SP-1257 (3)

EarthCARE - Earth Clouds, Aerosols and Radiation Explorer

WALES - Water Vapour Lidar Experiment in Space

WATS - Water Vapour and Temperature in the Troposphere and Stratosphere

ACECHEM - Atmospheric Composition Explorer for Chemistry and Climate Interaction

SPECTRA - Surface Processes and Ecosystem Changes Through Response Analysis

European Space Agency
Agence spatiale européenne

REPORTS FOR ASSESSMENT

THE FIVE CANDIDATE EARTH EXPLORER CORE MISSIONS

ESA SP-1257(3)
September 2001

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WATS –
Water Vapour and Temperature in the Troposphere and Stratosphere

European Space Agency
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ESA SP-1257(3) – The Five Candidate Earth Explorer Core Missions -
WATS – Water Vapour in Atmospheric Troposphere and Stratosphere

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1 Introduction

The ESA Living Planet Programme includes two types of complementary user driven missions: the research oriented Earth Explorer missions and the operational service oriented Earth Watch missions. These missions are implemented via two programmes: the Earth Observation Envelope Programme (EOEP) and the Earth Watch Programme. The Earth Explorer missions are completely covered by the EOEP.

There are two classes of Earth Explorer mission. The Core missions are larger missions addressing complex issues of wide scientific interest. The Opportunity missions are smaller missions in terms of cost to ESA, addressing more limited issues. Both types address the research objectives of the Earth Explorers, which are being implemented according to well-established mechanisms (ESA, 1998a). The missions are proposed, defined, evaluated and recommended by the scientific community.

Core and Opportunity missions are implemented in separate cycles. A new cycle is started every four years. Two missions are implemented per cycle. The two missions selected in the first cycle of the Earth Explorer Core missions are underway: the Gravity field and steady-state Ocean Circulation Explorer (GOCE) and the Atmospheric Dynamics Mission (ADM-Aeolus), scheduled for launch in 2005 and 2007, respectively. The first cycle of Earth Explorer Opportunity missions is also on-going and will result in the CryoSat and the Soil Moisture and Ocean Salinity (SMOS) missions planned to be launched in 2004 and 2006. respectively.

This report concerns the second cycle of Earth Explorer Core missions. As a result of the second call for ideas for Earth Explorer Core missions, which was released in June 2000, five missions were selected in Autumn 2000 for the second step of the implementation mechanism, i.e. the assessment. These missions are ACECHEM (Atmospheric Composition Explorer for CHEMistry and climate interaction), EarthCARE (Earth Clouds Aerosol and Radiation Explorer), SPECTRA (Surface Processes and Ecosystems Changes Through Response Analysis), WALES (WAter vapour Lidar Experiment in Space), and WATS (WAter vapour and temperature in the Troposphere and Stratosphere). Reports for Assessment have been prepared for each of these candidate missions .

These reports will be circulated among the Earth Observation research community in preparation for the ‘Earth Explorers Granada 2001 User Consultation Meeting’, which will be held in Granada, Spain, at the end of October 2001. The consultation meeting is part of the evaluation of the candidates that should lead to the selection of three candidates for feasibility studies in 2002-2003 and further to the selection of the next two Earth Explorer Core missions to be launched in 2008 (Core-3) and 2010 (Core-4).

This particular Report for Assessment is concerned with the WATS (WAter vapour and temperature in the Troposphere and Stratosphere) mission. It has been prepared by one of the five Scientific Preparatory Groups that have been established to provide scientific advice on the candidate missions. The (external non-ESA) members of this particular Science Preparatory Groups are Gunnar Elgered (Chalmers University of Technology, Gothenburg, Sweden), Alain Hauchecorne (Service d'Aeronomie, Verrières-le-Buisson, France), Eigil Kaas (Danish Meteorological Institute, Copenhagen, Denmark), Gottfried Kirchengast (University of Graz, Graz, Austria), and David Offiler (Met Office, Bracknell, United Kingdom). They were supported by an external consultant, Stephen Leroy (Danish Meteorological Institute, Copenhagen, Denmark) and by members of the Agency (J. Guijarro, P. Silvestrin) who advised on technical aspects and took the lead in drafting the technical and programmatic sections. Einar-Arne Herland and Alberto Tobias (ESA) should also be acknowledged for their time and effort in reviewing this document and Drusilla Wishart for preparing it for publication.

The WATS (WAter vapour and temperature in the Troposphere and Stratosphere) mission seeks to observe humidity fields throughout the troposphere together with temperature fields in the troposphere and stratosphere. It will do so by employing the radio occultation technique, the impressive properties of which are an unprecedented vertical resolution and absolute calibration. Its absolute calibration allows future users to refer to a WATS data set in comparison with future data in a straightforward way, because they need not make any adjustments or corrections in performing a comparison. Moreover, the WATS experiment, and radio occultation in general, offers the potential to provide measurements of both temperature and humidity in a highly cost-effective way.

The main objectives of the WATS mission are to:

- establish a highly accurate (< 0.003 g/kg or <3%, whichever is larger) and vertically resolved (0.5 km) climatology of water vapour in the troposphere with global measurements of its concentration;
- establish a highly accurate (< 0.2 K) and vertically resolved (0.5 to 1 km) climatology of temperature in the troposphere and the stratosphere with global measurements of its vertical profile;
- support research on climate variability and climate change and on validation and improvement of atmospheric models;
- demonstrate a novel active atmospheric sounding method.

All the 'Reports for Assessment' follow a common general structure comprising seven chapters. Following this introduction, the report is divided into six chapters:

Chapter 2 addresses the background and provides the scientific justification for the mission, set in the context of issues of concern and the associated need to advance current scientific understanding. The chapter identifies the problem and gives the relevant background. It identifies the need for the observations by comparing the data that will be provided by this mission with that available from existing and planned data sources, highlighting the unique contribution of the mission.

Drawing on these arguments, Chapter 3 discusses the importance of the scientific objectives.

Chapter 4 focuses on observational requirements based on generic requirements and derives, in the context of the scientific objectives, the mission specific observational requirements.

Chapter 5 provides an overview of the mission elements such as space and ground segments and external data sources required, but also of other missions benefitting from the mission.

Drawing on Chapter 5, Chapter 6 provides a summary description of the proposed technical concept (space and ground segments), establishes basic system feasibility and provides a preliminary assessment of the expected performances.

Chapter 7 outlines programme implementation, including risks. In particular, drawing on the previous chapters, Chapter 7 discusses WATS in the context of related missions.

2 Background and Scientific Justification

The WATS ('WAter vapour and temperature in the Troposphere and Stratosphere') mission seeks to observe humidity fields throughout the troposphere and temperature fields in the troposphere and stratosphere. It will do so by employing the radio occultation technique, which has the impressive properties of unprecedented vertical resolution and self-calibration. Its calibration allows future users to refer to a WATS data set in comparison with future data in a straightforward way, because they need not make any adjustments or corrections in performing a comparison. Moreover, the WATS experiment, and radio occultation in general, offers the potential to provide measurements of both temperature and humidity in a highly cost-effective way.

So far, approved Earth observing missions based on the radio occultation technique have been based on occultations of low Earth orbiting (LEO) satellites relative to the Global Positioning System (GPS). This means that only vertical profiles of the microwave refractive index (1.2 and 1.6 GHz) have been used to extract combined information of temperature and humidity in the troposphere. In order to separate the contributions of water vapour and temperature in a tropospheric microwave occultation (without using external data), WATS will actively sound the atmosphere in a LEO-LEO geometry at three frequencies (e.g. 10.3, 17.2 and 22.6 GHz) around the 22 GHz water vapour absorption line. By careful measurement of the phase and amplitude of the electric field produced by occulted rays, a sufficient number of measurements is available to deduce independent information on both atmospheric temperature and water vapour profiles.

Some scientific background of the mission is provided in Section 2.1. Section 2.2 describes the atmospheric processes and parameters addressed by the WATS mission in the context of understanding and predicting weather and climate more precisely. In Section 2.3 the existing observation systems are described and the need for improved observations is discussed in connection with climate monitoring, weather forecasting, atmospheric modelling and detection of external forcing of climate. Section 2.4 reviews the measurement principles of WATS in more detail. Finally, Sections 2.5 and 2.6 explain the complementary role of WATS in relation to existing observing systems and methodologies.

2.1 The Scientific Problems

2.1.1 Climate Research

Recently, the IPCC published its third scientific assessment regarding the human impact on climate (IPCC, 2001). It was concluded that the bulk of the observed global warming (see Figure 2.1) in the beginning of the 20th century was most probably due to natural processes, i.e. changes in volcanic activity, solar activity and possibly internal climate variability. However, the more recent warming after approximately

1975 is likely to be due to human activity – mainly the increasing emissions of greenhouse gases. It is important to note that these conclusions are largely based on simulations with coupled atmosphere – ocean models assuming that these models have realistic climate sensitivity, i.e. the 'correct' size of climate change for a given forcing.

It has recently been suggested (e.g. Marsh and Svensmark, 2000) that indirect solar effects relating low level clouds in the tropics and subtropics to cosmic ray flux could have been underestimated, and that this mechanism may have contributed to the recent global warming. If true, this would imply that the climatic forcing related to the suggested mechanism has been of the same order of magnitude as that due to increased greenhouse forcing. But the implication would furthermore be that the model used in Figure 2.1 would have a far too large climate sensitivity, since it is well able to simulate the recent observed warming, even without inclusion of the suggested indirect solar forcing mechanism[1]. This first example illustrates the importance of having a realistic climate model sensitivity when attributing the causes of climate change.

As discussed below, most climate feedbacks defining the sensitivity of climate to external forcing are related to water vapour in one way or another. Therefore it is very important to monitor humidity trends accurately. Although the quality of the existing measurements is often insufficient, there is observational evidence that the recent global warming has been accompanied by an increase of several percent per decade in the lower tropospheric water vapour content over many regions of the Northern Hemisphere. Changes in lower tropospheric water vapour over two to three decades have been analysed for selected regions, using *in-situ* surface observations, as well measurements from satellites and weather balloons. Figure 2.2 shows a trend analysis by Ross and Elliott (2001) based on weather balloons. Overall, the figure shows an increase in lower-tropospheric water vapour over the past few decades, but with regional variations in the trends. Although the data used in Figure 2.2 were quality controlled it can not be excluded that some of the trends displayed are masked by time-dependent biases (inhomogeneities) in the data. Therefore higher accuracy and consistency are required in the water vapour measurements to improve our ability to detect trends in this parameter.

Upper tropospheric long term trends in the water vapour content have been difficult to observe from radiosondes because the sensor performance tends to be of poor quality at low temperatures and pressures. Furthermore, there have been numerous changes in the radiosonde instrumentation over the last 40 years which complicate (or exclude) the use of these data for trend assessments in the upper troposphere and the stratosphere.

[1] In principle there is an alternative explanation, stating that the model sensitivity and the indirect solar forcing are both correct, but that the cooling from tropospheric aerosols in the same period has been severely underestimated, leaving room for an indirect source forcing to be as important as – or more important than – the increasing greenhouse forcing.

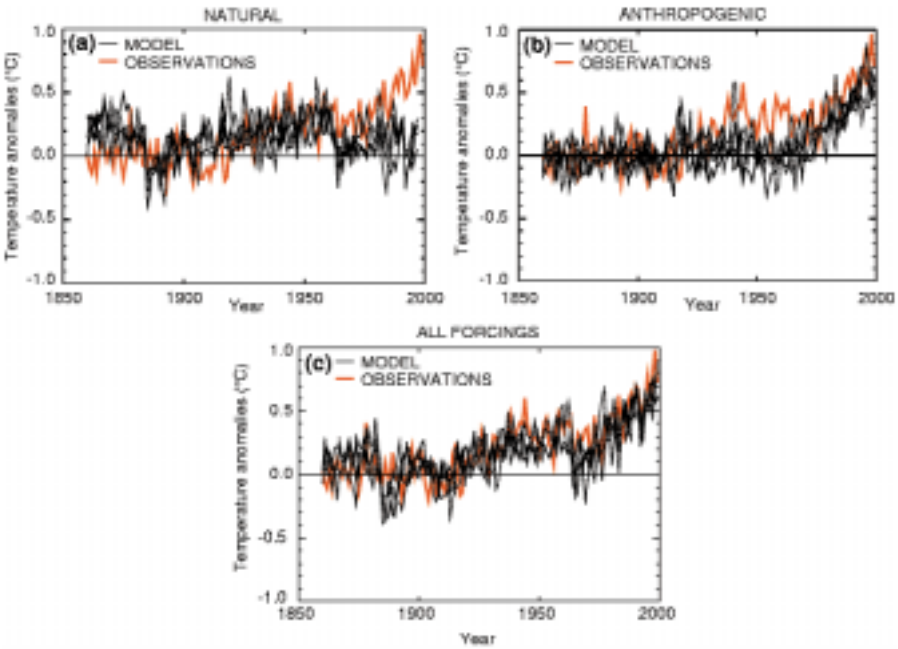

Figure 2.1: *Global mean near-surface temperature anomalies relative to the 1961-1990 average. The red curves in each plot are identical and show the observed data while the black curves show individual 4 member ensembles simulated with a coupled atmosphere ocean model. In part (a) the model was forced with estimated natural forcings, i.e. direct solar forcing (irradiance) and volcanic aerosols. In part (b) only anthropogenic forcing including well mixed greenhouse gases, changes in stratospheric and tropospheric ozone and the direct and indirect effects of sulphate aerosols are used. In part (c) the model simulations are run with all forcings, both natural and anthropogenic. From Tett et al. (2000); Stott et al. (2000); and IPCC (2001).*

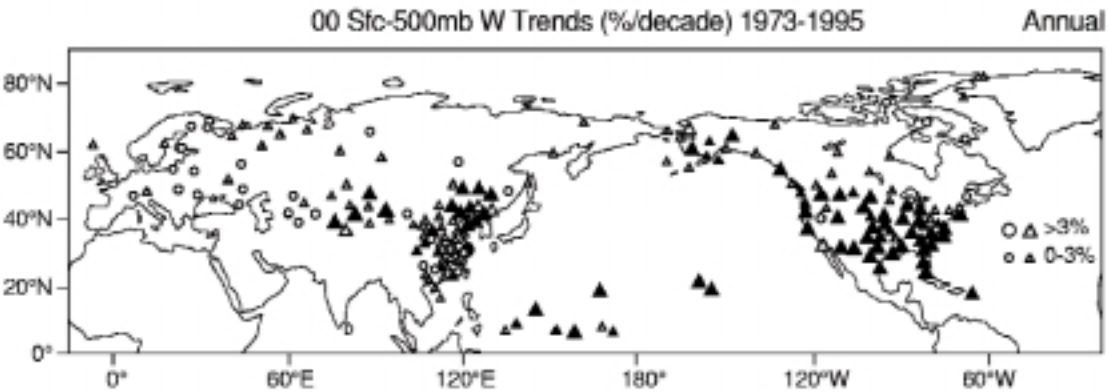

Figure 2.2: *Annually-averaged trends in surface to 500 hPa precipitable water at 0000UTC for the period 1973-1995 based on radiosonde measurements. Positive trends are indicated by triangles and negative trends by circles. Filled symbols indicate that the trends were statistically significant at the 5% level according to a Spearman test. The two sizes of symbols give an indication of the magnitude of the trend. (From Ross and Elliott, 2001).*

During the last 20 years, where satellite measurements of moderate accuracy but poor vertical resolution have been available, no striking global trends in upper tropospheric water vapour content have been observed, but the level of natural variability due to processes internal to the climate system (e.g. ENSO) tends to dominate decadal trends. The SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapour (SPARC, 2000) estimates that the stratospheric water vapour has increased by 2 parts per million by volume (ppmv) since the middle 1950s. There is some controversy concerning the validity of this estimate because it is based on the compilation of several time series of water vapour measurements, made by various instruments, which do not always overlap in time and are calibrated independently. A possible explanation for the observed increase of water vapour is the *in-situ* production by the photochemical oxidation in methane. However, the increase of methane in the troposphere during the same time period can explain only half of the water vapour increase.

One of the intriguing subjects discussed in IPCC (2001) and references therein is an apparent discrepancy between the trends in the observed near-surface temperature (typical measurement height is about 2 m) and in the trend in the lower troposphere. During the last 20 years or so, the near-surface temperature has risen much faster than the temperature in the free troposphere, as illustrated in Figure 2.3. However, considering the longer period of 1958 to 1999 where only radiosondes are available in the free atmosphere, there seems to be little difference between near-surface and lower tropospheric temperature trends. The recent difference in trends cannot be fully explained by global climate models whose long term trends show a temperature rise near the surface as well as in the free troposphere. The intensive work on the problem in recent years has demonstrated that very few of the present spaceborne instruments can be used in a straightforward way for inter-annual trend detection. This is basically because the vertical soundings (e.g. via the HIRS instrument on NOAA's TIROS satellites) are not self-calibrating and need a complicated calibration from one generation of satellites to the next. This cannot always be achieved in a proper way because of missing overlapping mission periods and because there are temporal drifts in the sensitivity of the instruments and in the orbits. In fact, only the Microwave Sounding Units (MSU instruments) have been calibrated with reasonable accuracy (Christy et al., 2000), although there have been many problems and considerable criticism of this work (Hurrell and Trenberth, 1998). A main problem with the MSU data is that there are considerable overlaps in the vertical weighting functions for the individual spectral channels. This strongly limits the effective number of degrees of freedom in the vertical. In order to obtain a firmer observational base new and more accurate observations are needed both to enhance the vertical resolution and to reduce the overall uncertainties.

There is little doubt that the global temperatures in the stratosphere have been steadily decreasing, as seen in Figure 2.3b, except for a few short lived warm episodes following volcanic eruptions. This is consistent with a thinning of the stratospheric ozone layer and, for the higher parts of the stratosphere, with an increasing greenhouse

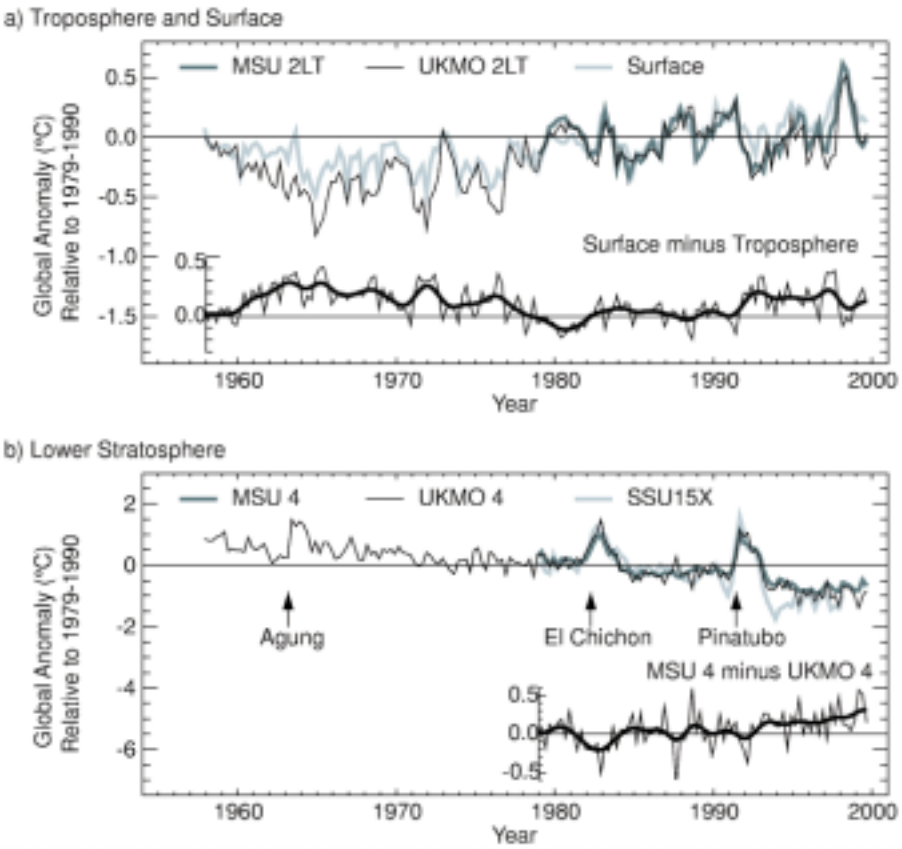

Figure 2.3: *(a) Time series of global seasonal temperature anomalies of the troposphere based on balloon (HadRT2.0 1958-1999) and satellite (MSU 2LT 1979-1999) measurements in addition to the surface data (HadCRUT 1958-1999). The difference time series between balloons and satellites is presented in the inset. (b) Time series of seasonal temperature anomalies of the lower stratosphere from balloons (HadRT2.1s 1958-1999) and satellites (MSU 4 1979-1999). Differences are shown in the inset. (From IPCC, 2001).*

effect from the well mixed greenhouse gases. The volcanic warmings are generally well understood. The fact that only a few MSU channels can be considered reasonably well inter-calibrated is a severe problem for stratospheric and upper tropospheric soundings, in a similar way to what happens in lower and middle troposphere. In the upper stratosphere, local temperature measurements made by ground-based lidars in the frame of NDSC (Network for Detection of Stratospheric Change) and by rocketsondes indicate a significant cooling of 1 to 3 K/decade during the last 20 years (Keckhut et al., 1999). However, satellite observations with enough vertical resolution to extend this result to the global scale are missing. Furthermore, it is very important to understand if the expected recovery of the ozone layer, following the reduction of anthropogenic halogen emissions, will affect the observed downward temperature trend.

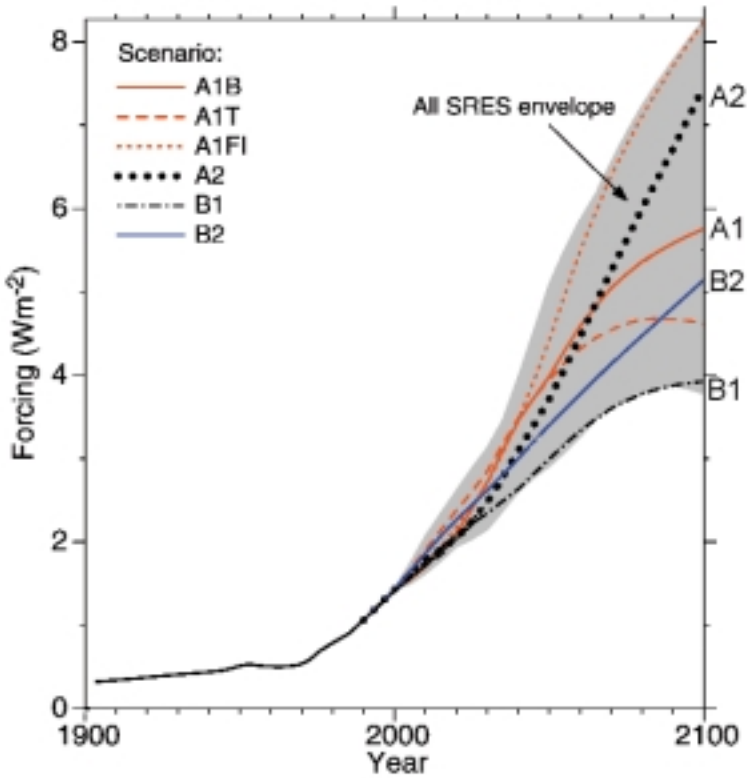

Figure 2.4: *Radiative forcing due to greenhouse gases and tropospheric aerosols according to the recent SRES emission scenarios constructed by IPCC (2000). The four marker scenarios (A1, A2, B1 and B2) and the total SRES envelope are indicated.*

IPCC (2001) has used a number of recent emission scenarios (IPCC, 2000) to estimate the future climate forcing due to greenhouse gases and anthropogenic aerosols. These forcings are shown in Figure 2.4 and it can be seen that they are very large compared to those we have seen until now, with approximately 1.5 W/m^2 in year 2000 relative to the pre-industrial period. This is the case for all scenarios including those reflecting little or no growth in global population and considerable reductions in the emissions (the B1 family). IPCC (2001) also reports on results from a number of simulations where global coupled atmosphere-ocean climate models have been forced with concentrations from the different scenarios. Figure 2.5 is adapted from Stendel et al. (2000), and shows a few results from one of the European simulations entering IPCC (2001). The simulation is based on the A2 marker scenario, which broadly speaking is a 'business as usual' scenario with continued but gradually somewhat reduced growth in global population – see IPCC (2000) for details. It can be seen that the model simulates very strong warming in northern winter at high latitudes near the end of the present century and that the warming is generally larger over the land masses than over the oceans. High latitude precipitation is strongly enhanced particularly in winter, with some regions showing more than a doubling. This is consistent with an increased poleward transport of water vapour in the atmosphere. In the tropics the Hadley cell is

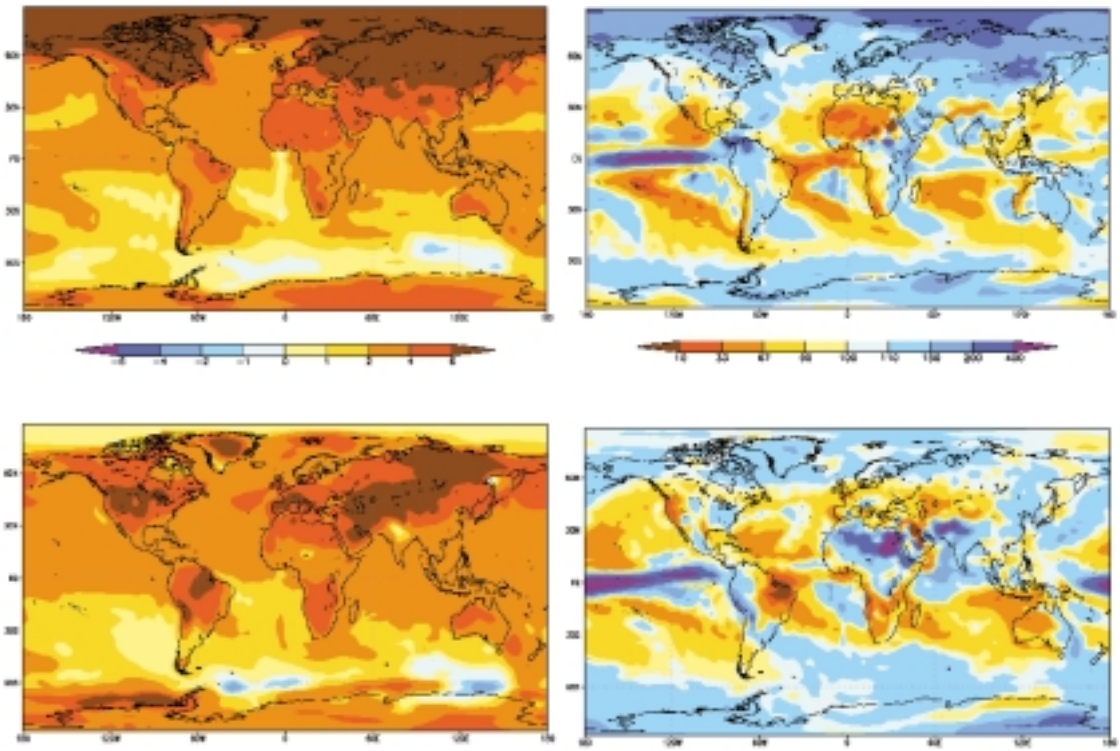

Figure 2.5: *Results from recent simulations with the ECHAM4/OPYC coupled atmosphere ocean model. The four panels show differences between the long term mean fields in the period 2071-2100 and the period 1961-1990. Upper left: Near-surface temperature (°C) in DJF. Lower left: Near-surface temperature(°C) in JJA. Upper right: Accumulated precipitation (% change) in DJF. Lower right: Accumulated precipitation (% change) in JJA.*

generally intensified with stronger precipitation in the ITCZ and reduced precipitation in several subtropical subsidence regions.

