the performance of models to be compared. This is sorely needed, as Figure 2.9 makes clear. Here, biomass calculated by three DVMs: ORCHIDEE (Krinner et al., 2005), Lund-Potsdam-Jena (LPJ) Dynamic Global Vegetation Model (Sitch et al., 2003) and SDGVM (Woodward and Lomas, 2004) is displayed along an African transect with marked ecological gradients. Both the...
absolute values and the latitudinal distribution vary significantly between models, and there is currently no mechanism to determine which model, if any, is correct. Measurements from BIOMASS will be able to test whether any of the models is capable of reproducing true patterns of biomass distribution.

2.2.4.3 Summary

DVMs and Earth System Models suffer from a lack of global datasets to constrain their calculations. This contributes to the wide discrepancies between predictions produced by different models. A consistent, up-to-date, global, gridded biomass dataset is needed to test such models, particularly their predictions of the slow processes of carbon uptake in forest ecosystems. Such data are also needed to support the developing field of data assimilation into complex process models, building on already demonstrated methods with simpler ecosystem models. Estimates of biomass produced at resolutions of around 1 ha are needed to improve the current poorly-constrained representations of disturbance and ensuing forest biomass (age) structure in the models. These are fundamental in describing forest populations in the models, and hence predicting their future carbon balance.

2.2.5 Additional benefits of forest biomass information for climate and management of the Earth’s resources

Accurate forest biomass measurements will greatly improve land carbon-cycle calculations and the Earth System Models of which they are fundamental components. They will also bring information basic to quantifying and managing ecosystems services and resources for human well-being. These wider connections are briefly discussed below.

Biomass and the water cycle: The Earth’s vegetation cover acts as an important moderator of biogeochemical cycles and has a profound influence on energy,
momentum, trace gas and water transport between the atmosphere and the soil. Particularly strong connections exist between vegetation structure and the water cycle. Vegetation actively and directly controls evaporation through leaf processes, and vegetation canopies intercept rain and remove subsurface water, affecting the lateral distribution of water in soils and modifying the transport of nutrients and sediments. Changes in biomass are fundamentally important to the water cycle because they affect evapotranspiration (globally, the volume of transpired water is nearly equal to the total river runoff). This strongly affects freshwater supply in river runoff (Gedney et al., 2006). Use of correct values of biomass in DVM calculations has been shown to have large effects on evapotranspiration and brought calculations of runoff much closer to observations (2008; unpublished ESA report based on Beer et al., 2006). Changes in the water cycle also feed back on the production of biomass through their effects on water available for vegetation growth. At a basic level, carbon and water are inextricably linked in biophysical processes, and knowledge about one can be used to constrain the other (for example, Picard et al., 2005), since carbon-cycle models are also water-balance models. Exploitation of BIOMASS measurements will therefore greatly improve water-cycle calculations.

**Biomass and climate**: Use of biomass data to improve carbon and water-cycle calculations will lead directly to improved climate and Earth system models. However, biomass has wider value in understanding and predicting the behaviour of the climate system, since it is strongly related to surface roughness. This acts as a control on turbulent transfer of latent heat flux from the surface to the atmosphere. In fact, changes in biomass due to deforestation lead to two opposing factors in the land energy balance, which are embedded in current climate models. Conversion of forest to other types of land cover tends to reduce latent heat flux and warm the surface but it also increases surface albedo, thus reducing the energy absorbed at the surface (Bala et al., 2007; Betts, 2000).

The importance of biomass for climate led to its being identified as an ECV in the Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC (Global Carbon Observing System (GCOS), 2003, 2006). However, the original view taken by GCOS of biomass as a control on climate has subsequently been widened due to its growing use for generation of bio-energy (Herold et al., in GTOS-52, 2007).

**Biomass and international climate treaties**: The UNFCCC and the related Kyoto Protocol are the only international treaties focused on slowing climate change. The principal mechanism of the Kyoto Protocol, apart from reducing emissions, is to increase the carbon stored in forest biomass and the associated forest ecosystems; it also encourages and rewards efforts to reduce carbon emissions from land-use change. All developed countries are currently required to estimate and report on greenhouse gas emissions from land use change and forestry using the IPCC Good Practice Guidelines (Eggleston et al., 2006). The post-2012 climate agreement currently under negotiation in the UNFCCC (COP-13 Bali Action Plan), supported by intense scientific development, is expected to include a much stronger role
for developing countries in climate change mitigation and adaptation through the Reduction of Emissions due to Deforestation and Forest Degradation (REDD) mechanism. This will require substantial efforts to build national carbon accounting systems in developing countries, with major input from remote sensing (Herold and Johns, 2007).

A prerequisite for implementing the climate policies currently under discussion is a sustained global carbon monitoring system that improves over time. In particular, systems to monitor carbon emissions due to loss of biomass in deforestation and forest degradation, together with carbon uptake due to afforestation and reforestation, are basic requirements of UNFCCC mechanisms for mitigating climate change. Although coming part way through the next assessment period, BIOMASS will produce measurements of unique value to meeting these requirements.

In summary, reducing current uncertainties in climate models needs better descriptions of the interaction and feedbacks between the land and the atmosphere. Improved measurements of forest biomass and forest disturbance would improve the description of the transfer of trace gases, water, energy and momentum between the land and the atmosphere. In addition, biomass and biomass change measurements at around 1 ha scale are needed as a basic component of the monitoring and measurement systems for future climate treaties under the UNFCCC.

**Biomass, forest structure and biodiversity:** Disturbance strongly affects ecosystem biodiversity (Grime, 1973), so that habitat loss and ecosystem fragmentation are recognised as basic mechanisms behind worldwide loss of biodiversity (Pimm and Raven, 2000). Field studies have shown how large-scale and rapid changes in the dynamics and biomass of tropical forests lead to forest fragmentation and increase in the vulnerability of plants and animals to fires (Malhi and Phillips, 2004). Bunker et al., (2005) also showed that above-ground biomass was strongly related to biodiversity. Regional to global information on human impacts on biodiversity therefore require accurate determination of forest structure and forest degradation, especially in areas of fragmented forest cover. This is also fundamental for ecological conservation. Current sensors are inadequate for providing such information, but the provision of regular, consistent, high-resolution mapping of biomass and its changes would be a major step forward in closing this information gap.

**Biomass and human use of ecosystems:** Above-ground biomass stocks are a key factor in the economic and biofuel potential of land surfaces. Biomass is a major energy source in subsistence economies, contributing around 9–13% of the global supply of energy (i.e. 35–55 × 10^18 Joule y^-1, Haberl and Erb, 2006). The FAO provides the most widely used information source on biomass harvest, but other studies differ from the FAO estimates of the wood-fuel harvest and forest energy potential by a factor of two or more (Smeets and Faaij, 2007; Smeets et al., 2007; Krausmann et al., 2008; Houghton and Hackler, 2003; Whiteman et al., 2002). The total cut of firewood could be at least 50% greater than indicated by firewood harvest data (Scurlock and Hall, 1990). Reducing these large uncertainties in the use of forests as energy sources requires frequently updated information on woody biomass stocks.
and their change over time, to be combined with other data on human populations and socio-economic indicators.

2.3 The contribution of the BIOMASS mission

2.3.1 Introduction

Section 2.2 sets out the pressing need for improved measurements of forest biomass, its spatial distribution and its change with time, and emphasises the severe limitations of existing sources of information, including existing or planned satellite missions. This section outlines the role of the BIOMASS mission in filling this crucial forest biomass ‘information gap’.

BIOMASS is envisaged as a polarimetric P-band Synthetic Aperture Radar (SAR) mission. Key characteristics of the mission are:

- coverage of the full range of the Earth’s above-ground biomass, by combining a range of complementary SAR measurement techniques,
- delivery of forest biomass geophysical products whose accuracy and spatial resolution are compatible with the needs of national scale inventory and carbon flux calculations,
- global repeated coverage of forested regions, enabling mapping of forest biomass and forest biomass temporal change.

The mission marks a very large step forward (the ‘delta’) relative to all other methods, including existing or planned Earth observation missions, because of the unique capabilities of P-band SAR for forest biomass and height retrieval, stemming from the following characteristics:

- highest sensitivity of the radar backscattering coefficient (equivalent to radar intensity) to forest biomass, leading to well-documented methods of biomass retrieval developed from experiments with airborne radar systems,
- first mission that enables forest-height retrieval based on polarimetric interferometry, which has been validated in numerous airborne experiments,
- high sensitivity to disturbances and forest biomass temporal change.

By exploiting these capabilities within a dedicated observation strategy, a unique archive of information about the world’s forest and their dynamics will be built up. This legacy will have enormous value that will last well beyond the end of the BIOMASS mission.

2.3.2 Forest biomass retrieval using P-band SAR

The capabilities of P-band SAR to provide biomass information are summarised in this section. It discusses the sensitivity of P-band radar to forest biomass, together with the performance of forest biomass retrieval from P-band SAR data.
2.3.2.1 Forest biomass retrieval using radar backscattering coefficients

The sensitivity of P-band SAR backscatter to forest biomass has been studied and documented since the first airborne P-band SAR systems became available in the early 1990s. Numerous airborne campaigns have taken place over a wide variety of forest biomes, including multiple sites in temperate, tropical and boreal forests.

Most initial work focused on the cross-polarisation Horizontal Vertical (HV) backscatter, which has the largest dynamic range and the highest correlation with biomass. Figure 2.10 summarises the key characteristics of the observed relationship between forest biomass and the HV radar backscattering coefficient. The data shown come from experiments conducted over five different forests: Landes, France, temperate coniferous forest (Le Toan et al., 1992; Beaudoin et al., 1994); Howland, Maine, USA, northern temperate forest mixture of coniferous and deciduous species (Ranson et al., 1997); Guaviare, Columbia, tropical forest (Hoekman et al., 2000); Queensland, Australia, coniferous and deciduous subtropical forest (Lucas et al., 2004); Remningstorp, sub-boreal coniferous and deciduous forest, Sweden (Hajnsek et al., 2008a). Of note is the fact that the range of forest biomass included in the data – from 0 to 400 t ha\(^{-1}\) – can be considered as representative of the full forest biomass range encountered at global scale.

An important feature in the figure, which provides the basis for global retrieval of forest biomass, is the stability of the biomass-backscatter relationship across this highly varied set of forest biomes. The residual variability around the mean trend includes statistical errors in the estimates of the radar backscattering coefficient (mainly due to radar speckle), errors in the \textit{in situ} estimates of forest biomass, geolocation errors and errors due to the spatial scale of estimation, in addition to site-to-site variations that might exist in the biomass-radar backscatter relationship. Forest biomass variability and thus the biomass estimation error may be reduced when larger areas (> 1 ha) are used for retrieval (Chave et al., 2003).

Figure 2.10 also demonstrates key characteristics of P-band SAR that make it particularly suitable for meeting the biomass information needs set out in Section 2.2. Specifically, these are:

- the high dynamic range of P-band (> 12 dB) over the range of above-ground forest biomass levels, combined with good stability in the backscatter-biomass relationship across biomes, thus providing a solid basis for biomass retrieval,
- the large contrast in the P-band backscatter between high and low biomass areas means that major disturbances, such as the clearing of forests, can be easily identified,
- the large rate of increase of the backscatter in the low biomass range means that retrieving temporal change in forest biomass due to regrowth in the first years after disturbances is possible.

Figure 2.10 also shows that the sensitivity of P-band HV backscatter to biomass decreases for higher biomass levels, especially those exceeding around 150 t ha\(^{-1}\).
Extending the retrieval over a wider range of biomass can benefit from the use of the full set of polarisations. Because the backscatter at each polarisation results from different dominant interaction mechanisms, they bring complementary information on both forest biomass and structure. Electromagnetic scattering models developed to better understand interactions between the radar signal and forest vegetation have shown that HV backscattering is dominated by volume scattering in the tree crown, Horizontal Horizontal (HH) backscattering comes mainly from trunk-ground scattering, while Vertical Vertical (VV) results from both mechanisms (Ulaby et al., 1990; Karam et al., 1992; Hsu et al., 1994; Lang et al., 1994; Fung 1994; Ferrazzoli et al., 1997). In this case, biomass components (stem, crown) and thus above-ground biomass can be related to the HH, HV and VV intensities through a quadratic form to simplify the complex modelling formulation (Saatchi et al., 2007). Since HH and VV also contain information on ground conditions, the inversion requires topography as an input and forest training plots for model calibration.

Algorithms to transform SAR backscatter into biomass are reported in the literature and include calibration, geocoding, filtering and inversion (for example, Beaudoin et al., 1994, Saatchi et al., 2007). The inversion is usually based on regression using simple polynomial expressions. The accuracy of inversion results vary between studies, and depend on the range of biomass and the methods used to estimate in situ biomass. Figure 2.11 shows biomass estimation for the Landes forest based on the full set of polarisations.
Reported biomass inversion errors fall in the range 15% to 35% of the mean biomass, with the higher uncertainties found when the test site has a larger range of biomass (for example, up to 300 t ha⁻¹). Account must also be taken of radiometric uncertainty due to speckle, which is not always reported. Reaching the aim of 20% error in biomass (see Chapter 3) requires the intensity to be averaged over areas of 100 m × 100 m, as explained in the performance analysis in Chapter 4. This resolution is consistent with the needs for forest biomass information expressed in Section 2.2.

In summary, experiments across a wide variety of forest biomes have demonstrated a stable relationship between P-band HV SAR backscatter and forest biomass. The large dynamic range and simple form of the backscatter-biomass relationship provides an excellent basis for a global forest biomass-retrieval algorithm. Baseline inversion algorithms exploiting such relationships exist, and will be thoroughly assessed and improved during the next phase of the project. To compensate for the lower sensitivity of P-band HV backscatter to forest biomass above 150 t ha⁻¹ the full set of polarisations may be used in the retrieval or in addition (as we shall see in the following section), forest height information may be exploited.

### 2.3.2.2 Improving biomass estimates using forest height from SAR polarimetric interferometry

To cover the full range of the world’s biomass, and to estimate the carbon emission from deforestation in the tropics, new methods need to be explored. Measurement of forest height is the other approach giving access to biomass and the basis of the operational use of airborne lidar. With a SAR system, forest height can be derived using measurement technique known as polarimetric interferometry or Pol-InSAR.
A major advantage of this technique is that the sensitivity to height increases with height (and hence biomass). It is therefore complementary to methods based on backscatter intensity. Methods to be assessed and explored for deriving biomass information from Pol-InSAR consist of: a) using allometric relationships between biomass and height, and b) combining intensity with Pol-InSAR height in biomass retrieval based on regression.

**The link between forest biomass and forest height**

Deriving biomass from forest height relies on relations between these tree parameters. In general, trees are constrained in their geometry and display striking regularities in their structure. These arise from the constraints involved in constructing tall structures of wood and transporting water up a tall structure made of hollow tubes. Trees ‘solve’ both of these constraints, resulting in the observed allometric relations (West et al., 1999; Enquist et al., 1998)

A general relation between above-ground biomass $B$ and forest height $H$ is (Mette, 2007):

$$\text{Eq. 2.4} \quad B = N \pi \left( \frac{d}{2} \right)^2 H \rho f$$

where $N$ is the tree number per area unit, $f$ is a form factor (0.4 to 0.5), $d$ is the mean diameter at breast height and $\rho$ is wood density. Enquist et al., (1998) on theoretical grounds predicted a power law relationship between the maximum number of individuals and biomass. Taken together, these yield a key theoretical relationship for the BIOMASS mission, namely that for a given species:

$$\text{Eq. 2.5} \quad B \propto H^\alpha$$

with variations in $\alpha$ being mainly due to natural or artificial thinning (Woodhouse 2006). Equations of this form have been developed for trees in different forest zones, with $\alpha$ ranging from 0 to 4. For example, for four common European forest species (spruce, pine, oak and beech), Mette (2007) found:

$$\text{Eq. 2.6} \quad B = 1.801 H_{100}^{1.748}$$

where $H$ denotes top height and is defined as the mean height of 100 trees with the largest diameter in a 1 ha area. For most forests, the value of $\alpha$ becomes more stable as the plot sizes used to estimate $\alpha$ become larger. This applies particularly to tropical forests, where mixed species and mixed stands are found, and has been demonstrated in studies in Malaysia, French Guyana, Venezuela/Paraguay, Mexico and Brazil (for example, Chave et al., 2001; Chave et al., 2003; Kohler and Huth, 1998). These authors further showed that the large variability in mean biomass and height found for small plots is substantially reduced at a scale of 1 ha, and that a single regression equation ($r^2 = 0.9$) could be used for both disturbed and undisturbed tropical forests:

$$\text{Eq. 2.7} \quad B(t/ha) \sim 0.07 H^{2.4}$$
In summary, there are stable but biome-specific relationships between above-ground biomass and height, which makes height information derived from Pol-InSAR of great value in improving estimates of biomass.

