SP-1196 (7)

REPORTS FOR ASSESSMENT

THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Atmospheric Profiling Mission

European Space Agency
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Atmospheric Profiling Mission

ESA SP-1196 (7) – The Nine Candidate Earth Explorer Missions –

ATMOSPHERIC PROFILING MISSION

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1. Introduction

For the post-2000 time frame two general classes of Earth Observation missions have been identified to address user requirements, namely:

> **Earth Explorer Missions** – these are research/demonstration missions with the emphasis on advancing understanding of the different Earth system processes. The demonstration of specific new observing techniques would also fall under this category.
>
> **Earth Watch Missions** – these are pre-operational missions addressing the requirements of specific Earth observation application areas. The responsibility for this type of mission would eventually be transferred to operational (European) entities and the private sector.

Nine Earth Explorer missions have been identified as potential candidates for Phase A study. For each of these candidate missions Reports for Assessment have been produced.

This particular Report for Assessment is concerned with the Earth Explorer Atmospheric Profiling Mission. It has been prepared by one of the nine Mission Working Groups that have been established to produce these Reports. The four (external non-ESA) members of this particular Mission Working Group are Lennart Bengtsson (Max-Planck Institut für Meteorologie, Hamburg, Germany), John Eyre (Meteorological Office, Bracknell, United Kingdom), Alain Hauchecorne (Service d'Aeronomie, Verrières-le-Buisson, France), and Gottfried Kirchengast (Universität Graz, Graz, Austria). They were supported by members of the Agency who advised on technical aspects and took the lead in drafting technical/programmatic sections. This Report, together with those of the other eight candidate Earth Explorer missions, is being circulated amongst the Earth Observation research community in anticipation of a Workshop which will be held in Spain in May 1996.

The major concern of this mission is climate change research. There are indications that tropospheric temperatures are increasing and stratospheric temperatures are decreasing. Atmospheric temperature and water vapour are measured routinely by a global network of radiosonde stations, complemented by satellite soundings and aircraft reports. However, while efforts are ongoing to improve temporal and spatial resolution of existing systems, other techniques need to be sought to provide not only additional data but also atmospheric data of higher quality. Such data could be provided by this mission. The prime objective of the Earth Explorer Atmospheric Profiling Mission is to provide global observations of temperatures in the upper troposphere and lower stratosphere and water vapour profiles in the lower troposphere for climate research. Such data would also be of importance to the meteorology community for application in forecasting. Furthermore, unique observations of electron densities would be provided for ionospheric research.

All the Reports for Assessment follow a common general structure comprising seven chapters. They each start by addressing the scientific justification for a particular mission and move on to detail its specific objectives. This is followed by a detailing of the specification of observation requirements and a listing of the various mission elements required to satisfy the observational requirements. Then consideration is given to the implications of meeting the observational requirements in terms of both the space and ground segment as well as requisite advances in scientific algorithms and processing/assimilation techniques. Finally programmatic aspects are considered.

2. Background and Scientific Justification

2.1. Background

The Atmospheric Profiling Earth Explorer Mission will employ the radio occultation technique – a powerful technique for sounding atmospheres from space with high accuracy and vertical resolution. It offers the potential to provide measurements of temperature and humidity profiles in a cost-effective way and to make a major advance in the observation of the ionosphere's electron density field.

From the mid-1960s onwards, the radio occultation technique has been used with great success by planetary missions to measure vertical profiles of density and temperature for the atmospheres of Venus, Mars and the outer planets. With the advent of Global Navigation Satellite Systems (GNSS) (i.e. the USA's Global Positioning System (GPS) and the Russian Global Navigation Satellite System (GLONASS)) using high performance radio transmitters in suitably high orbits, along with receivers on low Earth orbiting (LEO) platforms, it is now possible to make radio occultation measurements for the Earth's atmosphere with an accuracy useful for applications in operational meteorology and in climate and ionospheric research (see Kursinski et al. 1996, Ware et al. 1996, and their references).

The scientific basis of the radio occultation technique is as follows. When radio waves pass through the atmosphere, they are refracted through an angle determined by the refractivity gradients along the path (see Figure 2.1). These, in turn, depend on the gradients of density (and hence temperature), water vapour and electron density, and so a measurement of the refracted angle contains information on these atmospheric variables. These effects are most pronounced when the radiation traverses a long atmospheric limb path, and measurements for a series of such paths at different tangent heights contain information on the vertical profile of refractivity. At radio frequencies it is not possible to measure the refracted angle directly. However, the refraction introduces an additional Doppler shift into the retrieved signal, and this (or the related phase shift) can be measured very accurately and is directly related to the refracted angle.

Figure 2.2 illustrates the configuration through which a receiver on a LEO satellite uses the GNSS signals both to locate itself precisely and to make occultation measurements. A radio occultation profile is measured from a LEO satellite over a period of about 1 minute, just before or after eclipse (with respect to the transmitter). A receiver capable of observing both setting and rising occultations can obtain up to 29 occultation profiles per day for each GNSS transmitter. Given the current network of GNSS transmitters, this will allow, under ideal conditions, about 1100 useful soundings per day for each receiver, globally distributed, with an average spacing of about 700 km.