Given the gradually increasing certainty that humans are influencing the climate, and that this influence will increase, the next step is to focus on making model predictions of climate change more precise. The globally averaged surface temperature is projected to increase by 1.4 to 5.8°C (IPCC, 2001) over the period 1990 to 2100. Even this broad range of predictions does not completely consider the uncertainties of several parameterised physical processes. One of the most important reasons for the large range of uncertainty is the difference in climate model sensitivity caused by the multiplicity of climate feedbacks. The least understood internal feedbacks of climate models are those associated with water vapour. Mechanisms related to water vapour remain ill-understood, mainly because the climatology and processes have not yet been observed with the necessary accuracy, precision, and coverage.

To summarise, accurate observations of the present temperature and humidity, including their variability, are highly important in climate change research for the following reasons:

- To monitor climatic variations and trends at different vertical levels and for each season. Trend analysis is of particular importance in connection with the detection of the different fingerprints from global warming, which are sometimes used as a proof of human impact on climate. Accurate monitoring of natural climate variations such as El Niño is important in improving our understanding of the climate system.
- To improve the understanding of the climatic feedback defining the magnitude of climate changes for a given forcing.
- To validate the simulated mean climate and its variability in global climate models.

Furthermore, such data can be used – via data assimilation – to improve/tune the parameterisation of unresolved processes in the climate models (e.g. radiation, convection, clouds) and to detect inter-annual variations in external forcing of climate (e.g. volcanic forcing or direct/indirect variations in solar forcing)

It is obvious from the new IPCC report (IPCC, 2001) and from other sources that considerable uncertainties still exist in the field of climate research. In relation to the present proposal it is of particular relevance to note the following:

1. Present spaceborne high-resolution infrared vertical temperature sounders (HIRS) are not self-calibrating and complications with instrument and orbit drift prevent accurate calibration. Thus there is a general lack of homogenous spaceborne soundings with high vertical resolution.
2. There are large observational uncertainties in the global distribution of recent trends in water vapour concentrations in the free troposphere.
3. The absolute values of upper tropospheric concentrations of water vapour are not known sufficiently well.
4. Global climate models are very important tools to estimate climate sensitivity and thus the expected future climate. The models do, however, require continuous development and improvements to reduce uncertainties in their sensitivity.
5. Some hypotheses on forcing mechanisms, e.g. indirect solar forcing via clouds, are poorly understood and the magnitude of the forcing needs to be estimated more accurately.

The WATS mission will address all these and other issues as described in the following sections.

2.1.2 Numerical Weather Prediction (NWP)

The mission is designed mainly for research on the atmosphere and climate, but it is important to note that the data produced also have high value for weather forecasting. At present, our observational information on the three-dimensional temperature and humidity over the oceans and the tropics is limited to very few radiosonde stations and the relatively inaccurate and coarse vertical soundings of temperature and humidity from the orbiting NOAA satellites. This severely limits the predictability over Europe, for example, which is exposed to synoptic disturbances developing over the North Atlantic. There are numerous examples of poorly forecast severe extra-tropical lows, which can be ascribed to missing or incomplete upper air information over the North Atlantic. Some examples are mentioned in Pailleux and Böttger (2000). Therefore, deficiencies, including coverage and frequency of observations, in the current observing system hamper the progress in NWP.

There is no doubt that more accurate temperature and humidity observations with improved vertical resolution will result in better skill for any NWP system. However, even perfect mass field (defined by temperature, humidity and surface pressure) information on the atmosphere has to be combined with wind field information since the level of imbalance between the three-dimensional wind and mass fields is very important to the development of many synoptic systems. Therefore, high resolution and high quality observations of both wind and mass field must enter the operational data assimilation systems. Generally, according to geostrophic adjustment theory, information about the wind field is relatively much more important for short term synoptic scale weather prediction than mass field information in the tropics as compared to the extra-tropics. Wind observations are also crucial for the prediction of small-scale and some mesoscale extra-tropical phenomena. For synoptic and larger scale disturbances in the extra-tropics, however, the lack of high quality three-dimensional mass field observations over the oceans is a main factor limiting the skill of operational numerical weather prediction systems.

There is an obvious spin-off from advances in NWP to those in climate studies. This is because the objective analyses – a by-product from the NWP systems – are highly valuable and intensively used in climate process studies and climate modelling. In particular, this applies to the so-called “re-analyses”. This is further described in Sections 2.3.2, 2.3.4 and 2.3.5.

2.2 The Role of Water Vapour and Temperature in the Atmosphere

The purpose of the WATS mission is to establish unbiased observations of global water humidity fields throughout the troposphere and temperature fields in the troposphere and stratosphere. Climate research as well as operational weather prediction will benefit from improved observations of these two variables.

Water vapour is at the heart of those atmospheric processes that are very important but remain relatively poorly understood in the field of climate change. First of all, water vapour is the dominant greenhouse gas, and thus the radiative feedback related to possible changing water vapour concentration in response to external climate forcing (be it variations in solar activity, volcanic eruptions or anthropogenic emissions) is fundamental. Secondly, massive amounts of latent heat are transported via the atmospheric dynamics and released in areas of condensation. In this way water vapour plays a dominating role in controlling the atmospheric circulation in both the tropics and the extra-tropics.

The temperature is of course a key parameter characterising the Earth's atmosphere and the climate. Together with water vapour and surface pressure, the temperature fully characterises the atmospheric mass field[2] and thereby, via the approximate geostrophic balance, also the main features of the large scale atmospheric wind systems.

In the following sub-sections we briefly describe basic atmospheric processes and the climatic feedback mechanisms related to water vapour and temperature.

2.2.1 Water Vapour

The relative concentration of water vapour in the troposphere encompasses several orders of magnitude, from up to more than 30g/kg locally in the tropics to less than 0.1g/kg in many regions in the upper troposphere. One of the main reasons for the large variation in this concentration comes from the Clausius-Clapeyron equation leading to an exponential relationship between maximum partial water vapour pressure (e_s) and temperature. For typical tropospheric conditions an increase/decrease in temperature of 1K will lead to an approximately 7% increase/decrease in e_s.

The physical role of water vapour in the atmosphere is mainly associated with two processes: condensation/evaporation and radiation:

- The role of condensation is very important, since it constitutes a main diabatic heat source within the troposphere. This heating is generally very strong in the Inter-Tropical Convergence Zone and in the monsoon areas. It is thus a key player in the maintenance of the Hadley cell and the monsoons. Furthermore, the overall poleward and vertical transports of water vapour (i.e. latent heat) via the atmospheric dynamics are highly important to the maintenance of the general circulation of the atmosphere – including the high latitudes.
- Furthermore, the release of latent heat associated with condensation is the main mechanism driving several regional and local atmospheric circulation phenomena, like tropical storms/hurricanes and severe thunderstorms.

[2] i.e. the geopotential height field in vertical pressure co-ordinates.

- For extra-tropical storms the release of latent heat plays a fundamental role, which for explosive cyclogenesis can amount for up to 50% of the entire development (Kuo and Donall, 1991; Kuo and Low-Nam, 1990; Langland et al., 1996).
- From a radiative point of view water vapour is important because it is the dominant greenhouse gas in the atmosphere due to its high concentration relative to the well mixed greenhouse gases like CO_2, CH_4, N_2O and CFCs. Furthermore, water vapour plays a dominant indirect radiative role via clouds and precipitation.

Because of its role in these processes water vapour is a key parameter in the climate system, both for the stability of the present climate and for its internal variability. Most climatic feedback mechanisms directly or indirectly involve water vapour. These feedback mechanisms determine the sensitivity of the Earth's climate, i.e. the magnitude of the climatic change in response to external forcings such as stratospheric sulphate aerosols originating from volcanic eruptions, changed solar activity, increased anthropogenic greenhouse gas and particle emissions, changed land use, etc. Some of the feedback mechanisms involving water (vapour) are:

- Radiative water vapour feedback. This is a major positive[3] feedback accounting for approximately half or more of the warming predicted by climate models in response to an increase in CO_2. Its existence is due to the fact that an increase in the temperature of the atmosphere increases its water holding capacity. Within the boundary layer (roughly the lowest 1–2 km of the atmosphere), there is little doubt that water vapour increases with increasing temperature. In the free troposphere above the boundary layer, where the water vapour greenhouse effect is most important, the situation is, however, harder to quantify. Current models are capable of simulating the moist and very dry regions observed in the tropics and subtropics and how they evolve with the seasons and from year to year. Nonetheless, considerable uncertainty remains in observations of water vapour and in the ability of models to properly treat upper tropospheric humidity, and this is critical for the water vapour feedback.
- Ice-snow albedo feedback. This is also an important positive climate feedback related to the amount of reflected sunlight at the Earth's surface: As climate warms, some snow and (sea-) ice melts, making the surface darker and more absorptive to solar radiation, thereby heating the Earth.

[3] Climate feedbacks are termed positive when they increase the change resulting from a given forcing, and negative if they reduce the change.

- Cloud feedback. Probably the greatest uncertainty in future projections of climate arises from clouds and their interactions with radiation. Clouds can both absorb and reflect solar radiation (thereby cooling the surface) and absorb and emit long wave radiation (thereby enhancing the greenhouse effect). The competition between those effects depends on cloud height, thickness, and radiative properties. The radiative properties and evolution of clouds depend on the distribution of atmospheric water vapour, water drops, ice particles, atmospheric aerosols, and cloud thickness. The sign of the net cloud feedback is still a matter of uncertainty.
- Angular momentum/evaporation feedback. This is a negative feedback proposed by Bates (1999). It counteracts the otherwise 'runaway' positive water vapour feedback in the tropics. If the tropics warm more than the extra-tropics the meridional transports of angular momentum in the atmosphere are also enhanced. Thereby the surface winds become stronger and an excessive cooling via evaporation is initiated at the surface. This feedback seems to be reasonably well represented in global climate models.

It is very difficult to deduce the climate feedback mechanisms directly from observations because they typically involve interactions between different types of variables and they act in an atmosphere dominated by a high level of non-forced internal variability. Nevertheless, it is essential to collect improved observational evidence regarding water vapour, particularly in the upper half of the troposphere since improved knowledge about the present climate will help in judging the relative importance of the different feedbacks, including certain hypothesised negative feedbacks involving deep convection in the tropics (e.g. Lindzen et al., 2000).

2.2.2 Temperature

The long term atmospheric temperature generally varies from 30–40ºC near the surface in the tropics to about -85ºC in polar night stratospheres. Ultimately the long term global mean temperature of the atmosphere is controlled by the Earth's radiation budget involving:

– the total solar energy input at the top of the atmosphere,

– the planetary albedo (i.e. the amount of solar radiation reflected to space by the atmosphere, including clouds, and by the Earth's surface), and

– the strength of the greenhouse effect (i.e. the amount of infrared radiation trapped and re-emitted into the atmosphere by greenhouse gases and clouds).

The three-dimensional distribution of temperature in the atmosphere is not only determined by local diabatic processes like radiation and release of latent heat. The atmospheric dynamics involving adiabatic processes also play a key role mainly because a diabatic heating or cooling in one region will force circulations with direct or indirect impact far away. This means that a long-term isolated heating anomaly will generally impact the entire global atmospheric state in one way or another. It is

essential to be aware of the dynamical processes at work which interconnect the mean atmospheric state in different regions. This is of particular relevance – as discussed in Section 2.3.3 – when one wants to use measurements to improve our understanding of the physical processes in the atmosphere.

The most fundamental negative feedback in the climate system that contributes to keeping it stable is directly related to temperature. It is the Stefan-Boltzmann feedback; basically the warmer the planet becomes, the more radiative energy is emitted to space. The energy loss is proportional to σT^4, where σ is the Stefan-Boltzman constant and T the effective emission temperature which for the Earth is about 30 deg lower than the actual surface temperature due to the influence of the atmosphere.

2.3 The Need for Improved Water Vapour and Temperature Measurements

2.3.1 Present Observations of Water Vapour and Temperature

The different types of observing systems currently available in the Global Observing System (GOS) are documented in ESA (1996). Many of these contribute to current observations of atmospheric temperature and humidity for use in climate studies and operational NWP.

Radiosondes give high resolution in the vertical but measurements are only available at moderately high density over the land masses of the Northern Hemisphere mid-latitudes, with most areas of the World observed sparsely or not at all. Around 700 stations provide, usually twice daily at 00 and 12 UT, vertical profiles of temperature and wind from the surface to 25–30 km, and of water vapour in the troposphere (surface to ~10 km). Their humidity accuracy is generally good (~10% in Relative Humidity), but varies from station to station, and they have substantial biases in near-saturation conditions and at low temperatures. There is continuous pressure to reduce the radiosonde network, particularly at remote sites, because of the high operational costs.

Commercial aircraft provide accurate temperature measurements through the AMDAR (Aircraft Meteorological Data Relay) but mainly at flight level (typically ~10 km) and for major air routes. Most areas of the World are not well covered. Profiles are available only on ascent and descent (i.e. near well-populated areas). Due to technical difficulties with developing accurate, robust and reliable sensors, there are currently no operational humidity observations from commercial aircraft.

The current operational system on the TIROS-N/NOAA series of polar orbiting satellites consists of the High-resolution Infra-Red Sounder (HIRS), and the Advanced Microwave Sounding Unit (AMSU-A for temperature sounding, AMSU-B for humidity), collectively known as the Advanced TIROS Operational Vertical Sounder (ATOVS). These instruments provide information on tropospheric and stratospheric

temperature and on tropospheric humidity, with global coverage at high horizontal resolution. Both systems are deficient in vertical resolution; individual spectral channels have weighting functions of width 7–10 km, and the combined vertical resolution of the system is only 2–3 km in cloud-free areas and worse in cloudy areas. The accuracy of the present system for humidity is perhaps equivalent to 20% in RH. The future Microwave Sounder (MHS) will replace AMSU-B on MetOp and TIROS, but will have similar performance. The SSMIS instrument, on DMSP platforms, will be similar to AMSU, with the first launch in November 2001. Future sounders on geostationary satellites, such as SEVIRI on Meteosat Second Generation (MSG), will equally not improve on today's vertical resolution or accuracy, but will greatly improve on the coverage and repeat rate of observations. The IASI passive-IR instrument on MetOp promises to greatly improve on vertical resolution through high spectral sampling, but only in cloud free (or in clear air above clouds) conditions.

As mentioned in Section 4.1 none of these systems meet all of the requirement goals, either individually or collectively. However, they all generally make a contribution above the minimum requirement in some geographical regions and/or meteorological conditions and have very different strengths and weaknesses.

Radio Occultation (RO)-derived profiles of temperature and humidity have the potential to make a significant contribution beyond the state of the art in our knowledge of water vapour structures in the atmosphere and in the availability of accurate, high vertical resolution, temperature observations in the troposphere and stratosphere. RO provides all-weather observations and these profiles will greatly increase the global distribution. The signal source has a long term stability that is very attractive for climate applications.

Other techniques have been developed or are being developed to provide atmospheric profiles of temperature, water vapour and other atmospheric species, with improved vertical resolution. They are based on the observation of the spectrum of the Sun occulted by the atmosphere or of the emission of the atmospheric limb in the infrared and microwave spectrum. They are in general limited to the upper troposphere/stratosphere due to the atmospheric opacity and refraction. Furthermore, their use for detection of climate changes is limited by some weaknesses. Solar occultation instruments have a geographical coverage limited to two occultations per orbit, one at sunrise and one at sunset. Passive limb-sounding instruments depend on radiometric calibration for the determination of absolute values.

2.3.2 Improved Climate Monitoring and Detection of Trends

We can monitor the climate in two fundamentally different ways. The most direct is to perform a set of observations of the basic atmospheric variables, i.e. temperature, surface pressure, winds and water vapour, and then investigate the mean values, variability and trends in these data. Obviously, if the data cover the whole globe as is

the case for inverted WATS data, one may introduce direct interpolation schemes enabling calculation of global mean values including trends and variability. It is clear from the discussion in Sections 2.1 and 2.3.1 that spaceborne soundings of temperature and humidity with improved accuracy, vertical resolution and temporal homogeneity are needed to reduce some of the uncertainties in such direct climate monitoring exemplified in Figures 2.2. and 2.3.

A very different way to monitor the climate system is to assimilate all available observed information into atmospheric models. Such data assimilation is performed on a routine basis at all centres running operational numerical weather prediction systems and the output – an objective analysis – is a full three-dimensional picture of the instantaneous state of the atmosphere. Modern objective analyses (3D-VAR and 4D-VAR) are consecutive sets of atmospheric states which in a least square sense fit all available observations (with proper weightings related to observational accuracy and error) as well as the prognostic differential equations governing the temporal evolution of the atmosphere (also with weightings describing the short term forecast errors). In four-dimensional variational assimilation schemes (4D-VAR) the fitting is performed over an entire temporal window while 3D-VAR is fitted at specific hours. An overview of data assimilation algorithms and problems can be found in Meteorological Society of Japan (1997), while a description of a typical modern 4D-VAR scheme can be found in Rabier et al., (1998). Variational data assimilation schemes based on the adjoint technique have the significant feature that it is possible to assimilate many different types of data, like refraction of GNSS signals as well as the LEO-LEO attenuation. Once built into the assimilation system it 'automatically' inverts this indirect information about the mass field of the atmosphere into meteorological model quantities like temperature and humidity. Thus in the case of variational data assimilation it is unnecessary to perform an *a priori* inversion of the data retrieved in WATS.

Long time series of data based on operational data assimilation suffer from the problem of inhomogeneity†, i.e. small, but sudden, artificial jumps in the data which are due to updates of the weather prediction model and/or changes in the analysis program which combines the information from the raw observations with the weather prediction model. To avoid this problem, the European Centre for Medium-range Weather Forecasts (ECMWF) and the National Centre for Environmental Prediction (NOAA/NCEP) produce re-analyses. These are basically identical to operational analyses, but they are performed with 'frozen' data assimilation systems and as far as possible with the same observational system over a long period (several recent decades). Thus re-analyses are reproductions of past weather constituting the best available estimate of the three-dimensional evolution of the atmosphere. Note that even re-analyses suffer from inhomogeneities since the type of raw data that enters the assimilation systems changes over time.

† Data contamination due to changes in instrumental accuracies, environmental conditions near the instrument, observational practices and analysis routines.

There seems to be a general agreement that the ECMWF re-analyses are the most accurate in terms of realistic fit to observations and in terms of spatial resolution. Currently only the period 1979–1993 has been re-analysed by ECMWF (Gibson et al., 1997). ECMWF has an ongoing project (ERA40), which will re-analyse the entire period 1957–present.

Direct climate monitoring making use of a single or a few types of 'raw' observation or inverted occultation data provides a much less complete picture of the climate system than that which can be obtained with the re-analyses, but it has the advantage that possible inhomogeneities hidden in the large amount of data impacting the re-analyses can be avoided by considering a single well documented data source (e.g. from a fixed set of quality controlled radiosondes). On the other hand ERA provides large amounts of additional information on parameters not – or not well – observed, and all the data at a given time are analysed to be consistent with each other, within their errors. For this reason re-analyses are highly valuable for validation of output from the atmospheric component of climate models. Generally, our understanding of the atmosphere and its variability is based to a large extent on the analysed fields from continuous data assimilation, so that progress in climate analysis is closely linked to corresponding progress in NWP. As we shall discuss in Sections 2.3.4 and 2.3.5 high-quality re-analyses may even be used for atmospheric model development and detection of temporarily varying external forcing of climate.

Better quality and denser observations of temperature and humidity are required to gain better insight into the important feedbacks defining the sensitivity of the Earth's climate. The improved data produced in WATS could be used for simple direct monitoring of the climate, but more importantly they should also be directly assimilated into a climate re-analysis† system in near-real time. This means that the mission has to include a data assimilation component enabling real-time climate monitoring. Furthermore, this component reduces an otherwise multi-year delay in the use of the data for the purposes described in Sections 2.3.4 and 2.3.5. The WATS data assimilation must be processed in a consistent way over the lifetime of the mission, mimicking the procedures used during production of the much longer ERA40 data set. In this way the risk of artificial jumps in the analyses produced is reduced. It is important to note that these analyses cannot be produced without inclusion of additional types of data. During the production it should, however, be investigated whether some types of data presently entering, for example, ERA40 can be excluded. Similarly, it must be estimated how much the analyses are improved/changed by the inclusion of the WATS occultation data.

† The result of a data-assimilation covering many years (decades) of past observations into a dynamical model using a frozen set of model and assimilation software.

2.3.3 Weather Forecasting and Data Assimilation

It is probable that improved quality and denser (in time and space) observations of temperature and water vapour will improve the forecasting skill achieved with operational numerical weather prediction and data assimilation systems. This is because the development of extreme and devastating weather systems is often highly sensitive to relatively small and small scale variations in the free atmosphere conditions one or a few days before their mature state. Several examples of the improvements in NWP and the sensitivity to initial conditions can be found in, for example, Pailleux and Böttger (2000).

Although WATS will be optimised as a climate research mission it is very likely that the use of the data produced in WATS will considerably improve the forecast skill of operational weather prediction systems.

2.3.4 Atmospheric Model Improvements

In the IPCC's review of the validation of climate models (IPCC, 2001), it is clear that most climate model validation activities focus on the simple and naive matching of long term mean atmospheric states between model and data – normally supplemented by comparisons of the simulated and observed climatic variability. Improved model performance has been largely accomplished through the tuning of loosely-constrained 'climate parameters.' Such unknown parameters refer to the formation and dissipation of clouds, their radiative properties, the water vapour processes that control them, and the lower tropospheric radiative balance. As a result it is difficult to say whether we have any better understanding of the feedbacks internal to the atmospheric system, largely related to clouds and radiation, after having tuned the model – or if we simply obtained this apparent improvement through the introduction of other errors. Without a better understanding of these feedbacks and any others internal to the climate system, we are left with models not fully suited for predicting future climate change.