**Measurement of forest height using Pol-InSAR**

Over the last decade, techniques have been developed that use polarisation diversity in interferometric measurements to derive the vertical structure of the scatterers in a forest, from which forest height can be retrieved. This measurement is derived by forming the complex correlation coefficient between two images of a scene acquired at different times and slightly different geometries. The interferometric coherence, which is the modulus of the complex correlation coefficient, can be decomposed into three main contributions:

\[ \gamma = \gamma_T \gamma_{SNR} \gamma_{vol} \]

The noise decorrelation (\( \gamma_{SNR} \)) is of secondary importance in forest observations and the two important terms are the temporal coherence (\( \gamma_T \)), which measures the stability of the scatterers between the two acquisitions, and the volume decorrelation (\( \gamma_{vol} \)). The latter is related to the vertical distribution of scatterers, \( F(z) \) also known as the vertical structure function, where \( z \) is height, through a Fourier Transform relationship. Accordingly, \( \gamma_{vol} \) contains information about the vertical structure of the scatterers and is therefore a key observable for quantitative forest parameter estimation (Treuhaft and Siqueira, 2000; Askne et al., 1997; Cloude and Papathanassiou, 1998; Papathanassiou and Cloude, 2001). An important special case of \( F(z) \) is the exponential profile which, when combined with a Dirac delta function for the ground contribution, forms the basis for the widely used Random-Volume-over-Ground (RVoG) model. The RVoG model is used to estimate forest height from the observed complex coherence by inverting a two-layer coherent model consisting of a volume and a ground layer (Treuhaft and Siqueira, 2000; Papathanassiou and Cloude, 2001).

The RVoG model, despite its simplicity, has been used very successfully to estimate forest top height from interferometric observations. For optimum performance, its inversion requires fully polarimetric interferometric measurements (Papathanassiou and Cloude, 2001; Cloude and Papathanassiou, 2003). Several experiments in recent years have validated Pol-InSAR forest height inversion through comparison of height inversion results with independent height information from ground data and lidar measurements. These experiments were carried out primarily at L- and P-band and took place in temperate forests (Papathanassiou and Cloude, 2001; Mette et al., 2004; Dubois-Fernandez et al., 2008; Garestier et al., 2008a, 2008b; Garestier and Le Toan, 2008), boreal forests (Praaks et al., 2007; Lee et al., 2008) and tropical forests (Kugler et al., 2006; Kugler et al., 2007; Hajnsek et al., 2008a). Height errors in the retrievals at P-band were generally found to be about 2–4 m, which means that the relative error for high biomass forests with heights greater than 20 m is 20% or less.
Figure 2.12 shows a P-band height map of the Mawas region, Indonesia, acquired during the ESA INDREX campaign in 2004. The estimated height has been compared with lidar measurements of $H_{100}$ (the mean height of the 100 trees with largest diameter in 1 ha), giving a Root Mean Square Error (RMSE) of 1.73 m over heights ranging from 4–27 m (Hajnsek et al., 2008a).

While the Pol-InSAR technique is now well established, a critical issue in the case of repeat-pass spaceborne measurements is the decrease of temporal coherence (also referred to as temporal decorrelation) due to weather and environmental changes between acquisitions. Temporal decorrelation biases Pol-InSAR forest height estimates and increases their dispersion (Lee et al., 2008). A fundamental advantage of BIOMASS and its P-band implementation, with respect to radar missions at other frequencies, is the much higher temporal coherence of P-band which provides a solid basis for accurate forest height inversion. This aspect is discussed in detail in Chapter 5.

Retrieving biomass from combined intensity and polarimetric interferometry

The independent estimates of biomass derived from intensity methods and height derived from Pol-InSAR can be combined to improve accuracy and extend the range of forest biomass that can be retrieved to all forest biomass classes. This is due to the fact that sensitivity of the two approaches complements each other. At low-biomass levels, P-band radar backscatter is highly sensitive to biomass but height retrieval is difficult and has large errors relative to the actual forest height. As biomass increases, retrieval errors based on radar backscattering increase, while height retrieval errors decrease. Making both measurements with the same sensor will enable the advantages of the two complementary sources of information to be exploited.
Two approaches can be used to combine the information. The first consists of using allometric equations to convert height into biomass. In this case, there will be no limit imposed by high values of biomass (400 t ha$^{-1}$ and more). Further work is required to consolidate allometric relationships for major forest biomes and integrate these into the BIOMASS mission context. However, as discussed above, general relations between above-ground biomass and forest height already exist.

The second approach is to combine intensity and Pol-InSAR information directly in the regression between radar observations and forest biomass which is then inverted and used for retrieval. Preliminary work on the BioSAR 2007 data indicates this could be a fruitful approach. Figure 2.13 (left) shows the P-band SAR intensity in an HH, VV and HV colour composite. Non-forested areas (grass, bare fields) have low backscatter intensity (black), whereas forests exhibit a range of colours, showing the information content brought by polarisation. Figure 2.13 (middle) presents biomass inversion using HV and HH intensity and Figure 2.13 (right) is the Pol-InSAR height map. Although the patterns in the biomass map and the height map are similar, they contain independent information.

Figure 2.14 shows an example of the improvement in the relationship between SAR measurements and biomass when HV, HH and Pol-InSAR height are used together. The scatterplot in Figure 2.14 (left) compares biomass estimates from regression using HH and HV intensity with ground data; the RMSE is 35.6 t ha$^{-1}$ (25% of the mean biomass). By introducing Pol-InSAR height into the regression, the RMSE is reduced to 16.3 t ha$^{-1}$ (15% of the mean biomass). This preliminary result illustrates that new approaches can be developed to combine the measurements provided by the P-band SAR to improve the measurable range of biomass and constrain measurement errors.
2.3.3 Measuring forest biomass change with time

In Section 2.2, the need for information on forest-biomass change with time was identified in order to estimate land carbon-fluxes. Decreases in biomass, including total loss of above-ground biomass due to disturbances, are a major source of land carbon-emission whereas increases in forest biomass due to forest regrowth provide information on the uptake of carbon by vegetation.

The BIOMASS mission will contribute in three unique ways:

- by quantifying the loss of forest biomass due to major disturbances across the whole forest biomass range,
- by quantifying the increases in forest biomass due to forest regrowth, taking full advantage of the enhanced sensitivity of the BIOMASS SAR measurements to biomass changes,
- by providing maps of the spatial distribution of forest disturbance and regrowth biomass levels with the highest accuracy to date.

The first point is a direct consequence of the discussion previous section. By greatly extending the range of forest biomass that can accurately be mapped and retrieved from space, the BIOMASS mission will allow a direct quantification of the change in biomass (ΔB) due to major disturbances across main forest biomes for the first time.

For the second contribution ‘forest regrowth’, BIOMASS will contribute to and significantly extend parallel efforts at L-band to monitor and map forest regrowth over time. The higher sensitivity of P-band to forest biomass is expected extend the range of regrowth stages that can be monitored from space and provide more accurate estimates of as a function of time. A detailed calculation of the sensitivity of BIOMASS is provided in Chapter 4.

The third contribution ‘spatial distribution’ is linked to the first two points. By providing the spatial distribution of forest biomass and forest-biomass change with time.
time, the BIOMASS mission will provide information, both on the spatial pattern of disturbances as well as the biomass information within each disturbed forest stand. As biomass levels are effectively linked to the growth stage of the forest, BIOMASS will be providing unique information on the long-term dynamics of forests.

The potential of P-band SAR to detect disturbance and to map forest age after disturbance is demonstrated by the airborne data for a region in the Yellowstone Park, USA, shown in Figure 2.15.

Although Figure 2.15 is from a single time, it clearly indicates that a regular time-series of P-band images will allow the changes associated with forest disturbance to be readily detected. The abrupt change of biomass caused by logging or stand-replacing fires will cause changes in the P-band HV backscatter exceeding 12 dB (in Figure 2.15, the change from a 60–80 year forest to burn forest is 15 dB). This should be detectable even at 50 m resolution (see Chapter 4). Other types of fires (ground fires, partial fires) that are difficult to detect using optical or higher frequency SAR data may be detectable using BIOMASS from the change in above-ground biomass, although the limitations of the measurements for this purpose remain to be explored.

The information on forest-biomass change with time is also optimised through the fact that BIOMASS represents a dedicated mission characterised by consistent and repeated observations of global forests throughout the mission lifetime. Alternative SAR missions at other frequencies follow several objectives and do not provide the continuous consistent coverage as BIOMASS will.

Figure 2.15: Airborne P-band SAR data over a region in the Yellowstone National Park, together with photos of individual areas at different phases of recovery after burn. The P-HV backscattering coefficients of these areas are indicated below the photos. The SAR image is a colour composite of HH (Red), VV (blue) and HV (green). [Credits: Saatchi]
In summary, the enhanced forest biomass retrieval possibilities of BIOMASS with respect to existing sensors, combined with an observational strategy dedicated to forest monitoring, are expected to provide accurate estimates of the temporal change in forest biomass required by vegetation models to estimate land carbon fluxes.

2.3.4 Mapping forest disturbance area

As discussed in Section 2.2, the detection of forest disturbances at SAR frequencies other than P-band has been successfully demonstrated. The BIOMASS mission is expected to complement other missions providing this information and contribute to a better mapping of forest disturbances in two ways:

- the contrast between forest and disturbed forest is expected to be higher for BIOMASS leading to more robust and consistent detection and mapping of the disturbance and its area estimates,
- the continuous dedicated monitoring of forest regions providing multiple observations of forested regions each year gives a unique basis for mapping disturbances with respect to other missions, which often have multiple objectives and observation modes.

2.3.5 New information on forests through SAR tomography

The proposed approach for BIOMASS to retrieve forest biomass from P-band polarimetric interferometric measurements detailed in the above sections relies mainly on statistical regressions and height inversion using Pol-InSAR. Improvements in the understanding and modelling of the interaction between radar waves and the complex forest canopy structure would likely benefit the mission by providing more insight into the physical link between the radar signatures, the underlying scattering mechanisms and forest bio-physical properties.

For BIOMASS, a short-duration experimental phase is proposed to retrieve new information in this area. Tomography exploits multi-baseline InSAR observations to reconstruct the scattering behaviour of vegetation as a function of height. A major advantage of this method is that the contributions to the total radar signal due to scattering within the forest canopy and on the ground can be separated physically using this technique (Tebaldini 2008). The potential of this technique has been validated recently using data collected during the BioSAR 2007 campaign using BIOMASS sensor parameters. Tebaldini and Rocca (2008), were able to demonstrate that SAR tomography can separate the backscatter from the canopy layer and from the ground layer for each polarisation channel.

In summary, the tomography phase for BIOMASS is expected to help answer the following fundamental questions:

- What are the main P-band scattering mechanisms at forest and ground level and what is their relative contribution to the total observed radar signal?
• How do the scattering mechanisms vary as a function of radar polarisation?
• How do the scattering mechanisms vary over the global forest biomes?

By providing answers to these questions, tomography is expected to bring completely new insights with respect to P-band wave interaction with forests, and provide a physical basis linking forest biomass and radar observables, which could be used to improve forest biomass and height inversion retrieval methods.

2.4 Secondary mission objectives

Secondary mission objectives of BIOMASS arise from the opportunity for exploring the Earth’s surface for the first time with a long-wavelength SAR system. New information is expected in the following areas:

• subsurface geomorphology in arid areas,
• ice structure and ice flow,
• forest inundation.

Other products with scientific potential, including soil moisture, permafrost, and ocean salinity, may be investigated over limited areas.

2.4.1 Subsurface geomorphology

Low frequency SAR has the capability to map the subsurface down to several metres in arid areas, thus having a high potential for terrestrial applications in arid and semi-arid environments: hydrology, geology, water and oil resources, and archaeology (Abdelsalam et al., 2000). In particular, the major drainage basins in North Africa are key features for understanding climate change in the recent past, but are very poorly known.

Early illustrations of the potential of long-wavelength radar used images from the L-band Shuttle Imaging Radar. These revealed many previously unknown palaeo-drainage channels, including subsurface basement structures that control the Nile’s course in north-east Sudan (Stern and Abdelsalam, 1996; Abdelsalam and Stern, 1996). The limited coverage by the Shuttle Imaging Radar hindered regional studies, but complete coverage of the eastern Sahara was provided by the Japanese JERS-1 L-band satellite, allowing the creation of the first regional-scale radar mosaic covering Egypt, northern Sudan, eastern Libya and northern Chad (Paillou et al., 2003a). This led to the discovery of numerous geological structures. For example, JERS-1 images of northern Sudan clearly reveal a palaeo-drainage network, while optical images mainly show a sandy area (Figure 2.16). Continental-scale exploration is being continued with the new PALSAR L-band radar on the JAXA ALOS satellite. Its improved data quality has allowed mapping of a 1 200 km-long palaeo-drainage system in eastern Libya that could have linked the Kufrah Basin to the Mediterranean coast (Paillou et al., 2008). Such a major drainage system has important implications for understanding the environments and climates of
northern Africa from the Late Miocene to the Holocene, with consequences for fauna, flora, hominid and human dispersal.

2.4.2 Ice structure and interferometric ice flow measurements

The high penetration potential of P-band into ice layers is of advantage for the detection of subsurface ice structures. Figure 2.17 shows such structures as observed over the Austfonna glacier at L- (top) and P-band (bottom) during the IceSAR 2007 campaign. The interpretation of such structures observable in the P-band signal is currently a subject of research.

Identifying the nature of such structures would help determine the potential of P-band for interferometric ice flow measurements from space. A limitation of shorter wavelength systems (for example, C-band), is that they do not penetrate into ice surface change processes can produce a loss of coherence in interferometric data. It is expected that a longer wavelength such as P-band will allow penetration of tens of metres into the ice, and reach bigger, more stable and consequently more permanent scatterers deep under the surface. Interferometric coherence over ice at P-band should then remain very high and should allow the monitoring of glacier displacements over months. A P-band SAR would then be able to fill the time scale between days and years, providing valuable information about glacier dynamics over periods that correspond to annual change. However, further work is required to confirm this potential before optimising the mission for this additional objective.
2.4.3 Forest inundation

Inundated forests and peat swamp forests in the tropical belt contain very large amounts of carbon which may be released as a result of increasing disturbances. The most basic requirement for modelling methane or carbon dioxide emissions from wetland forests is information on the spatial and temporal distributions of inundated areas, combined with wetland type and information on the functioning of these ecosystems. The ability to map the timing and duration of flooding over entire catchments (for example, the Amazon and the Congo basins) using long wavelength radar has been spectacularly displayed by the ALOS-PAL SAR L-band SAR sensor (see http://www.eorc.jaxa.jp/ALOS/kyoto/jan2008/pdf/kc9_hess.pdf). The BIOMASS sensor will systematically acquire data that add to the time-series being produced by PALSAR and allow the study of decadal trends and interannual variations.

2.5 Conclusions

At present, the status, dynamics and evolution of the terrestrial biosphere are the least understood elements in the global carbon cycle, which is deeply embedded in the functioning of the Earth and climate systems. There are very large uncertainties in the distribution of carbon stocks and carbon exchange, in the estimates of carbon emissions due to land use change, and in the uptake of carbon due to forest regrowth. Forest biomass is the main repository of vegetation carbon and hence is a crucial quantity needed to reduce these uncertainties. Both its spatial distribution and its change with time are critical for improved knowledge of the terrestrial component of the carbon cycle. This is recognised by the UNFCCC, both in its identification of biomass as an ECV and in its procedures for reporting on emissions from land-use, land-use change and forestry under IPCC Guidelines.
There are no current biomass datasets that are global, up-to-date, consistent, at spatial resolutions comparable with the scales of land-use change, or that are systematically updated to track biomass changes due to land-use change and regrowth. Such datasets are crucial to improve estimates of the terrestrial carbon sources and sinks, whether by simple or by complex models. They are also needed to calibrate and test the land-surface models that are basic components of climate models, and as part of the next generation of data-assimilation schemes needed to constrain coupled climate-carbon-cycle models. In addition, they will aid in building a sustained global carbon-monitoring system that improves over time; this will help nations quantify and manage ecosystem resources, and improve national reporting.

Many airborne observations in tropical, temperate and boreal forest have demonstrated that P-band SAR has unique capabilities for measuring the worldwide range of forest biomass. It can achieve this by combining complementary techniques: forest biomass is retrieved directly from multi-polarised backscatter measurements, with decreasing sensitivity as biomass increases, while forest height is derived from Pol-InSAR, with increasing sensitivity as height and biomass increase. Both forms of measurement depend strongly on the special capabilities of P-band radar, in two principal ways:

- the long P-band wavelength significantly extends the range of sensitivity of backscatter to biomass compared to shorter wavelengths, such as L-band,
- scattering at P-band is primarily from large, stable forest components, which contain the major part of biomass. An additional major advantage is that the long wavelength makes P-band Pol-InSAR resistant to small displacements of the scatterers. These yield only small phase perturbations, so that repeat pass Pol-InSAR measurements are possible using pairs of images with long temporal separation.

The combination of both height and direct biomass measurements brings significant increases in the accuracy of biomass measurements, with height being particularly valuable in biomass-rich tropical forests.

The large dynamic range of P-band and its sensitivity to biomass have big advantages for detecting forest disturbance and the subsequent gain of biomass due to regrowth.