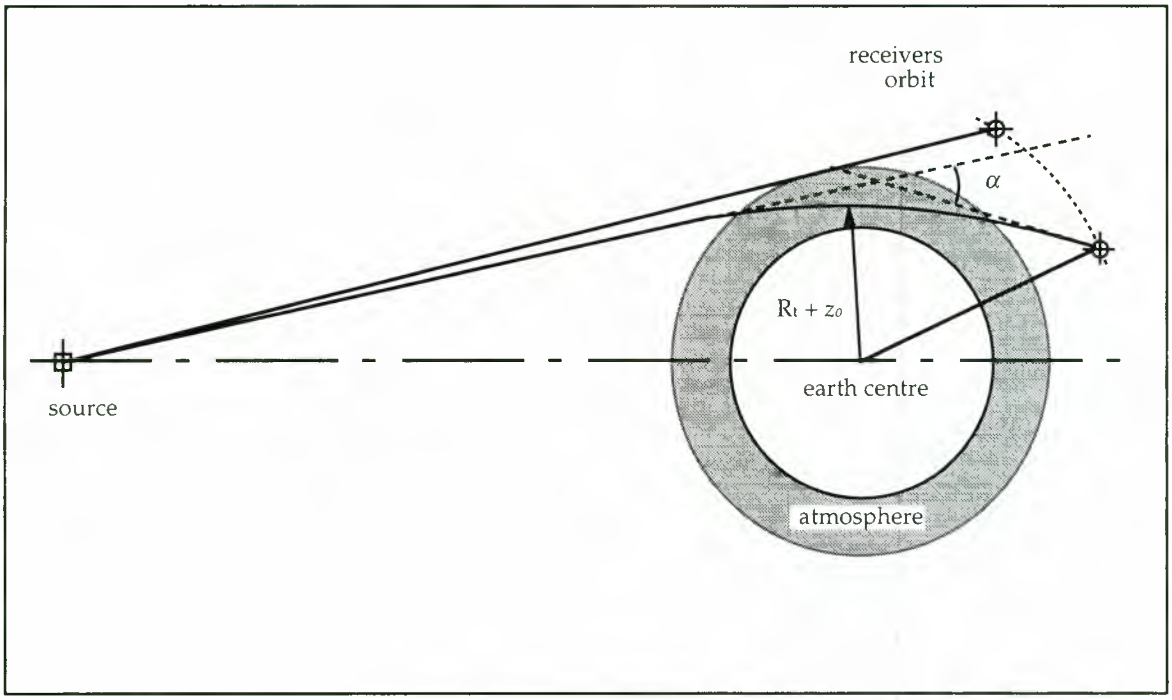

Figure 2.1. *Illustrating the geometry of radio occultation (from Høeg et al., 1996)*

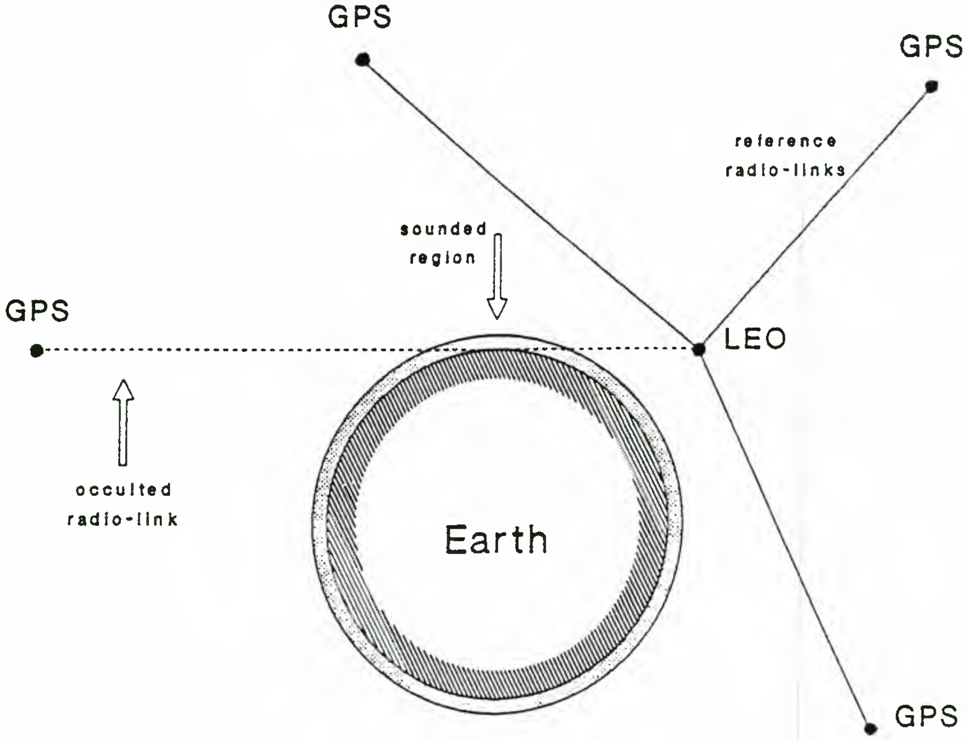

Figure 2.2. *Illustrating the configuration for locating the LEO satellite and making occultation measurements using GPS (from Gorbunov and Sokolovskij, 1993)*

In the stratosphere and upper troposphere, where the water vapour density is low, refraction is dominated by vertical temperature gradients, and the temperature profile can be retrieved accurately. In the lower troposphere, the water vapour effects are dominant, and the water vapour profile can be retrieved, even allowing for typical uncertainties in the prior knowledge of temperature. The height below which the information in the measurements is predominantly dependent on water vapour varies with absolute humidity (and hence latitude); in the tropics it is typically around 7-8 km, whereas in the dry polar atmosphere, accurate temperature sounding is possible down into the atmospheric boundary layer.

For both temperature and humidity sounding, it is necessary to account for the effects on the signals of refraction in the ionosphere. Correction for these effects can be made using the radio occultation signals at two radio frequencies at which the effects of the ionosphere are substantially different. In addition, the presence of such effects provides information on the ionosphere's electron density field.