There are, however, alternative approaches to improving models which should reduce the risk of error compensation. Using assimilation of 'observed' data (with errors) into a climate model it is, in principle, possible to distil *forcing* in the prognostic differential equations (e.g. the first equation of thermodynamics) not already built into the assimilating model. This can be done since there is typically a tiny but systematic offset (R) between the initial temporal development in atmospheric forecasts and that in the analyses (observations):

$$\left.\frac{\partial \psi}{\partial t}\right|_0 = \left.\frac{\partial \psi}{\partial t}\right|_M + R \qquad (2.1)$$

where ψ is a prognostic variable (temperature, wind components, humidity) at a given location in the atmosphere and subscript *O* denotes the instantaneous temporal tendency in the analyses (observations) for a given total atmospheric state vector. Similarly, *M* indicates the temporal tendency simulated by the assimilating model given the same observed atmospheric state vector. This means that *R* is a residual forcing not simulated by the model as it should have been, i.e. a proxy for the model deficiency. Due to different technical obstacles, e.g. related to misinterpretation of mainly moisture spin up in the assimilating model and to some extent to gravity wave noise, it causes certain problems in calculating *R* at a given time for the three-dimensional atmosphere. The European research project POTENTIALS investigated different possibilities for solving these problems. The results from POTENTIALS as well as other studies suggest that a four dimensional data assimilation technique is needed, i.e. both time and space are considered simultaneously. The simplest technique is a nudging or relaxation technique which allows assimilation of data at non-synoptic hours and which was used for many years at the U.K. Met Office. A variational data assimilation may, however, be relevant since it provides a very elegant and accurate way to estimate *R*. See, for example, D'Andrea and Vautard (2000) for a description of this method in the framework of a simple three-level quasi-geostrophic model.

In order to use the methodology outlined to squeeze meaningful information out of *R* it is crucial to use basic 'observed' data that are global, of reasonably high spatial and temporal resolution and homogenous. By homogenous we mean that the data must not be influenced by changing instrumental accuracy, environmental conditions or observational practices. The WATS data have the property of being highly homogenous, and they are therefore perfectly suited for detection of atmospheric forcing using this technique. In the framework of WATS, it is, however, unavoidable to include some complementary observational information, mainly because the profiles obtained provide no information about the atmospheric wind field, which is needed to obtain stable estimates of *R*. For practical purposes it is judged advisable to re-assimilate (regarding the calculation of *R*) already processed data like the near real time analyses produced in WATS, because these data already include all this complementary information.

Using 'perfect' (error free) data and assimilation techniques, the term *R* represents errors in the formulation of the assimilating atmospheric model which are mainly due to problems in the parameterisation of unresolved physical processes and the use of inadequate numerical techniques to solve the basic adiabatic equations. Because *R* reflects instantaneous forcing errors in the model relative to the analyses there is – in principle – no time for compensating response errors to develop during the assimilation of the analyses. Thus the *R* vectors are highly valuable guidelines for improving the atmospheric component of climate models as in, for example, Klinker and Sardeshmukh (1992) or Kaas et al., (1999).

Yet another approach to the validation and eventual improvement of climate models is provided by the statistical fluctuation-dissipation theorem. This theorem shows that a system's response to an external forcing is directly related to the natural fluctuations of that system (Leith, 1975). When applied to the climate system and its modelling, it implies that the models most useful for prediction are those which best simulate the variability and inter-variability of all components of the climate system (Leith, 1978). Such inter-comparison is beginning to take place with thermal infrared radiances (Haskins et al., 1997, 1999), and early results show a surprising lack of agreement between modelled and measured variability. Obviously, WATS would permit a direct comparison of observed temperature-water vapour covariances throughout the troposphere with those simulated by a model. This provides an unbiased validation of the feedbacks internal to the climate model responsible for climatic predictive capability of that model.

2.3.5 Detection of External Forcing of Climate.

Within the planned WATS mission lifetime, by far the largest fraction of climate variations will be random, i.e. tthe result of chaotic processes in the non-linear climate system and *not* a consequence of external forcing of climate related to, for example, varying solar activity, changed greenhouse effect, stratospheric ozone depletion or volcanic activity. Thus there is a sampling problem when one wants to use say 5 years of data to study climate change and it is not a trivial task to isolate the presumably small fraction of the externally forced variations/trends.

By performing an assimilation of high quality measurements into a state of the art atmospheric model it is, however, possible to detect and quantify varying external forcing of climate which varies over time. Such detection is very important since not all climatic forcings are well known, well understood, or even accepted as such. One example which clearly demonstrates this is the ongoing debate concerning the possible indirect effect of solar activity on climate (e.g. Marsh and Svensmark, 2000).

To understand how we can estimate external forcing of the atmosphere we need to re-consider the above equation in the case of the first equation of thermodynamics, i.e. with ψ equal to temperature. The residual heating, R, generally consists of:

- Multi-year average tendency error of the model relative to the observations. This is the systematic heating residual we want to minimise when an atmospheric model needs improvement (Section 2.3.4).
- Short term temporal variations reflecting such weather variations (internal to the atmosphere) that are not well simulated by the atmospheric model. This term is generally small, as modern state-of-the-art models are capable of making very accurate forecasts a few hours into the future from a given observed state.

- Inter-annual variations which can be due to either observational inhomogeneities[4] or changing external forcing of the atmosphere not known to the model.

To the extent that we can exclude observational inhomogeneities, the last contribution is interesting since it describes the spatial distribution and magnitude of the heating processes in the atmosphere that are due to varying external heating. In other words, one can use the offsets in the first equation of thermodynamics in a given period to estimate the magnitude of the anomalous heating by comparing with the offsets in other periods. This approach is not to be confused with classical climate fingerprinting, the main goal of which is to detect and attribute changes in anticipated climate response to various external forcings. Instead of detecting changes in the basic meteorological quantities like temperature, the method detects the more fundamental anomalous forcing of climate which can be due to varying solar activity, changed greenhouse effect, stratospheric ozone depletion or volcanic activity, for example. The method may in this way be considered a filter which excludes the impact of the non-externally forced climate variations.

The ongoing EU project DETECT seeks to use the technique outlined above to detect trends in forcing during the period of ECMWF re-analyses (ERA40).

An Example

A simple and rather inaccurate way to estimate the residual forcing, *R*, is to use the so-called analysis increments (i.e. differences between very short term forecasts and the verifying analyses) from the existing European re-analyses, ERA15 (Gibson et al., 1997). Figure 2.6 shows an example taken from Andersen et al. (2001) of varying zonal

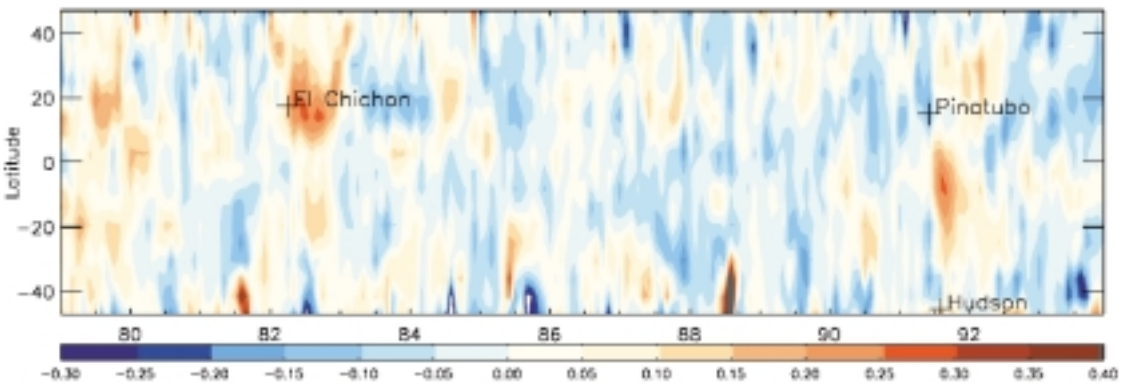

Figure 2.6: *Anomalies from the average annual cycle in the zonal mean of 24 hour temperature analysis increments for the period 1979-1993 using ERA-data. The vertical axis shows the latitude and the horizontal direction the time. Units: K/day.*

[4] i.e. artificial trends in the observed data that are due to changes of instrument or drifts in the instrument characteristics or in their surroundings etc.

averages of the analysis increments in the lower stratosphere (30 hPa) in the period 1979–1993[5]. The two volcanoes, El Chichon in 1982 and Pinatubo in 1991, are seen to result in anomalous zonal mean heating rates of about 0.25–0.30 K/day, which is of the same order of magnitude as suggested by radiative transfer models (Stenchikov et al., 1998). It is clear from the Figure that there is some noise, which is due to varying observational data quality in the re-analyses and due to missing ability of the model to simulate some atmospheric phenomena. On top of the volcanic forcings, there seems to be a long term cooling trend. It is, however, hard to judge if all this cooling is real since the raw data assimilated in ERA15 are by no means homogenous. Both the noise problems and the inhomogeneities in the basic data available in ERA15 underline the need for more accurate data for such detection of external forcing of climate.

2.4 WATS Measurement Principles

In this section we describe the roots of the WATS proposal in the technique of GNSS occultation, the logic behind the WATS technique and our intended inversion methodology. We also provide a brief discussion of uncertainties in attenuation coefficients for microwaves in the atmosphere. Many of the details behind the field of active microwave limb-sounding of the Earth's atmosphere are available elsewhere in the scientific literature, and so here we will only give an overview of how the WATS effort ties these other works together.

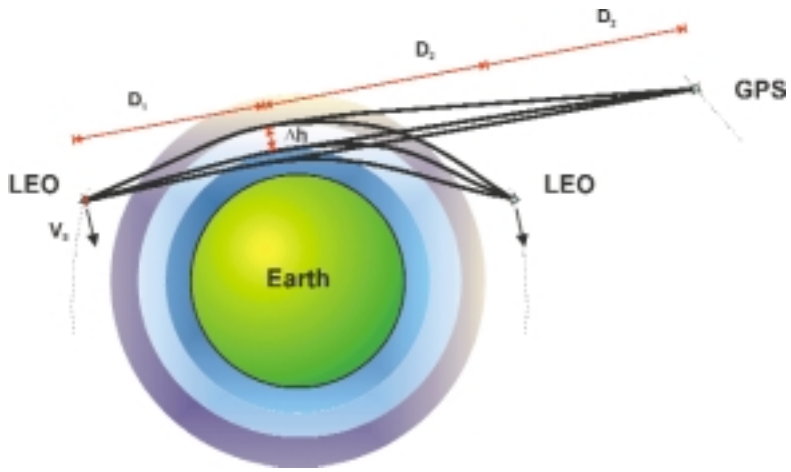

Figure 2.7: *WATS will profile water vapour accurately from the surface to the upper troposphere by active limb sounding at frequencies around 22 GHz. The project will consist of a constellation of LEO transmitters and receivers which should achieve good spatial and temporal coverage around the globe.*

[5] It should be noted that the effect of the Quasi Biennial Oscillation (QBO) also contributes to the analysis increments, but this was removed by filtering the data before plotting the figure.

Figure 2.7 schematically illustrates the concept of limb sounding in the special case of simultaneous occultation between two LEO satellites and between one of the LEO satellites and a GPS satellite. The possibility of multipath rays is indicated.

2.4.1 GNSS Occultation

GNSS-LEO occultation is a technique for sounding the Earth's atmosphere, which grew out of the planetary science community. Every interplanetary spacecraft carries an ultra-stable oscillator (USO), primarily for navigation purposes. Radio scientists, though, recognised another powerful use for the USO: when the radio link between the spacecraft and Earth is occulted by a planetary atmosphere, the phase of the carrier signal is modulated by the atmospheric refraction. The deeper the ray penetrates into the planetary atmosphere, the more the ray is bent and the more the apparent phase of the radio wave is delayed. Thus, a planetary atmosphere behaves like a refracting lens through which the radio link must pass. After simple geometric reductions and an integral transform, the easily measured phase delay of the radio signal can be inverted to a temperature profile of that planetary atmosphere. All of this can be done by tracking only the phase of the received signal; thus the temperature measured in this way is insensitive to the usual problems associated with calibrating measured intensities of radiation[6].

While this technique was used to study planetary atmospheres, it was only recently applied to sounding the Earth's atmosphere. When the Global Positioning System (GPS), a set of 24 satellites with on-board USO's broadcasting at 1.2276 and 1.57542 GHz in approximately 20 000 km orbits, was established it became possible to exploit radio-occultation missions by placing customised GPS receivers in a low-Earth orbit (LEO). Just one receiver could obtain 500 globally distributed soundings of the atmosphere every day. Obtaining a temperature profile in an occultation requires a relationship between the refractive index and the mass density. The refractivity of the Earth's atmosphere is related to atmospheric variables through

$$N = (n - 1) \times 10^6 = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} \tag{2.2}$$

6 It has been pointed out many times that radio occultation gives refractivity measurements that are insensitive to GPS receiver type, independent of epoch, and almost free of calibration error. This quality comes about because it is based on a measurement of timing whereas conventional remote sensing instruments are measurements of radiation intensity, and it is easier to calibrate timing measurements than intensity measurements.

where n is the index of refraction, P is total pressure, T is temperature, and P_W is the partial pressure of water vapour (a_1 = 77.60 K hPa^{-1} and a_2 = 3.73×10^5 K^2 hPa^{-1}). The first term on the right is commonly referred to as the 'dry' term and the second as the 'wet' term, because the first represents the contribution by the non-polar oxygen molecules to refractivity and the second the contribution by the strongly dipolar water vapour molecule. As it turns out, the wet term is a negligible contributor to refractivity above the lower troposphere. In the lower troposphere, it is still the lesser contributor but nonetheless dominates the spatial and temporal variability of refractivity. Overall, a single measurement of refractivity – even in conjunction with hydrostatic balance – is not enough to independently retrieve pressure, temperature, and water vapour pressure. This is called the 'wet-dry' ambiguity in occultation of the troposphere.

2.4.2 GNSS Occultation Missions

In 1995, the GPS/MET project was flown as a proof-of-concept of the GNSS occultation technique. It was shown that as a temperature sounder, GPS occultation agreed with the ECMWF global analysis to within 1 K from ~3 km altitude up through the lower stratosphere (Kursinski et al., 1997; Rocken et al., 1997). As a sounder of geopotential heights, GPS occultation agrees with the ECMWF global analysis to within 10 metres in the same altitude region, but only in those areas where radiosondes are abundant. In other areas where radiosonde coverage is poor, agreement between GPS/MET and ECMWF analysis is worse; hence, GPS occultation showed that it could measure temperatures and heights accurately and provide a significant advantage in weather analysis where radiosonde stations do not exist.

Planned operational radio occultation missions include the GRAS instrument on MetOp scheduled for launch in 2005. The GRAS-derived GPSOS instrument on the US NPOESS satellites may also provide useful data. Various groups have proposed to fly a constellation of GNSS receivers for purposes of weather and climate, but only two such proposals are currently supported: COSMIC and ACE. COSMIC – the Constellation Observing System for Meteorology, Ionosphere, and Climate – is a Taiwanese project, supported by a variety of interested agencies in the USA (Rocken et al., 2000). It is a constellation of 6 GPS receivers scheduled for launch in 2005. ACE – Atmospheric Climate Experiment – is an ESA Earth Explorer Opportunity Mission which currently has 'hot standby' status and is also considering 6 receivers.

While no dedicated GNSS receiver constellation is completely approved at this time, GPS receivers have been embarked aboard flights of opportunity (Ørsted, CHAMP and others, with various results). However, these isolated RO instruments – while increasing the experience with the technique – fall short of meeting the scientific requirements for climate research.

2.4.3 WATS Mission: Resolving the Tropospheric 'Wet-Dry' Ambiguity

The WATS mission seeks to resolve the wet-dry ambiguity of Earth occultation in order to retrieve water vapour amounts throughout the troposphere. Ideally, this could be done by measuring refractivity at another frequency if Equation 2.2 were dispersive, but this is not true in the range of wavelengths considered. However, the absorption spectrum of water vapour shows a strong (and highly dispersive) feature at 22 GHz, and thus in order to resolve the wet-dry ambiguity one can carefully measure relative amplitude as well as phase during an occultation at 22 GHz.

Measuring amplitude during an occultation is different from measuring phase. For an occultation there are three main terms that govern the intensity of the received signal: (1) the natural spreading and convergence (focussing and defocussing) of adjacent rays due to ray propagation geometry, (2) variations in the gains within the transmitter and receiver and of their antennas (for the duration of an occultation, i.e. < 30 sec), and (3) absorption within the atmosphere. The first term can be accurately removed by forecasting the effects of geometric spreading from the phase information (Leroy, 2001). In fact, recently an advanced technique based on the Maslov-Fourier theory has been proposed to simultaneously determine atmospheric refraction and absorption (Gorbunov, 2000, 2001). The second term can be eliminated through accurate pointing information, a stable design, modelling of the antenna gain patterns and by using normalised amplitudes. Thus, the absorption of microwaves by the atmosphere – the third term – can be estimated by carefully observing radio signal amplitude during an occultation and removing the first two terms. With measurements of phase and amplitude in an occultation, enough information is available to profile the complex refractivity of the atmosphere and solve for pressure, temperature, and water vapour independently. This is the core concept of the WATS technique.

Near 22 GHz, there is a strong water vapour absorption feature superimposed on continuum absorption by water vapour (and air). The imaginary part of the refractivity N_i near 22 GHz is given by

$$N_i \cong \frac{S\gamma\left(\frac{\nu}{\nu_0}\right)}{(\nu - \nu_0)^2 + \gamma^2} \tag{2.3}$$

in which ν is the frequency, ν_0=22.235080 GHz is the line centre, S is the line strength, and g is the line width. The line strength S is directly proportional to the water vapour partial pressure. The line strength and the line width depend on temperature and pressure as well, and an analytical model of the microwave spectrum of water vapour has been constructed (Liebe, 1989). Figure 2.8 shows the imaginary part of the refractivity for varying relative humidities. These curves would be relevant to an occultation ray, which grazes the surface of the Earth.

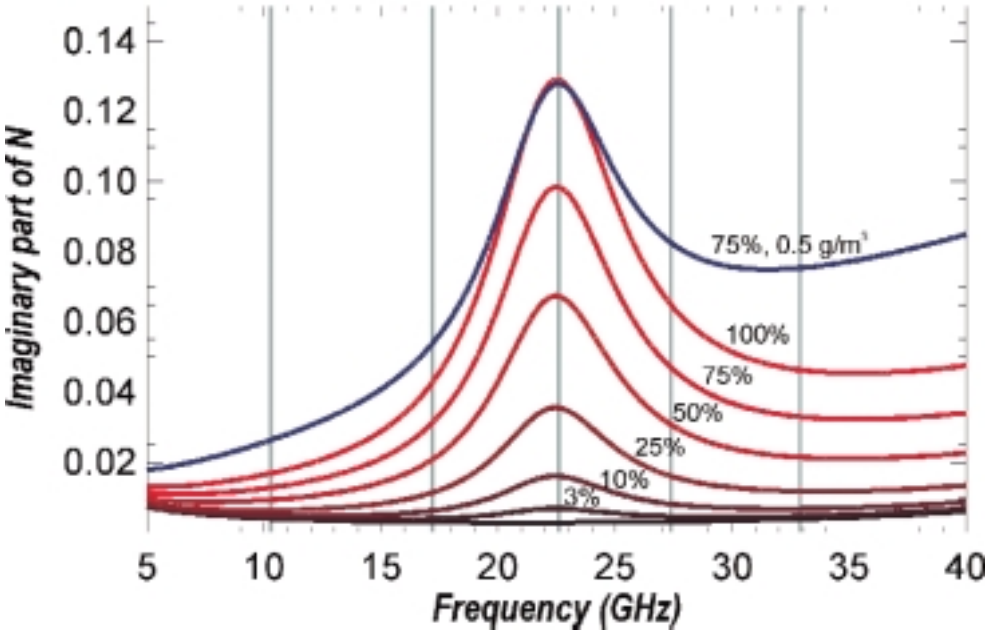

Figure 2.8: *Imaginary part of the refractivity as a function of frequency for various relative humidities (0%, 3%, 10%, 25%, 50%, 75%, and 100%). A curve with 0.5 g/m^3 of liquid water and 75% humidity is in blue. The pressure (1013 hPa) and temperature (25 °C) used are typical of surface air conditions. The five frequencies (10.3, 17.2, 22.6, 27.4 and 32.9 GHz) under consideration in WATS are indicated by grey vertical lines.*

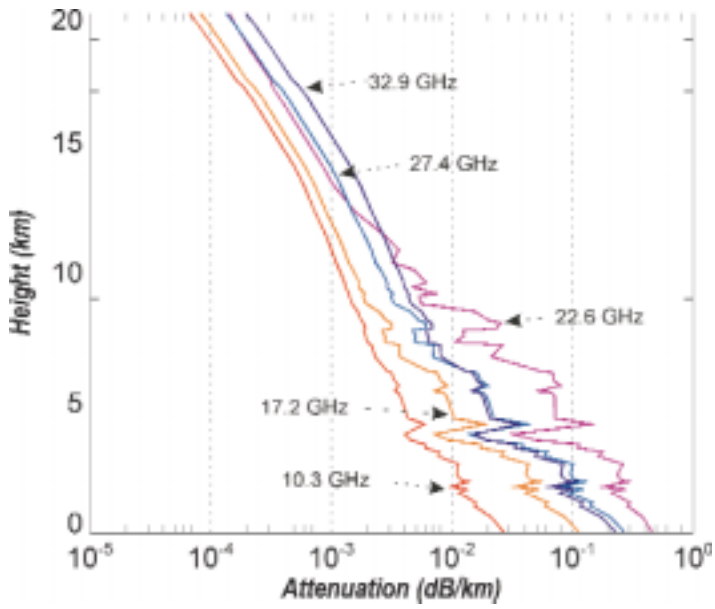

Figure 2.9:. *Attenuation as a function of height using the Millimetre-wave Propagation Model of Liebe (1989) and a radiosonde profile from Lihue, Hawaii, taken on 2 October 2000 at 12Z. The red line is for 10.3 GHz, the yellow for 17.2 GHz, the purple for 22.6 GHz, the cyan for 27.4 GHz, and the dark blue for 32.9 GHz.*

The 22 GHz line is just strong enough at line centre to sense water vapour in the upper troposphere and weak enough in the wings to probe the middle and lower troposphere for water vapour. Figure 2.9 shows the attenuation per unit length of horizontal path at five frequencies as a function of height in a tropical atmosphere. At line centre the total attenuation is >200 dB at the surface but 2 dB at 10 km altitude, meaning the beam disappears at the surface but can detect water vapour in the upper troposphere. In the wings of the 22 GHz, line water vapour absorbs about 10 dB near the surface, an amount that can be detected. Because of these different sensitivities, each frequency can contribute to the retrieval of water vapour in a different vertical domain of the troposphere. Consequently, it is advisable to obtain occultation data at a few frequencies at and around the line centre, so that water vapour in most of the troposphere can be profiled.

Active limb sounding at several frequencies around the 22 GHz line contributes two additional benefits: reduction of drifts in total system gain, and detection and removal of cloud effects in all weather conditions. During an occultation, the perturbing effects caused by the variability of the system gain or by the geometric spreading of the rays may be correlated between the different frequencies. As a result, combining frequencies could reduce the effect of system gain drifts on the measurement. Secondly, clouds are known to be contributors to absorption at microwave frequencies, and it will be necessary to remove their effects if water vapour is the main interest. Since the signature of clouds in the imaginary part of refractivity is linear in frequency at 22 GHz, it should be possible to distinguish the contribution of clouds from that of water vapour by sounding at several frequencies in this range, as their signatures differ enough to make each uniquely identifiable. Figure 2.8 shows an example of a spectrum containing 0.5 g/m^3 of liquid water, typical of a low level fog or thick cumulus.

As a result, to optimise the performance of the water vapour retrieval, it is recommended to use one frequency close to the 22.2 GHz water vapour line centre as well as two frequencies on the wing(s). Additional considerations such as radio regulations and technical feasibility also influence the choice of frequencies. A baseline proposal is to use 10.3, 17.2 and 22.6 GHz.

2.4.4 Assessing the Uncertainties in Present Attenuation Models

The most widely accepted model for water vapour absorption near 22 GHz is the Millimetre wave Propagation Model (MPM) (Liebe, 1989). Several updates have been made to this model over the years and care must be taken to combine the correct set of line parameters with the appropriate formula for the continuum contribution. Rosenkranz (1993) gives an extensive review of both water vapour and oxygen attenuation. A simplified representation of the full MPM model (Liebe, 1989), where the contributions from all the water vapour lines above the 22 GHz line are included in the so called continuum component, was used by Cruz Pol et al. (1998). Ground-based microwave radiometer observations acquired in the humid climate of Florida and the

less humid climate of California were used together with simultaneously acquired radiosonde data to fit three different model parameters. The result is shown in Figure 2.10.