Although the BIOMASS mission is strongly focussed on measuring biomass, this automatically brings substantial extra benefits:

- measuring biomass and its changes, and using this information in carbon models, will simultaneously provide invaluable information for understanding the water cycle, assessing biodiversity, and evaluating the resources available for human use and how they are actually being used,
- the use of the long P-band wavelength opens up new opportunities that are not available from other sensors or significantly extend current capabilities, giving
insight into subsurface geomorphology in arid areas, ice structure and flow of ice masses, and forest flooding.

In summary, a P-band radar is the only sensor capable of providing global knowledge about biomass needed to address fundamental uncertainties about the carbon cycle. The allocation of a P-band frequency for remote sensing by the International Telecommunication Union (ITU) in 2003 provided, for the first time, the opportunity to exploit this capability. The BIOMASS mission is designed to grasp this opportunity.
Chapter 3  Research Objectives

Despite its crucial importance in the carbon cycle and hence in the whole Earth system, biomass is the least well quantified vegetation parameter across most parts of the planet. This is due to the great difficulties in measuring biomass over extended areas on the ground and consistently aggregating measurements across scales. A space-based mission that could provide global, high-resolution and repetitive estimates of forest biomass would play a major role in answering two of the most outstanding questions for the current carbon cycle:

• what is the rate of emissions due to deforestation, mainly in the tropics?
• where and how large is the terrestrial sink in the northern mid-latitudes?

Wrapped into the first of these is also the question of how much carbon is being taken up in the tropics due to regrowth after disturbance. The BIOMASS mission is defined to answer these questions, as well as provide information of major importance about climate, the water cycle, the dynamics of wetlands and the associated methane production, biodiversity, human use and management of forest resources, the subsurface structure of arid regions (with implications for water resource and mineral exploration) and the subsurface structure of ice masses.

3.1 Primary mission objectives

The primary objective of BIOMASS is to measure, in a consistent manner, the global distribution of above-ground forest biomass and changes in forest biomass. By combining complementary radar techniques based on polarimetric data and further combining these with interferometry, the measurements will cover the full biomass range encountered in boreal, temperate and tropical forests. These data will greatly reduce the current large uncertainties in calculations of both carbon stocks and the fluxes associated with forest disturbance and regrowth. At present, these uncertainties are so large that we do not even know whether unspecified processes are necessary to explain temporal and spatial patterns of carbon fluxes. Specifically, the mission will measure:

• carbon stocks, by providing global measurements of forest biomass,
• carbon sources, by measuring losses of biomass due to deforestation and forest degradation; a by-product will be changes in forest area due to deforestation,
• carbon sinks, by measuring uptake in forest biomass (regrowth after disturbance, afforestation and woody encroachment).

These data will be provided as time series in gridded form with spatial resolution comparable to the spatial scale of forest disturbance (around 1 ha). This will make them directly usable in forest inventory (at regional, national and global scales) and emissions and carbon uptake calculations. BIOMASS data will be compatible with current emission calculation methods recommended in the IPCC Good Practice Guidelines. Hence, because forest biomass changes slowly, the biomass maps produced will be applicable within these methods up to decades after the end of
the mission. In addition, assuming a launch date around 2016, the mission will make a unique contribution to monitoring tropical forests within the time-period of the UNFCCC ‘Reduced Emissions from Deforestation and Degradation’ mechanism proposed in the Kyoto Protocol second commitment period after 2012.

Because the data will be gridded and global, they will be ideal for exploitation within land surface models and dynamic vegetation models, both in stand-alone form and embedded in climate and Earth system models. They will provide a strong constraint on land surface models and will be readily integrated into a framework including other forms of Earth observation data, ground data, atmospheric measurements, ecological process models, and climate models. Their value is likely to be greatly enhanced by the continuing development of data assimilation methods that exploit diverse data sources in order to reduce the uncertainty in land surface, carbon cycle and climate calculations.

The primary scientific requirements and the associated mission characteristics are given in Table 3.1.

<table>
<thead>
<tr>
<th>Primary Science Objectives</th>
<th>Measurement Requirements</th>
<th>Retrieval Methods</th>
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</thead>
<tbody>
<tr>
<td>Quantify magnitude and distribution of forest biomass globally to improve resource assessment, carbon accounting and carbon models</td>
<td>Above-ground forest biomass from 70° N to 56° S with ± 20% accuracy (see note below) at spatial scales of 100–200 m.</td>
<td>Biomass inversion based on multi-polarised backscatter and its combination with height derived from Pol-InSAR.</td>
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<td></td>
<td>Forest height accuracy of ± 4 m.</td>
<td>Forest mapping at spatial scales of 100–200 m.</td>
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<tr>
<td></td>
<td>Forest mapping at spatial scales of 100–200 m.</td>
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<tr>
<td>Monitor and quantify changes in terrestrial forest biomass globally, leading to greatly improved estimates of:</td>
<td>Biomass loss due to deforestation and forest degradation, annually or better, at spatial scales of 100–200 m.</td>
<td>Mapping of changes in time series of biomass and forest area maps</td>
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<tr>
<td>– terrestrial carbon sources (primarily from deforestation) using carbon accounting methods</td>
<td>Biomass accumulation from forest growth, at spatial scales of 100 m; 1 estimate per yr in tropical forest, 1 estimate over 5 years in other forests.</td>
<td></td>
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<tr>
<td>– terrestrial carbon sinks due to forest regrowth and afforestation.</td>
<td>Changes in forest height caused by deforestation (ability to measure increase in height in growing forests is not clear).</td>
<td></td>
</tr>
<tr>
<td>Both forms of information will also be used to test and calibrate terrestrial carbon cycle models.</td>
<td>Changes in forest area at spatial scales of 100–200 m, annually or better.</td>
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</table>

Table 3.1: BIOMASS primary science objectives and mission requirements
Note: The stated aim of achieving 20% accuracy in biomass is to reduce the uncertainty in the emissions from land-use change to a level comparable with the uncertainty in the net ocean flux (see Figure 2.1). This value is very demanding and may not be achievable globally by the BIOMASS mission, though is likely to be met in many regions of the Earth, especially in temperate and boreal forests. However, given the huge current uncertainties in biomass reported in Section 2.2, measurements with larger uncertainties would still be immensely valuable, as long as they are unbiased, so that error cancellation would be effective.

### 3.2 Secondary mission objectives

Important secondary objectives of the BIOMASS mission arise from this first chance to view the Earth from space with such a long radar wavelength. In particular, a P-band SAR will provide new information on subsurface structure in arid lands and polar ice. The associated mission requirements are almost all automatically satisfied, given the requirements arising from the primary focus on forest biomass and its changes. The exception is for ice structure, which would need operation at higher latitudes. The long wavelength of BIOMASS also makes it well-suited to observing the dynamics of forest inundation. Its dedicated forest acquisition plan will ensure that forest inundation data currently being systematically acquired by the ALOS-PALSAR L-band radar can be extended across decadal timescales. In addition, mapping of forest degradation and fragmentation will be a by-product of the primary objectives, supporting improved metrics for habitat quality and biodiversity. The secondary scientific requirements and associated measurement requirements are given in Table 3.2.

<table>
<thead>
<tr>
<th>Secondary Science Objectives</th>
<th>Measurement Requirements</th>
<th>Retrieval Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map subsurface lithology in arid regions</td>
<td>A single map during the mission is sufficient, though repeated maps may give information on temporal variation in subsurface moisture.</td>
<td>Visual analysis of backscatter.</td>
</tr>
<tr>
<td>Map subsurface structures in polar ice and study ice-stream flow regimes.</td>
<td>A single map is required for ice-structure detection. Interferometric acquisitions are required for ice-stream flow studies</td>
<td>Visual analysis of backscatter and interferometry</td>
</tr>
<tr>
<td>Monitor permanent and seasonal forest inundation; relate to methane emissions using models.</td>
<td>Approximately monthly observations during the flood season.</td>
<td>Changes in backscatter intensity in time-series of data</td>
</tr>
</tbody>
</table>

Table 3.2: BIOMASS secondary science objectives and measurement requirements
3.2 Related planned missions

The dataset to be produced by BIOMASS will be unique and not dependent on other satellite data for its value. However, many other satellite missions will add greatly to the value of BIOMASS in both a particular and general sense. Five types of missions of special relevance are:

**Space-based measurements of atmospheric CO$_2$**
In January 2009 NASA will launch the Orbiting Carbon Observatory (OCO) and JAXA will launch the Greenhouse gases Observing Satellite (GOSAT) around the same time. Both are designed to measure CO$_2$ flux globally, on spatial scales of 100–1000 km (after the necessary averaging). OCO has a planned lifetime of only two years but GOSAT is planned to be in orbit for at least five years. Assuming these missions are successful, we will have a much better idea of the general locations and magnitudes of land sources and sinks by the time BIOMASS flies. However, they will tell us nothing about the underlying processes that are causing carbon uptake or release. In addition, they will not have the spatial resolution offered by BIOMASS and needed to resolve whether fluxes are due to disturbances, regrowth, fires, deforestation, etc.

**Space-based measurements of emissions from fires**
Fire is one of the mechanisms by which land-use change gives rise to emissions, but is by no means the only mechanism (for example, see Houghton, 2005) and its relative contribution to emissions varies geographically and with circumstances. Fire is also endemic in many biomes where there is little woody biomass, such as savannah. However, newly-developing methods using Fire Radiated Power to estimate biomass consumed by fire (for example, Wooster et al., 2005) will provide valuable complementary estimates of how much of the biomass lost by land-use change is due to fire. It seems likely that the next generation of meteorological satellites will support measurement of Fire Radiated Power, though this concept is still under development.

**Space-based lidar for forest vertical structure**
The combination of long-wavelength radar for biomass mapping with a spaceborne waveform lidar that can sample forest vertical structure would provide an excellent way to map the 3D distribution of vegetation in forests. This pairing becomes even stronger in the context of using Pol-InSAR to measure height and the experimental tomography phase of the BIOMASS mission. The possibility of such pairing becoming reality seems currently to be dependent on progress with the proposed NASA DESDynI mission concept.

**L-band radar**
The current ALOS-PALSAR mission is already providing valuable information on forest extent and change, and the dynamics of inundated forests. Within the context of the Kyoto and Carbon Initiative, a systematic archive of worldwide forest observations will be built up over the five years of the mission. Although very valuable for mapping forest and changes in its extent, this will have limited value for biomass measurements. A successor to PALSAR is already planned, but
with a stronger focus on disaster monitoring, and it is currently unclear whether it will sustain the systematic acquisition strategy that has been such an enlightened aspect of PALSAR operations.

**C-band radar**

Continuity in C-band SAR missions is ensured during the time frame of BIOMASS through the ESA Sentinel-1 SAR missions and the Canadian Space Agency (CSA) Radarsat constellation. The Sentinel-1 mission in particular is expected to image land surfaces at global scale every 14 days. These missions are not expected to provide forest biomass information but could provide valuable complementary information to the BIOMASS mission in other areas, including the detection and mapping of forest disturbances at high resolution and generating up-to-date land cover maps.

The more general relevance of BIOMASS to other satellite missions is best explained within the context of the data assimilation concept set out in the Integrated Global Carbon Observing Strategy (IGCOS) (Ciais et al., 2003). This is illustrated in Figure 3.1 and provides a complete framework for integrating ground data, satellite data and models into a greatly improved carbon cycle observation and prediction system. Biomass from space is recognised as a specific satellite contribution within this scheme, along with fires, radiation (for example, the fraction of Absorbed Photosynthetically Absorbed Active Radiation or fAPAR), landcover/land use, vegetation growth cycle, and atmospheric CO₂. The realisation of such a scheme would have immediate effects on climate modelling, since the carbon cycle is so deeply embedded in the climate system and the observation requirements for carbon cycle overlap completely with those needed by climate.

![Figure 3.1](adapted from Ciais et.al., 2003) [Credits: Ciais]
BIOMASS will benefit greatly from ground data networks, including the large amount of inventory data and data from the continually developing network of research-oriented sites, particularly those associated with flux tower measurements (for example, the global FluxNet network; http://www.fluxnet.ornl.gov/fluxnet/index.cfm). These data will be used for validation and in better understanding the role of biomass in studies of carbon exchange, for example in model calibration.
Chapter 4 Observation Requirements

4.1 Introduction

As summarised in Chapters 2 and 3, the main BIOMASS scientific objectives will be realised through systematic P-band SAR acquisitions over all major forested areas on the globe, and the transformation of these observations into the key geophysical data products of the mission. The main data products identified were the following:

- forest biomass,
- forest biomass changes with time,
- forest height,
- forest disturbance.

The aim of this chapter is to specify the observation requirements of the BIOMASS mission. An overview of these requirements is given in Figure 4.1 below. The chapter is structured as follows:

In Section 4.2 the observational approach is detailed. A general framework for transforming the Level 1 radar data into geophysical products is provided. The need to specify the number of independent radar samples averaged before applying the geophysical retrieval algorithm is highlighted.

In Section 4.3 the BIOMASS geophysical products are identified, including the nature of the product (physical or otherwise), accuracy and resolution requirements.

Figure 4.1: BIOMASS observation requirements addressed in Chapter 4, divided into sections on the observational approach, geophysical product definition, retrieval performance and sampling requirements.

[Credits: ESA]
In Section 4.4 the baseline retrieval methods are briefly identified and exploited to establish retrieval performance and identify the number of independent radar samples required to achieve the scientific objectives.

In Section 4.5 the sampling requirements for BIOMASS are discussed.

### 4.2 Observational approach

Figure 4.2 depicts the general observational approach for the BIOMASS mission. The BIOMASS satellite will systematically acquire calibrated polarimetric radar images over forested areas on the globe. For a polarimetric SAR sensor, the information collected for each resolution cell is summarised by the complex scattering matrix $S$ (Oliver and Quegan, 1998; Ulaby and Elachi, 1990):

$$S = \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix}$$

where $S_{HH}$, $S_{HV}$, $S_{VH}$ and $S_{VV}$ represent the complex scattering amplitudes at HH, HV, VH and VV polarisations respectively. The scattering matrix $S$ serves as the basis for generating all Level 1 radar data products including the radar backscattering coefficients (equivalent to radar intensity) at each of the different polarisation combinations, i.e. $\sigma_{HH}$, $\sigma_{HV}$, $\sigma_{VH}$ and $\sigma_{VV}$, and the complex correlation coefficients between the different polarisation channels. The BIOMASS mission will generate a temporal series of measurements of $S$.

These Level 1 products are then transformed into the geophysical products through pre-processing of the data and the application of the appropriate retrieval algorithms. A critical consideration regarding the pre-processing stage is the amount of filtering that needs to be applied to the input data before applying the geophysical retrieval algorithm. Radar intensity images where no averaging has been performed – referred to as single-look images – are characterised by a strong noise-like quality called speckle which arises from interference between the different scatterers within a single SAR resolution cell. This leads to an uncertainty in the estimate of the radar backscattering coefficients which follow well known distributions (see Oliver and Quegan, 1998, and Lee, 1994, for an extensive discussion). A general function of the filtering step in Figure 4.2 is to reduce uncertainty in the radar measurements by averaging a number of independent samples where the independent samples are referred to in the radar literature as looks. The number of independent samples averaged to produce the final input image to the retrieval algorithm is therefore referred to as the Equivalent Number of Looks (ENL) or simply the number of looks.

It is important to note that uncertainties due to speckle can be very large and strongly degrade the geophysical inversion performance. This is illustrated in Table 4.1, where the 80% confidence intervals in radar intensity are given as a function of the number of looks. We see that for a single-look image, the uncertainty in the estimate is more than 13 dB or roughly equivalent to the entire dynamic range of radar intensity over all forest biomass classes. Through the
In terms of geophysical retrieval and observation requirements this has two implications:

- speckle will strongly affect the accuracy of the geophysical product and needs to be quantified as a function of the filtering (averaging or looking) applied to the input data,
- spatial filtering will in turn impact the achievable resolution for the geophysical data product.
As a consequence, a full specification of the BIOMASS geophysical data product needs to specify both the resolution of the geophysical product as well as the number of looks that are required to achieve the accuracy objectives.

### 4.3 Geophysical product definition

A summary of the main Level 2 products proposed for the BIOMASS mission is given in Table 4.2. The information requirements are derived directly from the discussion in Chapters 2 and 3.