An important feature of the radio occultation technique is its ‘all-weather’ capability. Most clouds have negligible effects on the measured signals. Even when a signal is attenuated a little (e.g. by rain), the measurement is not significantly degraded since the important measurement is of frequency (or phase) not of amplitude. For the same reason, the measurements have intrinsically a high long-term stability, with no significant calibration problems. This feature is particularly important for climate monitoring.

The potential of the radio occultation technique has recently been demonstrated by early results from the GPS/MET (GPS Meteorology) experiments launched in April 1995 on the US satellite Microlab 1. The initial results for temperature profile retrieval are already approaching the accuracies originally claimed for the technique (Kursinski et al., 1996; Ware et al., 1996). In the Northern hemisphere extra-tropics, standard deviations of the difference between GPS/MET retrievals and ECMWF (European Centre for Medium-range Weather Forecasts) analyses are around 1-1.5 K, with biases below 0.5 K (see Figure 2.3). In the Southern hemisphere, agreement is also good in general, but there is clear evidence that radio occultation measurements can identify where the ECMWF temperature analysis is deficient through lack of observations. A particularly impressive result of the early GPS/MET data has been the demonstrated ability to resolve the detailed temperature structure around the tropopause, in good agreement with collocated radiosondes (Figure 2.4). Most of the results are consistent with expected errors for this technique – less than 1 K, at a vertical resolution of 0.5-1 km in the upper troposphere and lower stratosphere.

For water vapour, Kursinski et al. (1995) have assessed the potential accuracy of radio occultation retrievals. They estimate accuracies of better than 10% in the lower troposphere, throughout the mid-latitudes and the tropics, and also at low latitudes in the mid-troposphere at pressures greater than about 600 hPa (see Figure 2.5).

Regarding electron density, the potential of the radio occultation technique has long been demonstrated by studies of the ionospheres of other planets such as Mars and Venus (e.g. see

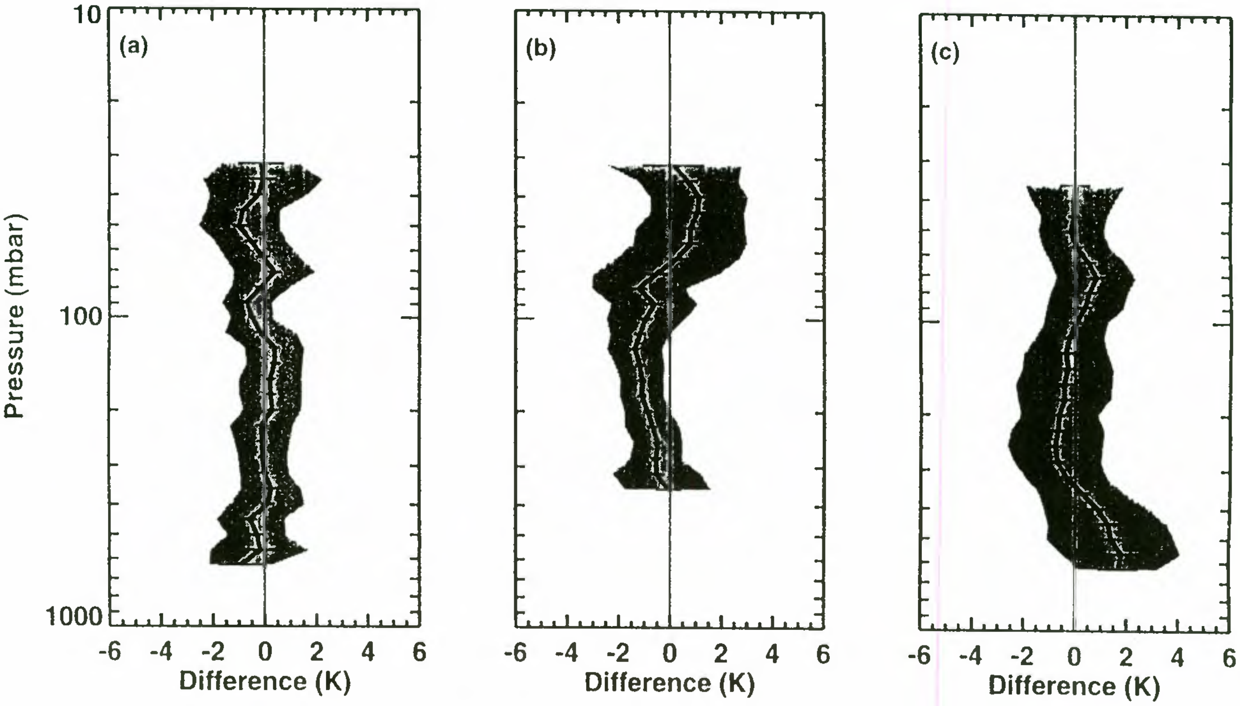

Figure 2.3. *Statistics of differences between temperature profiles retrieved from GPS/MET data and collocated profiles from ECMWF analyses. A solid line marks mean difference, shading indicates standard deviation of difference.* ***(a)*** *30°-90° N,* ***(b)*** *30° S-30° N,* ***(c)*** *30°–90°S. About 30 profiles in each zone for the period 4-5 May 1995 (from Kursinski et al.,1996).*