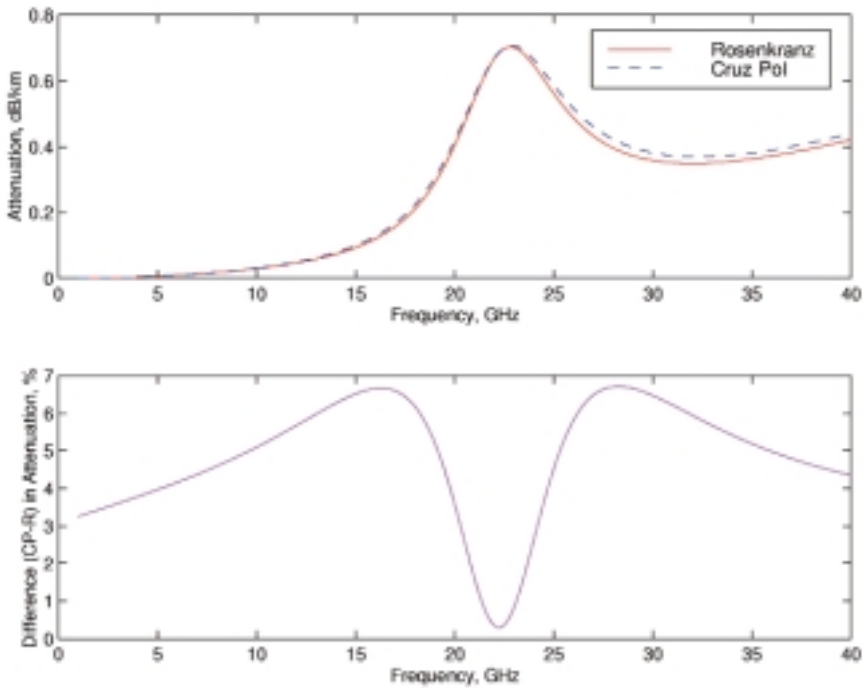

Figure 2.10: *Comparison of two similar attenuation models for water vapour. The upper graph shows the attenuation for humid conditions at the ground surface using the following parameter values: total pressure 1013 hPa, temperature +30°C, relative humidity 100% (meaning a partial pressure of water vapour equal to 43 hPa). The lower graph shows the difference between the two models. This difference can be seen as an indication of the uncertainties in the attenuation models for water vapour. Similar values for the differences are obtained for the drier and colder conditions at higher altitudes.*

For this frequency range it is seen that relative differences between these two sets of model parameters range between 0 and 7 percent. Many years of ground-based microwave radiometer data and simultaneous radiosonde launches from the Swedish west coast have failed to show which of these two representations is the more accurate. Results from different years give an inconsistent picture (Elgered et al., unpublished). These data suffer from being acquired 37 km apart but a conservative statement is still that the differences seen in Figure 2.10 are an indication of the uncertainty of the presently available water vapour attenuation models.

The oxygen attenuation is less variable at these frequencies. Assuming that pressure and temperature are well known (from the WATS propagation delay data) it should be possible to correct for its contribution to the transmission with high accuracy.

The attenuation due to liquid water droplets is approximately proportional to the frequency squared (Staelin, 1966). The MPM model includes more parameters and can be seen as an improvement. Figure 2.11 shows the results for a dense cloud with a liquid water density of 1 g/m^3 for three different temperatures. The MPM model (red solid line) gives attenuation values which are of comparable size to the water vapour attenuation. Although the propagation path through this type of clouds may be one to two orders of magnitude shorter than that through the water vapour, the effect must be taken into account.

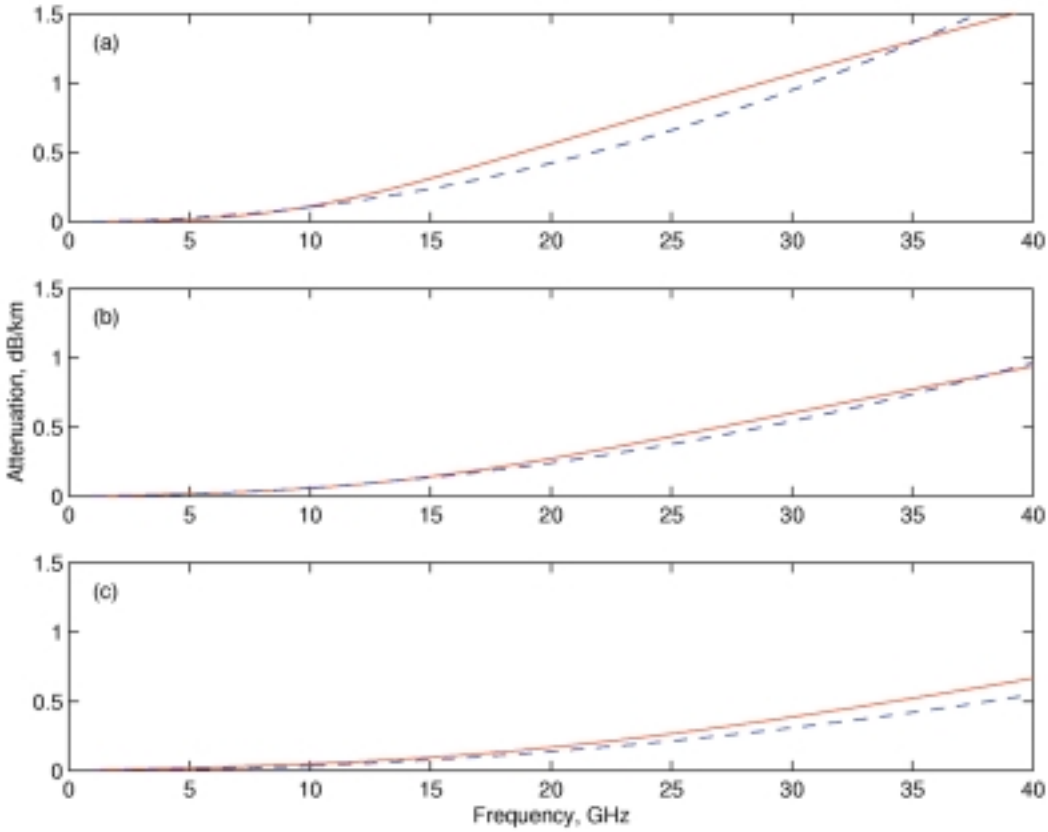

Figure 2.11: *Attenuation due to water droplets (diameter less then 50 microns) with a liquid water density of 1g/m^3 and three different temperatures: (a) -10°C, (b) +10°C, and (c) +30°C. The red solid line is the MPM model (Liebe, 1989) and the dotted blue line is a less accurate model (but using a much simpler formulation) published by Staelin (1966).*

Separation of the contributions from water vapour and liquid water emission seen by microwave radiometers on the ground is often accomplished through the use of two well-separated frequencies, e.g. at one frequency on either side of the 22.2 GHz line (21.0 or 23.6 GHz are commonly used) together with one frequency in the transmission window just above 30 GHz (Elgered, 1993). Comparing Figures 2.10 and 2.11 it is clear that the lower frequency is more sensitive to water vapour while the higher frequency is more sensitive to liquid water. On the other hand, if the sensitivity difference between liquid and vapour is similar for two frequencies, then the separation will be more difficult and the requirement on the accuracy of the transmission measurement stricter.

2.4.5 Inversion Methodology

Given that during a LEO-LEO occultation measurement the electric field will be measured as a function of time at several frequencies, the methodology of inversion must transform electric field measurements to profiles of geophysical variables. The methodology must directly address issues identified from experience in GPS occultation analysis. Those complications are atmospheric multipath and diffraction. The first originates from the layered structure of water vapour in the atmosphere and the second from atmospheric features that occur on vertical scales smaller than the size of the occultation beam. Methods have been developed to properly account for these effects.

The first step must disentangle the multipath which results from water vapour layering in the lower atmosphere; the second must profile the complex refractivity at several frequencies from the multipath-corrected data; and the final step must invert for the geophysical variables pressure, temperature, and water vapour.

Multipath, Backpropagation, and Canonical Transform

Multipath is the phenomenon wherein several rays occulted by the atmosphere connect the transmitting LEO and the receiving LEO simultaneously. From the standpoint of Fermat's principle of least time, this happens because rays can minimise their travel time near a patch of water vapour in the atmosphere by passing both above and below it. While multipath may occur only infrequently in occultations, it does occur in regions of high interest to WATS, namely when complicated water vapour structures occur in the lower troposphere. To an observer aboard the receiving LEO, multipath causes the transmitting LEO to appear in several different places on the limb in the vicinity of the water vapour patch. Moreover, each apparent transmitter will have a different 'colour' (for one carrier frequency) because refraction causes each of the multipath rays to be bent differently. The result is that the measured electric field contains an irregular beating phenomenon. Nestled into that are the complicated 'knife-edge' diffraction patterns characteristic of Fresnel diffraction off sharp vertical structures – such as the moist planetary boundary layer.

In the past, radio-holographic methods were implemented to address multipath (Lindal et al., 1987; Lindal, 1992). In this method, one Fourier-transforms the measured electric field amplitude in narrow time windows in a search for multiple tones, retrieves the Doppler-shifted frequency of each tone, and thereafter employs the usual methods of analysing the refractive index in the atmosphere. This method is impractical in the Earth's lower troposphere because of the presence of strong diffraction effects and the large number of tones possible. Thus, the more sophisticated techniques of 'backpropagation' and canonical transformation will be implemented in the analysis of WATS data.

The combination of backpropagation (Gorbunov, 1998) and canonical transformation (Gorbunov, 2000) has the powerful property that it can correct for multipath and diffraction, and determine the bending profile through the atmosphere within a single technique. Backpropagation is based on the Helmholtz-Kirchhoff diffraction integral (Born and Wolf, 1980, p. 377), which can fully recreate the electric field in two dimensions as it appeared at the time of the occultation. Recreating the field closer to the atmosphere than the LEO position effectively unwinds multipath and much of the diffraction. Canonical transformation further improves upon backpropagation by incorporating the direct retrieval of the bending angle profile and the absorption profile produced by the atmosphere. Both backpropagation and canonical transformation have been demonstrated in the case of GPS occultation (Gorbunov, 2001). Both will be straightforward to implement in the retrieval of WATS data.

Retrieval of Complex Refractivity

It is customary to use an Abel transform to obtain profiles of the real part of refractivity from bending angle profiles in GNSS occultation. This technique has been in use since the landmark paper by Fjeldbo et al. (1971). In parallel, WATS will incorporate a related Abelian-type transform to obtain profiles of the imaginary part of the refractivity from attenuation profiles as a function of the ray altitude.

Retrieving Pressure, Temperature, Water Vapour

With profiles of complex refractivity at many frequencies, determining profiles of pressure, temperature, and water vapour (and possibly cloud liquid water) is an over-determined problem. In the stratosphere, the real part of the refractivity dominates in the determination of pressure and temperature, and even then it only gives information on density. Thus, in the topmost layer, it is necessary to incorporate climatological information on pressure and temperature. Below that, all geophysical variables can be accurately retrieved given the retrieval of the level above and the hydrostatic equation and the equation of state as constraints. This can be done, for example, by a variational minimisation procedure.

It is expected that the dominant contributions to retrieval error will stem from the upper boundary conditions. Firstly, the Abelian transform used to obtain the profiles of complex refractivity requires an asymptotic approximation at the 'top' of the atmosphere, which can lead to errors in the complex refractivity at the uppermost levels. Secondly, the method used to obtain temperature and pressure given the refractivity at the top of the atmosphere will yield an offset in pressure throughout the profile, but the resultant temperature error decreases exponentially with depth on the scale of an atmospheric scale height. This behaviour is well known in GPS occultation (e.g. Kursinski et al., 1997).

2.5 Links to GOS, GCOS and International Research Programmes

Although any observation type can be used on its own for particular studies, the most powerful usage is normally achieved though modern four-dimensional data assimilation systems combining the different types of observations of temperature, moisture, pressure and wind. This is particularly clear in NWP, but also for climate research and atmospheric process studies since the synergetic use of observations and numerical models (based on the physical laws) provides the best estimate in a least squares sense of the atmospheric states which have been attained in the past.

A general and fundamental data requirement in climate research is to minimise observational and processing biases. In practice, it is often difficult to obtain fully bias-free measurements and therefore as a minimal requirement we want to control changes in observational biases over time, i.e. to ensure so-called observational homogeneity. While drifting biases related to data-processing can be eliminated by reprocessing observations (re-analysis activities), long term drifts – or even jumps – in observational biases constitute a serious problem. This has so far obscured the use of re-analyses for visualisation of important trends in, for example, global mean temperatures at different altitudes. Furthermore, the errors in passive satellite profiles of temperature and moisture depend on meteorological conditions and are, for example, larger in intense frontal zones with precipitation and clouds than in clear air conditions. The existing vertical profiles also have insufficient vertical resolution, in particular near the tropopause which is dominated by sharp vertical gradients and hence sharp gradients in greenhouse gas forcing.

The combined use of GNSS-LEO and LEO-LEO radio occultation measurements would constitute an excellent contribution to the global observing system for weather and climate because it would circumvent the main problems with the present passive satellite sounding data, i.e. their potential drifts and jumps in observational biases and their relatively low vertical resolution. We cannot expect the WATS data to be totally free of biases, but we can expect them to be much more homogenous than existing profiling data because they are connected in an absolute sense though Equations 2.2 and 2.3 to the atmospheric state. Furthermore, the measurement technique is in principle independent of *a posteriori* calibration. It is of particular importance that this

is obtained under all weather conditions so that valuable information is retained even in cloudy and precipitating areas.

For the reasons stated above, the WATS mission would be highly supportive to the WCRP, whose main objectives are to observe, understand, model, and predict climate variations and changes. In particular WATS could support WCRP strongly through its CLIVAR and GEWEX programmes. The CLIVAR and its European implementation, Euroclivar, aims at improving our understanding of those physical processes in the climate system that are responsible for climate variability on time scales ranging from seasons to centuries. CLIVAR considers natural variability as well as anthropogenic influences on climate with prediction – if possible – as a main goal. GEWEX focuses on observation, understanding and modelling of the hydrological cycle and energy fluxes in the atmosphere, at the land surface and in the upper oceans. The goal of GEWEX is to reproduce and predict variations of the global hydrological regime, its impact on atmospheric and surface dynamics, and variations in regional hydrological processes and water resources and their response to changes in the environment, such as the increase in greenhouse gases.

From a technical point of view, all data being produced in WATS should be made available on the World Weather Watch (WWW) network to the meteorological services, universities and other institutions in a similar way to other satellite observations. Because of economic limits, mainly related to the number of ground installations, it is not expected that all WATS data can be distributed in near-real time for use in NWP, but availability of the largest possible fraction of the data for use at the NWP centres should be a goal.

2.6 Unique Contributions of WATS

2.6.1 Climate Research

Climate monitoring of tropospheric and stratospheric water vapour and temperature is achieved at the present time in two ways, using the international network of radiosondes and the operational meteorological satellites. Both methods suffer from a number of limitations, such as potential inhomogeneities, low accuracy and low vertical resolution.

The water vapour and temperature data obtained by the LEO-LEO and GNSS-LEO radio occultation techniques have several advantages compared to existing techniques:

- The basic measurements in WATS are the Doppler shift (or time delay) of the GNSS and LEO occulted signals and the Doppler shift and relative attenuation of LEO signals at appropriate frequencies. The measurements can be made with high accuracy, and from a climate monitoring point of view it is essential that basic data are much more homogenous than existing observations, i.e. data from different

satellites can be used without requiring large inter-calibration efforts. As a consequence, it is possible to compare two data sets separated by many years and taken by different RO sensors.

- The measurements have a global coverage, which is not the case for radiosondes which are mainly limited to continental areas.
- The measurements inherently have an all-weather capability, which is not the case for passive infrared sounders.
- The measurements have very high vertical resolution (0.5–1 km), which is not the case for the present nadir viewing sounders.

For these reasons the type of data proposed in WATS are expected to be ideal for accurate detection of climatic trends and monitoring of natural variations internal to the climate system.

When the data are used in combination with other types of data in atmospheric data assimilation systems, they will improve our understanding of the full atmospheric system. As described in Sections 2.3.4 the data assimilation can be used to identify fundamental flaws in the atmospheric components of climate models and thus, indirectly, the proposed occultation data can help reduce the uncertainties in future climate projections. Furthermore, data assimilation can be used to detect and quantify temporal variations in the external forcing of the atmosphere (Section 2.3.5).

WATS is unique among planned and developing missions in that it profiles water vapour throughout the upper and lower troposphere regardless of weather conditions. It offers a key complement to the planned nadir-sounding high spectral resolution infrared instruments (AIRS, IASI, CrIS) in that clouds are largely transparent to WATS. It also offers a fundamentally different alternative to the traditional sounding techniques, thus providing an invaluable source for intervalidation where data products are similar in nature. But primarily, the WATS mission is driven by climate research with applications to weather, whereas conventional water vapour sounders are weather instruments with applications to climate. WATS is designed to obtain a climatology of tropospheric water vapour with unprecedented precision on a global scale over several years. Its self-calibration allows an accurate tracking of secular changes in atmospheric water vapour content on short and long time scales.

2.6.2 Numerical Weather Prediction

The proposed WATS measurements will be complementary to those provided by present/planned observation networks:

- The radio occultation observations will be uniformly distributed around the World.

- They will provide soundings with higher accuracy and higher vertical resolution, but lower horizontal resolution, than the existing and planned passive infrared and microwave sounders, and thus address the main limitation of the present systems.
- They will be particularly valuable in cloudy areas, which will not be covered adequately even by future advanced infrared sounders.

In terms of accuracy, the proposed radio occultations will provide:

- Tropospheric water vapour observations of high accuracy and high vertical resolution (1 km or better). Such observations would be a major new source of information, particularly valuable over data-sparse regions and in cloudy areas.
- Temperature observations of high accuracy in the troposphere and over the full depth of the stratosphere with high vertical resolution (1 km or better).

Summarising, the skill in short and medium range weather forecasting should improve significantly if the proposed combined measurements of bending angle (refractive index) and attenuation of occulted microwave signals are implemented. Concerning the use of GNSS occultations alone, it has been shown (Kornblueh et al., 2000) that the impact increases with the size of the LEO constellation, with saturation occurring with slightly more than 12 receivers, when 48 GNSS transmitters are available.

3 Research Objectives

3.1 Research Objectives

As described in detail in Chapter 2, the concentration of greenhouse gases will continue to increase during the next decades due to anthropogenic activities. In spite of international protocols initiated to limit man-made emissions of greenhouse gases, there is a general agreement that this will lead to a warming of the surface and the lower atmosphere but the amplitude of this warming is still very uncertain and depends on feedback mechanisms involving radiation, release of latent heat and dynamical processes (IPCC, 2001). Water vapour plays a central role in these mechanisms. It is the dominant greenhouse gas in the atmosphere, it is associated with condensation/evaporation processes and it is involved indirectly in the radiative budget via clouds. However, its climatology (mean state and variability) is still poorly known, especially in the middle and upper troposphere.

The main objectives of the WATS mission are to:

- establish a highly accurate (<0.003 g/kg or <3%, whichever is larger) and vertically resolved (0.5 km) climatology of water vapour in the troposphere with global measurements of its concentration
- establish a highly accurate (<0.2 K) and vertically resolved (0.5 to 1 km) climatology of temperature in the troposphere and the stratosphere with global measurements of its vertical profile
- support research on climate variability and climate change and on validation and improvement of atmospheric models
- demonstrate a novel active atmospheric sounding method.

3.2 Limitations of Existing and Planned Data Sources

At the present time, humidity and temperature observations available for climate monitoring and atmospheric analysis suffer from several limitations:

- radiosondes are mainly available over Northern Hemisphere land masses, with most areas of the world observed sparsely or not at all
- commercial aircraft data cover only major air routes, with most areas of the world not covered
- operational satellite sounding radiometers have a limited vertical resolution and measurements are degraded in cloudy areas; they are based on radiometric measurements and their absolute accuracy is dependent upon calibration

- currently planned radio-occultation missions, such as GRAS on MetOp, do not allow separation of the contributions of humidity and dry air (temperature) terms to the refractive index of the troposphere (without use of external data); additionally, single satellite missions have limited horizontal sampling.

3.3 Uniqueness of the Contribution of the WATS Mission

The WATS mission will make a major contribution to the improvement of water vapour and temperature climatology and atmospheric modelling due to its unique characteristics:

- the independent measurement of water vapour absorption allows a rigorous separation between the contributions of water vapour and dry air (temperature) to the refractive index
- it is possible to achieve a very high absolute accuracy for climate monitoring because the refractive index is derived from very accurate time-based measurements
- accurate water vapour fields are obtained from self-calibrating attenuation measurements
- the deployment of a LEO satellite constellation provides a dense array of measurements, allowing climate monitoring even on regional scales
- high vertical resolution will allow a fine description of vertical gradients and structures in the atmosphere, such as around the tropopause and near the top of the boundary layer.

4 Observation Requirements

4.1 Generic Requirements for Sounding Data

4.1.1 Introduction

Generic requirements for the observation of meteorological parameters (i.e. independent of any particular technology) are specified by WMO/CBS and are expressed in WMO (1996) (with minor updates in WMO, 2000a) and WMO (2000b) in terms of:

- accuracy
- resolution (horizontal and vertical sampling)
- repeat frequency (sampling in time) and
- timeliness (delay from observation to delivery).

Note that the terms ‘resolution’ and ‘spatial sampling’ are often used interchangeably. In the present context, the former term does *not* imply the inherent resolution (pixel or voxel size) of any instrument in engineering terms, but rather the mean spacing between independent observations. The term ‘sampling’ is used hereafter.

These requirements do not represent hard cut-off ‘good/no good’ values; rather there is often a broad range of acceptability. Where a low tolerance is given, data may have marginal use (impact) whereas data exceeding a high tolerance may be over-specified, as the additional ‘quality’ cannot be exploited by the application. Hence, WMO/CBS express requirements as ‘minimum’ and ‘maximum’ thresholds (sometimes called ‘threshold’ and ‘target’ – or ‘goal’ or similar terms). If a system falls within this range, some useful benefit will be obtained – though it may or may not be cost-effective. WMO/CBS requirements make no judgement on the cost involved in meeting the requirements. The requirements in this chapter use the same concept of minima and maxima thresholds.

It is not essential (or expected) that any single observing system should meet all requirements; complementarity with other observing systems – each having its own strengths and weaknesses – is relevant.

Following WMO (1996), we break down the requirements for atmospheric sounding by atmospheric layers. These are defined as:

Lower Troposphere	(LT)	100 hPa to 500 hPa	(Surface to 5 km)
Higher Troposphere	HT)	500 hPa to 100 hPa	(5 km to 15 km)
Lower Stratosphere	(LS)	100 hPa to 10 hPa	(15 km to 35 km)
Higher Stratosphere	(HS)	10 hPa to 1 hPa	(35 km to 50 km)

Vertical profiles are commonly specified as a function of pressure, height above mean sea level or geopotential height, depending on the specific application. It is implicit that the accuracy of the vertical co-ordinate should be better than the required vertical resolution.

The GRAS SAG (ESA, 1998b) has identified several classes of users for radio occultation data. For the purposes of WATS, requirements are presented for the two major classes of application – Climate Monitoring and Prediction (‘Climate’) and Atmospheric Analysis and Modelling (‘Analysis’). Other classes, such as ‘Space Weather’ are considered as spin-off applications, which should not drive the WATS mission. For WATS, climate applications constitute the prime mission objectives.

The requirements in this assessment report can be traced back to the World Meteorological Organization (WMO). WMO documents (WMO, 1996 & 2000a) and database (WMO, 2000b) synthesise the consensus of the whole user community – representing WMO Members – at that time. Observation requirements are always evolving due, for instance, to developments in climate models and assimilation and forecasting systems. The WMO updates the requirements in response to these changes, but inevitably they can become somewhat out of date and anyway tend to represent current requirements, not necessarily those pertaining at the probable time of the WATS mission.

Recognising this, the WMO requirements in WMO (1996) were adapted to satellite sounding (ESA, 1996) and later modified in the light of foreseen Climate and NWP systems at the time of MetOp. WMO have recently released an updated document (WMO, 2000a), but the requirements for sounding are essentially unchanged from those in WMO (1996). These requirements have been developed and incorporated into the GRAS SAF User Requirements Document (Eumetsat, 2000) for the GRAS instrument on MetOp; the requirements for WATS are essentially those in that document.

In order to detect and monitor long-term climate changes, data must be available for long periods and instrumental or bias drift must be kept small and very stable. Although RMS accuracies for climate monitoring are required to be very much smaller than for atmospheric analysis, this can be achieved by averaging individual profiles over relatively large areas (typically in latitude and longitude boxes of 1°×1° or 2.5°×2.5°) for a suitable period – typically from a month to a year. The observing system need only meet the per-profile accuracy and minimum repeat sampling requirements; the

averaging is application-dependent and effectively a Level-3 product; these are the requirements for humidity and temperature referred to in Section 3.1.

4.1.2 Climate Monitoring and Prediction

The goal of climate monitoring is to obtain a good description of the mean state and variability of the atmosphere in order to detect any small trends over long periods. The main observational requirement for climate monitoring is therefore to retrieve temperature and water vapour profiles largely free of systematic biases. The expected trends in temperature due to anthropogenic changes are of the order of a few tenths of a degree per decade, as shown in the changes predicted by climate models during the next 30 years (IPCC, 2001). These trends may be masked by the natural variability of the atmosphere, such as that caused by the El Niño–Southern Oscillation, Quasi-Biannual Oscillation and volcanic eruptions. The data will be used by fitting them to climate models that include natural variability.

In order to have sufficient accuracy for such fitting, the climatology of temperature should be obtained with an absolute accuracy better than expected changes (of the order of 0.2 K), which is probably not achievable in one single radio occultation profile due to instrumental and atmospheric noise. For climatological studies, it is possible to average a large number of individual profiles to decrease the uncertainty by a factor equal to the square root of the number of profiles, if the errors in each profile are random and if each profile can be considered as independent of the others. This implies that any systematic bias in the retrieved temperature profile should be less than the expected accuracy of the averaged temperature (0.2 K) or water vapour content (2% RH[7]). Any bias caused by the diurnal cycle must be considered in the selection of orbits. It is particularly important that any residual bias that may exist should be stable over long periods.