<table>
<thead>
<tr>
<th>Level 2 Product</th>
<th>Definition</th>
<th>Information Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest biomass</td>
<td>Above ground biomass (dry weight of woody matter + leaves) expressed in tons/ha</td>
<td>• &lt; 20% error</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 100–200 m resolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 2 biomass maps/year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Global coverage of forested areas</td>
</tr>
<tr>
<td>Forest biomass temporal change</td>
<td>The product is defined in terms of changes in forest biomass as a function of time, i.e. $\Delta B/\Delta t$, expressed in tons/ha/unit time</td>
<td>• &lt; 20% error</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 100–200 m resolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 2 revisits per year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Global coverage of forested areas</td>
</tr>
<tr>
<td>Forest disturbance</td>
<td>Classification map applicable to forest regions with two categories – disturbed and undisturbed</td>
<td>• Map of disturbance with 90% classification accuracy (all products)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 50 m resolution (major disturbances)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 200 m resolution (partial disturbances)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 1 product per 2 months</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Global coverage of forested areas</td>
</tr>
<tr>
<td>Forest height</td>
<td>Canopy height defined according to the H100 standard used in forestry</td>
<td>• &lt; 20–30% error</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 100 × 100 m resolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 1 height map per year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Coverage of all major forest areas on globe</td>
</tr>
</tbody>
</table>

Table 4.2: Summary of main Level 2 products

Forest biomass refers to the above-ground biomass (dry weight of woody matter + leaves) expressed in t ha$^{-1}$. The measurements are applicable to forest and woodland areas and are linked to above-ground carbon stock, expressed in kg carbon per square metre, by a factor converting dry vegetation material into carbon, as 50% of biomass is carbon (IPCC Good Practice Guide, 2003). Thus, the forest biomass maps produced by BIOMASS can be directly converted into global maps of above-ground carbon stock.

The forest biomass temporal change product is defined in terms of changes in forest biomass as a function of time, i.e. $\Delta B/\Delta t$, expressed in t ha$^{-1}$ per unit time. This product is directly linked to the scientific objectives discussed in Chapter 2 of monitoring changes in biomass due to disturbances and forest regrowth.

The forest disturbance product takes the form of a map in which forest is classified in two categories: disturbed and undisturbed. The disturbance map will provide
information both on the location and extent of the disturbed areas. For BIOMASS, the disturbance products will be generated at two different resolutions: a high resolution disturbance product at 50 m × 50 m resolution and a lower-resolution product at 200 m × 200 m resolution. The high-resolution product will be used to map stand-replacing disturbances (for example, deforestation, major fires) and will help identify the nature of these disturbances. The lower-resolution product will be used to map within forest-stand disturbances (for example, thinning, degradation) for which more averaging of samples is required to achieve the stated classification accuracy.

The forest height product will provide spatial estimates of forest height based on the ‘H100’ metric commonly used in forestry.

4.4 Retrieval performance

4.4.1 Introduction

A detailed discussion on the individual products, their information requirements, retrieval methods and performance is given in this section. The aims of the section are to identify baseline retrieval algorithms for each product, make a preliminary assessment of retrieval performance comparing the results with the mission objectives above, and identify the main requirements regarding the input Level 1 data.

4.4.2 Forest biomass using radar intensity information

State-of-the-art retrieval of forest biomass based on radar intensity was discussed in Chapter 2. The retrieval algorithms proposed for forest biomass rely on statistical approaches based on the regression of radar intensity at a single polarisation (HV) and/or the full set of intensity measurements at HH, VV and HV with forest biomass. The single polarisation approach using HV is expected to be more robust but has limitations at the higher levels of biomass. Using the full HV, HH and VV set of intensities provides more information about forest biomass and structure and can help extend the retrieval range.

A convenient method for linking the retrieval algorithms to performance and accuracy assessment, is to formulate the inversion problem using a Bayesian approach (Tarantola, 2005; Mattia et al., 2006). The inversion maximises the posterior probability \( P(B|\sigma^0) \) of biomass \( B \) given the observation \( \sigma \) (which may be vector valued for multiple channels) using:

\[
\text{Eq. 4.2} \quad P(B \mid \sigma^0) = \frac{P(\sigma \mid B) P(B)}{P(\sigma)}
\]

This method has several advantages in specifying Level 2 product performance:

- this equation represents a general formulation of the inversion problem where the output \( P(B|\sigma^0) \) takes the form of an probability distribution summarising the available information about biomass. A flat distribution for \( P(B|\sigma^0) \) indicates
a complete lack of information about biomass as all biomass levels are equally probable whereas a sharply peaked $P(B|\sigma^0)$ implies that the inversion problem is well posed, leading to a well-defined biomass prediction and low uncertainties in the retrieval result,

- it provides a baseline retrieval algorithm as the maximum likelihood estimate of $B$ is given by the mode of $P(B|\sigma^0)$, i.e. the best estimate of biomass for a given observation along with uncertainties in the retrieved value in the form of a distribution,

- the formulation is general and can be extended to include all major uncertainties affecting the measurement and consequently retrieval performance, in particular radiometric and geophysical errors,

- this approach provides a framework to exploit prior information on biomass distribution $P(B)$ available from *in situ* or ecological knowledge of the region of interest.

In the absence of prior information about $\sigma^0$ and $B$, only a computation of the likelihood function $P(B|\sigma^0)$ is necessary. To derive the number of looks required to achieve the performance goals of BIOMASS we specify the forward problem as:

\[
\sigma^0 = f(B) + \varepsilon_{\text{speckle}}
\]

where $\sigma^0$ is the radar backscattering coefficient (expressed in dBs), $f(B)$ is the forward model relating biomass $B$ to the radar observable, and $\varepsilon_{\text{speckle}}$ the radiometric uncertainty in the estimate of the backscattering due to speckle. It is important to note that $\varepsilon_{\text{speckle}}$ is a function of the number of looks applied to radar data before geophysical inversion. The forward model $f(B)$ used for HH is the mean trend discussed in Chapter 2. For HH we use the regression equation published by Saatchi et al. (2007).
Based on this method, the performance of the Level 2 forest biomass product as a function of looks was calculated and the results are summarised in Figure 4.4 for two candidate intensity algorithms. One is based on the HV channel only and the second exploits both HH and HV polarisation channels.

![Figure 4.4: Forest biomass retrieval performance as a function of biomass for two intensity channel combinations (P-HV and P-HV+P-HH). Performance is plotted as a function of forest biomass and the curves correspond to different number of looks. The dotted line and blue region below correspond to a retrieval performance better than 20%. [Credits: ESA]](image)

The results indicate that the accuracy objectives of BIOMASS can be achieved at system level through sufficient filtering of the radar data. For forest biomass derived using only P-HV input data, about 300 looks are required to push the retrieval error below 20% of above-ground biomass. For biomass derived using both P-HV and P-HH intensity information the retrieval error is less than 20% for 128 looks or more. At 512 looks, the contribution to the total retrieval error from radiometric uncertainty is less than 10% and significantly better than the 20% objective.

### 4.4.3 Forest height using polarimetric interferometry

The potential for mapping forest height from space at long wavelengths and using this information to improve forest biomass estimates was presented in Chapter 2. The algorithms for forest-height retrieval are based on Pol-InSAR, which requires interferometric acquisitions of the fully-polarimetric complex scattering matrix.

While there are several sources of error affecting height retrieval, the largest impact on the retrieved height accuracy is expected from temporal decorrelation. Temporal decorrelation biases Pol-InSAR forest height estimates and increases their dispersion. While the dispersion can be compensated at the cost of spatial resolution, the bias (i.e. overestimation of forest heights) cannot yet be compensated.
The biases due to temporal decorrelation have been studied both theoretically and experimentally using airborne SAR data. Typical error curves as a function of forest height are provided in Figure 4.5. The main characteristics of the height errors are:

- a rapid decrease in height error as the height of the forest increases. For forest heights up to 20 m the height error is about 4 m or 20% of the value and rapidly decreases for taller forest stands,
- a significant increase in height error as temporal decorrelation increases – this strongly affects the ability to retrieve height for short forest stands, for example less than 15 m.

The results from a recent airborne campaign addressing this issue have shown that temporal decorrelation levels of 0.9 or better are achievable at P-band, whereas temporal decorrelation is more severe at L-band and severely degrades forest height retrieval (Hajnsek et al., 2008a). Using the experimental value of 0.9 for temporal coherence as a baseline and Figure 4.5 as a reference, we then expect height biases of 20% or less of the actual height for trees 20 m or taller. The impact of the selection of the BIOMASS SAR frequency is discussed in more detail in Chapter 5.

4.4.4 Forest biomass using radar intensity and radar-derived height

A novel forest biomass product foreseen for the BIOMASS mission combines radar intensity information and forest height estimates provided via polarimetric-interferometric techniques. The relationship between forest height and forest biomass was discussed in Section 2. An advantage of such a product is that it exploits the strength of each technique, i.e. the higher accuracy of intensity-based retrieval at lower forest biomass levels and the higher accuracy of Pol-InSAR techniques for forest heights above 20 m.
A first estimate of retrieval performance for this product can be obtained by extending the formulation of the likelihood function $P(B|\sigma)$ in equations 4.2 and 4.3 to include a forest height channel. A useful relationship between forest height and biomass is given by Mette, 2007. Figure 4.6 shows the results, assuming a height retrieval error of 4 m. The improvement in biomass retrieval above 100 t ha$^{-1}$ of biomass due to independent height information is especially marked for the 128 look and 256 look products. The theoretical performance is better than 20% for all numbers of looks considered.

![Figure 4.6: Forest biomass retrieval performance as a function of biomass exploiting forest height information and the HH and HV radar intensity channels. The dotted line and blue region below correspond to a retrieval performance better than 20%. [Credits: ESA]](image)

**4.4.5 Forest biomass temporal change**

The requirement of 20% error or less in the detection of change in forest biomass constrains the minimum value of biomass change that can be detected. A first performance estimate for this geophysical product can be obtained by calculating the posterior distributions for two different backscattering coefficients representing a change in biomass, and integrating over the regions of overlap between the two distributions. The threshold values are obtained by systematically searching for the value that satisfies the error requirements. The results from a simulation using 256 looks, and HH and HV channels for the geophysical inversion, are given in Table 4.3. The increase in detectable change as a function of biomass $B$ is due to the decreasing sensitivity of radar signal to forest biomass with increasing biomass. Overall, Table 4.3 tells us that changes of roughly 34% of the initial biomass $B$ can be detected with the desired accuracy of 20%.

**4.4.6 Forest disturbance**

The BIOMASS forest disturbance product will be generated by dividing the input radar image into two classes: disturbed and undisturbed. The accuracy requirement
for the disturbance product is 90%. Typically such products are generated using multi-temporal change detection algorithms (Rignot and Van Zyl, 1993).

<table>
<thead>
<tr>
<th>Forest biomass (tons/ha)</th>
<th>Change in forest biomass (tons/ha) detectable with error ≤ 20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>17</td>
</tr>
<tr>
<td>100</td>
<td>34</td>
</tr>
<tr>
<td>200</td>
<td>68</td>
</tr>
</tbody>
</table>

Table 4.3: Estimates of the minimum change in forest biomass that can be detected with 20% error or less. The simulation assumed 256 looks and geophysical retrieval using HH and HV channels.

For the single-channel case a requirement in terms of number of looks and radar contrast in dBs required to classify with 90% accuracy, is readily calculated based on expressions in the literature. A paper (Rignot and Van Zyl, 1993) has derived an expression that relates the probability of error in detecting changes in radar backscattering to the number of looks and contrast between disturbed/non-disturbed areas (equation 12 in their paper). It important to note that these expressions provide the worst-case estimates of performance, as only a single channel and not the fully-polarimetric scattering matrix is considered. For fully-polarimetric radar data, the sensitivity to change due to disturbance is expected to improve significantly with respect to a single radar channel (Conradsen et al., 2003).

Applying this equation we get the result found in Figure 4.7. The graph provides concrete indications about the type of disturbances that can be mapped for a given number of looks. When only four looks are applied (it is possible to map large disturbances causing changes in radar intensity of more than 8 dB with 90% accuracy. For deforestation where the forest is completely removed and above-ground biomass is close to zero, the contrast with mature forest is of the order of 10–12 dB at P-band. Thus, the classification requirement can be achieved, especially as the calculation provides a worst-case scenario. For more subtle disturbances (for example, thinning) with much lower contrast Figure 4.7 provides a useful detection threshold. Relatively subtle changes in radar intensity can be mapped if enough filtering is applied. For 256 looks, for instance, changes in backscatter of less than 1 dB can be detected and mapped with the required classification accuracy.

### 4.4.7 Concluding remarks

The results of section 4.4 on retrieval performance are summarised in Table 4.4. The main purpose of the chapter was to identify baseline retrieval algorithms and exploit these to define the requirements of the geophysical products in terms of input radar data (type, polarisation channels, number of looks required). Preliminary performance assessments also indicate that the accuracy objectives of the mission can be achieved if the requirements in terms of the number of looks are met.
### 4.5 Sampling requirements

#### 4.5.1 Spatial sampling

A key aspect of the BIOMASS mission is its global coverage. The main mission products require coverage of the global forested areas including tropical, temperate and boreal forests. Information on the location and extent of global forests can be derived from global land-cover maps such as GLC2000 produced by the European Commission Joint Research Council at a resolution of 1 km, or more recently GLOBECOVER which has a resolution of 300 m.
Basic requirements regarding the spatial sampling can be derived through analysis and a rescaling of the GLC2000 map into fewer, more general classes applicable to the BIOMASS mission. The result of this rescaling is provided in Figure 4.7 with forest in green areas (corresponding to classes numbered 1–10 in the original GLC2000 map), arid zones in yellow (class number 19 in GLC2000) and extended ice caps in grey (class number 21 in GLC2000). In latitude terms, the map provides upper and lower limits of 75°N and 56°S respectively to ensure coverage of global forests. In addition, major regions of forests on the globe are identified in the map and provide a basic coverage requirement. Lastly, the regions related to secondary mission objectives (arid zones, ice sheets) are clearly identified in the map and provide a baseline coverage requirement. For the tomography acquisitions discussed in Chapter 2, only data samples of the different forest biomes are required.

A refinement of this map during Phase A would enable a more detailed analysis of the latitudinal limits and regional coverage requirements at a higher resolution using the GLOBCOVER land-cover map for 2005 at 300 m, which became available in 2008. In particular, the definition of forest cover and its suitability in the context of the BIOMASS mission can be analysed as definitions vary from product to product (Herold et al., 2006).

4.5.2 Time sampling

As discussed in Chapter 2, forest biomass under natural conditions does not change rapidly with time and is not a driver in terms of revisit requirements. Regrowth in the tropics, which has the highest regrowth rates of all forests, is the order of 5–10 t ha\(^{-1}\) per year. Thus, the forest biomass and biomass temporal change product would require only a revisit every six months in order to adequately sample the regrowth curve.

The main driver for revisit requirements is related to the need to minimise the impact of temporal decorrelation on the BIOMASS forest height product. The
selection of P-band as the operating frequency for BIOMASS (discussed in detail in Chapter 5) is expected to minimise temporal decorrelation in a repeat-pass SAR mission. Airborne measurements over a boreal forest site (Hajnsek et al., 2007) have shown that at 30 days the decorrelation at P-band can be relatively small (0.1), while it becomes moderate (0.3) at 50 days. This suggests that repeat time intervals of about 25 days should provide sufficiently high temporal coherence to enable accurate Pol-InSAR forest height retrievals that meet the mission objectives. Additional advantages of short revisit times include:

- selection of optimal dates. Temporal decorrelation may vary with time due to changing environmental parameters. Repeated acquisitions of given sites using the same polarimetric imaging mode will enable the selection of optimal interferometric pairs with a minimum in temporal decorrelation for the retrieval,
- improved filtering of the radar input data using multi-temporal filters (Quegan and Yu, 2001). These methods use multiple images from different dates (and polarisations) to increase the number of looks with minimal loss of resolution.

Further optimisation of the revisit requirement should be carried out during Phase A, with additional campaign data to determine typical temporal decorrelation profiles for the main forest biomes of the Earth.

4.5.3 Data latency

The update frequency for BIOMASS higher-level products is generally monthly or lower. From the exploitation perspective there is no specific timing or 'data latency' requirement and no clearly identified need for real-time access to the products. Data access is thus generally expected to take place off-line via subscription to the mission archive.

4.5.4 Mission duration

Mission duration will primarily affect the amount of forest regrowth (and degradation) that can be monitored during the mission. A five-year mission combined with a forest growth rate of 5 t ha\(^{-1}\) per year would imply a change in biomass \(\Delta B = 25\ t\ ha^{-1}\), from the beginning to the end of the mission. Comparing this to the detection thresholds calculated in Table 4.3 we see that regrowth in forests up to about 50–100 t ha\(^{-1}\) could be monitored directly. Additional information on temporal biomass dynamics beyond this threshold can be retrieved from the static biomass map and disturbance features within this map, as discussed in Chapter 2. However, a five-year mission would be desirable to monitor regrowth rates directly through the BIOMASS products.
Chapter 5  Mission Elements

5.1  Introduction and overview

In this chapter the observational requirements discussed in Chapter 4 are translated into the required mission elements which include:

- the space segment comprising requirements on the SAR payload and mission characteristics;
- the ground segment.

The key mission elements related to each of these segments are illustrated in Figure 5.1. A basic characteristic of the BIOMASS mission is that the space segment will be implemented in terms of a single satellite carrying one payload: a side-ways looking SAR imaging system operating at 435 MHz (P-band). The ground segment is expected to support mission operations, data processing including calibration of Level 1 products, product distribution and archiving.