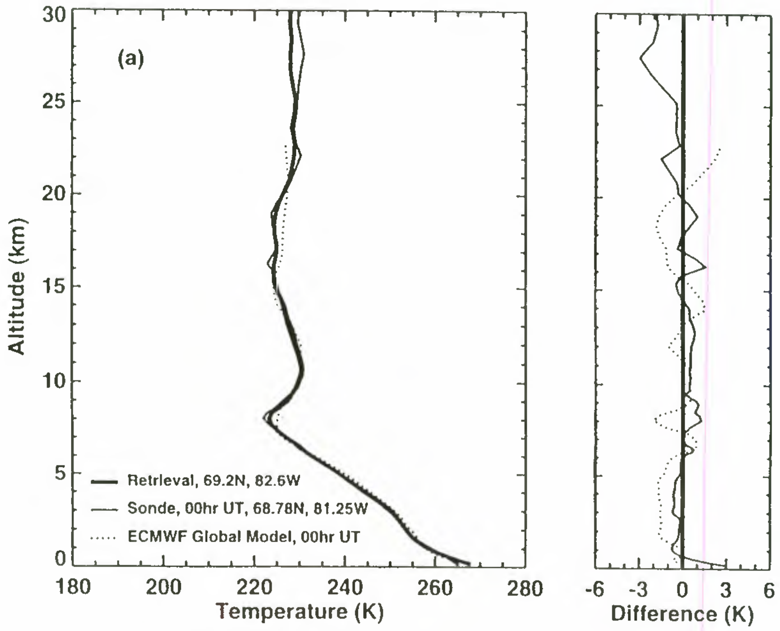

Figure 2.4. *Comparison between one temperature profile retrieved from GPS/MET data and collocated radiosonde profile and ECMWF analysis on 5 May 1995 (from Kursinski et al., 1996).*

Fjeldbo and Eshleman, 1968). First results for the Earth, based on GPS/MET data, promise that electron density can be observed throughout the ionosphere up to about the altitude of the satellite at the 1% accuracy level. This, together with the global coverage potential of the technique, can open up a new era for ionospheric remote sensing of unprecedented resolution and quality.

There is continuing activity in the US to carry forward the use of the radio occultation technique: to continue and improve exploitation of GPS/MET data, to prepare for further experimental missions, and to make plans for the operational implementation of such a system. Experimental demonstration missions are also in preparation elsewhere (e.g. the Danish Oersted project and the German CHAMP (Catastrophe and Hazard Monitoring and Prediction)).

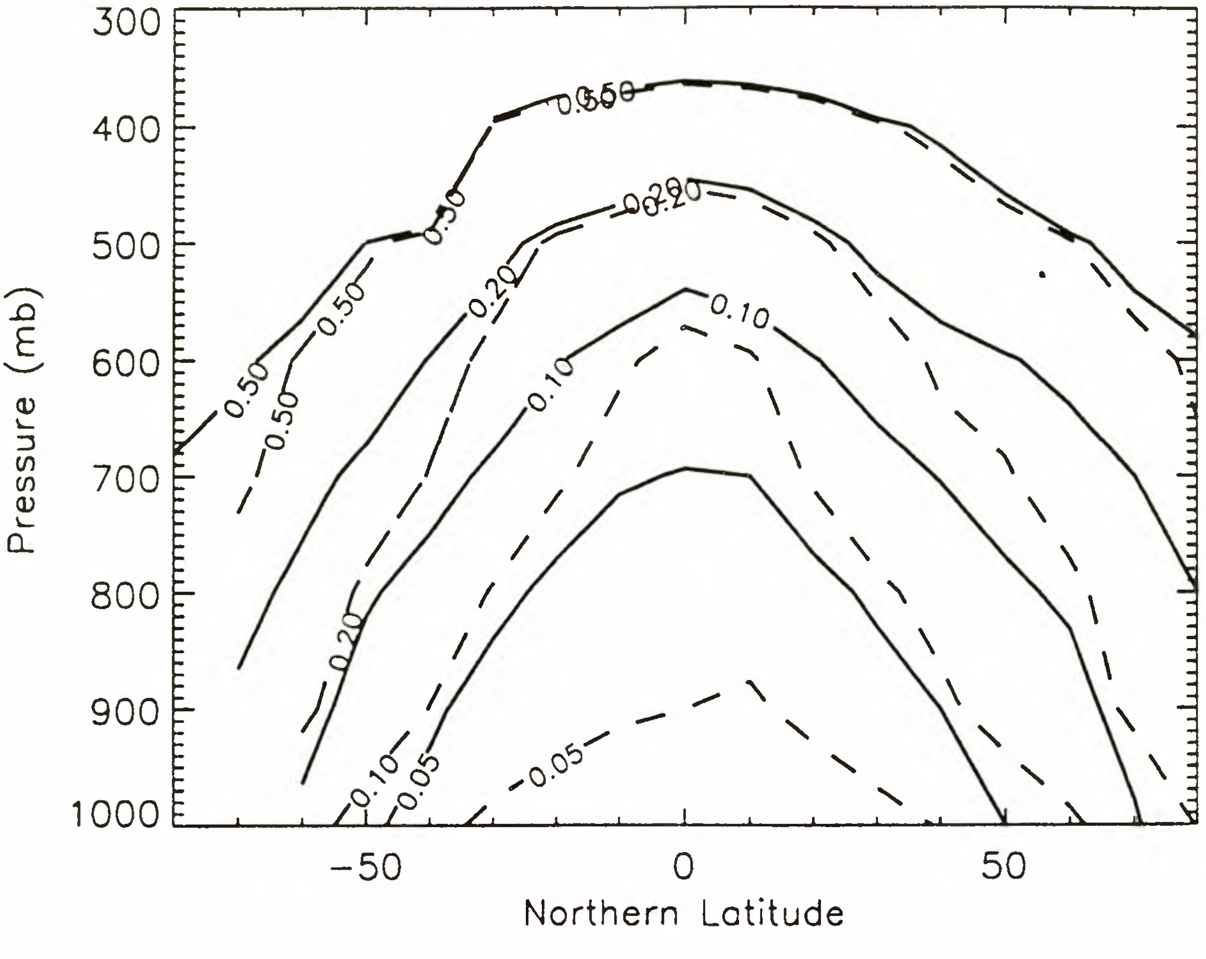

Figure 2.5. *Expected fractional errors (in %) in retrieved specific humidity using a climatological distribution of temperature and water vapour. Solid contours show errors resulting from errors in assumed temperature (taken to be 1.5 K, standard deviation) and assuming surface pressure (taken to be 3 hPa, standard deviation). Dashed contours indicate humidity errors when errors in retrieved refractivity are also included (from Kursinski et al.,1995).*