A summary of the requirements for climate applications – using the heritage referenced in Section 4.1.1 – is shown in Table 4.1. These requirements are generic, and independent of any particular observing system.

It should be noted that for many climate GCM runs, observational data are not assimilated directly, but pre-analysed 3D fields are used for initialisation. These fields often come from operational NWP analyses or – for long-term consistency – off-line analyses, for instance the ECMWF or NCEP re-analysis products. For these applications, the requirements for analysis (in Section 4.1.3) are the drivers.

[7] Overall accuracy and stability are specified in terms of Relative Humidity as this is a quantity with well-defined and linear range over the vertical domain. There are standard methods to convert between

		Specific Humidity	Temperature
Horizontal Domain		Global	Global
Horizontal Sampling	LT HT LS HS	50–100 km 50–100 km 50–250 km 50–250 km	50–500 km 50–500 km 50–500 km 50–500 km
Vertical Doman		Surface to 1 hPa	Surface to 1 hPa
Vertical Sampling	LT HT LS HS	0.5–2 km 0.5–2 km 0.5–2 km 1–3 km	0.3–3 km 1–3 km 1–3 km 5–10 km
Time Sampling		3–12 hr	3–12 hr
RMS Accuracy	LT HT LS HS	0.25–1 g/kg 0.025–0.1 g/kg 0.0025–0.01 g/kg 0.00025–0.001 g/kg	0.5–3 K 0.5–3 K 0.5–3 K 1–3 K
Timeliness		30–60 days	30–60 days
Time Domain		>10 years	>10 years
Long-term Stability		<2% RH/decade	<0.1 K/decade

Table 4.1: *Generic observation requirements for global climate.*

4.1.3 Atmospheric Analysis and Modelling

Atmospheric analysis and modelling applications include both operational meteorology and atmospheric process studies using Numerical Weather Prediction (NWP) models. These applications cover a wide spectrum of activities related to the prediction of how the atmosphere, and in particular the associated weather conditions, will (or have) change(d) with time.

The most well known activity of operational meteorology is the provision of routine weather forecasts, including marine, aviation or agro-oriented forecasts, as well as the creation of climatological archives. The geographical extent of the forecasts ranges from small areas needing specialist local products, through regional forecasts at the national and continental scales, and up to the global scale. Most of the atmosphere is considered, from the surface to more than 30 kilometres in altitude. The forecasts range from very short periods (detailed local forecasts over the next few hours, termed ‘nowcasting’), up to 14-day forecasts of the basic global weather patterns (medium range forecasts). A strong driver for any operational observation system is the ability

to deliver data to the assimilation centres in near-real time – i.e. with a delay not exceeding a few hours.

Accurate forecasts from an NWP system require, in addition to a good model representing the atmosphere's dynamical and physical processes, an accurate description of the initial three-dimensional state of the atmosphere. Small errors in the initial specification of temperature, wind and humidity can grow rapidly to dominate errors in the subsequent forecast. The best initial state is obtained by assimilating into the model available measurements from many different observing systems.

Atmospheric process studies equally have a wide spread of scales, but are generally performed 'off-line'. Although the timeliness requirements of process studies are not critical – and more akin to those for climate – the data reception, quality control and archiving, etc, are much more efficiently handled within the operational environment – i.e. in near-real time.

A summary of the requirements – using the heritage referenced in Section 4.1.1 – is shown in Table 4.2 for global atmospheric analysis, which includes applications for operational NWP and atmospheric process studies. Again, it should be stressed that these requirements are generic, and independent of any particular observing system.

		Specific Humidity	**Temperature**
Horizontal Domain		Global	Global
Horizontal Sampling		50–250 km	50–500 km
Vertical Doman		Surface to 100 hPa	Surface to 1 hPa
Vertical Sampling	LT HT LS HS	0.4–2 km 1–3 km – –	0.3–3 km 1–3 km 1–3 km 1–3 km
Time Sampling		1–12 hr	1–12 hr
RMS Accuracy	LT HT LS HS	0.25–1 g/kg 0.025–0.1 g/kg – –	0.5–3 K 0.5–3 K 0.5–3 K 0.5–5 K
Timeliness		1–3 hr	1–3 hr

Table 4.2*: Generic observation requirements for global atmospheric analysis.*

Requirements for regional and/or very short period forecasting (‘nowcasting’) are very similar, but they are more demanding in terms of horizontal sampling (10–50 km), time sampling (30–60 mins) and timeliness (10–30 mins).

From recent studies, it is now clear that pre-retrieval of temperature and humidity profiles which are then assimilated into NWP models is not optimal. Rather, indirect assimilation of either RO refractivity or even bending angle can be statistically optimal using variational techniques, now common in assimilating passive radiance data from satellites. This method can overcome the ‘water vapour ambiguity’ problem of conventional RO retrieval.

4.2 WATS Mission Specific Requirements

In this section, the technology-independent user requirements in Section 4.1 are adapted to the WATS mission. The generic user requirements are modified taking account of the proposed measurement solution, and accepting that any one observing system is unlikely to meet all the higher-level requirements. This section therefore reflects the User Requirements in order to meet the scientific objectives of the WATS Mission.

From a user requirement point of view, the term ‘occultation’ (GNSS–LEO or LEO–LEO) is limited to those events, with:

- a vertical span (acquisition to loss of signal) between (as a minimum range) 1 km to 80 km (GNSS–LEO) or 1 km to 15 km (LEO–LEO)
- a horizontal drift in location of not more than 500 km.

4.2.1 Climate Monitoring and Prediction

In order to have statistical consistency, the global horizontal sampling should be as homogeneous as possible. Further, avoidance of any bias caused by the diurnal cycle must be considered in the selection of orbits, which implies a homogeneous spread of local observation times. There is no specific requirement for Sun-synchronous orbits. In order to meet the ‘Level-3’ (grid box averaged) accuracies, there is a requirement to have a minimum number of single-profile events per (2.5°×2.5° lat/lon) grid box per month. For climate applications, it is particularly important that any residual bias that may exist should be stable over long periods.

A summary of the requirements for climate applications, appropriate to a large constellation such as proposed for WATS, is shown in Table 4.3. The WATS mission is not designed to measure humidity in the highest levels of the atmosphere, so there is no requirement for specific humidity in the stratosphere (above 15 km). The requirements for humidity are independent of the RO technique used – GNSS–LEO or LEO–LEO.

		Specific Humidity	Temperature
Horizontal Domain		Global	Global
Horizontal Sampling		50–500 km	50–500 km
Vertical Doman		Surface to 1 hPa	Surface to 1 hPa
Vertical Sampling	LT HT LS HS	0.5–2 km 0.5–2 km – –	0.3–3 km 1–3 km 1–3 km 5–10 km
Time Sampling		3–24 hr	3–24 hr
RMS Accuracy	LT HT LS HS	0.25–1 g/kg 0.025–0.1 g/kg – –	0.5–3 K 0.5–3 K 0.5–3 K 1–3 K
Timeliness		30–60 days	30–60 days
Time Domain		>5 years	>5 years
Long-term Stability		< 2% RH/decade	< 0.1 K/decade
No. of profiles/grid box/month		> 40	> 40

Table 4.3: *WATS mission observation requirements for global climate.*

4.2.2 Atmospheric Analysis and Modelling

In order to maximise the benefits of WATS data, it is essential that the data be provided to assimilation centres in near-real time to enable the operational infrastructures to optimally use this data. Many climate applications will depend on WATS data having been assimilated together with all other forms of atmospheric and surface observations, and will use the analyses for their own studies. Therefore, there is a strong need to provide WATS data on short time-scales. If data can be made available in near-real time, then operational centres will also use and benefit from this data source. A threshold should be to provide a minimum of 30% of all WATS data to users within 3 hours of observation time, and a target to provide all data within this time limit.

WATS data should be provided with a horizontal coverage as globally homogeneous as possible, but, unlike the climate application, wide coverage in 6-hour windows is desirable, rather than over (say) a month. For operational use, data gaps over parts of the globe (e.g. in 6- or 12-hour windows) are inevitable and accepted for most satellite data, as long as the gaps are filled in subsequent time windows.

A summary of the requirements for atmospheric analysis applications, appropriate to a large constellation such as proposed for WATS, is shown in Table 4.4. The WATS

		Specific Humidity	Temperature
Horizontal Domain		Global	Global
Horizontal Sampling		100–1000 km	100–1000 km
Vertical Doman		Surface to 100 hPa	Surface to 1 hPa
Vertical Sampling	LT HT LS HS	0.4–2 km 1–3 km – –	0.3–3 km 1–3 km 1–3 km 1–3 km
Time Sampling		1–12 hr	1–12 hr
RMS Accuracy	LT HT LS HS	0.25–1 g/kg 0.025–0.1 g/kg – –	0.5–3 K 0.5–3 K 0.5–3 K 0.5–5 K
Timeliness		1–3 hr	1–3 hr

Table 4.4: *WATS mission observation requirements for global atmospheric analysis.*

mission is not designed to measure humidity in the highest levels of the atmosphere, so there is no requirement for specific humidity in the lower and higher stratosphere. The requirements for humidity are independent of the RO technique used – GNSS–LEO or LEO–LEO.

4.3 Processing Requirements and Products

The high-level requirements for the processing of WATS data and the products for end-users are:

- Data should be pre-processed to provide refraction (bending) angle profiles, corrected for ionospheric effects as a function of impact parameter and attenuation (normalised amplitude) profiles, corrected for defocusing and antenna gain patterns (Level-1b products).
- Derived refractivity and absorption profiles, and retrieved profiles of humidity, temperature and pressure, as a function of height (Level-2 products).
- For climatology, processing at all Levels should be performed with a consistent methodology over the lifetime of the mission.
- A substantial proportion of both Level-1b and Level-2 products should be made available to data assimilation centres in near-real time.

5 Mission Elements

A cautious consideration of the observational requirements, described in Chapter 4, for the different scientific issues to be addressed by the WATS mission, leads to a set of requirements for the data products, as expressed in Table 5.1. These requirements take into account the technical specificity of the mission and are consistent with those expressed in Chapter 4:

- vertical resolution ⇔ sampling of the signal + bandwidth of the signal
- refractivity ⇔ bending angle of the ray
- accuracy on water vapour measurement ⇔ amplitude accuracy of the measurement.

	GNSS–LEO	**LEO–LEO**
Horizontal Domain	Global	Global
Number of Profiles	> 6000 daily (> 12000)	> 1000 daily
Vertical Domain		Surface to 15 km for amplitude Surface to 80 km for bending
Sampling Rate	50 Hz	1 kHz
Time Sampling	1–12 hr	1–12 hr
RMS Accuracy (bending angle)	max {1 µrad, 0.4%}	max {1 µrad, 0.4%}
RMS Accuracy (amplitude)	< 2 dB over 100 s	< 0.025 dB over one occultation
Timeliness	1–3 hr for a significant fraction of the data	1–3 hr for a significant fraction of the data

Table 5.1: *WATS related requirements on data products (figures in brackets assume the availability of Galileo in addition to GPS).*

The requirement on sampling rate is derived from the required vertical resolution of the measurement, taking into account the vertical extension of the Fresnel zone as well as the need to correct for multipath effects.

The requirement on RMS amplitude accuracy for the LEO–LEO case is derived from the accuracy required for water vapour, taking into account the 'self-calibrating' technique applied during the occultation.

5.1 Description of Mission Elements

The system implementing the candidate Earth Explorer WATS mission has four main elements (described in detail in Chapter 6):

- the GNSS radio-navigation signal transmitters
- the instrumentation, carried on-board LEO spacecraft, divided into two specific payloads
  - the precision L-band receivers and related antennas
  - the precision X/K-band transmitters/receivers and related antennas
- the ground network of reference GNSS receivers
- the data collection and processing ground facilities.

5.1.1 Space Segment

A non-negligible part of the space infrastructure already exists, namely the GNSS radio-navigation satellite constellation. This ensures that the L-band active part of the GNSS radio occultation sounding will be available for several decades with progressively enhanced performance when the navigation system is augmented by the European Galileo system currently under development.

This mission can be implemented in steps, starting from a minimal configuration of a few LEO satellites, up to a full constellation (see Figure 5.1). Concerning the GNSS occultation part, even a couple of satellites would be able to provide a number of atmospheric profiles comparable to that obtained from the existing network of radiosondes, and with the observations well distributed over the entire Earth. Novel assimilation techniques enable the smooth integration of profile measurements and take advantage of their growing number to provide an improved accuracy of the atmospheric parameters.

The conclusions on possible implementation options for this mission are discussed below, according to increasing levels of usefulness and value, and are finally summarised.

The primary ingredient for adding value is increasing the size of the LEO satellite constellation. It should be kept in mind that the two payloads may have different requirements in terms of optimal orbits, and that they may exhibit different behaviour sin terms of added value when their number is increased. As it is assumed that each

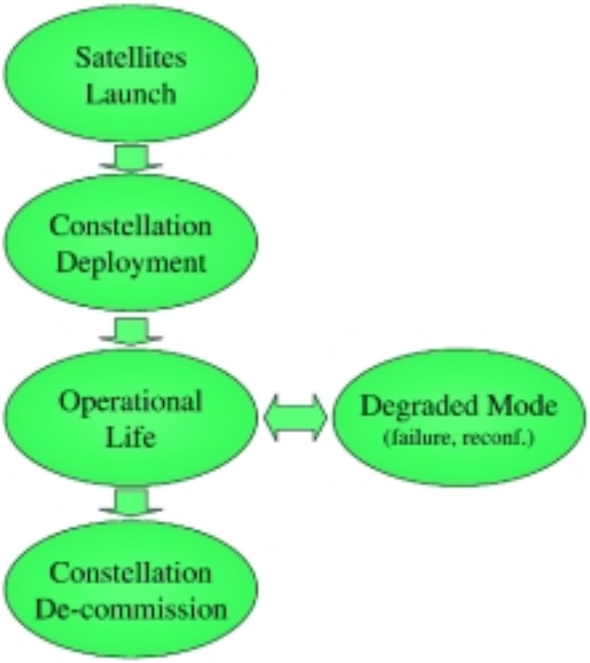

Figure 5.1: *System life phases.*

LEO satellite carries both instruments, the resulting constellation should be the result of a compromise.

– Concerning the L-band receivers, as long as the total number of satellites in the constellation is small, the addition of a new LEO is very valuable to the total system. More generally, if we consider WATS as well as the other missions providing the same kind of measurements (e.g. GRAS/MetOp), and assume both GPS and Galileo availability, a total of 12 satellites is considered an acceptable limit, after which we approach saturation in the incremental benefit of a new satellite to end user applications.

– For the X/K-band LEO–LEO inter-satellite link part, a minimal constellation is expanded in steps. As long as the constellation is sparsely populated, each transmitter/receiver subsequently added may be valuable in terms of improving the spatial/temporal resolution of the whole system. However, the added value brought by a new LEO satellite will vary with the selected orbit and with the current status of the constellation. As the LEO–LEO occultations are sparser than the GNSS–LEO occultations, their number will not be the saturating factor in terms of impact on applications.

For both instruments, a relevant aspect besides the mere number of transmitters/receivers is their distribution. The orbit selection strategy is based on the optimisation for balanced global and temporal coverage, systematically avoiding

sparser regions (both in space and local time), as seen in the definition of requirements (Chapter 4).

In summary, the choice of constellation results from a trade-off between such requirements as:

– a sufficient number of measurements
– an homogeneous global coverage, and
– an adequate sampling of the diurnal cycle,

and what is affordable for the Earth Explorer WATS mission. In addition, the choice of the constellation configuration has a non-negligible impact on the constraints put on the instruments. The analysis of constellation configuration is presented in Chapter 6.

5.1.2 Ground Segment

The ground segment for the WATS mission will comprise classical elements like command/control and data receiving stations and the mission operation and satellite control centre. It will also include elements specific to a radio occultation mission like geo-referenced ground stations (fiducial network) for clock error corrections as well as a data processing and archiving centre.

Figure 5.2 shows a possible implementation of the WATS operation, as well as how its measurements may be integrated into a retrieval scheme. Part of the ground segment should be dedicated to the preparation of WATS measurements for their assimilation together with other atmospheric and surface observations for re-analysis purposes.

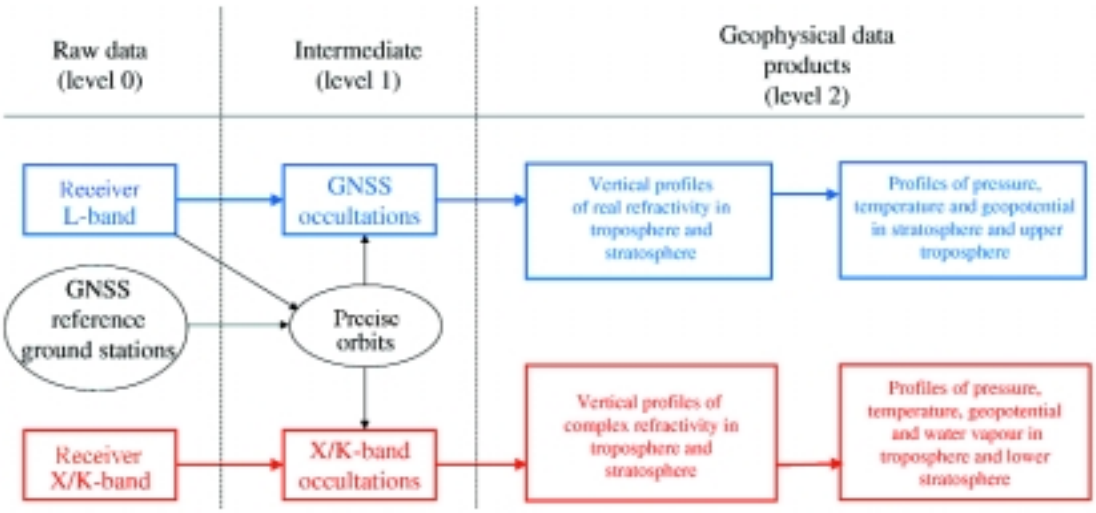

Figure 5.2: *Generation of WATS products.*

- Data receiving stations: The ground segment will include sufficient ground stations to ensure a timeliness of better than 3 hours for at least 30% of the data. These data should be made available in time for assimilation into atmosphere analysis models. The rest of the data will be provided within 30 days.
- The command and control stations could be combined with the data receiving stations, taking into account the management of several satellites operating simultaneously.
- The network of reference ground stations, needed for the Precise Orbit Determination of the LEO spacecraft will probably be identical to the stations selected for GRAS/MetOp. There has recently been a lot of development related to this network of fiducial stations.
- The Mission Operations and Satellite Control Element.
- The data processing and archiving centre, where raw data are processed and combined with auxiliary data to generate Level 2 products, could be the same centre as for GRAS/MetOp, provided that it is upgraded.

5.2 Contribution From/To Other Missions – Mission Spin-Offs

The Earth Explorer WATS mission will provide a major improvement in the determination of the three-dimensional structure of water vapour and temperature in the atmosphere. Due to the characteristics of the system, data with an excellent homogeneous coverage will be provided. It is also expected that the system will maintain its technical characteristics over a long period and thus be particularly suitable for determining the slow changes in the climate system, which are difficult to obtain from present observing systems. A particular advantage is the high vertical resolution in the upper troposphere and lower stratosphere.

5.2.1 Benefits for Other Missions

The operation of WATS will benefit several other missions planned in a similar time frame. It will greatly extend the measurements made by GRAS on MetOp and GPSOS on NPOESS. It will add complementary mass field measurements to the wind field measurements performed by ADM-Aeolus.

5.2.2 Spin-offs

In addition to the mission objectives, as defined in Chapter 3, the information provided by WATS will be critical to other fields of study.

Ionospheric Studies and Space Weather

Space Weather refers to the time-variable conditions in the space environment that may damage spaceborne or ground-based technological systems and, in the worst case,

endanger human health or life. One of the components of Space Weather is the ionosphere, composed of plasma layers exerting large influences on the propagation of radio waves, which are refracted, reflected, absorbed and distorted in various ways according to its highly dispersive properties. A good characterisation of the ionosphere is needed in several research fields:

- monitoring and modelling of electron density climatology
- ionospheric data assimilation advancement
- ionospheric weather prediction
- travelling ionospheric disturbances and ionospheric storm effects
- ionospheric currents and geomagnetic field analysis
- ionospheric irregularities and scintillations.

This characterisation of the ionosphere requires an adequate measurement of its critical parameters: the Total Electron Content (TEC) and the electron densities in various ionospheric layers.

The GNSS–LEO radio occultation technique yields the TEC along the occultation ray as a basic data product. In regimes with large electron density gradients, the ionospheric bending angle is also a useful basic parameter. Data assimilation (as in the lower atmosphere) can be performed and imaging and tomography products can be synthesised to yield 4-dimensional electron density distributions. Comparisons with other sources of TEC such as ionosonde measurements lead to an agreement to 10–20% at 1-sigma level (Haji et al., 1994; Haji and Romans, 1998). Ionospheric data as provided by the radio occultation technique are unique in their space/time coverage and vertical resolution for electron density measurements. The combination of a multi-LEO receiver constellation with ground-receiver network opens an entirely new era for ionospheric remote sensing of unprecedented resolution and quality.

Feedback on Attenuation Models

The atmospheric propagation delay caused by water vapour is one of the major sources of error in space geodetic techniques using radio waves. Radio telescopes and GPS receivers on the ground are used to study the dynamics of the Earth’s crust, such as motions at the boundaries of the tectonic plates and post-glacial isostatic adjustment (Haas et al., 2000; Milne et al., 2001). One method of independently assessing and studying the atmospheric error is to use ground-based microwave radiometry. The absolute measurement uncertainty of this method is in the models used for the attenuation coefficient of water vapour. Comparisons between radiometry and radiosonde data often result in just a scaling of line strengths since the radiometer observes an integrated quantity (Cruz-Pol et al., 1998).

The WATS mission will provide additional fundamental knowledge of the attenuation coefficient of water vapour. Although the WATS observations are integrated quantities, the different geometry (compared to ground-space paths) means that the effect of water vapour is sampled more homogeneously in terms of its temperature. Through the validation of the WATS data (Figure 5.3), using airplanes and/or highly accurate radiosondes, the absolute accuracy of the attenuation coefficient can be assessed at different heights and therefore the modelling of its temperature dependence can also be improved.

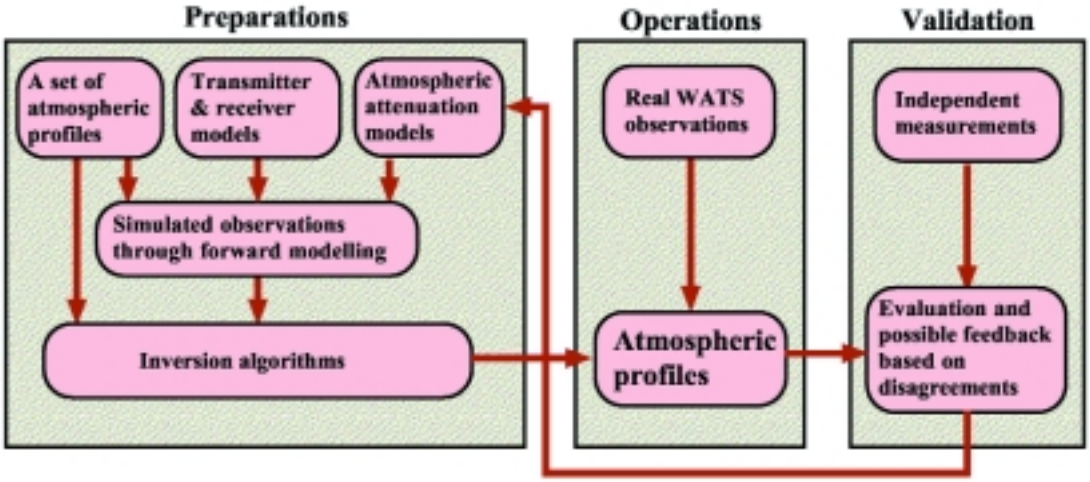

Figure 5.3: *Scheme for using WATS data to assess attenuation models.*

6 System Concept

6.1 Introduction

As described in Chapter 5, the proposed WATS system consists of:

A Space Segment composed of:

- A constellation of small satellites. The constellation can be optimised for temporal or spatial coverage or for observation performance, with different resulting characteristics. In all cases, occultation measurements are made between satellites at different altitudes (around 600 and 800 km). A constellation of 12 satellites is assumed as the baseline.
- Each satellite carries two instruments: (1) a GRAS+ receiver (i.e. an enhanced version of the GRAS instrument for MetOp) to observe the occultations of GNSS satellites (GPS/GLONASS/Galileo); (2) CALL, a LEO–LEO occultation instrument to observe the propagation of signals from other LEO satellites during their mutual rising and setting.