Figure 5.1: BIOMASS mission elements addressed in Chapter 5 divided into sections on space segment, ground segment and mission context. [Credits: ESA]

5.2  Space segment

5.2.1  Selection of frequency

The proposed implementation of BIOMASS is based on a P-band SAR sensor operating at the centre frequency of 435 MHz and with a bandwidth of 6 MHz, which corresponds to the actual International Telecommunications Union (ITU) allocation. This global frequency allocation enabling P-band spaceborne radar missions was established at the World Radiocommunications Conference 2003 (WRC-03) and fixed to the frequency range 432–438 MHz (see Article 5 in ITU radio
regulations from 2004). One of the main drivers in the frequency allocation request was Earth observation missions at P-band.

As discussed in Chapter 2, SAR images at lower frequencies have a documented sensitivity to forest biomass. For BIOMASS, the selection of the P-band frequency is justified in terms of the main goal of the mission, which is to map global forest biomass across the entire range of biomass including biomass-rich tropical forests. Critical to achieving this objective is the combination of radar intensity information with forest height to improve biomass estimates for high-biomass forests.

The high dynamic range of P-band backscattering with respect to forest biomass has already been discussed in Chapter 2. In addition, in the case of a single-satellite SAR mission such as BIOMASS, the ability to retrieve forest height with sufficient accuracy depends crucially on high temporal coherence between acquisitions. There is both theoretical and experimental evidence to indicate that the choice of L- or P-band strongly impacts the levels of temporal coherence between successive image acquisitions.

Temporal decorrelation is related primarily to the temporal stability of the location and dielectric properties of the scatterers within a SAR resolution cell. Pol-InSAR height inversion is affected because temporal decorrelation is superimposed on the volume decorrelation contribution, which carries the information about vertical forest structure in general, and forest height in particular. Moderate temporal decorrelation of about 10%, corresponding to $\gamma_T = 0.9$, is sufficient to introduce errors larger than the specification of the Level 2 height product (20%).

With respect to temporal decorrelation, the use of the longer P-band wavelength has two main advantages:

- long wavelengths penetrate deeper into the vegetation layer and interact more with the ground beneath the canopy as well as with larger tree structures. Both the ground and large tree structures are more stable scatterers as a function of time than smaller tree elements, leading to higher temporal coherence at P-band than for shorter wavelengths,
- the decorrelation caused by a given displacement (movement) of the scatterers within the resolution cell scales is a function of wavelength and is therefore lower for longer wavelengths. Figure 5.2 shows the temporal decorrelation due to different magnitudes of movement as a function of wavelength making clear the advantage of P-band.

As a consequence, the interferometric coherence at P-band as a function of time is expected to decrease more slowly than for any other frequency band allocated to Earth observation.

These theoretical considerations have been validated through recent experimental results derived from airborne campaigns (Hajnsek et al., 2008a; Hajnsek et al., 2008b). Figure 5.3 highlights the impact of temporal decorrelation over boreal forest
Figure 5.2: Simulated temporal decorrelation expressed as interferometric coherence caused by the movement of scatterers as a function of wavelength for three movement amplitudes (1 cm, 3 cm and 5 cm). The C-, L- and P-band regions are indicated in shades of blue from left (light blue) to right (dark blue). An important feature of the figure is that movement of the radar scatterers between acquisitions within a forest canopy of 3 cm leads to a drop in temporal coherence to 0.5 at L-band and only a slight drop to 0.9 at P-band. Accordingly, accurate forest height retrieval for this scenario is only possible at P-band. [Credits: DLR]

Figure 5.3: Forest height retrieval error levels at P-band and L-band due to temporal decorrelation over 30 days. The L-band retrieval height errors (right image) are significantly higher than the ones at P-band (left image) due to more temporal decorrelation at L-band. The airborne radar data was collected over the Remningstorp test site in Sweden during the BioSAR airborne campaign (Hajnsek et al., 2008a). [Credits: DLR]
obtained in the frame of the BIOSAR airborne experiment. For a temporal baseline of 30 days the level of temporal coherence remains high at P-band ($\gamma_T=0.9$) but has already dropped significantly at L-band ($\gamma_T=0.65$). For even longer time intervals, 56-day temporal coherence at P-band ($\gamma_T=0.7$) remains significantly higher than for L-band ($\gamma_T=0.3$).

As a consequence, the retrieval of forest height at L-band based on a repeat pass system such BIOMASS is subject to strong errors and the basic objective of mapping forest biomass at global scale severely compromised. Achieving the BIOMASS objectives at L-band would likely require simultaneous acquisitions from two satellites, i.e. single pass interferometry, and would need to be studied in detail. For a single-satellite repeat-pass SAR mission, only the higher coherence of P-band is expected to permit forest height retrieval at global scale, and fulfil the BIOMASS scientific objectives.

### 5.2.2 Polarimetry

A detailed list of polarisation observation requirements is provided in Table 4.4 in Chapter 4. Forest height retrieval based on Pol-InSAR requires fully-polarimetric data, which includes the amplitude and relative phases of all polarisation channels (HH/HV/VH/VV).

Other BIOMASS geophysical products will benefit from the availability of calibrated polarimetric data as discussed in Chapter 2 and underlined by the Level 2 retrieval performance assessment in Chapter 4. Further enhancements in mission products related to estimates of areas of disturbance and monitoring of forest recovery with time, forest wetland and secondary mission objectives such as mapping ice structures over land can also be expected through polarimetric data. Polarimetry also plays an important role in improving the radiometric accuracy of Level 1 products through multi-channel filtering techniques, as discussed in Section 5.2.3.

A second consideration in connecting observation requirements to polarisation modes is the need to correct for ionospheric effects on the radar signal. This is examined in detail later in this chapter. In general, polarimetric measurements are required for accurate ionospheric correction of the Level 1 data.

In summary, in order to achieve the portfolio of mission products, correct for the ionosphere and meet the stated objectives, BIOMASS will need to support and operate in a fully polarimetric mode. At this point in the mission definition, an option for one other mode should be maintained. Recent developments in Compact Polarimetry (CP), an instrument mode which involves emitting a circular polarisation and receiving using H and V polarisations, have shown that it is a promising technique for minimising the impact of Faraday rotation while preserving a larger ground swath. The link of this novel mode to existing retrieval algorithms, however, needs to be established and needs to be further investigated during the next phase of the mission definition.
5.2.3 Spatial resolution

In Chapter 4 the resolution requirements are summarised for the BIOMASS geophysical (Level 2) product in Table 4.2. Also affecting resolution requirements are the number of independent samples (looks) that need to be averaged in order to meet the accuracy objectives. This was studied in detail in Chapter 4.

The range resolution \( r_g \) is given by the formula:
\[
 r_g = \frac{c}{2B \sin (\theta)}
\]

Eq. 5.1

where \( c \) represents the speed of light, \( B \) the bandwidth of the system and \( \theta \) the incidence angle. Applying this formula to BIOMASS operating at P-band we obtain a range resolution of 50 m at 30 degrees incidence. For steeper incidences the range resolution is slightly lower. With an azimuth (along-track) resolution of about 12.5 m the above calculation indicates that BIOMASS can provide Level 1 products with 4 looks at 50 m \( \times \) 50 m, 16 looks at 100 m \( \times \) 100 m and 64 looks at 200 m pixel scales. Assuming polarimetric acquisitions and applying well-established multi-channel filtering techniques documented in the open literature, this can be increased by a factor of more than two, i.e. 128 looks at 200 m for a single acquisition (Quegan and Yu, 2001).

A baseline resolution of 50 \( \times \) 50 m and 4 looks is compatible with the observation requirements expressed in Chapters 2 and 4. For instance, forest biomass retrieval based scenarios exploiting the HV + HH or HV + HH + Height information were found to require 128 looks equivalent to about 200 m resolution after filtering. The observation requirements of other products are also satisfied at this resolution. The only exception identified in Chapter 4 was forest biomass information based only on the HV intensity channel, where 300 looks were required to achieve 20% accuracy. This would require either a degradation of the resolution to about 500 m \( \times \) 500 m or, preferably, could achieved by applying multi-temporal filtering techniques to a timeseries of BIOMASS radar images. It can be shown that the equivalent number of looks \( (ENL) \) for \( M \) images acquired at different times and for images with \( L \) looks using a filter of size \( N \) pixels is given by (Quegan and Yu, 2001):
\[
 ENL = \frac{MNL}{M + N - 1}
\]

Eq. 5.2

Applying this formula to a characteristic case where \( M=6 \) (a stack of 6 multi-temporal images), \( L = 64 \) corresponding to a 200 m resolution cell and \( N = 25 \) corresponding to a 5 \( \times \) 5 filter window we get \( ENL=320 \), sufficient to meet the accuracy objectives of BIOMASS.

To summarise, the SAR payload for BIOMASS should support a resolution of the order of 50 m \( \times \) 50 m (> 4 looks) in order to meet the documented science objectives and associated observation requirements.
5.2.4 Radiometric resolution & stability

The absolute radiometric accuracy is defined as the RMS measured radar cross section within a homogeneous scene and over time. It includes errors from processing and calibration. For retrieval of forest biomass, P-band SAR is expected to provide >12 dB increase over the biomass range of ~0–300 t ha\(^{-1}\). Over this range, the backscatter coefficients for the HV channel vary from −25 to −12 dB. The baseline retrieval technique relies on the inversion of a fitted curve relating biomass to absolute P-band backscatter levels. This implies that an absolute radiometric calibration of the P-band signal must be of the order of ±1.0 dB in order not to degrade retrieval accuracy beyond the requirement of 20% for forest biomass retrieval. In practice, absolute calibration is likely not to be critical as any shift in the biomass-radar backscatter curve due to instrument calibration can be compensated for over time in the retrieval algorithm.

Radiometric stability is defined by the standard deviation of the radiometric error of known scatterers measured at different times. In the BIOMASS mission context, radiometric stability is critical as radar intensity retrieval relies on the stability of the relationship between absolute backscatter levels with forest biomass. As a consequence, systematic or random changes in radiometric error as function of time will lead directly to errors and biases in the retrieved biomass values. As a guideline radiometric stability should be kept lower than the radiometric uncertainty, typically <0.5 dB, to minimise its negative impact on biomass retrieval accuracy.

5.2.5 Instrument noise

The Noise Equivalent Sigma Nought (NESN) represents the normalised backscatter equivalent to the background noise in the SAR image. It is caused by thermal noise, digital converter and A/D quantisation noise. In terms of observation requirements, NESN will have an impact especially on the retrieval of lower biomass ranges and for the secondary mission objective of mapping subsurface geomorphology in arid zones. The impact is highest for the HV channel, which has lower backscatter than both co-polar channels. For low-biomass areas, the backscatter at HV is typically around −25 dB. Therefore, an NESN above −25 dB would reduce the available dynamic range for intensity retrieval and the sensitivity of the system to the early regrowth phase in forest when biomass is still low. These considerations imply an NESN below −27 dB to ensure a sufficient Signal-to-Noise Ratio (SNR) level \((SNR=\sigma^0/\text{NESN})\) for low biomass forest stands. Assuming a zero-biomass backscattering \(\sigma^0 = −25 \text{ dB}\) leads to a SNR of 2 dB ensuring that the full dynamic range of P-band \(\sigma^0\) as a function of biomass is not reduced and retrieval performance is maintained.

The selection of a level for NESN also impacts interferometric measurements introducing a decorrelation contribution given by:

\[
\gamma_{\text{SNR}} = \frac{1}{1 + \text{SNR}^{-1}}
\]
Setting NESN to -27 dB for the BIOMASS sensor guarantees a reasonably high \( \gamma_{SNR} \) around 0.95 for mature forested areas (\( \sigma^0 \approx -12 \text{dB} \)), for which interferometric measurements are most needed.

### 5.2.5 Range and azimuth ambiguities

Range and azimuth ambiguities are important design parameters for the SAR payload as they directly influence technical choices such as the antenna dimensions. Quantitative guidelines based on user requirements are, however, difficult to establish. Nevertheless, there is a broad consensus based on experience with SAR missions at other frequencies that total ambiguity levels < -20 dB do not strongly affect applications over natural surfaces.

For interferometry, range and azimuth ambiguities in the individual images combine incoherently when forming the interferogram, reducing the interferometric coherence. Taking the range/azimuth ambiguity contribution as an additive noise contribution to the ambiguity decorrelation we get:

\[
\gamma_{AMB} = \frac{1}{1 + RASR} \frac{1}{1 + AASR}
\]

where \( RASR \) and \( AASR \) the range and azimuth ambiguity-to-signal ratio. The ambiguity-to-signal ratio (ASR) depends on system and operation parameters as well as the scattering characteristics of the individual scene. Reasonable ASR values on the order of about -20 dB lead to a high value for temporal coherence \( \hat{\gamma}_{AMB} = 0.98 \).

### 5.2.6 Incidence angle

Results derived from airborne radar datasets, as well as theoretical considerations, demonstrate that steeper incidence angles, in general, reduce the dynamic range between bare surfaces and mature forest, increasing biomass retrieval errors based on intensity techniques. The polarimetric information used for retrieval techniques based on classification and Pol-InSAR is also reduced with steeper incidence angles, leading to higher retrieval errors. As a general rule, therefore, flatter incidence angles are desirable. However system considerations are expected to favour steeper incidence angles and place strong constraints on possible incidence ranges. Research based on airborne data have shown that incidence angles above 25 degrees are acceptable and do not endanger forest biomass retrieval (Dubois et al., 2004).

### 5.2.7 Orbit

In Chapter 4, one key driver in the orbit selection was identified in the section on time sampling requirements. To enable forest-height inversion using Pol-InSAR the time interval should be sufficiently small so that high temporal coherence is maintained between SAR acquisitions over the same area. As a guideline, a time interval of 25–45 days was suggested.
A second important driver in orbit selection concerns the ionosphere which is discussed in Section 5.3.3. The main outcome of the discussion is that the selection of a Sun-synchronous dawn-dusk orbit will minimise ionospheric disturbances for the dawn acquisition.

A third requirement in selecting the BIOMASS orbit is derived from the accuracy requirements of the Pol-InSAR height inversion. Large baselines between acquisitions are advantageous as they compensate, in part, for errors in forest height retrieval introduced by temporal and other decorrelation sources. However, the maximum baseline is limited by the 6 MHz system bandwidth available at P-band because of range spectral decorrelation and terrain conditions. The critical (horizontal) baseline $B_c$ between successive acquisitions given by:

$$B_c = \frac{\lambda h}{2r_g \cos^2 \theta}$$

where $\lambda$ represents the wavelength, $h$ the orbit height, $r_g$ the SAR range resolution and $\theta$ the incidence angle. A baseline of about 60% of $B_c$ provides an optimal compromise between the accuracy of forest height retrieval and range spectral decorrelation. The orbit control should be sufficient to avoid spectral decorrelation, requiring orbit maintenance within 10% of $B_c$. The same reasoning applies to orbit control requirements for the tomographic phase which are similar to those for forest height.

5.2.8 Mission duration and phases

The requirements for mission length are derived from the observation requirements to monitor and quantify forest biomass change as a function of time. As discussed in Chapter 4, a mission length of 5 years would allow sufficient samples of change (disturbance) measurements in order to reduce systematic and stochastic uncertainties.

At this point of development, the BIOMASS mission is envisaged to be implemented in two phases:

- nominal phase: The nominal phase main mission phase (minimum 97% of the total mission duration) during which repeat polarimetric interferometric observations are made to address the major mission objectives and products as well as secondary objectives,
- tomographic phase: A single tomographic phase (maximum 50 days or 3% of the total mission duration) where tomographic measurements are made using 10–12 spatial baselines and a revisit time of 1–4 days.
5.3 Ground Segment

5.3.1 Mission operations

To develop consistent maps of biophysical parameters over space and time requires revisiting the coverage areas with the same observation mode. In addition, fully-polarimetric acquisitions are required for forest height inversion using Pol-InSAR and ionospheric correction. As a result, the main operation mode for BIOMASS will be fully-polarimetric. Added benefits of adopting a single-mode of observation include greatly simplified operations, no mode conflicts, and a consistent archive leading to the reliable global data quality required for the mission.

At this stage in the development of the mission, some flexibility in choosing other instrument modes should be maintained, in particular regarding the CP mode which has shown promise in terms of robustness to ionospheric impact on the signal.

5.3.2 Processing, archiving and data distribution

Data availability for the development and validation of the retrieval algorithms necessitate the processing of all data to Level 0 and Level 1b. The transformation from Level 0 to Level 1 will require correction for the ionospheric impact on the data, as discussed below. Further processing to transform the Level 1 data into geocoded geophysical products at Level 2 and beyond is also required from the ground segment.

All data acquired throughout the mission need to be archived to support the long-term time-series of observations. There are no near real-time requirements and distribution of data is expected to take place via the BIOMASS mission archive.

5.3.3 Calibration

The calibration of spaceborne P-band SAR data can be subdivided into calibration steps that are purely instrument based and steps that address the correction for ionospheric effects on the P-band SAR signal.

5.3.3.1 Instrument calibration

Instrument calibration represents the first steps in calibrating Level 1 BIOMASS data and is performed by the Level 1 processor within the ground segment. The main steps in sequence are:

- radiometric correction,
- cross-talk removal.