2.2. Scientific Issues

2.2.1. Climate Monitoring and Modelling

Temperature and water vapour are key parameters to characterise the mean state of the atmosphere and its long-term evolution. The temperature and humidity structure of the atmosphere is likely to change under the impact of three types of anthropogenic forcing: the increase of greenhouse gases, the change in atmospheric aerosol concentrations and the depletion of stratospheric ozone. All these are expected to change the radiation budget of the atmosphere and thereby the Earth's climate.

The global mean temperature of the troposphere and the ground is mainly controlled by the radiative balance of the atmosphere. The total solar input radiation of the Earth is 343 Wm^{-2} (annually and globally averaged). About a third of the incoming solar radiation (103 Wm^{-2}) is reflected and the remainder is absorbed in the atmosphere and at the surface. The outgoing long-wave radiation from the surface is strongly absorbed by water vapour and greenhouse gases keeping the surface and the atmosphere about 33 K warmer than they would otherwise be.

The increase of greenhouse gases plays the major role in determining changes in the Earth's radiative budget (presently an increase of about 2.7 Wm^{-2} since the beginning of industrialisation). It is estimated to have led to an increase in the temperature of the Earth by about 0.6 K over the last 100 years or so. Observational results are consistent with model simulations, but also natural variability, such as internal dynamical processes, volcanic eruptions or solar variations, may have contributed to this temperature increase.

During recent years climate modelling has undergone rapid development including the specific treatment of all the different greenhouse gases and the incorporation of the effect of sulphate aerosols. Transient integrations, starting in the middle of the last century and integrated until present time have been found to agree in their large scale evolution with current observations. The models, when integrated further into the future, indicate rather rapid climate changes over the next 20-30 years. Over the 20 year period 1990-2010 a global surface temperature increase by about one degree is predicted, (Figure 2.6a). In the upper stratosphere a corresponding cooling is predicted (Figure 2.6b).

Figure 2.7 shows the temperature changes 1990-2010 as calculated by the latest climate model at the Max-Planck-Institute for Meteorology in Hamburg. These results, which are in broad agreement with other models, indicate a marked warming in the tropical upper troposphere and an overall stratospheric cooling.

These model calculations have not yet incorporated the effect of changes in stratospheric ozone. If the ozone depletion continues over the next 20 years this is likely to further enhance the stratospheric cooling effect.