A Ground Segment composed of:

- A Command and Data Acquisition Element (CDAE), responsible for the TT&C links with the satellite and of the scientific data acquisition. Ground stations are preferably located at a high latitude (e.g. Svålbard or Kiruna).
- a ground network of GNSS reference receivers (fiducial stations) observing the GNSS satellite signals;
- A Mission Operations and Satellite Control Element (MSCE), for mission operations and constellation planning and control.
- A Processing and Archiving Element (PAE), responsible for further processing, archiving and quality control of the scientific data.
- A Science Data Centre (SDC).

Figure 6.1 summarises the system concept.

6.2 Observation Principles

Two types of observations will be produced by the WATS constellation after Level-1 processing:

– Refractivity profiles from radio occultation events exploiting the L-band signals of the global navigation satellite system (GNSS), based on GPS, GLONASS and the

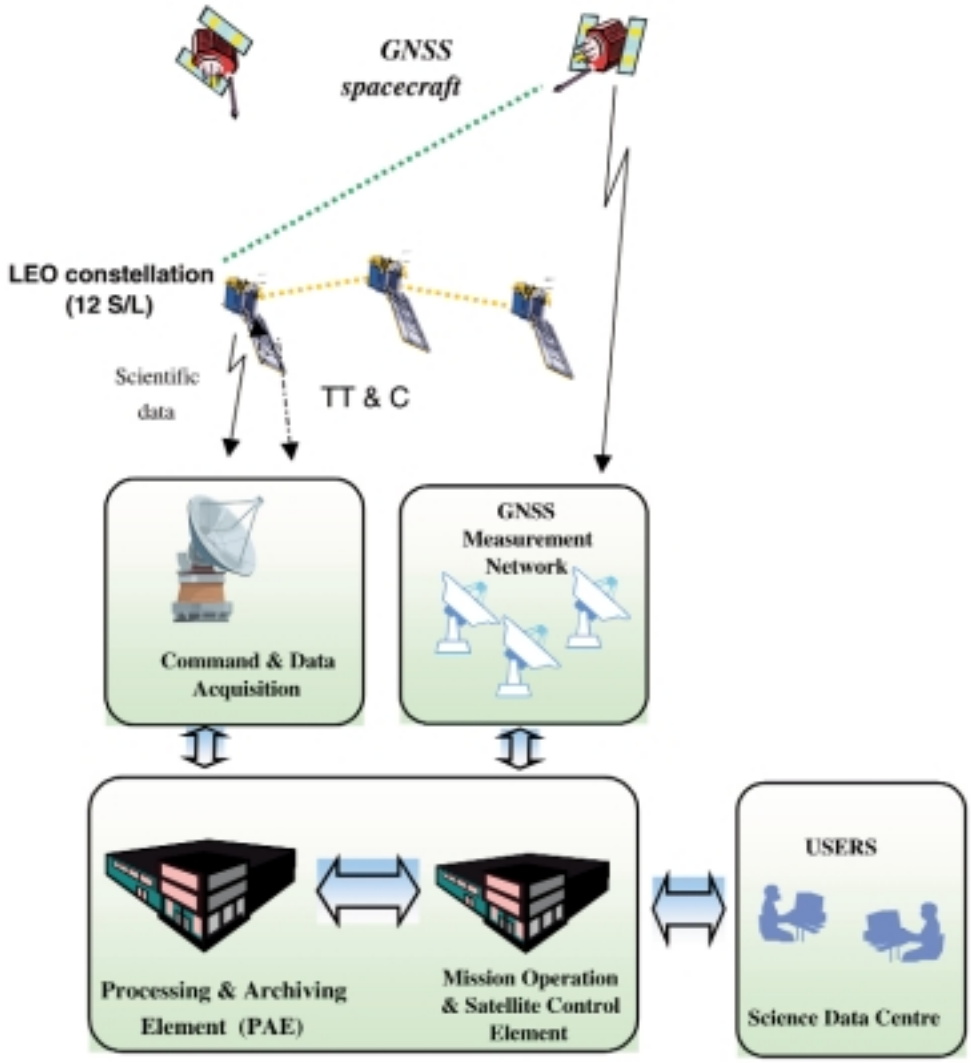

Figure 6.1: *WATS mission architecture overview.*

European Galileo system, for the derivation of temperature profiles in the stratosphere, the upper troposphere and, for dry regions, in the lower troposphere.

– Refractivity and absorption profiles by LEO–LEO cross-link occultation using X- and K-band signals emitted by each LEO of the WATS constellation for the derivation of water vapour absorption profiles.

LEO–LEO cross-links and GNSS–LEO data obtained by this active limb sounding method will provide new and complementary geophysical measurements, including precise global water vapour distribution from the surface to the tropopause and above.

6.2.1 GNSS–LEO Occultations

The GRAS+ instrument on the LEOs observes the dual-frequency signals from GNSS satellites while these signals are occultated by the atmosphere. The main data type is the carrier phase on the microwave links. After removal of the nominal carrier frequency, of the effects of the relative motion between the GNSS satellite and the LEO and of the effects of transmitter and receiver clock drifts, the residual phase is related to the bending of the radio waves in the atmosphere. By applying certain criteria for the variability of the refractive index of the propagation medium, these residual phase change measurements yield refractivity profiles. These can then be converted into profiles of other geophysical parameters, such as pressure and temperature. The GNSS–LEO radio occultation technique, the GRAS instrument and the results of in-orbit experiments have been extensively described in the scientific and technical literature (e.g. Melbourne et al., 1994; Kursinski et al., 1997; Loiselet et al., 2000; Silvestrin et al., 2000).

6.2.2 LEO–LEO X/K-Band Crosslinks

The amplitudes of the LEO–LEO crosslink signals are measured during the immersion of the rays in the atmosphere for both descending and ascending occultations. After subtracting amplitude variations caused by changes in range, by signal defocussing and by (monitored or predicted) instrument variations, the remaining attenuation is caused by absorption in the atmosphere. These amplitude variations are converted into attenuation profiles and in a subsequent step into profiles of water vapour content.

The use of several frequencies ensures a constant measurement quality for different altitudes, as explained is Section 2.4.3.

When liquid water is present, e.g. in the form of clouds, it can contribute to a large error in the measurement, since a single frequency measurement cannot discriminate between water in liquid and vapour states. The attenuations due to liquid and vapour have, however, very different frequency dependencies. With measurements made at several frequencies, the two contributions can be properly discriminated.

It is also necessary to measure the phase modulation on the X/K-band crosslinks caused by the atmosphere. This information provides, just as for normal GNSS–LEO occultation measurements, the ray tangent height of the occultation, in addition to the refractivity profiles. From the latter, precise temperature profiles can be derived.

The refractivity profiles are also used to derive the signal defocussing losses.

6.3 Summary of the Observation Requirements

The requirements for the WATS mission – as expressed in Chapter 4 – can be separated into two classes. On one hand, temporal and spatial sampling requirements, drive the mission and constellation design. On the other hand, the performance requirements on individual occultation events drive the instrument design.

Sampling Requirements

Number of GNSS–LEO occultation events	>6000 events per day, continuously over the mission lifetime. (>13 000 if Galileo is considered)
Number of LEO–LEO crosslink occultation events	>1000 events per day, continuously over the mission lifetime.
Geographical distribution	Geographical distribution of event locations per day as homogeneous as possible, i.e. aiming at a uniform density of events per unit area over the globe.
Temporal distribution	Local time (LT) distribution of event local times as homogeneous as possible, i.e. aiming at a uniform density of events per unit per local time. The coverage of all local times should be as rapid as possible.
Timeliness	About 30% of the data to be made available in near-real time. This data will be made available to NWP centres for assimilation, whereas all data will be made available for climate research.

Domain Covered

Minimum Vertical Atmospheric Domain to be covered by a LEO–LEO event	1–50 km
Minimum Vertical Atmospheric Domain to be covered by a GNSS–LEO event	1–90 km

Mission Lifetime

A mission lifetime of 5 years is baselined for the WATS mission.

Performance Requirements on the Individual Occultation Event

To maximise the scientific usefulness of occultation measurements, each occultation event should have certain qualities with respect to both its geometry and to the accuracy of the measurement. These are the main drivers for the instrument design.

Accuracy on the GNSS–LEO bending angle measurement (2 σ)	max (1 µrad, 0.4%)
Accuracy on the LEO–LEO bending angle measurement (2 σ)	max (1 µrad, 0.4%)
Relative accuracy of LEO–LEO attenuation profiles during one occultation (RMS)	0.025 dB over one occultation
Maximum horizontal atmospheric domain to be spanned during the vertical crossing of the 'Minimal Vertical Atmospheric Domain'	500 km (measured as the maximum distance travelled by the perigees of all rays)
Vertical resolution	0.5–1.0 km

6.4 Mission Analysis

The scientific requirements lead to the identification of two major mission design requirements:

– large number of occultations of suitable geometric quality (not too skewed) and homogeneously distributed in both space and time

– high (relative) accuracy for the LEO–LEO measurements during the occultation, and hence an adequate link budget to ensure the measurement resolution and good temporal stability of the system.

These considerations as well as the requirements expressed in Section 6.3 lead naturally to some choices for the mission. These options are listed in Table 6.1.

Constellation Concept

The selected concept is based on a constellation of microsatellites in LEO with several polar or near-polar orbital planes. The X/K-band occultations occur between satellites orbiting in the same or close orbital planes, at two different altitudes and in opposite directions. Since the occultations occur along velocity and anti-velocity directions (azimuth close to 0° and 180°):

• the antenna beam can be narrow, which ensures a better link budget

Requirement	Concept
Temporal sampling	Constellation with at least two orbital planes
Global coverage	High-inclination orbits
Good link budget for the LEO–LEO crosslink	High directivity for the antennas. The links should be between satellites in close orbital planes
Good stability of the system for the LEO–LEO crosslinks	Short duration of the occultations. Satellites flying in opposite directions
Small horizontal extension for the LEO–LEO link	Short duration of the occultations. Satellites flying in opposite directions
Homogeneous distribution of latitudes for the LEO–LEO crosslink events	Links between satellites at different altitudes
Homogeneous temporal distribution of events over a long time period	Non-Sun-synchronous orbits

Table 6.1: *Impact of the requirements on the mission design*

- the derived profiles are of high-quality (short occultation length and duration, small 'skew'); the short duration is an important advantage for the instrument since it relaxes requirements on the LEO–LEO link gain temporal stability of the transmit/receive equipment
- a good distribution of latitudes because of the different altitudes of the orbits.

The requirement to achieve good sampling of the local solar times can be fulfilled by taking advantage of the relative drift between the orbital planes and the local solar time at the sub-satellite point. This leads to a full 24-hour distribution of local times of acquisitions within a few months. For example, Figure 6.2 shows the evolution of three polar planes over one month with respect to the sub-satellite local time. In this particular case the local times of acquisition present a 2 hour drift after 1 month and the complete coverage of local times is obtained in two months.

At this stage, for a given number of satellites, several alternatives are applicable depending on the priorities put on the measurements:

– More orbital planes result in a more homogeneous distribution of local times of acquisition (over a long time period), at the cost of fewer occultations.
– Reducing the azimuthal beamwidth of the antennas improves the link budget (and thus the quality of the amplitude measurements), at the cost of fewer occultations.

The deployment strategy depends on the number of satellites and their relative positioning. It will be necessary to place satellites of different planes into orbit by individual launches to minimise the time to achieve a full constellation. Even then, the time between the first and the last launch of the constellation will mainly determine the build-up period. For the constellations being considered this is in the order of one year.

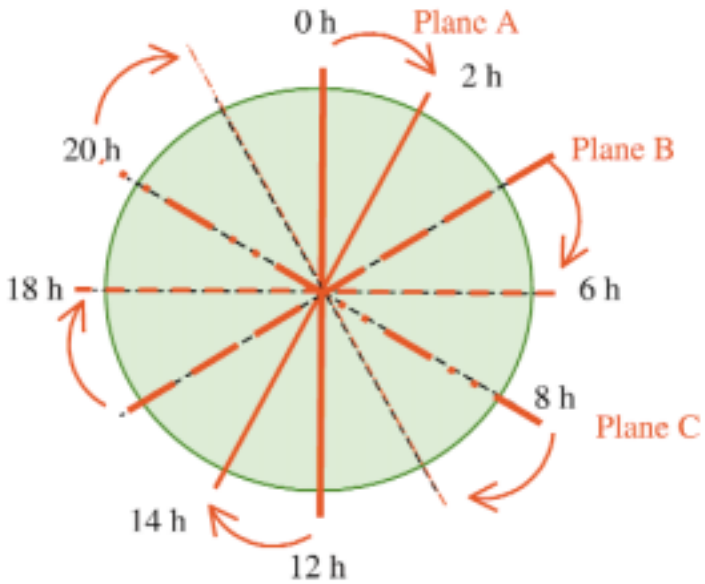

Figure 6.2: *Orbital drift and local time coverage (as seen from above the North Pole).*

Occultation measurements can already be made in the deployment phase, although with a reduced temporal and spatial coverage.

In the following sections, two concepts are presented to illustrate of these options. Each has the potential to be further optimised to achieve the best possible coverage performance.

Concept 1: Narrow azimuthal beam – Four orbital planes at I = 90°

In this concept, the constellation of LEO satellites consists of four polar orbital planes, separated by 90° in ascending node. The relative geometry of the planes is maintained over the satellite lifetime because of the exact polar inclination, implying that the planes do not precess. Each plane contains three satellites equally spaced along the orbit. The satellites in one plane and those on the plane with ascending node at 180° with respect to the first appear to be orbiting in opposite directions and are at different altitudes (approximately 600 and 800 km). Within each group, the satellites are spaced by 120°. The performance of this polar concept has been analysed for:

- LEO–LEO crosslinks with 7° fore and aft antennas azimuthal beamwidths, with occultations between satellites in the same plane at different altitudes (quasi-‘counter-rotating’).
- LEO–GNSS crosslinks with 45° fore and aft antennas azimuthal beamwidths.

The number of LEO–LEO occultations obtained per day is slightly above 1000. All events have a horizontal extension shorter than 500 km. The geographical repartition

of occultation events is quite homogeneous: in each latitude band, more than 20% of the 500 km× 500 km area elements are measured per day.

Figure 6.3 shows the spatial distribution of LEO–LEO occultation events for this concept.

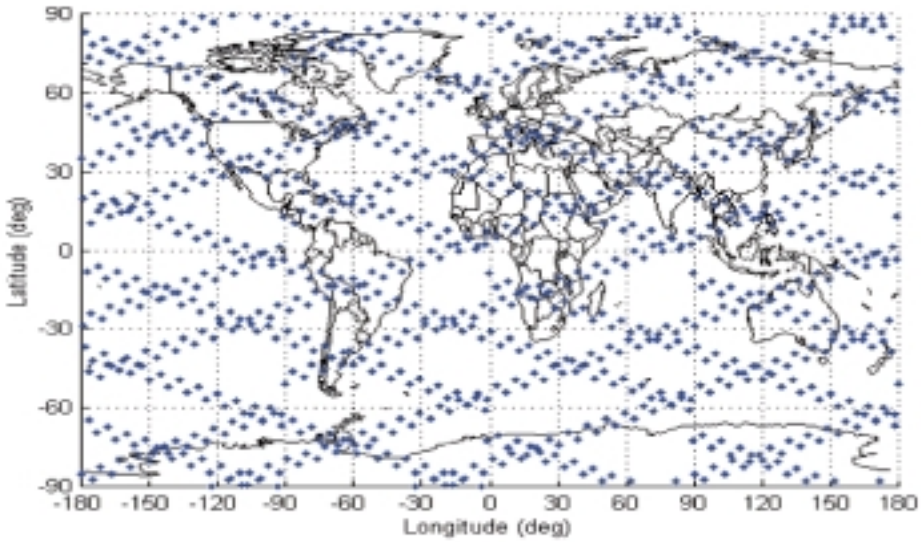

Figure 6.3: *Location of the LEO–LEO occultations (24-hour period) – Constellation Concept 1*

With this configuration, the local time of acquisition evolves in such a way that complete coverage of local times of acquisition is achieved in three months. Since occultations occur only among counter-orbiting satellites, each occultation is rather short, less than 30 s, an advantage for both the instrument and the geometry of the profiles. For the instrument, the narrow antenna beam (7° in azimuth) allows it to be designed for high directivity (~28 dB).

Figure 6.4 shows the GNSS–LEO occultation features for this constellation concept. The total number of occultations per day is approximately 7000 when 28 GPS satellites are taken into account, and grows to approximately 14 000 with the addition of the full Galileo constellation in orbit.

Concept 2: Wider azimuthal beam – Four orbital planes at I = 80°

In this alternative concept, the constellation is made up of four highly inclined orbital planes (around 80°), also separated by 90° in ascending node. Each plane contains three satellites equally spaced along the orbit. The satellites in one plane and those in the plane with ascending node at 180° with respect to the first are, to a good approximation,

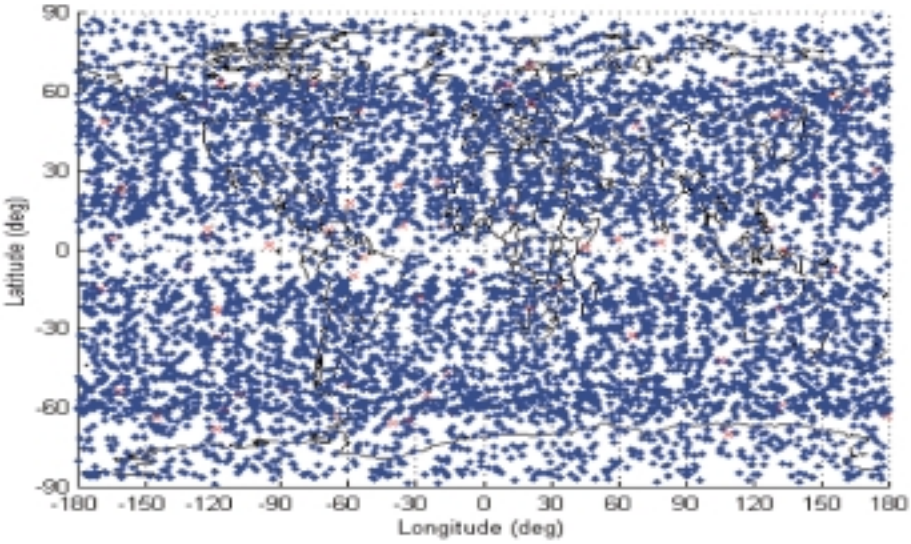

Figure 6.4: *Location of the GNSS–LEO occultations with GPS transmitters only (24-hour period) – Constellation Concept 1*

then orbiting in opposite directions at low and mid latitudes and are significantly separated only over the polar regions. The satellites are placed at different altitudes (approximately 650 and 850 km) and the inclinations of the orbits are slightly adjusted to produce a geometrically stable constellation, i.e. one in which the angular separation among planes is constant. The resulting geometry is presented in Figure 6.5.

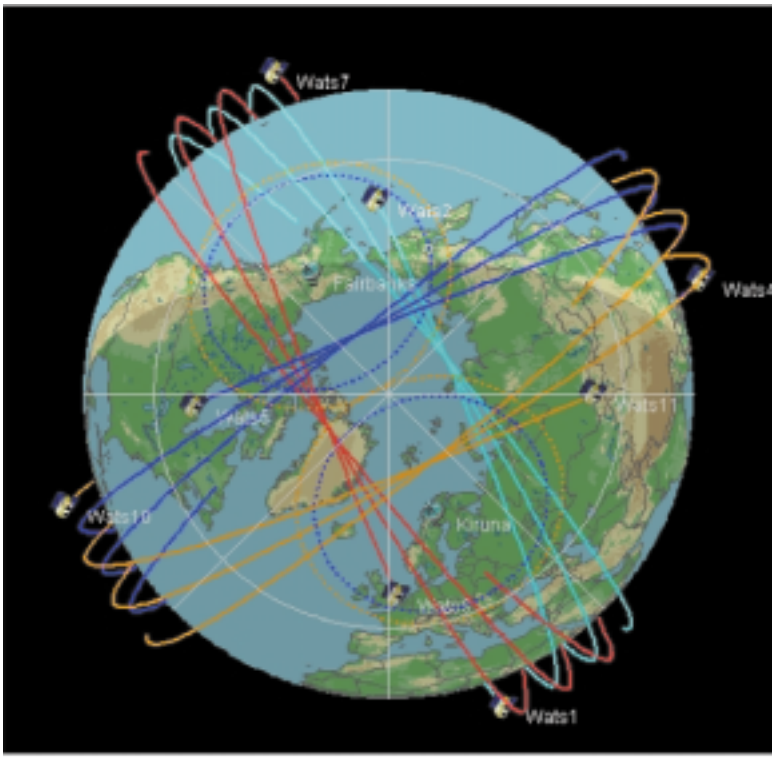

Figure 6.5: *Configuration for constellation Concept 2 as seen from above the North Pole.*

The performance of this concept has been analysed for:

- LEO–LEO crosslinks with 25° fore and aft antenna azimuthal beamwidths
- LEO–GNSS crosslinks with 45° fore and aft antenna azimuthal beamwidths

Also in this case the number of LEO–LEO occultations obtained per day is slightly above 1000 and all of them have a horizontal extension shorter than 500 km. The geographical repartition of occultation events is rather homogeneous, as shown in Figure 6.6. Complete coverage of local times for the LEO–LEO crosslinks is obtained in slightly more than one month. In this case the requirement for a greater azimuthal beamwidth imposes a larger antenna aperture than for concept 1 to achieve adequate directivity, which is more difficult to realise.

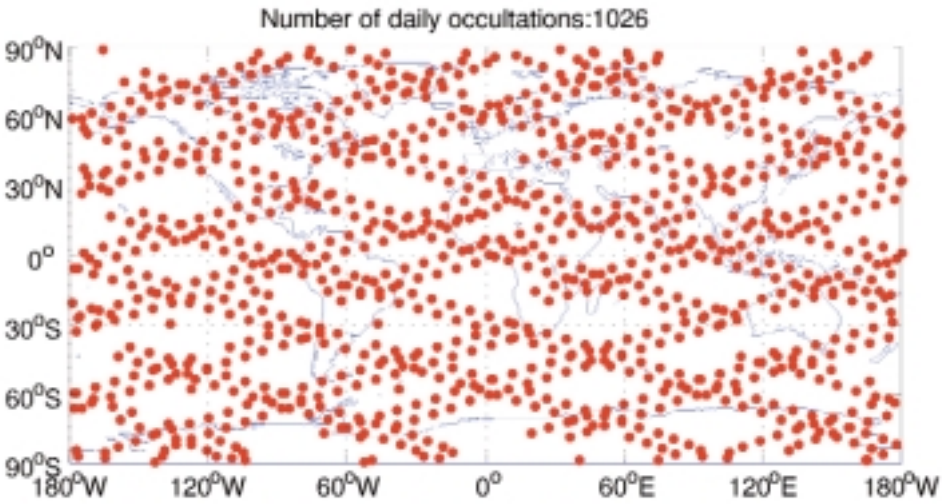

Figure 6.6: *Location of the LEO–LEO occultations (24-hour period) – Constellation Concept 2*

The corresponding number of GNSS–LEO occultations per day is approximately the same as in the previous concept.

The characteristics of the two concepts presented above are summarised in Table 6.2. Both concepts are presented here for a total number of 12 satellites in the constellation. However, the number of occultations directly depends implicitly on the total number of satellites in the constellation. Alternative constellation concepts can be proposed. For instance, a concept with six orbital planes leads to a faster sweep of local times and some decrease in the number of occultations, which can be compensated by increasing the number of satellites in the constellation, e.g. to 15 (which again provides about 1000 occultations per day). Another example is the use of planes at lower inclinations, leading however to the need for mechanical antenna pointing.

	Requirement	Concept 1 4 planes 90° inclination FOV ± 7°	Concept 2 4 planes ~80° inclination FOV ± 25°
Daily number of LEO–LEO occultation events	>1000	1044	1026
Spatial distribution of the LEO–LEO occultations	Homogeneous	Fairly homogeneous	Improved at mid-low latitudes
Temporal distribution of the LEO–LEO occultations	Local time (LT) distribution of event occurrence times per month as homogeneous as possible	A complete distribution of local times is obtained after 3 months	A complete distribution of local times is obtained after approximately 1 month
Daily number of GNSS–LEO occultations	>6000 (>13000)*	~7000 (GPS) (~14000 GPS + Galileo)	~7000 (GPS) (~14000 GPS + Galileo)

* Figures between parentheses assume GNSS = 28 GPS + 30 Galileo

Table 6.2: *Performances of the two constellation concepts.*

6.5 Payload Design

6.5.1 Payload Overview

In principle, two instruments are necessary to perform LEO–LEO and LEO–GNSS measurements, one operating in the X/K-band and the other in the L-band. The proposed payload design combines the functionality of these two instruments in such a way as to optimise performance and accommodation. It exploits the enhanced design of the new GNSS Receiver for Atmospheric Sounding (GRAS) being developed in the frame of the ACE mission (referred to as GRAS+), as outlined in Figure 6.7. In particular, the digital signal processing for both LEO–LEO and LEO–GNSS measurements is performed in the GRAS+. GRAS will collect measurements on MetOp of GPS signals received via fixed-beam antennas. GRAS+ features additional channels for antenna digital beam-forming and observation of all types of GNSS signals. These enhancements are supported by improved miniaturisation based on CMOS technology for both analogue and digital sections.