Radiometric correction involves correcting data using pre-determined antenna patterns, range variation, transmit power and receiver gain. Cross-talk removal should be performed based on prior on-ground estimates.
5.3.3.2 Ionospheric correction

Following instrument correction, Level 1 BIOMASS data will require additional correction for ionospheric perturbations. SAR systems operating at lower frequencies (e.g. L- and/or P-band), are particularly affected by an active ionosphere. The strength of the ionospheric impact on P-band SAR acquisitions depends on the degree of ionisation of the ionosphere. The latter is expressed in terms of electron density. Integrating the electron density along the propagation path of the radar waves travelling through the ionosphere, one obtains the Total Electron Content (TEC) which quantifies to a great extent the ionospheric impact on long-wavelength (L- and P-band) SAR measurements. TEC has large diurnal and seasonal variations, a strong dependence on the 11-year solar cycle, and further stochastic time-variation due to magnetic disturbances. It also exhibits marked large-scale spatial structure, with different types of behaviour in the tropics, mid-latitudes, auroral zones and polar caps. The associated broadly predictable patterns of behaviour allow us to make representative maps of TEC that may be perturbed by stochastic events such as magnetic storms.

An example simulation, based on the International Reference Ionosphere (IRI), is provided in Figure 5.4, which shows a representative global map of TEC simulated at midnight GMT. The lowest values for TEC occur between approximately 5 and 6 am local time indicating that SAR acquisitions at this time would be least affected by ionospheric disturbances. As this represents a general feature in most simulations, an important conclusion is that the impact of the ionosphere on BIOMASS SAR measurements can be minimised by choosing a Sun-synchronous orbit with a dawn-dusk Equator crossing time and exploiting the dawn crossing orbital passes. Such an orbit would also avoid the equatorial post-sunset scintillations.

The ionosphere is expected to affect the BIOMASS radar signal in two major ways, Faraday rotation, which is directly proportional to TEC, and phase scintillations.

Figure 5.4: Global TEC map measured in TEC Units [TECU] at midnight GMT 1 Jan 1994, based on an IRI simulation. The red line represents the transition from night to dawn (6 am). We observe that the period between 5 and 6 am correspond to a minimum of ionospheric disturbance with characteristic low TEC values. [Credits: SCEOS]
Correcting Faraday rotation is important, as theoretical studies show that a rotation of the polarisation plane of up to 300° is possible at P-band. However, several methods for the correction of Faraday rotation exploiting fully-polarimetric data have been proposed in the literature (Freeman, 2004; Freeman and Saatchi, 2004). More importantly, the good overall performance of these methods has been verified using real spaceborne datasets acquired at L-band by the JAXA ALOS-PALSAR instrument. These have shown that Faraday rotation can be estimated to an accuracy of better than one degree. This, in turn, can be translated into a radiometric bias in the radar backscattering coefficient, as shown in Figure 5.5, for HH, HV and VV polarisations. In the figure, we see that an uncorrected rotation of about 1 degree translates into a negligible bias for the HH and VV channels (< 0.1 dB) and approximately 0.5 dB for HV, which is roughly in the order of the radiometric stability specification discussed earlier in this chapter.

Phase scintillations are distinguished into high spatial-frequency phase disturbances induced by small-scale variations of the electron density and low-frequency phase variations caused by the finite ionosphere correlation interval. While the low frequency effects appear primarily as an ordinary azimuth shift that can be easily corrected, high frequency effects are more difficult to correct for and require special attention.

High-frequency phase scintillations are corrected using so called Auto-Focus (AF) techniques, i.e., adaptive techniques that allow the estimation and/or compensation of second and/or higher order phase errors along the synthetic aperture, improving image focus. In the case of natural scenes, coherent AF techniques are applied. Accordingly, the correction is performed by estimating the phase error along the
synthetic aperture on individual quasi-deterministic scatterers localised across the scene by varying the phase history in azimuth until optimised image parameters are determined. This is illustrated in Figure 5.6 where the impact of a moderate disturbance in the ionosphere is simulated for point-like scatterers (the upper left image) and corrected for using AF algorithms (the upper right image). The effectiveness of this correction technique is underlined by the recovery of the simulated point-like scatterers in the scene following correction and the excellent agreement in the simulated phase error and the phase error estimated using AF in the lower plot.

![Figure 5.6: Simulations of ionospheric disturbance due to scintillation and correction using Auto-Focus (AF) algorithms. The top row shows the disturbed (top left) as well as the corrected (top right) image of a P-band scene containing bright point scatterers. In the top left image, ionospheric scintillations cause the point scatters to be smeared across a number of pixels. By applying AF techniques to correct for the disturbance, the point scatterers are recovered (top right image). The accuracy of the correction can be evaluated by comparing the phase error due to the ionospheric scintillations (blue line) and the estimated phase error from the correction algorithm (red line). [Credits: DLR]](image)

To summarise, the overall performance of ionospheric correction methods validated through simulations and using L-band satellite data appears to be sufficient to guarantee high quality calibrated Level 1 data, even under non-favourable ionospheric conditions.

In spite of the effectiveness of the individual ionospheric correction techniques, the implementation of a data acquisition scenario optimised with respect to the ionospheric characteristics and structure, is still recommended to achieve optimal data quality. The fact that large, as well as small-scale, ionospheric patterns are, at
least statistically, localised in space and time allowing the optimisation of the data acquisition scenario. A Sun-synchronous orbit that minimises the TEC impact has dawn and dusk Equator crossings. Such an orbit also avoids the equatorial post-sunset scintillations.

5.4.4 Auxiliary data requirements

At this stage of the mission definition, auxiliary data is envisaged for BIOMASS in two areas:

- independent information on the ionosphere provided by existing sources, and
- forest maps provided by land-cover maps.

Information on ionospheric disturbances and their spatial distribution will be used to provide first-order corrections to the Level 1 products, flag possible data-quality issues and guide mission planning. The IRI provides a useful tool for long-term mission planning and simulation. This is particularly important as the solar maximum will occur in 2022, roughly 5 years after launch. For data processing, and since BIOMASS has no strong requirement on rapid data delivery, TEC products derived from GPS satellite measurements such as those produced by the International GPS Service (IGS) can be used. Additional information on the magnetic field of the Earth will also be required to optimally estimate and correct ionospheric disturbances.

Independent forest maps will be used to screen and segment Level 1 data into forest and non-forested regions prior to applying BIOMASS geophysical retrieval algorithms. Initiatives such as the ESA study GLOBCOVER, which is currently producing global land-cover map at 300 m resolution are expected to help delineate forested areas. In the post-2016 timeframe, further initiatives are expected. In addition, the potential of BIOMASS to provide general land-cover maps may be studied for forest/non-forest delineation prior to inversion.
Chapter 6  System Concept

6.1  Introduction

This chapter provides the technical description of the BIOMASS mission, as derived from the preparatory activities at Phase 0 level, for implementation as an Earth Explorer in the frame of ESA’s Living Planet Programme. It shows how candidate implementation concepts can respond to the scientific mission requirements defined in the previous chapters. To this end, the expected system performance at Level 1b will also be described.

The system description is mainly based on the results of the work performed during parallel Phase 0 system studies by two industrial consortia (EADS Astrium GmbH, 2008; Thales Alenia Space Italy, 2008). Three implementation concepts are described, which provide options capable of meeting the mission requirements.

After an overview of the mission architecture and the proposed orbit (see Sections 6.2 and 6.3), the space segment is described in detail (see Section 6.4) followed by the ground segment and operations concept (see Sections 6.5 and 6.6). The overall mission performance is summarised in Section 6.7.

6.2  Mission architecture overview

The main architectural elements of the BIOMASS mission are shown in Figure 6.1. The space segment comprises a single spacecraft carrying a P-band SAR, operating in a near-polar, Sun-synchronous orbit at an altitude in the range 639–643 km. The orbit is chosen to enable interferometric acquisitions throughout the mission operational lifetime and to minimise the impact of ionospheric disturbances.

The baseline Soyuz launcher will inject the spacecraft into its target orbit. Compatibility of the satellite with smaller launchers, such as Vega, has also been studied.

The mission is designed to exploit acquisitions made around pre-dawn, local time, in order to minimise the adverse influence of the ionosphere on the radar signal. The SAR data is delivered to a single high-latitude ground station via an X-band downlink.

Auxiliary data, which are required to quantify the characteristics of the propagation path of the radar signal, are used in the end-to-end system calibration and processing of the SAR data.

The BIOMASS mission lasts five years and comprises the nominal operational phase, augmented by an experimental tomographic phase of short duration (≤ 50 days). The nominal operational phase is characterised by orbit repeat periods between 23 days and 39 days, whereas the range of useful repeat periods for the tomographic phase lies between three and four days.
The ground segment uses the generic Earth Explorer ground segment infrastructure and is composed of:

- the Flight Operation Segment (FOS), which includes the Telemetry, Tracking and Command (TT&C) Ground Station and the Flight Operations Control Centre, and
- the Payload Data Ground Segment (PDGS), which includes the Science Data Acquisition Station, the Processing and Archiving Element and the Mission Planning and Monitoring Element.

6.3 Orbits

Sun-synchronous pre-dawn–dusk orbits have been chosen for both mission phases, as summarised in Table 6.1. To minimise the ionospheric impact on data quality, the preferred local time for SAR acquisitions is around 05:00, either at the ascending or descending node crossing.

The selection of orbit altitudes higher than 600 km is a result of the trade-off between temporal revisit performance and the constraints of the SAR instrument, in particular with respect to the maximum antenna size that can be accommodated in a small– or mid-class launcher. At such altitudes, the need for orbit maintenance manoeuvres is strongly reduced. For the tomographic phase, the baseline orbit has a four-day repeat cycle at 639 km altitude and requires a negligible amount of fuel for the transition from the nominal phase orbit. Implementation of the alternative three-day repeat orbit at 666 km would require more fuel, but is compatible with a Soyuz launcher.
The interferometric orbit requirements can be subdivided into interferometric baseline requirements and orbit maintenance requirements.

The interferometric baseline requirements are expressed in terms of a baseline $B$, which is maintained between orbit $i$ of cycle $n$ and the corresponding orbit of cycle $n + 1$ over the Equator, as illustrated in Figure 6.2. The optimum baseline requirement is different for the nominal and the tomographic phases and is a function of the critical baseline $B_c$, defined in Subsection 5.2.7. In the nominal Phase, $B$ must be 60% of $B_c$, whereas the tomographic phase requires that $B = 2 \times B_c/(N-1)$, where $N = 11$ to 13.

The strategy for meeting the interferometric baseline requirement is through the selection of an orbit with a 'controlled drift'. The amount of drift between orbital cycles is chosen to match the interferometric baseline requirement. As a result, the repeat cycles of the orbits listed in Table 6.1 are not exact but differ by ~10 seconds from the exact repeat. In practice, the baseline is achieved by putting the satellite in an orbit where the semi-major axis is a few metres higher or lower than that of the exact repeating orbit.

![Figure 6.2: Observation geometry with interferometric baseline.](image)

<table>
<thead>
<tr>
<th>Rev. per day</th>
<th>Reference altitude</th>
<th>Repeat cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal Phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 + 17/23</td>
<td>643 km</td>
<td>23 days</td>
</tr>
<tr>
<td>14 + 20/27</td>
<td>642 km</td>
<td>27 days</td>
</tr>
<tr>
<td>14 + 29/39</td>
<td>641 km</td>
<td>39 days</td>
</tr>
<tr>
<td><strong>Tomographic Phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 + 3/4</td>
<td>639 km</td>
<td>4 days</td>
</tr>
<tr>
<td>14 + 2/3</td>
<td>666 km</td>
<td>3 days</td>
</tr>
</tbody>
</table>

Table 6.1: Candidate orbit characteristics.
The mission requirements impose stringent constraints on the orbit maintenance in both nominal and tomographic phases. The ground track must be maintained in a dead-band of ± 10% of the critical baseline. This corresponds to a ground track control of about ± 350 m for the selected orbits.

The presence of a large antenna causes relatively rapid orbit decay and, as a result, small in-plane manoeuvres must be performed frequently to maintain the nominal orbit. Preliminary estimates indicate that the frequency of manoeuvres is variable during the mission lifetime, reaching a maximum of one every three days during periods of high solar activity. The ground-track shift at high latitudes caused by the inclination drift must be compensated by making out-of-plane manoeuvres every 70–120 days.

Figure 6.3 illustrates an example of the coverage pattern over the Amazonian forest for a 27-day repeat orbit and 102 km swath. Complete coverage is achieved by the end of each repeat cycle.

6.4 Space segment

The BIOMASS space segment consists of a single satellite carrying the P-band (435 MHz) SAR. The satellite configuration is driven by the accommodation of a very large aperture antenna in side-looking geometry. This large antenna must be folded for launch and deployed in orbit to form a stable aperture over the mission lifetime. The industrial teams investigated different antenna types and folding concepts, resulting in three implementation concepts, which are described below.

Following the payload concept description in Subsection 6.4.1, the satellite platform is described in Subsection 6.4.2 and complemented with the description of the overall satellite configuration and budgets in Subsection 6.4.3.
6.4.1 Payload

Observation principles

The BIOMASS payload is a P-band SAR with full polarimetric and multi-pass interferometric capabilities. The observation geometry of the instrument is shown in Figure 6.4. There are three distinct concepts for the instrument design, each based on a very large passive antenna, but presenting differing operational capabilities:

Concept 1: A deployable planar-array antenna (27.5 m × 2.82 m) on the ‘Snapdragon’ platform concept, for imaging a single stripmap swath;

Concept 2: A deployable planar-array antenna (20.16 m × 3.36 m) on a conventional platform, for imaging a single stripmap swath;

Concept 3: A deployable dual-beam reflector antenna (14.7 m × 9.7 m) on a conventional platform, for imaging two switchable sub-swaths, operating either in stripmap mode with switching between the sub-swaths from one orbit cycle to the next (interleaved coverage), or in ScanSAR mode covering both sub-swaths at the same time (see payload operation modes and characteristics).

The width of the different swaths, as depicted in Figure 6.4, depends on the concept, the antenna size and the operating mode (full polarimetry as a baseline or compact polarimetry as an option) as summarised in Table 6.2. For all concepts, the minimum incidence angle, corresponding to the near-edge of the swath, is equal to or larger than 25° to maintain compatibility with the scientific mission requirements.
**Instrument architecture**

Figure 6.5 shows a high-level instrument architecture block diagram, which is applicable to all concepts. The differences among the concepts are found at subsystem level and depend on the selected antenna technology (long planar antenna or reflector), as described below.

The 435 MHz single sideband radar signal, which is generated in the central electronics, drives a number of Solid State Power Amplifiers (SSPA) via a power divider. In the case of long planar antennas (Concepts 1 and 2), there is at least one SSPA per radiator row (all radiators are excited in phase). A further division of the power amplification per radiator row may be necessary for a very long antenna, as is the case for Concept 1 (27.5 m).

The switching network has the following functions:

- toggling between the V and H polarisation ports of the circulator assembly at each Pulse Repetition Interval (PRI) in the full-polarisation mode,
- dividing each SSPA output into the V- and quadrature phase-shifted H-polarisation channels in the compact-polarimetric mode (circular polarisation in transmit), and
- beamforming for the feed-array of the reflector-based design (Concept 3).

The circulator/power divider assembly routes the V- and H-polarisation signals to the antenna in transmit operation, and routes both signals from the antenna to
the low noise amplifiers (LNAs) in receive operation. A long, passive planar array antenna is used for Concepts 1 and 2, whereas for Concept 3 a deployable reflector is illuminated by an array-feed.

In receive operation, the V- and H-polarised signals from each of the radiator rows, are first amplified and then summed by their respective power combiners before routing to the central electronics subsystem, where they are down-converted, digitised and data-compressed using a Block Adaptive Quantiser (BAQ).

**Instrument concepts**

**Concept 1: 27.5 m × 2.82 m antenna on Snapdragon platform**

Concept 1 makes use of the Snapdragon platform concept to achieve the deployed antenna length of 27.5 m (see Subsection 6.4.3). The antenna is folded along the launcher longitudinal axis. The Soyuz fairing diameter constrains the maximum aperture elevation height to 2.82 m. This leads to a maximum of five radiator rows as shown in Figure 6.6. The large length of the antenna enables a reduction of the radar Pulse Repetition Frequency (PRF), which provides a wider swath, thus improving the coverage performance.

![Figure 6.6: Antenna consisting of four identical mechanical panels, each comprising ten linear sub-arrays with six dual-polarised annular slot radiators.](image)

The antenna aperture comprises four identical mechanical panels. Each panel contains two columns of linear sub-arrays, each containing six dual-polarised annular slot radiators made of thin (approximately 2 cm) quartz honeycomb and Kevlar face-skin sandwich. The four panels are doubly folded around three hinges: the central hinge, which deploys the Snapdragon platform first, and those at the two opposite ends of the platform for the second stage deployment of the outer panels. Each of the sub-arrays is connected by a pair of coaxial cables (for the two polarisations) to the circulator/power divider assembly.