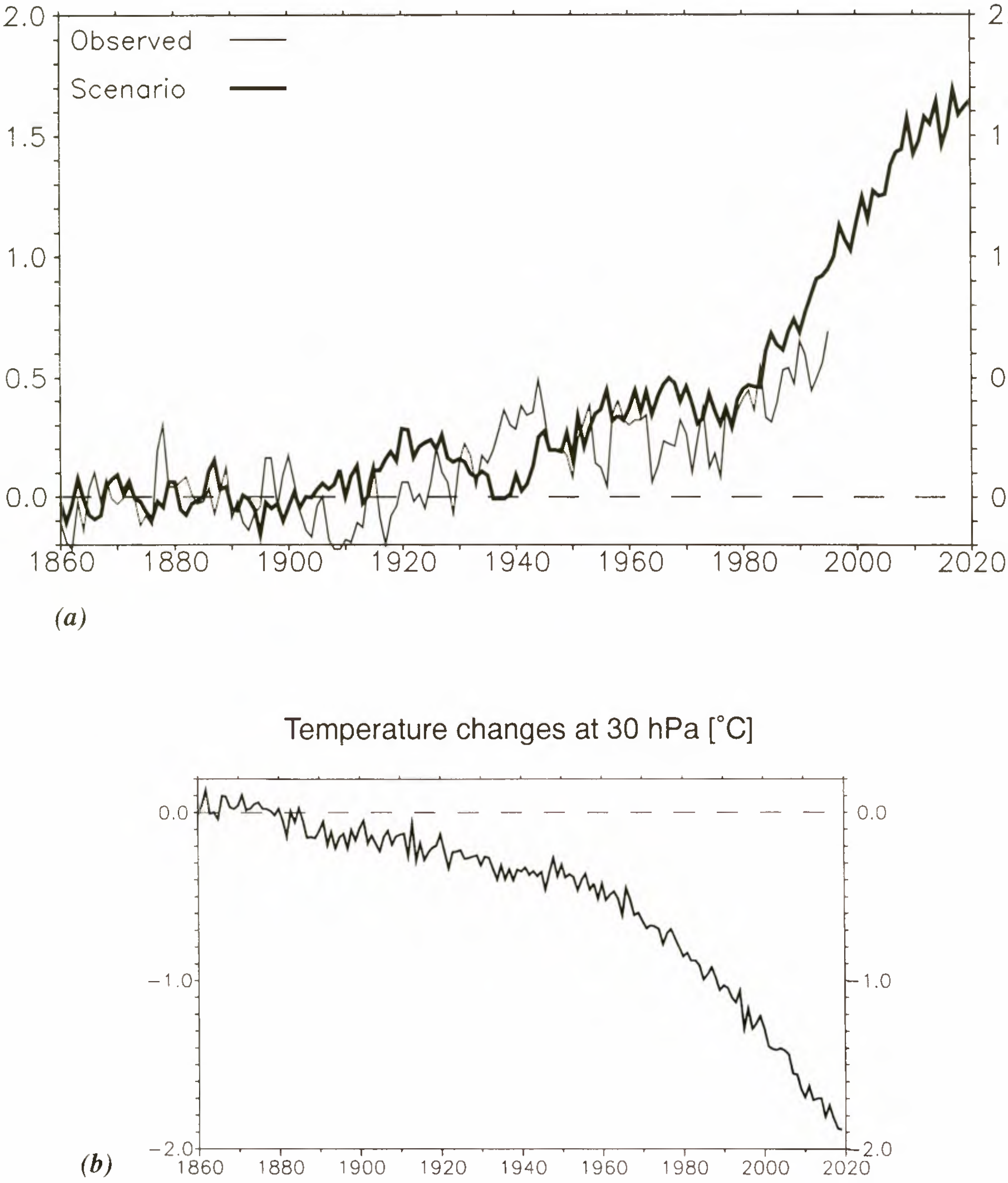

Figure 2.6. *Illustrating predicted and observed changes in global mean surface air temperature* ***(a)*** *and predicted global mean 30 hPa temperature changes* ***(b)*** *over the period 1860-2020 as obtained from the Max Planck Institute climate model.*

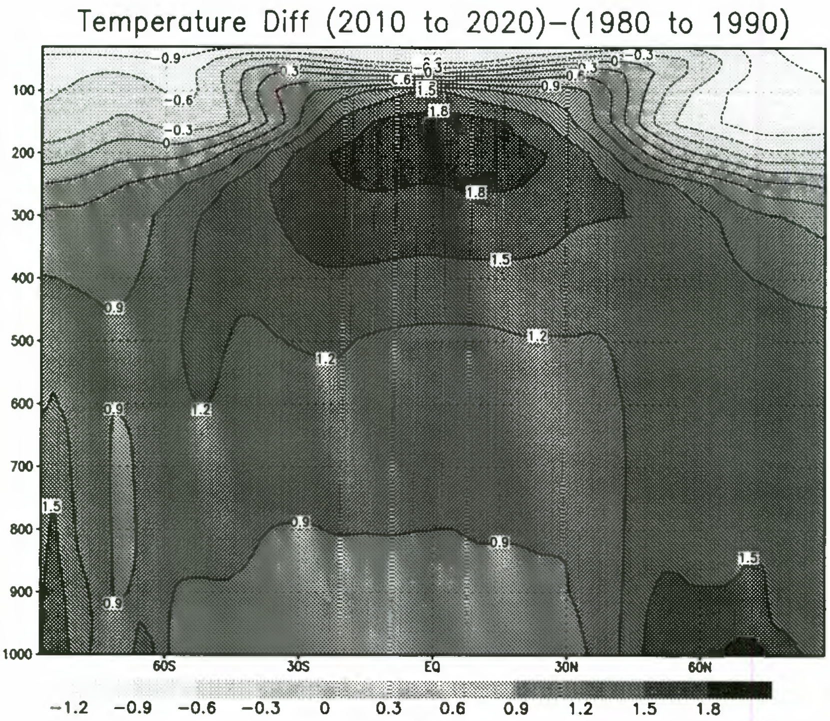

Figure 2.7. *Illustrating changes in the zonal mean atmospheric temperature cross-section (in K), decadal mean 2010-2020 minus decadal mean 1980-1990, as predicted by the Max Planck Institute climate model.*

Another pronounced effect of climate warming is a relatively rapid increase in atmospheric water vapour. It is calculated that the average amount of water in the atmosphere could increase by as much as 5% (globally averaged) over the next 20 years.

Several studies have been carried out to evaluate the evolution of temperature in the lower stratosphere during the past 30 years, using both the international network of radiosondes and temperature sensors on board meteorological satellites. As explained later, these systems suffer from several limitations in terms of geographical coverage (radiosondes), vertical resolution (satellites) and absolute calibration (both systems). In spite of these limitations, significant results have been obtained. Recently Oort and Liu (1993) studied temperature anomalies in the 100-50 hPa layer. At the global scale, the standard deviation of anomalies was found to be 0.4 K and negative trends of the order of -0.3 to-0.5 K per decade have been detected (Figure 2.8). During the period when MSU data were available (1979-1989) a similar negative trend had been observed. However, due to the problem of calibration of data, these results have to be treated with caution.

The determination of the 3-dimensional field of temperature in the upper troposphere and lower stratosphere with high vertical resolution (1 km) and absolute values, using the radio occultation technique, will allow a very accurate climatology of atmospheric temperature to be established and long-term trends to be inferred. In order to draw reliable conclusions from the inferred trends, the role of external forcing (volcanic eruptions, solar activity) as well as