The LEO–LEO equipment (including receiver, transmitter, antenna arrays and the software embedded in GRAS+) will be referred to as the CALL (Crosslink Atmospheric LEO–LEO) instrument. It represents a new development, which however builds upon many technology developments, in particular from the areas of X- and K-band space telecommunications.

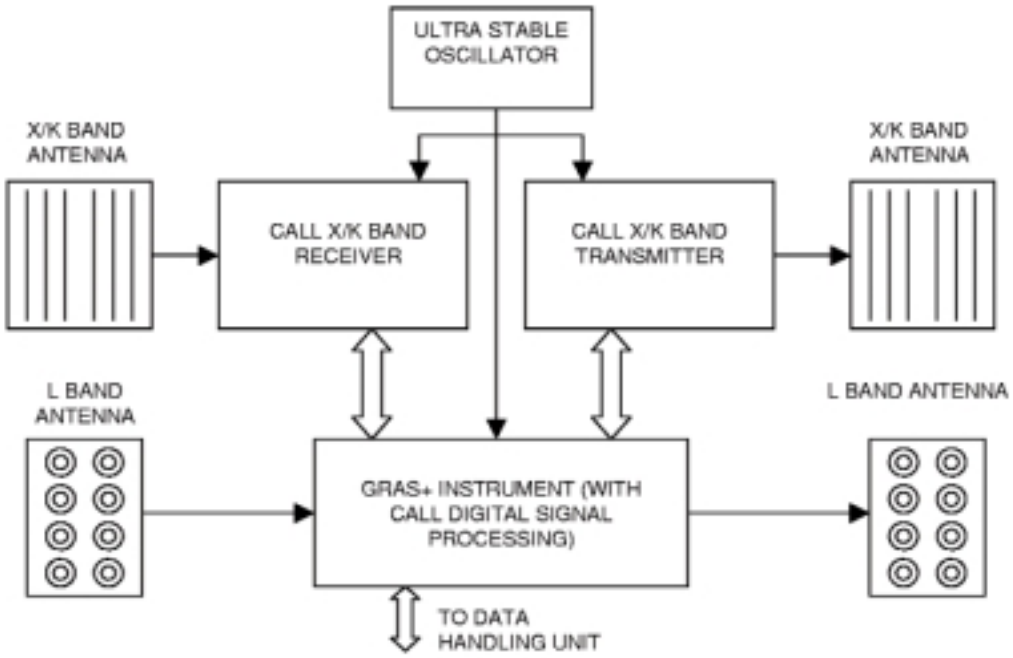

Figure 6.7: *Overall functional block diagram of the WATS payload (excluding GNSS navigation antenna).*

The receiving section of the CALL instrument provides low-noise amplification, filtering and frequency down-conversion of the X/K-band signals. The frequency-shifted signals are digitised before being applied to dedicated channels in the digital signal processing section of GRAS+. Here further processing takes place in a very similar way as for a GNSS–LEO signal, i.e. with the demodulation, acquisition and tracking processes realised by digital frequency-, phase- and delay-lock loops under software control. The local oscillator frequencies necessary for the down-conversion process as well as for the generation of X- and K-band signals are derived in a phase-coherent manner from an Ultra Stable Oscillator (USO), which is common to CALL and GRAS+. The overall stability of the USO signal is critical for the derivation of precise refractivity profiles, and hence of refractivity and temperature, from both CALL and GRAS+ data.

The transmitter section of the CALL instrument provides: generation of the three X/K-band carrier signals at approximately 10, 22 and 27 GHz; modulation of these carrier signals with a digital signal generated in GRAS+; and amplification of the resulting signals to a power of the order of 2 W each. Both receiver and transmitter are characterised by a very high stability of their transfer functions, in particular with respect to temperature and power supply fluctuations, which are both monitored for a possible on-ground calibration. The transmitter includes provisions for automatic level control.

LEO–LEO occultations occur in pairs, i.e. a rise event involving two specific satellites is always followed by a set event with the same satellites. In the baseline design, information is exchanged between the two LEO satellites during and between the rise/set events and includes the position of each of the satellites. In this way each satellite knows the precise position of all the counter-orbiting satellites in the same plane. This information supports the autonomous on-board operation of the instrument (e.g. to realise fast signal acquisition during a rise event). The same information can be up-loaded from the ground in a largely automated way.

6.5.2 GNSS–LEO Instrument (GRAS+)

Instrument Description

The GRAS+ instrument comprises two main subsystems: the GRAS antenna set and the GRAS electronic unit, as shown in Figure 6.8. The GRAS electronic subsystem is derived from the GRAS equipment (Loiselet et al., 2000; Silvestrin et al., 2000) with numerous technical improvements. These include: a large number of acquisition and tracking channels, capable of processing signals from all available satellite navigation systems; support for digital beam-forming; reduction of power, mass and volume with respect to GRAS for MetOp.

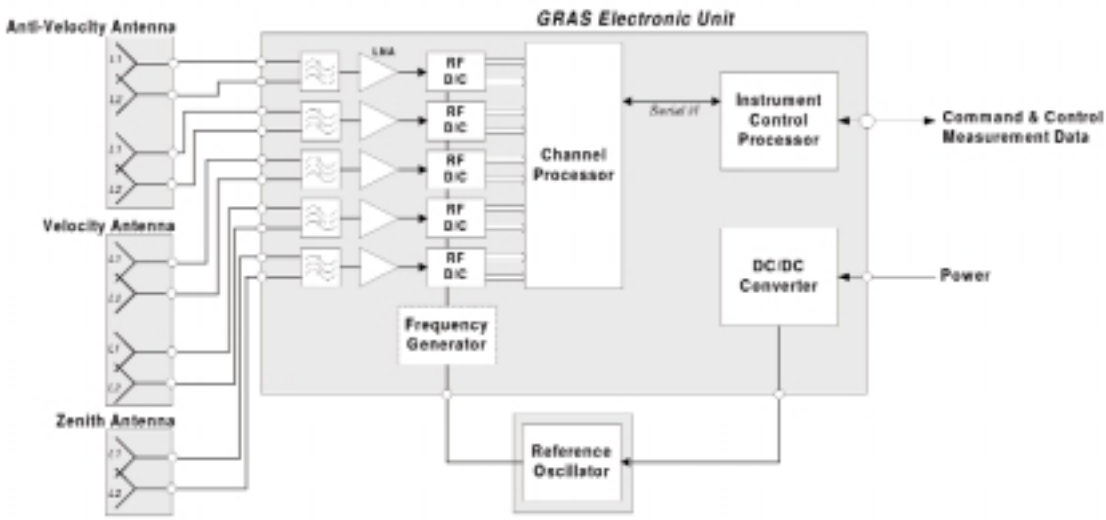

Figure 6.8: *Functional block diagram of the GRAS+ instrument.*

The GRAS+ antenna set comprises three antennas: two for occultation measurements, pointed in the velocity and anti-velocity directions of the spacecraft, and a third antenna pointed towards the zenith. The velocity and anti-velocity antennas track GNSS signals from rising and setting satellites, respectively. The third antenna is a wide-coverage

antenna for the reception of non-occulted GNSS signals, so as to compute the real-time position and velocity of the LEO satellite and of the GNSS constellations. Such computation is performed both on board and on the ground, in the latter case in a very precise way with the support of other ground tracking data from a global receiver network.

The GRAS+ fore and aft antennas and the smaller zenith antenna are shown in Figure 6.13. The antennas are arrays of 2×4 elements. Miniaturisation of the occultation antennas with respect to the MetOp GRAS antennas is achieved by digital beam-forming. The beam-forming is performed at baseband by phase shifting prior to combination of the (digitised) signals from each 1×4 column in the array. The arrays are 60 cm high and 36 cm wide and accommodated so that the boresight direction of the antenna elements is pointed towards the Earth's limb. The resulting patterns for the L2 (1227 MHz) frequency are shown in Figure 6.9. The baseline coverage from the two-occultation antennas is shown in Figure 6.10.

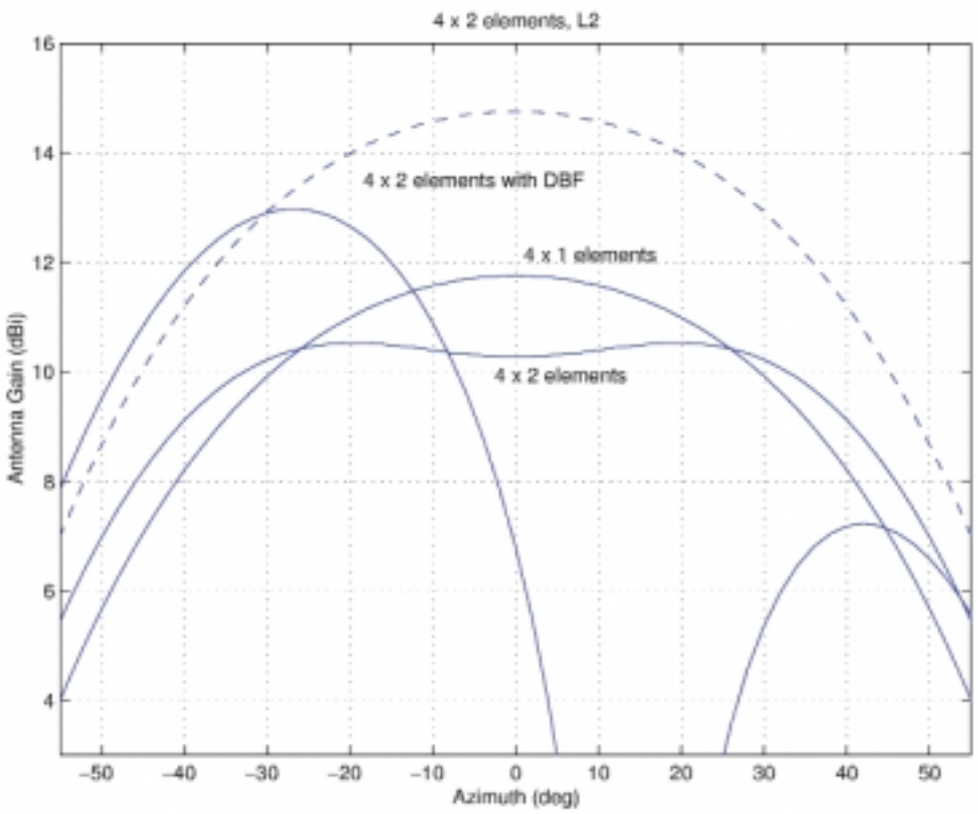

Figure 6.9: *Antenna gain patterns at frequency L2 for three different antenna concepts, after ohmic losses of 1.5 dB and a design margin of 0.5 dB. For digital beam-forming, the plot shows one example of beam steering to maximise the gain at -30° azimuth angle (solid line), as well as the peak gain envelope for different beam steering angles (dashed line).*

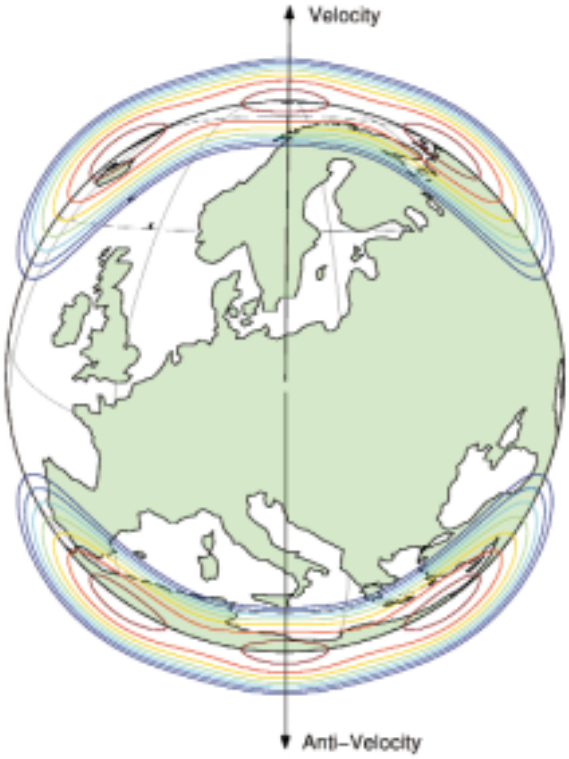

Figure 6.10: *Coverage of the GNSS–LEO occultation antennas, designed to follow the Earth's horizon. The coverage of the LEO–LEO antenna is designed in a similar way, though with a reduced azimuthal extension. The peak gain is 11 dB.*

The digital signal processing section of GRAS+ employs a new generation of GNSS application-specific integrated circuits (ASICs) with on-chip processors for acquisition, tracking and demodulation of received GNSS signals (one processor per tracked satellite). This reduces the computation load on the instrument control processor, which can then also be used for processing the received X- and K-band signals. Being modulated with a GPS-like (or Galileo-like) code, such signals are also acquired, tracked and demodulated in the ASICs.

The power consumption and mass of the GRAS+ instrument are around 20 W and 4 kg, respectively. The mean data rate is 40 kbit/s.

Instrument Performance

The performance of the GRAS+ instrument is based on results obtained in the studies for ACE and MetOp. The main parameters are summarised in Table 6.3.

Measurement	Performance
Bending angle	<0.46 µrad RMS at 30 km altitude (critical case)
Impact parameter	<6 m accuracy in altitude
Altitude measurement range	1 to 80 km

Table 6.3: *Main performance parameters of GRAS+.*

6.5.2 LEO–LEO Instrument (CALL)

Instrument Description

The X- and K-band signal transmission and reception of CALL are performed by two identical arrays of slotted waveguide antennas, assumed to be 50 cm long, which corresponds to 17, 28 and 38 wavelengths for 10, 17 and 23 GHz, respectively. The length of the antenna determines the quality of possible beam shaping. Each antenna will work in one of the frequency bands at approximately 10, 17 and 23 GHz (it should be noted that a small adjustment for the value of the 10 GHz frequency may be required to comply with regulations). The fixed antenna patterns are designed for maximum gain in the Earth limb direction. The elevation beam-width of each antenna is 3°, which allows for signal tracking from the surface to above 100 km. The directivity for all bands is around 28 dB when the azimuth beamwidth is limited to ± 7°, as shown in Figure 6.11 for the 10 GHz signal, and around 22 dB when the azimuth beamwidth is ± 25°. The effects of variations in the directivity are discussed below in relation to instrument performance. Alternative antenna concepts can also be considered, such as horn antennas or mechanical steering of very directive antennas.

The CALL transmitter consists of three transmitter sections, one for each frequency. The frequency plan is optimised to reduce the number of local oscillator frequencies used in the up-conversion process and to avoid interfering with the CALL receiver. The present baseline for the modulation is to use the same scheme as for GPS, i.e. the so-called C/A pseudo-random code at a rate of 1.023 MHz. This choice will be revised in Phase-A when the signal definition for Galileo has been completed. The C/A digital signal is generated in one of the ASICs of GRAS+. The information on the LEO–LEO links will be transmitted in a compressed format at a low bit rate to avoid constraining the coherent integration time on the receiving side.

Each transmitter channel design is optimised for high stability. For instance, filter specifications and technologies are driven by the need to minimise sensitivity to temperature variations. Each stage is decoupled from the next by means of isolators to avoid the impacts of mismatch variations on the overall gain stability. The final stage is a solid-state power amplifier with an output power of 2 W and efficiency of 25%. Specific thermal conditioning of this amplifier is included so that it can be switched off

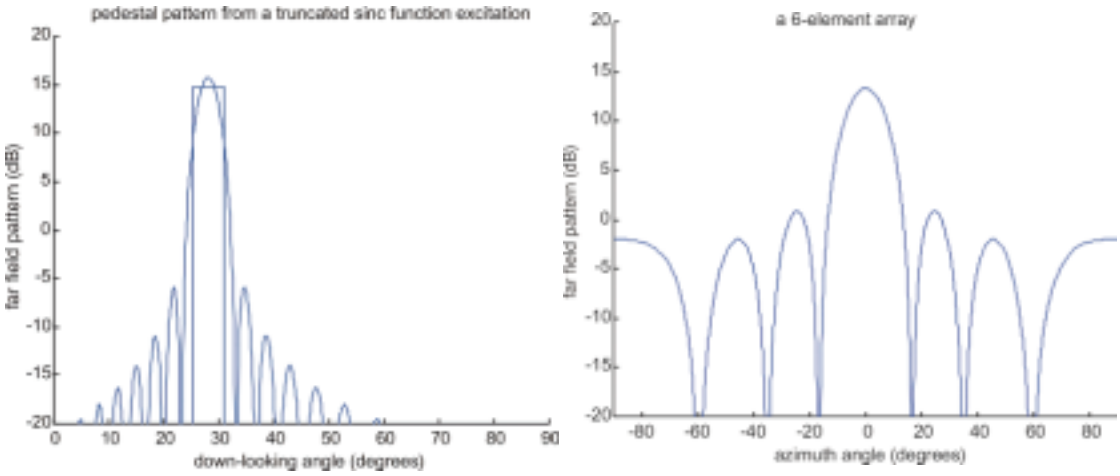

Figure 6.11: *Elevation (left) and azimuth (right) patterns at 10 GHz of the CALL slotted waveguide antenna (six-element array for azimuth). The partial directivities are 15.0 dB and 13.4 dB, respectively, for a total directivity of 28.4 dB.*

between occultation events to save power. In order to improve the overall stability performance, an automatic level control system is included, consisting of a coupler driving an adjustable attenuator placed in an early stage of the transmitter chain. Experience with previously flown space equipment (not optimised for stability) shows that such a system improves stability to 0.01 dB/K or better throughout the operating temperature range. This circuitry will be optimised for WATS and thermal control will anyway be applied such that hardware temperature variations do not exceed a few tenths of a degree Kelvin when the transmitter is active. The estimated power consumption and mass of the CALL transmitter are 24 W and 2 kg, respectively.

The design of the CALL receiver, also composed of three sections (with inputs at 10, 17 and 23 GHz), follows very similar principles, with priority given to achieving high gain stability for the duration of the occultation. Filter and amplifier design are optimised to reduce the sensitivity of existing components, which is nevertheless already good at 0.01 dB/K or less. Isolators are used, as for the transmitter. The design is made less critical by the fact that linearity is not an issue. Indeed the input signal is dominated by noise, thanks to the pseudo-random modulation. The equipment is thermally controlled to a few tenths of a degree Kelvin over the duration of an occultation. The receiver has three digital outputs, providing signals at the correct intermediate frequency for further processing in the GRAS+ ASICs. The receiver system noise temperature is conservatively estimated to range from ~270 K at 10 GHz to ~370 K at 23 GHz. The estimated power consumption and mass are 10 W and 2.5 kg, respectively.

On-ground characterisation of both transmitter and receiver response versus temperature is foreseen to generate precise models for correcting measurement data during processing to Level-1b. Temperature of all CALL equipment is monitored to 0.1 K or better.

Instrument Performance

The LEO–LEO occultation instrument provides the carrier phase and the amplitude of each of the three signals at 10, 17 and 23 GHz. The carrier phase measurements are used to determine refractivity and temperature profiles from about 60 km to the surface. The error analysis is very similar to that of the LEO–GNSS occultation case, with the advantage that now most error terms are greatly reduced. Thanks mainly to the excellent SNR and to the smaller wavelength of X/K-band signals, the additional propagation path due to refraction is measured with a precision better than 0.1 mm down to 1–2 km height. This, together with the greatly reduced effects of the ionosphere with respect to the L-band occultations, allows one to retrieve temperature profiles accurate to better than 1 K up to at least 60 km.

The main errors that affect the amplitude measurements are the thermal noise, caused by the finite SNR in the bandwidth of interest, and the overall stability of the system. The transmitted power and the antenna directivities have been selected so as to achieve adequate SNR for the three microwave links and to ensure that the amplitude measurement precision is within the required 0.025 dB RMS in an effective bandwidth consistent with the required vertical resolution. Since the immersion rate of the links varies considerably during an occultation, the effective bandwidth taken into account in the error budgets is also varying with height. As noted before, the transmitted RF power is 2 W and the antenna directivity is ~28 dB for all frequencies. If necessary, the power can be somewhat increased for one or two of the frequencies. With the above parameters and above 15 km, the carrier-to-noise power spectral density ranges from more than 70 dBHz for the 10 GHz link to more than 65 dBHz for the 23 GHz link. This ensures an SNR around 60 dB, which is very favourable. Below 15 km, in the presence of attenuation by absorption and defocussing, the SNR remains always better than 50 dB down to 2 km or less on at least two links, as needed to meet the amplitude measurement requirements.

The overall stability depends on various items, but mainly on the transmitter/receiver stability and on the effect of antenna pattern variations. It is worth recalling that only variations over a period of 15 – 20 s matter, since this is the duration of the critical part of a LEO–LEO occultation. For the transmitter and receiver, the expected gain stability for the combination of receiver and transmitter over such time interval is better than 0.015 dB (2 σ). For the antenna, one has to consider the variations in the gain as the ray path directions change (in the antenna frame and particularly in the elevation plane where antenna pattern changes are steeper). There are various ways to reduce these effects:

1) Considering that during the critical part of an occultation the ray path direction change in the elevation plane is very small (about 1°) and that such variations can be well determined on-board each satellite, it is possible for the satellite to perform a small pitch slew manoeuvre such that the signal direction is always kept at the same elevation angle in the antenna frame. The residual error after this compensation depends on the attitude control accuracy over 20 s, which can be 0.02° or better. Antenna pattern errors are then expected to be below 0.02 dB (2 σ).
2) An alternative method consists of calibrating the critical part of the antenna pattern by periodically de-pointing the antenna and deriving a very precise model of the pattern during calibration periods. The expected accuracy of this method is 0.025 dB (2 σ).

Possible temporal trends in the antenna gain patterns can be corrected by means of observations taken while the microwave links have just come out of the atmosphere (or are in a well-characterised part of it). Such observations allow to model pattern variations and to apply the model to the actual occultation measurements. In this way, the amplitude variations induced by antenna thermal variations in the critical measurement time can be filtered out.

The application of the system performance parameters outlined above to an average mid-latitude atmosphere leads to the following results, to be compared with the scientific requirements as expressed in Chapter 4. Figure 6.12 presents anestimation of the accuracy of water vapour retrieval as a function of altitude, in specific humidity units, derived from a simple sensitivity analysis. An average homogeneous atmosphere was considered, and multipath as well as cloud effects were disregarded. However, this indicates the potential of the technique for accurate measurement of water vapour.

6.6 Spacecraft

6.6.1 Satellite Configuration

The proposed WATS mission is based on a constellation of 12 micro-satellites. The following challenges have to be addressed in the design of these micro-satellites:

- a payload with relatively high power consumption
- demanding pointing stability requirements
- demanding thermal control requirements for the payload
- specific antenna accommodation (size, fields of view, etc.)
- overall stowed configuration for launch, trying to minimise the launch costs.

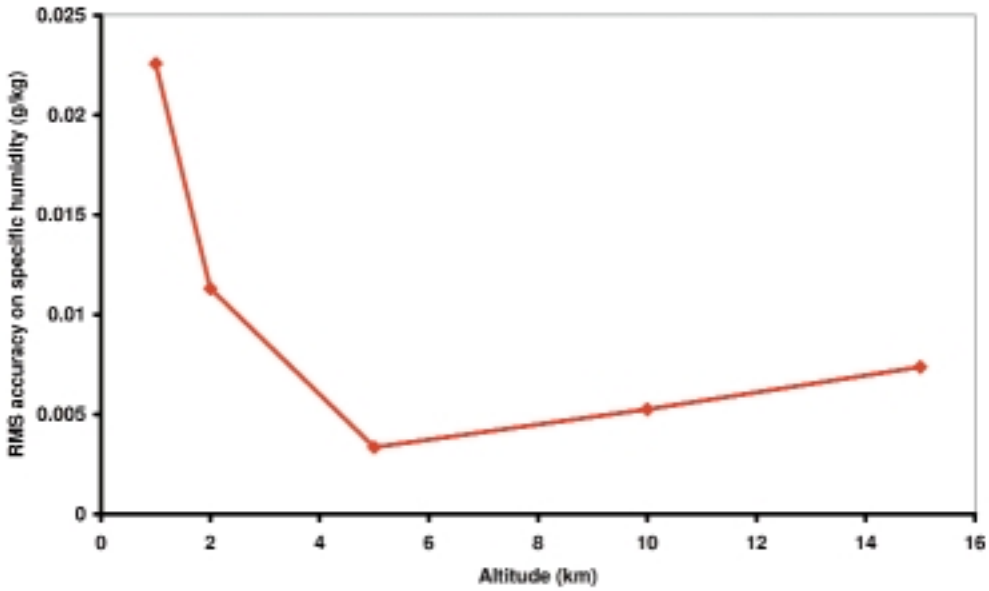

Figure 6.12: *Estimated accuracy of the water-vapour retrieval as a function of altitude for nominal atmosphere.*

In terms of system configuration, two choices are possible:

– Completely identical satellites, with both LEO–LEO transmitter and receiver on-board, which facilitates the design, test and interchangeability of the individual elements, at the cost of increased complexity.

– Satellites with either a LEO–LEO transmitter or receiver only, with the corresponding positive impact on the power and weight budgets.