As an alternative to the conventional power combiners for summing the signals from the antenna rows, a digital beamforming concept for achieving a scan-in-receive was also considered as an option. This technique optimises the sensitivity and ambiguity performance beyond that achievable with passive beamforming and offers a larger swath. In this case, the five amplified echo signals for each polarisation from the respective antenna rows are down-converted and directly
digitised. For each polarisation channel, the digital beamformer performs a time-dependent weighted summation of the five digital signals, effectively resulting in a scanning beam during echo reception.

**Concept 2: 20.16 m × 3.36 m antenna on a conventional platform**

Concept 2 consists of a deployable planar-array antenna on a conventional platform. The antenna aperture of 20.16 m × 3.36 m, as depicted in Figure 6.7, comprises nine mechanical/electrical panels connected by hinges. The central panel is directly mounted on the face of the payload module oriented towards the Earth, whereas two wings of four panels each are folded and stowed on the perpendicular faces for launch (see Subsections 6.4.3 and 6.4.4). There are six rows of radiators in elevation, with two SSPAs (one for each polarisation) per antenna row. Each SSPA feeds nine four-element sub-arrays through a polarisation switch, two circulators, two one-to-nine power dividers and eighteen coaxial cables. The self-supported panels use a Carbon-Fibre Reinforced Plastic (CFRP) sandwich structure to provide the required stiffness.

![Figure 6.7](image)

Figure 6.7: (a) Antenna configuration consisting of nine mechanical/electrical panels with six sub-array rows per panel; (b) Antenna panel showing the annular slot radiators (grey) and the embedded stripline feed-networks (copper-coloured); (c) Cross-section of the panel sandwich (about 36 mm thick).

The antenna structural and mechanical design makes use of technological heritage from the development of very large solar arrays, although the aluminum honeycomb spacer is replaced by dielectric honeycomb for RF-transparency. With this configuration, the accommodation constraints force the antenna length to be shorter than that of Concept 1, which results in a narrower swath (see Table 6.2 for the payload characteristics).
**Concept 3: 14.7 m × 9.7 m Deployable Reflector Antenna**

Concept 3 exploits the Large Deployable Antenna (LDA) technology developed under an ESA Telecommunication programme (Mini, 2006) in which an Engineering Qualification Model (EQM) was developed with a projected aperture of 12 m diameter, focal length of 6.3 m and offset clearance of 3 m. Figure 6.8 shows the original LDA geometry and a picture taken during a deployment test. The reflector is held at its central axis by a deployable arm. When stowed, the reflector fits in a cylindrical volume of 0.7 m diameter and 3.5 m length. The advantage of the concept is its compact stowed dimension, which, in principle, can be accommodated in the smaller Vega launcher (see Subsection 6.4.4).

![Figure 6.8: LDA geometry for 12 m projected aperture (left); LDA during a deployment test (right).](image)

The low aspect ratio of the antenna aperture requires a dual-beam capability to be implemented in order to meet the coverage requirement. This provides additional operational flexibility as explained earlier (observation principle) and under payload operation modes and characteristics.

The dual-beam capability is implemented at the level of the array-feed, which comprises four pairs of patch radiators distributed in elevation, as shown in Figure 6.9a, each pair being excited in phase. With the array-feed positioned at the focal plane of the reflector, a spot beam is generated over Sub-swath 1 or Sub-swath 2 (see Figure 6.4) according to the excitations of the radiator rows. This includes the capability to sub-illuminate the reflector in elevation, producing an elliptical beam with its major axis in elevation. An exploded view of one half of the array-feed sandwich structure is shown in Figure 6.9b. The patch radiators and feed networks are made of copper-clad Kevlar face skins supported by Kevlar honeycomb spacers, with metallised CFRP panels inserted to serve both as ground planes and as structural support elements.

**Payload operation modes and characteristics**

**Polarisation modes:**

All the concepts can be operated either in full (baseline) or compact (option) polarimetric mode. In the full-polarimetric mode, the polarisation is commuted between V and H at each transmitted pulse and the echo signals in both polarisations are received simultaneously during the inter-pulse period, as shown by
the timing sequence in Figure 6.10a. In the compact-polarimetric mode, the transmit pulse is in circular polarisation and the echo signals in V- and H-polarisations are received simultaneously during the inter-pulse period, as shown by the timing sequence in Figure 6.10b. In this mode, the instrument PRF is half that of the full-polarimetric mode, potentially offering twice the swath width.

**Observation modes:**
Concepts 1 and 2 operate in stripmap mode in full polarisation, whereas Concept 3 is able to accommodate stripmap, interleaved-stripmap and ScanSAR modes in full polarisation. The major advantage of Concepts 1 and 2 is their simplicity of operation, achieved through continuous stripmap data acquisition. The orbit is designed such that the required global coverage is achieved at the end of each cycle.

The interleaved stripmap-mode of operation for Concept 3 allows for the global coverage to be obtained after two orbit cycles by switching from one sub-swath to the other at the end of the first cycle, as illustrated in Figure 6.11. Alternatively, the
same sub-swath can be imaged over two consecutive orbit cycles before switching to the other sub-swath. The revisit time is consequently halved with respect to the pure stripmap operation at the expense of the coverage time.

![Figure 6.11: Example of area coverage pattern over the Amazonian forest in 'interleaved' stripmap-mode of operation with a 23-day repeat orbit and 60 km swath (only descending paths shown): (left) after cycle n (covered areas in green); (right) after cycle n +1 (covered areas in light blue). [Credits: ESA]](image)

Table 6.2 summarises the major characteristics of the three payload concepts. For Concepts 1 and 2, the achievable swath width in stripmap mode (in both full- and compact-polarimetry) is a function of the along-track (azimuth) antenna aperture dimension. A wider swath is achieved in the optional compact-polarimetric mode because the radar PRF is reduced by a factor of two in comparison to that of the baseline full-polarimetric mode. This is, however, not true for Concept 3, because the narrow elevation beam of the reflector antenna limits the across-track coverage. The minimum orbit repeat cycle, relevant to interferometry, is set by the stripmap swath width for Concepts 1 and 2, whereas for Concept 3 it is set by the sum of the two sub-swath widths (dual-beam capability).

<table>
<thead>
<tr>
<th>Payload characteristics</th>
<th>Concept 1 (stripmap)</th>
<th>Concept 2 (stripmap)</th>
<th>Concept 3 (2 sub-swaths)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna aperture dimension</td>
<td>27.5 m x 2.82 m</td>
<td>20.16 m x 3.36 m</td>
<td>14.7 m x 9.7 m</td>
</tr>
<tr>
<td>Peak RF-power (total)</td>
<td>320 W</td>
<td>300 W</td>
<td>300 W</td>
</tr>
<tr>
<td>Transmit duty cycle (full pol.)</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Stripmap swath – full pol.</td>
<td>102 km</td>
<td>70 km</td>
<td>65 km</td>
</tr>
<tr>
<td>Dual-beam or ScanSAR swath - full pol.</td>
<td>-</td>
<td>-</td>
<td>2 x 60 km</td>
</tr>
<tr>
<td>Stripmap swath – compact pol.</td>
<td>200 km</td>
<td>110 km</td>
<td>75 km</td>
</tr>
</tbody>
</table>

Table 6.2: Summary of the payload characteristics for the three concepts.

**6.4.2 Platform**

The main difference between the concepts outlined above is in the choice of the physical design of the antenna. This drives the satellite configuration, causing special attention to be given to the areas of attitude control, structural design and launch accommodation. All these platform elements are now outlined.
**Structure**

Two different implementation principles can be used for the structure, namely to integrate the platform into the antenna structure or to use a more conventional modular approach (see Subsection 6.4.3). The first principle provides the basis for Concept 1, which uses a Snapdragon platform, whereas the second principle applies to Concept 2 (deployable antenna panels) and Concept 3 (reflector). The satellite structural technology itself is standard, using aluminum or CFRP sandwich panels and standard attachments.

**Thermal control**

The BIOMASS orbit is very close to a dawn-dusk Sun-synchronous orbit, and the dissipated power levels are moderate. Therefore a mid-size radiator wall facing deep space is adequate. The preliminary thermal design did not identify any critical points in this subsystem.

**Power and energy storage**

The moderate power consumption of BIOMASS means that the power subsystem is not critical. The concept that consumes the most power, i.e. the Snapdragon, can be implemented with a fixed deployable solar array of 8 m² area and a battery with 150 Ah capacity. These are all Commercial-Off-The-Shelf (COTS) equipment.

**Payload Data Handling and Transmission**

The Payload Data Handling and Transmission (PDHT) constraints for BIOMASS are not stringent, given the payload data rate of up to 102 Mb/s and the orbit duty cycle of about 20%. Depending on the scenario, this results in down-link data rates between 100 and 250 Mb/s. Suitable X-band transmit chain and associated mass memory already exist.

**Telemetry, Tracking and Command**

Telemetry, Tracking and Command (TT&C) requirements are standard, and accordingly the proposed implementation is similar to the other Earth Explorers. A COTS S-band transceiver provides all required TT&C services, including ranging, range rate, polarisation discrimination and telemetry/telecommand transmission.

**AOCS**

The main driver for BIOMASS is the attitude control performance in view of the large deployables. Nevertheless, the analysis for all concepts shows that available actuators (magnetic torquers and reaction wheels) will be able to handle the large inertias, so a heritage three-axis control system is adequate.
The nominal phase control requires special attention as the pointing performance affects the SAR radiometric quality and, to a lesser extent, the geo-location knowledge. This issue is addressed by the three proposed concepts in different ways. The Attitude and Orbit Control System (AOCS) for the Snapdragon-type spacecraft (Concept 1) was studied at Phase B level in TerraSAR-L. A preliminary analysis of these results for BIOMASS shows that the attitude control requirements can be met. Concept 2 builds on similarity with previous missions with large deployables. For Concept 3, the attitude control performance is to be analysed in more detail in Phase A. In conclusion, the Phase 0 results indicate that the AOCS for BIOMASS is feasible with conventional means, but remains a subject for more detailed studies in Phase A, particularly for Concept 3.

**Propulsion**

The mission schedule places the BIOMASS lifetime during a low solar activity period. Consequently, the Delta-V budget and the propulsion requirements are moderate. Although alternatives were studied during Phase 0, all concepts are based on a standard hydrazine (N₂H₄) mono-propellant system, pressurised with helium, and operated in blow-down mode. For Concept 1, a detailed study of the placement and redundancy of the propulsion equipment on the two hinged halves of the Snapdragon platform remains to be performed in Phase A.

### 6.4.3 Satellite

The satellite physical configuration and functional system budgets are addressed below.

**Configuration**

Three possible implementation configurations have been studied for BIOMASS. They are depicted in Figure 6.12. These configurations are characterised by the presence of large antennas of different shapes, with avionics either in a module (deployable antenna panels and reflector concepts) or integrated within the foldable Snapdragon concept.

**Budgets**

Tables 6.3 to 6.6 summarise the satellite budgets. The ranges correspond to the budgets of the three concepts.

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-Band SAR Payload</td>
<td>430–630</td>
</tr>
<tr>
<td>Platform</td>
<td>700–1750</td>
</tr>
<tr>
<td>N₂H₄ Propellant</td>
<td>20–230</td>
</tr>
<tr>
<td>Total</td>
<td>1140–2600</td>
</tr>
</tbody>
</table>

Table 6-3: Satellite mass budget.
Figure 6.12: Satellite configurations: (a) Concept 1 – Snapdragon; (b) Concept 2 – deployable antenna panels on a conventional platform; (c) Concept 3 – large deployable reflector.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Average Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-Band SAR Payload</td>
<td>310–460</td>
</tr>
<tr>
<td>Platform</td>
<td>440–710</td>
</tr>
<tr>
<td>Total</td>
<td>750–1200</td>
</tr>
</tbody>
</table>

Table 6.4: Satellite power consumption budget (orbit average).

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Data Rate [Mb/s]</th>
<th>Duty Cycle [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total P-Band SAR Payload Data</td>
<td>54–102</td>
<td>20%–23%</td>
</tr>
<tr>
<td>Total Max On-board storage</td>
<td>400–700 Gb</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.5: Payload instantaneous data-rate budget.
6.4.4 Launcher

The baseline launcher is Soyuz for Concepts 1 and 2, and potentially Vega for Concept 3 as shown in Figure 6.13. The selection of Soyuz is required for the first two concepts, because of the large volume of the stowed satellites. A preliminary optimisation of Concept 3 has been carried out in order to assess the compatibility with Vega. Nevertheless, further analysis is required in Phase A.

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Delta-V [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Acquisition &amp; Maintenance</td>
<td>8–13</td>
</tr>
<tr>
<td>Orbit Maintenance</td>
<td>10–23</td>
</tr>
<tr>
<td>EOL Disposal</td>
<td>0–40</td>
</tr>
<tr>
<td>Tomographic Phase Manoeuvre</td>
<td>2–24</td>
</tr>
<tr>
<td>Total</td>
<td>33–96</td>
</tr>
</tbody>
</table>

Table 6.6: Satellite delta-V budget.

6.5 Ground segment and data processing

6.5.1 General

The ground segment is based on the infrastructure developed to support the Earth Explorers as well as other ESA missions. It consists of two main components, the Payload Data Ground Segment (PDGS) and the Flight Operation Segment (FOS).
6.5.2 Ground segment elements

The overall ground segment architecture is presented in Figure 6.14.

The FOS includes the TT&C Ground Station and the Flight Operations Control Centre.

The TT&C Ground Station provides the following main functions:

- house-keeping telemetry acquisition,
- telecommand uplink,
- satellite tracking, and
- data connection to the Flight Operations Control Centre.

A single S-band TT&C ground station with one contact per day is proposed. The TT&C ground station is co-located with the science data downlink station. During the Launch and Early Operations Phase (LEOP) (see Section 6.6), the operations are supported by a dedicated ground station network. This uses ESTRACK core and enhanced stations where possible (depending on the chosen launch site).

The Flight Operations Control Centre is based at the European Space Operations Centre (ESOC) and provides the following main functions:

- satellite monitoring and control,
• flight dynamics and manoeuvre planning,
• TT&C ground station network control,
• overall satellite operations planning,
• on-board software maintenance,
• mission simulation,
• FOS supervision,
• spacecraft system data distribution, and
• interface with the launch site for LEOP.

The PDGS consists of the Science Data Acquisition Station, the Processing and Archiving Element and the Mission Planning and Monitoring Element.

The Science Data Acquisition Station is in charge of acquiring the raw payload data and transmitting them to a Processing and Archiving Element. Preliminary analyses have indicated that a single station in either Svalbard or Kiruna can be used as the data rates and mass memory sizes are modest by the standards of other SAR and Sentinel missions.

The Processing and Archiving Element and the Mission Planning and Monitoring Element are implemented through maximal re-use of existing ESA multi-mission facility infrastructure elements, and their final location will be selected in later phases.

They provide the following main functions:
• acquisition of payload data from the Science Data Acquisition Ground Station(s),
• acquisition of required ancillary data from appropriate providers,
• generation and quality control of calibration, Level 1 and higher level products,
• long-term archiving of mission products and related auxiliary files and reports,
• implementing the payload planning strategy (routine and calibration) and forwarding it to the FOS,
• instrument/mission performance monitoring,
• systematic and on-request distribution of mission products to the user community, and
• provision of user services.

6.5.3 Data processing

A mission-specific SAR ground processor is required to provide the end-users with Level 1b data for higher level processing up to Level 2 and above. External calibration of the BIOMASS payload requires interactions with the ground segment to transfer information on the status of the on-ground calibration devices. A common, or very similar, sequence of operations for external calibration in both quad- and optional compact-polar modes is assumed.
Processing of the data from Level 0 to Level 1b necessitates access to information on the state of the Earth’s ionosphere and magnetic field, which affect the radar-signal propagation. A first-order ionospheric correction will be applied as part of the routine processing. In addition, independent forest maps such as those generated from ESA’s GLOBCOVER will be used to screen and segment Level 1 data.

There is no requirement for near-real-time data service provision, so the data-latency requirements place no problematic demands on the BIOMASS ground segment.

To summarise, the ground segment for the BIOMASS mission does not present any new technology or infrastructure requirements. The SAR ground processor and the P-band devices for instrument external calibration represent the principal mission-specific development activities.

6.6 Operation and utilisation concept

The nature of the observations made by the BIOMASS spacecraft, throughout its five-year lifetime, amounts to repetitive global coverage of a specified set of regions, which are defined by an imaging mask – defined, for example, by using independent forest maps for the primary mission. The data are acquired, preferably on a single (ascending or descending) pass per orbit, to confine data acquisition to the pre-dawn hours when the ionospheric disturbances are minimal. This process lends itself to an autonomous approach for data acquisition and processing up to Level 1b.

The precise orbit control required to deliver the interferometric baselines is achieved via orbit maintenance operations at a frequency that will nominally vary throughout the mission with the worst case requiring two manoeuvres per week towards the end of the mission.

Transitions between the Nominal Phase and the Tomographic Phase require dedicated, but small, orbit altitude change manoeuvres.

The need for a de-orbit burn is unlikely because atmospheric drag alone can de-orbit the spacecraft within 25 years. However, the mission delta-V budget has allowed for an appropriate de-orbit burn from the operational altitude. During Phase A, it will be defined whether the associated fuel mass is to be retained or the mass margin can be increased further.