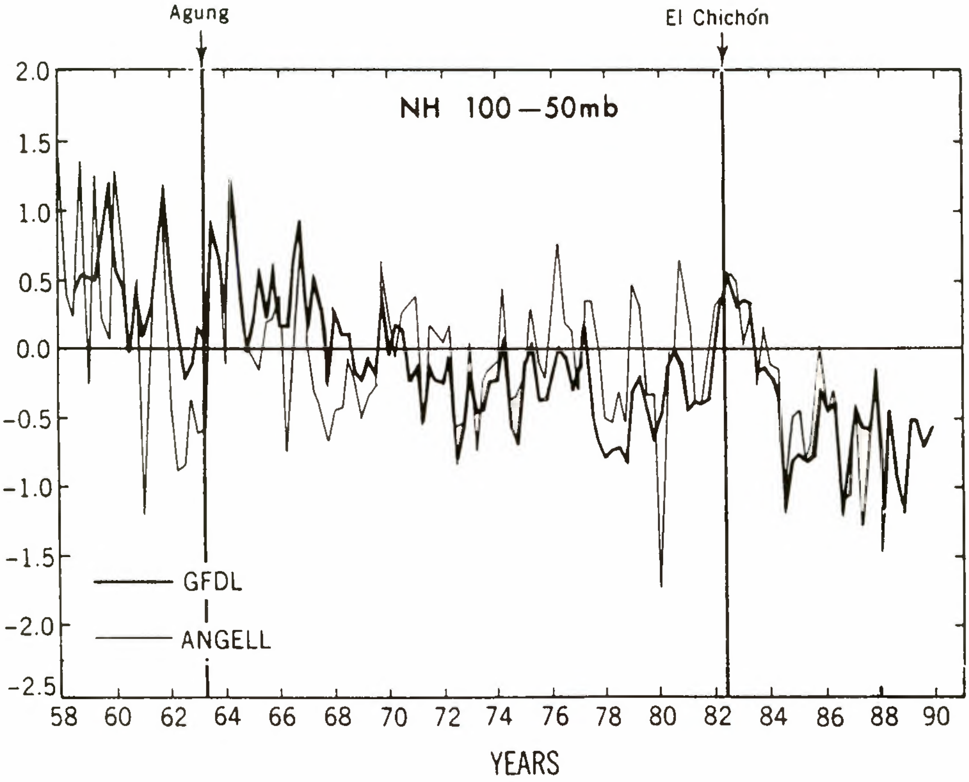

Figure 2.8. *The Northern Hemisphere mean temperature of the lower stratosphere over the period 1958 - 1990 from radiosonde observations (from Oort and Liu, 1993).*

internal forcing (Quasi Biennial Oscillation, El Niño/Southern Oscillation etc.) on the observed variability has to be understood first. The possibility of having global temperature data sets will also offer the opportunity to study regional phenomena, for instance at high latitudes in relation with the ozone hole inside the polar vortex or in conjunction with the injection of particles in the stratosphere by volcanic eruptions which leads to a modification of the radiative budget of the stratosphere.

Radio occultation measurements will also provide independent information on water vapour distribution in the lower part of the troposphere. These data will, in combination with, say, low level wind data, allow an accurate determination of moisture advection and hence provide a more precise knowledge of the hydrological cycle. Other important areas of application are the development and testing of parameterisation methods for clouds and precipitation.

At microwave wavelength, refractivity N in the Earth's lower atmosphere is related to atmospheric properties by the expression:

$$N = c_1 \frac{P}{T} + c_2 \frac{P_w}{T^2} \qquad (2.1)$$

where P is pressure, T is temperature, P_w is water vapour partial pressure and c_1 and c_2 are constants.

The determination of moisture will thus require the temperature to be assessed sufficiently accurately for this purpose by other means. It is believed that this is already the case, since the existing global observing system (WWW) (in conjunction with atmospheric models) allows lower tropospheric temperatures to be estimated with sufficient accuracy.

2.2.2. Atmospheric Analysis and Modelling

Accurate forecasts from a numerical weather prediction (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 rapidly grow 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.

Recent studies of the sensitivity of forecast errors to initial conditions (Rabier et al., 1996) have confirmed that it is particularly important to have an accurate description of certain geographical areas in the description of the initial state of the atmosphere, i.e. those in which small perturbations to the state (or errors in the state) will grow rapidly. Many of these are found in the vicinity of atmospheric fronts and jet streams – areas in which cloud cover is often extensive.

At present, temperature and humidity observations available for atmospheric analysis come from:

> *Radiosondes* – these give high resolution in the vertical but 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. Their accuracies are generally good but vary from station to station, with substantial radiation biases in the stratosphere (often >1 K above 20 km). There are many different types of radiosondes, and stations change the type used from time to time. Although this is not a major problem for NWP, it has implications for long-term trend studies in climate monitoring – see below. There is also continuing pressure to reduce the radiosonde network, particularly at remote sites, because of the high operational costs.
>
> *Aircraft* – accurate temperature measurements are available but mainly at flight level and on major air routes; most areas of the world are not covered. Profiles are available only on ascent and descent (i.e. near well-populated areas).
>
> *Satellite sounding radiometers (passive infrared and microwave)* – the current operational system on the TIROS-N/NOAA series of polar orbiting satellites consists of the High-resolution Infrared Radiation Sounder (HIRS), the Microwave Sounding Unit (MSU)

and the Stratospheric Sounding Unit (SSU). They are collectively known as the TIROS Operational Vertical Sounder (TOVS) and provide information on tropospheric and stratospheric temperature and tropospheric humidity with global coverage at high horizontal resolution. Their imminent successor – the Advanced TOVS (ATOVS) – consists of HIRS plus the Advanced Microwave Sounding Unit (AMSU). 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 3-4 km in clear areas, and worse in cloudy areas. The accuracy of present systems is of the order of > 2 K. The next generation of advanced infrared sounder (e.g. IASI, AIRS) will give higher vertical resolution (approaching 1 km in the lower troposphere and ~ 2 km in the lower stratosphere) but only in cloud-free areas (or, for cloudy areas, above the cloud-top). Their microwave counterpart (AMSU) will supply complementary information in cloud areas, but with poorer vertical resolution (3-4 km). For future sounders an improvement in accuracy to below 2 K is expected.

The contribution that radio occultation measurements will make to the total observing system is described below (section 2.5.2). In short, they will provide accurate profiles at high vertical resolution in all cloudy conditions and will be particularly important in resolving the fine structure around the tropopause.