6.6.2 Proposed Concept

Several configurations satisfy the mission requirements. Figure 6.13 shows two potential spacecraft configurations applicable to the WATS micro-satellite.

Configuration 1 is based on:

- solar panels on one rotating wing
- a 180° yaw slew twice per year to maintain thermal control under the best conditions
- a launch baseline of 4 DNEPR-1 launches (4 launches of 3 satellites).

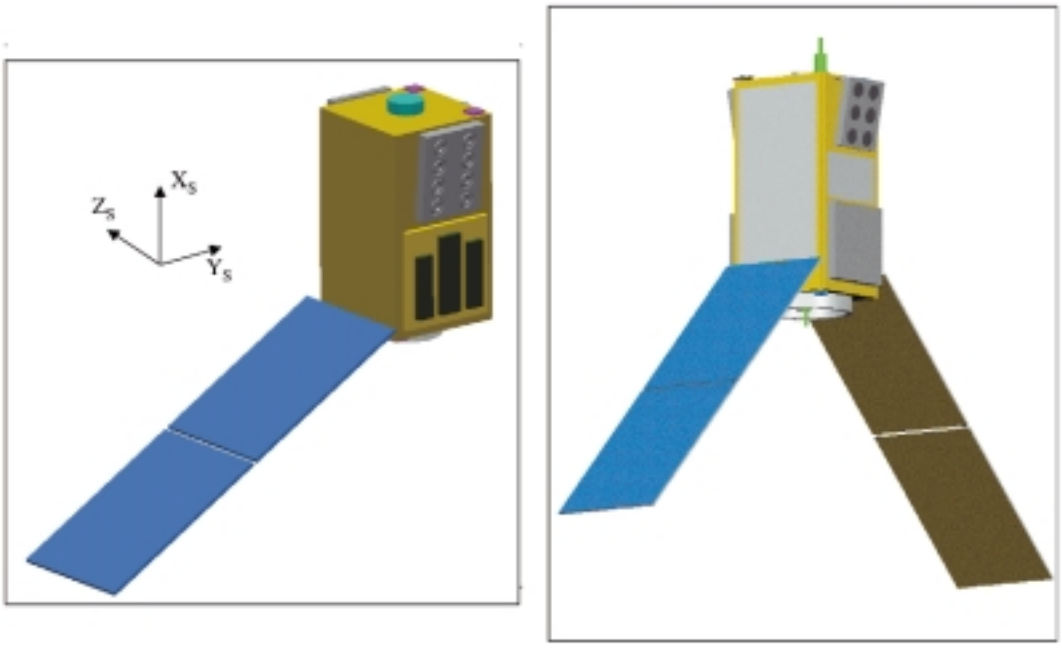

Figure 6.13: *Overview of WATS deployed configuration – Configuration 1 (left) and Configuration 2 (right)*

Configuration 2 is based on:

- solar panels on two fixed wings
- a launch baseline of 4 Rockot launches (1 launch of 3 satellites per plane).

Configuration 1: One-wing solar panel with one degree of freedom

In this concept, all of the WATS micro-satellites are identical. The CALL instrument consists of a receiving part and an emitting part. The related antennas are on a dedicated satellite face. The WATS orbit is a polar orbit, which implies a variable thermal environment for the satellite. In order to accommodate this constraint and to improve performance, all of the satellites will perform a 180° yaw slew each time the Sun crosses the orbit plane. This occurs twice per year and does not have a significant impact on the mission availability. This operation allows one to maintain one satellite face always in the anti-Sun direction, thus guaranteeing a stable thermal environment, and also to have only 1 wing for the solar array.

Figure 6.14 gives the main dimensions of the proposed WATS spacecraft.

The spacecraft structure is composed of a platform part and a payload part. Some payload antennas are to be accommodated on platform panels, where they will be mounted on a dedicated supporting panel.

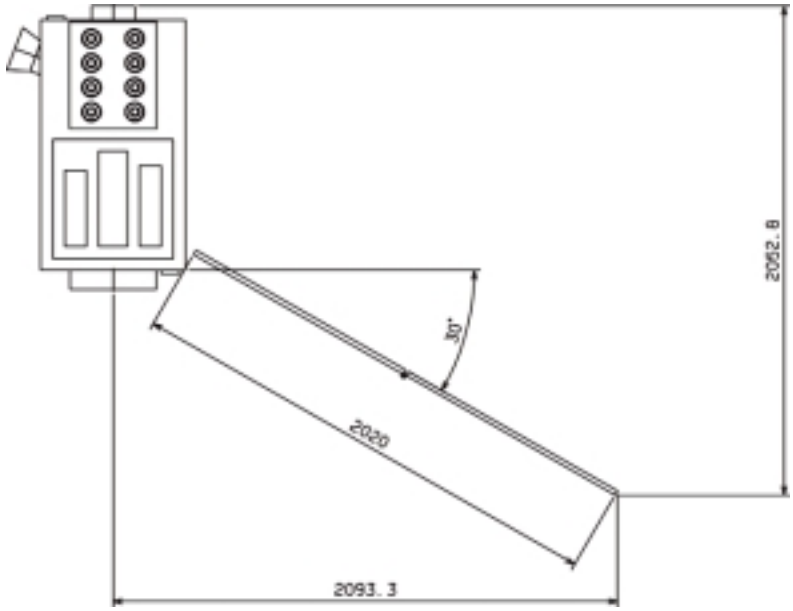

Figure 6.14: *Spacecraft dimensions (in mm) in deployed configuration – Configuration 1.*

In nominal operation phases, the thermal control baseline architecture will use passive means only. In addition, active thermal control based on thermistors and heaters will be provided for the sensitive payload units.

Thanks to the proposed operations concept and solar array accommodation, the +Ys panel will never see the Sun. Consequently, the battery and the payload units sensitive to thermal environment will be accommodated on this panel.

The power system features a GaAs solar array with one deployable wing providing power to the satellite through a Solar Array Drive Mechanism (SADM), a Li-ion 17.6 Ah battery, and a Power Control and Distribution Unit (PCDU).

Each solar panel is 0.7 m^2 (1.4 m^2 overall surface).

The attitude determination is based on three coarse Sun sensors, used for the acquisition phase and in the Sun-pointing safe hold modes, a three-axis magnetometer and a star tracker for precise attitude measurement. Three gyros provide attitude information during manoeuvres.

The attitude control is based on the use of up to four reaction wheels (for attitude control and manoeuvrability) and three magnetotorquers for wheel unloading or for coarse attitude control. Orbit control capacity is provided by a hydrazine propulsion system for modifying the initial orbit and controlling and maintaining the orbit. The

resulting pointing performance is compliant with the stability required during an occultation event.

As a deployment strategy based on nodal drift is not feasible in polar orbits, the number of launches is equal to the number of orbital planes for polar constellations.

Three satellites at a time can be launched directly into their final plane. This is followed by a spread manoeuvre to reach a 120° anomaly difference within one plane.

The concept therefore requires two launches of three satellites directly to 600 km, and two launches of three satellites directly to 800 km.

The proposed baseline launcher is DNEPR-1. Alternative launch strategies with the Rockot launcher can also be envisaged.

Configuration 2: Two fixed solar panels

The satellite is box shaped, with the side walls serving as the primary structure. The GRAS+ and CALL occultation antennas are fixed on the velocity and antivelocity sides. The solar arrays (two wings with two panels each) are stowed on the lateral side of the platform. Once deployed, they do not obstruct the satellite walls, which can then be used as radiators. The solar array orientation and dimensions are such that they will have a minimum impact on the CALL antenna patterns. The proposed solar array design is compatible with a mean orbital power demand of about 190 W.

Two S-band antennas are implemented on the zenith and nadir sides of the satellite, in order to provide omnidirectional coverage. Earth sensors are implemented on the nadir side within the launcher interface ring and with three different viewing directions. Sun sensors are mounted on both nadir and zenith floors.

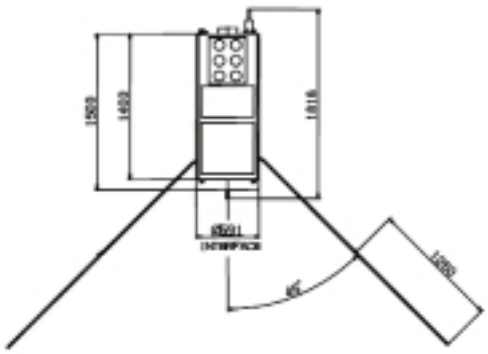

Figure 6.15: *Spacecraft dimensions (mm) in deployed configuration – Configuration 2.*

Thrusters are mounted on each corner of the antivelocity wall, so as to allow pure thrust along the velocity vector. Negative thrust is achieved by rotating the spacecraft by 180° around the Z-axis.

Passive thermal control is implemented in normal mode operations. External surfaces are protected by MLI, except for specific radiating areas. The thermal homogeneity inside the cavity is then maximised and the mean temperature is set between 0 and 10 °C.

The electrical power is generated by GaAs cells with an area of 3.4 m^2. The fixed solar panels are canted by 45°, to ensure power generation and a balanced energy budget at all local times. During eclipses, the required power is supplied by a 16 Ah Li-Ion battery.

The satellite attitude is three-axis controlled thanks to the attitude sensors (gyroscopes, star tracker) and to the set of four 0.4 Nms reaction wheels mounted in a tetrahedral configuration. Three magnetic torquer bars are used for wheel off-loading. Four 1 N hydrazine thrusters located on the anti-velocity side of the satellite provide pure thrust and are only used for orbit correction and maintenance manoeuvres.

GPS data acquired by GRAS+ are used for autonomous on-board orbit determination and propagation.

The performance of the WATS AOCS supports the CALL payload performance (the GRAS+ performance is less stringent and included therein).

The baseline is to launch the satellites in batches of three to the final operational orbital plane, leading to four launches.

Rockot is currently the best candidate for launching WATS. Its fairing diameter and height are compatible with the current satellite definition, and its launch mass capability (above 1500 kg at 650 km, above 1400 kg at 850 km) provides large margins.

6.6.3 Pointing/AOCS

Both concepts have similar AOCS performances, which are summarised in Table 6.4.

Average error between assumed pointing direction and actual pointing	< 0.2°
Pointing drift over 20 s	< 0.02°
Pointing knowledge over 20 s	< 0.01° in the bandwidth 0.05 Hz to 2 Hz

Table 6.4: *Performances of WATS AOCS.*

6.6.4 Budgets

The two concepts are comparable in terms of mass and power. The respective budgets are summarised in Tables 6.5 and 6.6.

Element	Mass (kg)
Payload	20
Platform	100
Miscellaneous (launch adaptor, balancing)	10
Margins 10%	13
Total dry mass	***143***
Fuel	5
Total launch mass	***148***

Table 6.5: *Satellite mass budget.*

Element	Approximate Power Consumption (W) (orbital average)
Payload	50
Platform	50
Margins	10
Total	***110***

Table 6.6: *Satellite power budget.*

6.7 Ground Segment and Data Processing

6.7.1 General Architecture

The key requirement of the WATS ground segment is to deliver the Level-1 products to the Science Data Processing Centre within 2–3 hours for at least 30% of the measurement data, and to manage the constellation.

The overall ground segment architecture is composed of the following items:

- the data receiving and command ground stations, which ensures communication with the spacecraft
- the control centre, which can be partly combined with the data receiving stations

- the reference ground stations (called Ground Fiducial stations), used for correcting clock errors on GNSS signals, in order to achieve Precise Orbit Determination for the WATS satellites
- the data processing and archiving centre and the science data centre, where all Level-0 data are processed and combined with data from the ground fiducial network to retrieve temperature and humidity profiles. The science data centre can also be dedicated to the preparation of WATS measurements for their assimilation into NWP systems together with other atmospheric and surface observations.

The resulting architecture is illustrated in Figure 6.16.

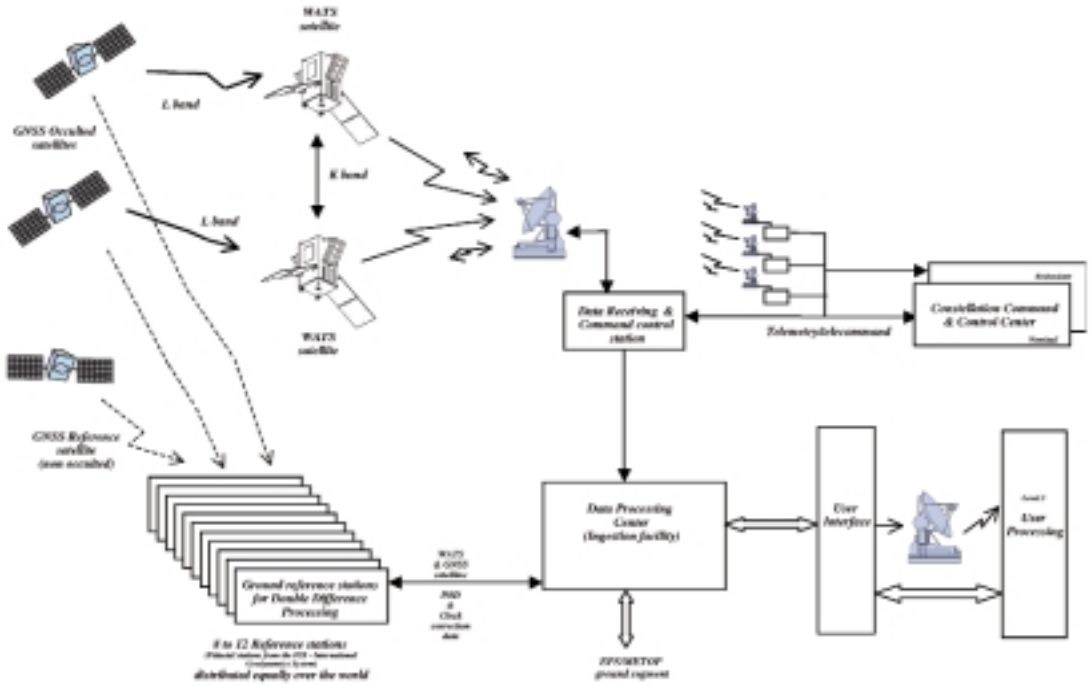

Figure 6.16: *WATS ground segment overall architecture.*

6.7.2 Data Reception and Command Ground Stations

The use of a single location at Svålbard for the data reception and command ground stations achieves the required timeliness of data delivery. Between 70% (Concept 2) and almost 100% (Concept 1) of all satellite passes are accessible. Because of the multiple satellites in range of the station, two antennas are required to meet the overall data delivery requirements.

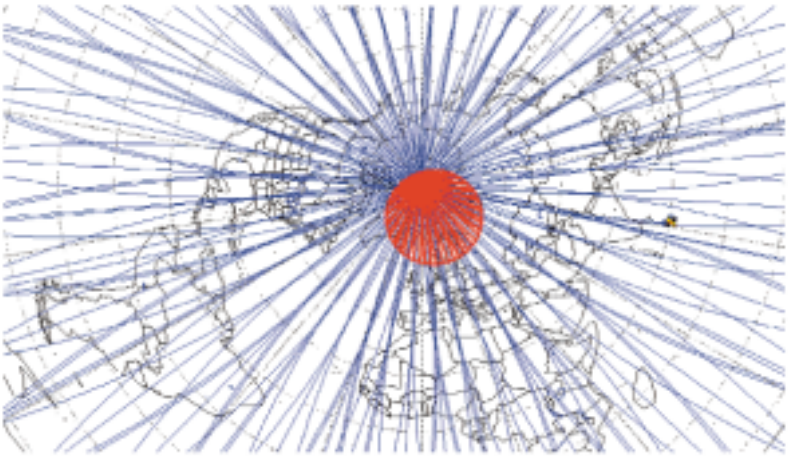

Figure 6.17: *Access between the Svålbard station and polar spacecraft at 600 km altitude (elevation > 10°) – Concept 1.*

An alternative would be the use of two ground stations: Kiruna (Sweden) and Fairbanks (Alaska). In this case there is visibility for each orbit and all data can be downlinked less than 2 hours after acquisition.

6.7.2 Mission Data Flow

Payload data (Level-0) will be received from the ground stations and then transmitted in real-time to the data processing centre, which performs processing to Level-1. Additional data, such as satellite tracking data from the GNSS ground network, and meteorological data from global models will be required.

The Science Data Centre will compute two kinds of products:

- a near-real-time solution for weather and space weather monitoring and forecasting applications with at least 30% of the data
- a more accurate and better-validated post-processed solution for climate and atmospheric research.

6.7.3 Command and Control, Data Acquisition

In order to improve overall efficiency and to reduce the cost of the system deployment and maintenance, it is assumed that the command and control centre's role will be as minimal as possible during the mission's operational lifetime. In particular, routine operations should be autonomously performed by the satellite without any operator intervention, except in the case of a reconfiguration need (satellite failure, software upload…). To carry out its monitoring functions, the control centre will also monitor satellite health information from the telemetry data. This data will provide information on the satellite sub-system status. Additional information on spacecraft and payload

performance will be derived from the scientific data analysis and fed back to the control centre if necessary.

6.7.4 Ground Network of GNSS Receivers

To calibrate the LEO–GNSS satellites occultation data, use of a ground network of GNSS receivers is assumed. This will enable the determination of precise GNSS positions, velocities and clock drifts. This network will be based on (or even coincide with) the network set up for GRAS on MetOp and for other missions.

In addition, synergies with existing networks for GNSS satellite monitoring, such as those existing for WAAS (Wide Area Augmentation Systems and in the future Galileo) should be carefully investigated.

7 Programmatics

7.1 Introduction

Section 7.2 presents the technical maturity, the heritage and the risk areas for the concepts developed in the pre-Phase-A studies. Section 7.3 presents the envisaged international cooperation for WATS and the related missions, both approved and planned. The contribution of WATS to enhanced Earth observation capabilities and its application potential are outlined in Section 7.4.

7.2 Technical Maturity, Critical Areas and Risk

The technical maturity of the WATS mission is compatible with launches starting in 2008. The system design allows for parallel development of payload, platform and ground segment. The GRAS+ receiver has a strong heritage from the GRAS instrument on MetOp, the GPSOS instrument on NPOESS, the US radio occultation receiver on CHAMP, and precise microwave tracking systems like DORIS and PRARE.

The LEO-LEO link instrument (CALL) requires a dedicated development programme. The high radiometric knowledge requirement remains challenging. Besides requiring very stable equipment and components that are temperature stabilised, the pre-launch characterisations and in-orbit calibrations impose high precision requirements.

Table 7.1 summarises the main aspects of the implementation and the heritages of key system elements.

WATS will benefit from developments initiated during the Phase-A of the Atmospheric Climate Experiment (ACE), proposed as an Earth Explorer Opportunity mission, in particular those addressing the enhanced GRAS instrument and the definition of advanced retrieval algorithms for the lower troposphere retrieval. The allocation of frequencies for the LEO-LEO links is in principle compliant with international regulations, although a small frequency adjustment may be necessary for the 10 GHz link. For the platform, a strong heritage exists from several European micro-satellite programmes. Experience with constellation design, development and deployment has been acquired through telecommunication programmes based on constellations. A proven capability to produce batches of identical satellites in a relatively short period of time is also available within the European space industry.

7.3 International Cooperation and Related Missions

Because of its expected role in collecting key information with which to understand the global climate and its changes, WATS is clearly of global interest and can play a major

Element	Implementation	Risk/Heritage
GRAS+	Enhanced GRAS receiver	GRAS on MetOp, GPSOS on NPOESS, CHAMP, DORIS, PRARE Enhanced GRAS receiver development on-going.
CALL (LEO–LEO)		
Transmitter & Receiver	Very stable electronics with temperature stabilisation (<0.1 K)	Pre-launch characterisations and in-orbit calibrations with very high precision.
Antenna	Slotted waveguide array with very high gain stability	Selection of appropriate material and fabrication method to attain required stability under varying thermal environment
Microsatellite	3-axis stabilised with star-tracker	Several on-going microsatellite programmes ACE phase-A study
Constellation	12 satellites with gradual build-up	Satellite constellations for mobile telecommunications

Table 7.1: *Risk assessment for the key system elements.*

role in the international effort to further our understanding of atmospheric processes. There is therefore strong potential for scientific and technical cooperation.

Cooperation can be envisaged with other European organisations, Eumetsat in particular, as their infrastructure could be used for the data archiving and near-real-time distribution to operational users. Collaboration with ECMWF can also be envisaged, especially in the data processing area.

Cooperation with NASA/NOAA could be sought for the provision of a high-latitude data acquisition station, e.g. Barrow in Alaska, to allow near-real-time provision of data.

The role of WATS in the GOS cannot be over-emphasised, considering the stress put by many scientific and operational bodies on the need to fill the gap in the observation of the Earth's atmosphere caused by the present lack of water vapour data of the required quality.

WATS could be implemented in the framework of a pre-operational set-up, based on near-real-time data ingestion into state-of-the-art numerical models of the atmosphere.

WATS will also strongly support and complement other missions aimed at observing other atmospheric processes, in particular those driving the Earth's radiation budget. WATS will provide precise water vapour and temperature profiles that can support the modelling of atmospheric processes observed with EarthCARE and ESSP-3/CENA.

7.4 Enhancement of Capabilities and Potential for Applications

The expected advances in science have been discussed in previous chapters. As also shown in previous chapters, this mission is also very relevant to the enhancement of capabilities to enable applications (NWP and future operational systems). The potential of a mission dedicated to water vapour determination has been recognised for many years. WATS will be another application of the substantial development effort on occultation instruments in Europe, confirming and consolidating the excellence of the European scientific and technical communities in the field of active limb sounding of the atmosphere.

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Acronyms

AMDAR	Aircraft Meteorological DAta Relay.
AMSU	Advanced MSU.
ATOVS	Advanced TOVS.
CALL	Crosslink Atmospheric LEO–LEO instrument.
CBS	Committee for Basic Systems (WMO).
CEOS	Committee on Earth Observation Systems.
CLIVAR	an international research programme under WCRP investigating CLImate VARiability and predictability.
DJF	Winter season (December, January, February)
DMSP	Defense Meteorological Satellite Program.
ECMWF	European Centre for Medium-range Weather Forecasts.
ENSO	El Niño/Southern Oscillation.
ERA15	ECMWF's first re-analysis covering the period 1979-1993.
ERA40	ECMWF's ongoing re-analysis project planned to cover the period 1957 to present.
Eumetsat	EUropean organisation for the exploitation of METeorological SATellites
Euroclivar	the European implementation of CLIVAR.
GALILEO	European future global navigation satellite system.
GCM	General (or Global) Climate Model.
GCOS	Global Climate Observing System.
GEWEX	Global Energy and Water cycle EXperiment, a programme under WCRP.
GLONASS	Russian global navigation satellite system.
GOS	Global Observing System.
GPS	Global Positioning System (USA).
GNSS	Global Navigation Satellite System – generic term.
GRAS	GNSS Receiver for Atmospheric Sounding.
HIRS	High-resolution Infrared Radiation Sounder.
IASI	Infrared Atmospheric Sounding Interferometer.
ICTZ	Inter-Tropical Convergence Zone.
IPCC	Intergovernmental Panel on Climate Change.
ITCZ	Inter-Tropical Convergence Zone.
JJA	Summer season (June, July, August)

K-band	Microwave frequency region above (roughly) 18 GHz.
L-band	Microwave frequency region between (roughly) 1 and 2 GHz.
LEO	Low Earth Orbiting satellite.
MetOp	Meteorological polar-orbiting satellite. European satellite to be launched in the middle of the present decade.
MSG	Meteosat Second Generation.
MHS	Microwave Humidity Sounder.
MSG	Meteosat Second Generation.
MSU	Microwave Sounding Unit.
NCEP	National Center for Environmental Prediction.
NOAA	National Oceanographic and Atmospheric Administration (USA).
NPOESS	National Polar-orbiting Operational Environmental Satellite System (USA)
NWP	Numerical Weather Prediction.
pixel	Picture element (two-dimensional)
POTENTIALS	Project On Tendency Evaluations using New Techniques to Improve Atmospheric Long-term Simulations (http://www.dmi.dk/pub/POTENTIALS)
RH	Relative Humidity.
RMS	Root Mean Square.
RO	Radio Occultation.
SAF	Satellite Application Facility.
SAG	Science Advisory Group.
SEVIRI	Spinning Enhanced Visible and InfraRed Imager.
SPARC	Stratospheric processes and their role in climate. A project under WCRP.
SSMIS	Satellite Scanning Microwave Image Sounder.
TIROS	Television and Infrared Observation Satellite.
TOVS	Tiros Operational Vertical Sounder.
UR	User Requirement.
URD	User Requirement Document.
USO	Ultra-Stable oscillator.
voxel	Volume element (three-dimensional).
WATS	WAter vapour and temperature in the Troposphere and Stratosphere (the present proposed mission).

WMO	World Meteorological Organization.
WCRP	World Climate Research Programme. Co-sponsored by the International Council for Science (ICSU), the World Meteorological Organization (WMO), and the Intergovernmental Oceanographic Commission (IOC) of UNESCO
X-band	Microwave frequency region between (roughly) 8 and 13 GHz.
4D-VAR	Four-Dimensional VARiational data assimilation.