6.7 Performance aspects

6.7.1 ITU constraints

The ITU constraints [Recommendation ITU-R RS.1260-1] imposed on a spaceborne P-band SAR can be divided into technical and operational constraints. The technical constraints for a P-band spaceborne SAR are the emitted signal bandwidth of 6 MHz
maximum, centred on 435 MHz, and the power flux density on the Earth’s surface, as listed in Table 6.7. The 6 MHz bandwidth limits the range resolution at the 25° incidence angle to 60 m (see Table 6.8), whereas the power flux density limits the maximum peak and average emitted power by the radar, and forces an antenna aperture illumination weighting for reducing the sidelobes. As a consequence, the antenna aperture efficiency is reduced, and hence it drives the antenna size. The technical constraints were taken into account in the design of the payload concepts. The operational constraints were not addressed during Phase 0, because discussion with the primary users required detailed information on the BIOMASS system characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value [W/(m²·Hz)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum peak PFD on Earth’s surface from antenna main-lobe</td>
<td>−140 dB</td>
</tr>
<tr>
<td>Maximum mean PFD on Earth’s surface from antenna main-lobe</td>
<td>−150 dB</td>
</tr>
<tr>
<td>Maximum mean PFD on Earth’s surface from 1st antenna side-lobe</td>
<td>−170 dB</td>
</tr>
</tbody>
</table>

Table 6.7: ITU Power Flux Density constraints for a spaceborne P-band SAR.

6.7.2 Internal and external calibration

The system design includes internal as well as external means of calibration. Considerable heritage exists in Europe for achieving high calibration accuracy for spaceborne SARs at C- and X-bands. This heritage is applied for the internal calibration of the BIOMASS payload. The payload concepts include calibration loops to monitor the transmitter power level, the receiver gain and the phase-delay changes.

For the external calibration, the BIOMASS mission presents a number of novel aspects associated with the fact that it is the first spaceborne mission to operate in P-band. Firstly, the long wavelength presents new challenges for the design of calibration devices to be deployed on the ground because of their large size. Secondly, the effects of ionospheric layers introduce calibration uncertainties due to the spatially and temporally varying propagation medium between the radar and the target scenes, as described under Subsection 5.3.3.

The three major impacts on the SAR observations are: (1) propagation delays; (2) signal scintillation; and (3) Faraday rotation, which need to be corrected in the process of the external calibration. These corrections will be performed on-ground as a part of the overall radiometric and phase calibrations of the complex image-products, using AF techniques and exploiting the full polarimetric set of measurements as described in Subsection 5.3.4. A further use of global ionospheric models will be required for removing phase biases in the multi-pass interferometric data set.
### 6.7.3 BIOMASS system performance

Table 6.8 summarises the major BIOMASS system performance figures. All the concepts meet the requirements within the goal and threshold range.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit altitudes (Nominal Phase)</td>
<td>n/a</td>
<td>642 km</td>
<td>641 km</td>
<td>643 km</td>
</tr>
<tr>
<td>Nominal Phase orbit repeat cycle</td>
<td>≤ 25 days goal; ≤ 45 days threshold</td>
<td>27 days</td>
<td>39 days</td>
<td>23 days in dual-beam</td>
</tr>
<tr>
<td>Nominal Phase global coverage</td>
<td>Complete coverage of forested areas (see Section 4.5) in ≤ 25 days goal; ≤ 45 days threshold</td>
<td>27 days</td>
<td>39 days</td>
<td>46 days in dual-beam</td>
</tr>
<tr>
<td>Cross-polar isolation</td>
<td>≥ 28 dB goal; ≥ 20 dB threshold</td>
<td>≥ 30 dB</td>
<td>≥ 30 dB</td>
<td>≥ 25 dB</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>≤ 50 m x 50 m (≥ 4 looks)†</td>
<td>≤ 61 m x 50 m</td>
<td>≤ 61 m x 50 m</td>
<td>≤ 55 m x 50 m</td>
</tr>
<tr>
<td>Noise equivalent $\sigma_0$ for full / compact pol.</td>
<td>≤ −30 dB goal; ≤ −27 dB threshold</td>
<td>≤ −30.4 / −28.8 dB</td>
<td>≤ −27.2 / −25.5 dB</td>
<td>≤ −30.5 / −29.6 dB</td>
</tr>
<tr>
<td>Absolute radiometric bias</td>
<td>≤ 1 dB</td>
<td>Compliant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total ambiguity ratio‡ for full / compact pol.</td>
<td>≤ −20 dB</td>
<td></td>
<td>Compliant</td>
<td></td>
</tr>
<tr>
<td>Radiometric stability</td>
<td>≤ 0.5 dB</td>
<td></td>
<td></td>
<td>Compliant</td>
</tr>
</tbody>
</table>

Table 6.8: Summary of system performance for the three concepts.

†) Range resolution requirement relaxed due to the ITU bandwidth constraint and minimum incidence requirement of ≥ 25°.
‡) Total ambiguity ratio estimation assumed a model $\sigma_0$-profile for a well-developed forest.

The sensitivity performance of each concept, i.e. the noise equivalent $\sigma_0$ as a function of the incidence angle, is shown in Figure 6.15. For all incidence angles, the instrument noise lies below the −27 dB threshold derived from the science requirements.

![Figure 6.15: Noise equivalent $\sigma_0$ as function of the incidence angle.](image-url)
Chapter 7 Programmatics

7.1 Introduction

This Chapter presents the technical maturity, the heritage and the risks associated with the implementation concepts developed in the frame of the Phase 0 studies. The overall development approach and schedule are briefly introduced and discussed with respect to the compatibility of a target launch date for the seventh Earth Explorer Core Mission during 2016.

7.2 Technical maturity, critical areas and risk

The challenging set of observation requirements, especially those associated with the full-polarimetric capability and the specified range of revisit times, requires a number of different concept options and their respective technical and programmatic risks to be considered. The technical maturity, critical areas and risk are discussed below, together with a brief description of present and future development activities supporting the BIOMASS mission.

7.2.1 Satellite development

Concept 1, tailored to accommodate a 27.5 m long antenna aperture, has strong similarities to TerraSAR-L, which is also based on a Snapdragon platform. TerraSAR-L was studied through to Phase B level and included the pre-development of critical mechanical parts, such as the central/master hinge and hold-down-release and latching mechanisms. However, since there is no flight heritage these parts will require space qualification.

Concept 2, based on the use of a conventional platform, has a good flight heritage from the existing SAR missions such as Radarsat-2 and Cosmo/Skymed, as well as Sentinel-1 (under development). In these missions, each satellite includes a long and massive deployable antenna (e.g. up to 15 m × 1.5 m for Radarsat-2). No critical elements have thus been identified at the level of the platform.

Concept 3, using the LDA reflector together with a conventional platform, requires further work during Phase A to consolidate the design and to confirm the feasibility of its accommodation in the Vega launcher. This is currently addressed, at antenna subsystem level, as a part of the on-going feed-array breadboarding activity under the EOEP.

For all concepts, the performance of the attitude control will require detailed analysis during Phase A, in view of the large deployable antennas, to assess the final impact on the radiometric stability.
7.2.2 Antenna and accommodation

All concepts are driven by the need to accommodate a very large antenna, which must be folded for launch, deployed, and kept stable in orbit. There is no flight heritage yet for such large deployable-antenna technology in Europe. Pre-development activities will be required for the selected concepts, starting in mid-Phase A.

For Concept 1, the proposed sub-arrays, each comprising six annular slot-radiators, have been derived as a scaled version of the TerraSAR-L design except for their thickness. Although the TerraSAR-L sub-arrays were fully tested and environmentally qualified at L-band, their applicability is limited due to the large dimensional scaling factor of three. Furthermore, the accommodation constraints in launch configuration, when re-using TerraSAR-L platform design heritage, limit the maximum sub-array thickness, resulting in a tight element-bandwidth. Thus, further work is required during Phase A. The feasibility of the large deployable antenna is being addressed through a study initiated under the Technical Research Programme (TRP) in 2006.

For Concept 2, the large solar-panel type antenna technology enables a classical development approach. The feasibility of the deployable antenna is being addressed through another study initiated under TRP in 2006 and a breadboarding activity under the General Support Technology Programme (GSTP) in 2007. In the latter activity, a complete 2.24 m × 3.3 m antenna panel using representative materials is being built and will be tested in early 2009. During Phase A, attention needs to be paid to the coaxial cables feeding the sub-arrays in terms of the losses, multipaction susceptibility, phase stability and mechanical robustness.

For Concept 3, the LDA with 12 m diameter reflector was developed up to EQM level under the Agency’s ARTES programme for geostationary mobile-communication applications (Mini, 2006). The required adaptation includes re-shaping of the reflector and the modification of the deployment arm for accommodation in Vega. The latter is being addressed within the breadboarding of the P-band feed-array under EOEP. A 2 × 4 elements breadboard will be built using partially representative materials.

7.2.3 Radar electronics

Due to the low system bandwidth, low radar frequency and low power, no part of the radio-frequency equipment, including the internal calibration subsystem, is considered critical. Nevertheless, a technology assessment study for a P-band SSPA was initiated in spring 2008 under EOEP, for anticipating the technology trend in this fast evolving field.

For Concept 1, the use of a digital beamformer to increase the imaged swath was identified as an option. Such equipment has no flight heritage and would represent a critical path for the system development. If this option were retained in Phase A, pre-development would be required.
7.2.4 End-to-end calibration

The end-to-end calibration of BIOMASS can benefit from the considerable heritage that has evolved over several SAR missions. The accuracy of the BIOMASS products, derived from the basic radar observation, depends largely on the performance of the applied ionospheric-correction methods, which form an integral part of the end-to-end system calibration.

Ionospheric disturbance studies have been initiated at national level (Sheffield Centre for Earth Observation Science, UK) and at ESA level under EOEP and TRP. The AF technique has successfully been applied in the frame of the MARSIS and SHARAD missions for the Martian ionosphere. The above studies will demonstrate its applicability to the Earth’s ionosphere during Phase A.

7.3 Development approach and schedule

The development approach proposed for the BIOMASS system assumes a platform model philosophy for the satellite based on a Structural and Thermal Model (STM) and a Proto-Flight Model (PFM) for both the conventional and Snapdragon concepts. For the latter, extra testing of the STM is proposed in order to account for the novelty of the concept, resulting in a tight window before the initiation of the PFM hardware procurement when aiming at a late 2016 launch.

The BIOMASS development may require adoption of some specific testing approach and philosophy due to the presence of very large deployables, for which no suitable facility might be found. Also, an adequate methodology to verify the overall payload performance needs to be developed.

The payload development model philosophy will depend on the outcome of Phase A, in particular on the final choice of the antenna concepts. For both Concepts 1 and 2, a pre-development of a complete electrical or mechanical panel (i.e. a single column of sub-arrays) needs to be initiated during Phase A, to ensure that a consolidated antenna panel design is available for the beginning of Phase B, including detailed material selection and development of suitable fabrication processes. For Concept 3, specific mechanical and structural aspects, related to the reflector re-shaping and the new deployment arm, will require a pre-development.

The payload development is on the critical path for a late 2016 launch, which is nevertheless considered feasible, provided that a suitable pre-development programme is started during Phase A.
References


Six Candidate Earth Explorer Core Missions

References


References

Six Candidate Earth Explorer Core Missions


### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AF</td>
<td>Auto-Focus</td>
</tr>
<tr>
<td>ALOS</td>
<td>Advanced Land Observing Satellite (Japan)</td>
</tr>
<tr>
<td>AOCS</td>
<td>Attitude and Orbit Control System</td>
</tr>
<tr>
<td>ARD</td>
<td>Afforestation, Reforestation, Deforestation</td>
</tr>
<tr>
<td>ASAR</td>
<td>Advanced Synthetic Aperture Radar on board ENVISAT</td>
</tr>
<tr>
<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer</td>
</tr>
<tr>
<td>BAQ</td>
<td>Block Adaptive Quantiser</td>
</tr>
<tr>
<td>BIOSAR</td>
<td>ESA BIOMASS SAR experiment (March-May 2007)</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fibre Reinforced Plastic</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial-Off-The-Shelf</td>
</tr>
<tr>
<td>CP</td>
<td>Compact Polarimetry</td>
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<tr>
<td>CSA</td>
<td>Canadian Space Agency</td>
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<td>DALEC</td>
<td>Data Assimilation Land Ecosystem Carbon model</td>
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<tr>
<td>dB</td>
<td>Decibels</td>
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<tr>
<td>DESDynl</td>
<td>Deformation Ecosystem Structure and Dynamics of Ice</td>
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<td>DGVM</td>
<td>Dynamic Global Vegetation Model</td>
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<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)</td>
</tr>
<tr>
<td>DVM</td>
<td>Dynamic Vegetation Model</td>
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<tr>
<td>ECV</td>
<td>Essential Climate Variable</td>
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<tr>
<td>ENL</td>
<td>Equivalent Number of Looks</td>
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<tr>
<td>Envisat</td>
<td>Environmental Satellite (ESA)</td>
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<tr>
<td>EO</td>
<td>Earth Observation</td>
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<tr>
<td>EOEP</td>
<td>Earth Observation Envelope Programme</td>
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<td>EQM</td>
<td>Engineering Qualification Model</td>
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<td>ERS</td>
<td>European Remote Sensing Satellite (ESA)</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<td>European Space Operations Centre</td>
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<td>ESTRACK</td>
<td>European Space Tracking</td>
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<tr>
<td>ETM</td>
<td>Enhanced Thematic Mapper</td>
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<tr>
<td>FAO</td>
<td>United Nations Food and Agriculture Organisation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
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<tr>
<td>fAPAR</td>
<td>fraction of Absorbed Photosynthetically Absorbed Active Radiation</td>
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<td>FOS</td>
<td>Flight Operation Segment</td>
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<td>FRA</td>
<td>Forest Resources Assessments (FAO)</td>
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<td>GCOS</td>
<td>Global Carbon Observing System</td>
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<td>GHG</td>
<td>Greenhouse Gases</td>
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<td>GIS</td>
<td>Geographic Information System</td>
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<tr>
<td>GLAS</td>
<td>Geoscience Laser Altimeter System</td>
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<td>GMES</td>
<td>Global Monitoring for Environment Security</td>
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<td>GOSAT</td>
<td>Greenhouse gases Observing SATellite</td>
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<td>GSTP</td>
<td>General Support Technology Programme</td>
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<td>GtC</td>
<td>Gigaton Carbon</td>
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<td>GTOS</td>
<td>Global Terrestrial Observing System</td>
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<tr>
<td>H</td>
<td>Horizontal</td>
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<tr>
<td>HH</td>
<td>Horizontal Polarisation transmitted- Horizontal Polarisation received</td>
</tr>
<tr>
<td>HPA</td>
<td>High Power Amplifier</td>
</tr>
<tr>
<td>HV</td>
<td>Horizontal Polarisation transmitted- Vertical Polarisation received</td>
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<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
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<tr>
<td>IGCOS</td>
<td>Integrated Global Carbon Observing Strategy</td>
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<tr>
<td>IGOS</td>
<td>Integrated Global Observing Strategy</td>
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<td>IGS</td>
<td>International GPS Service</td>
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<td>INDREX</td>
<td>Indonesian Radar Experiment (ESA campaign)</td>
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<td>InSAR</td>
<td>Interferometric Synthetic Aperture Radar</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>IRI</td>
<td>International Reference Ionosphere</td>
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<td>ITU</td>
<td>International Telecommunication Union</td>
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<td>LEO</td>
<td>Low Earth Orbit</td>
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<td>LEOP</td>
<td>Launch and Early Orbit Phase</td>
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<td>LNA</td>
<td>Low Noise Amplifier</td>
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<td>LPS</td>
<td>Lund-Potsdam-Jena</td>
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<tr>
<td>JAXA</td>
<td>National Space Development Agency (Japan)</td>
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<td>JERS</td>
<td>Japanese Earth Resource Satellite</td>
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<td>JPL</td>
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<td>LAI</td>
<td>Leaf Area Index</td>
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<td>LEOP</td>
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<td>LPJ</td>
<td>Lund-Potsdam-Jena Dynamic Global Vegetation Model</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>NBP</td>
<td>Net Biome Production</td>
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<td>NDVI</td>
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<td>OCO</td>
<td>Orbiting Carbon Observatory</td>
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<td>PALSAR</td>
<td>Phase Array L-band Synthetic Aperture Radar onboard ALOS satellite</td>
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<td>PDGS</td>
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<td>PFT</td>
<td>Plant Functional Type</td>
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<td>Pol-InSAR</td>
<td>SAR Polarimetric Interferometry</td>
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<tr>
<td>PRF</td>
<td>Pulse Repetition Frequency</td>
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<td>PRI</td>
<td>Pulse Repetition Interval</td>
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<tr>
<td>REDD</td>
<td>Reduction of Emissions due to Deforestation and Forest Degradation</td>
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<td>RF</td>
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<td>RGB</td>
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<td>RMS</td>
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<td>SNR</td>
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<td>SST</td>
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