In addition to their key role in operational forecasting, NWP data assimilation systems are now being used retrospectively to provide long, consistent sets of atmospheric analyses for numerous applications in the field of climate studies. Such 're-analysis' projects are under way at ECMWF, NOAA/NCEP and NASA/GSFC. Through this mechanism, radio occultation measurements (in addition to other observations) can be expected to provide valuable input to improved analyses of the climate of atmospheric temperature and humidity.

2.2.3. Ionospheric Research

The ionosphere, the ionised part of the upper atmosphere spanning the height range from 80 km to 1000 km, is a layered magneto-plasma of considerable dynamical complexity. It is intimately coupled – chemically, dynamically and energetically – to the thermosphere, the neutral part of the upper atmosphere. The fundamental parameter characterising it is the number density of free electrons, i.e., the electron density distribution is the principal field variable for describing the physical behaviour of the ionosphere. Figure 2.9 which shows a global map of vertically integrated electron density based on an empirical model, illustrates large-scale features of ionospheric climatology.

The ionospheric plasma exerts severe influences on the propagation of radio waves which are refracted, reflected, absorbed and distorted in various ways according to its highly dispersive properties (e.g. Budden, 1985). For this reason radio waves are used for probing the ionosphere and constitute the principal means for acquiring experimental ionospheric information (Hunsucker, 1991, gives an overview). Well established ground-based techniques

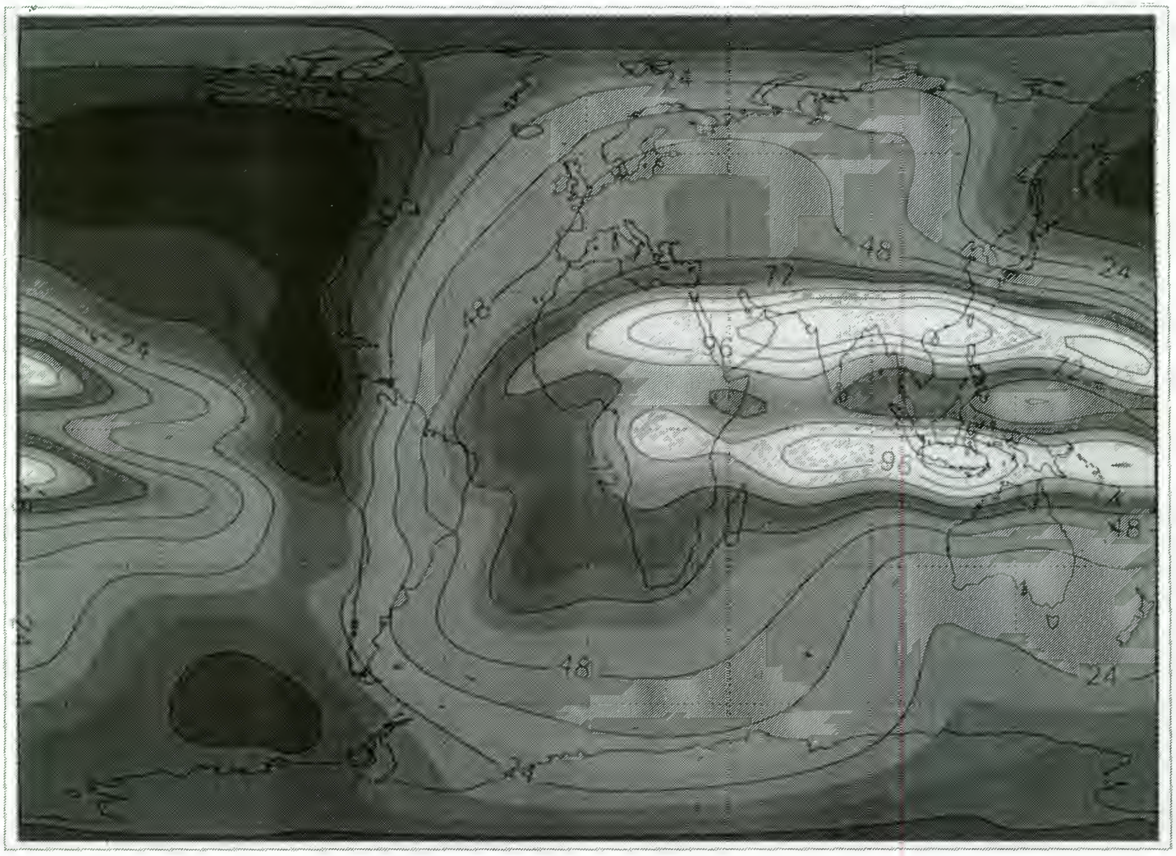

Figure 2.9. *Global map of vertically integrated electron density in 'TEC units' [10^{16} m^{-2}] for high solar activity conditions during equinox (autumn) at noontime over Europe (11:00 UT). The large-scale climatological variation according to a global empirical model is illustrated. The modelling and monitoring of features missing in this climatology due to lack of data (e.g., the 'ionospheric trough' and auroral/polar latitude variability) would be enabled by employing the radio occultation technique. (from Leitinger et al., 1996)*

use ionosondes, measuring electron density below the ionospheric peak employing HF (high frequency) reflection, and radiobeacon methods yielding Total Electron Content (TEC) along ground-to-satellite links. The incoherent-scatter technique yields, in addition to electron density, the plasma drift, and the ion and electron temperatures. Spaceborne ionosondes ("topside sounders") have been used for sensing the electron density above the main ionospheric peak.

From a different perspective, the ionosphere can be considered as a source of 'errors' rather than a geophysical signal; ionospheric effects in ground-to-satellite and satellite-to-satellite radio links in the HF/VHF/UHF/long-microwave regime necessitate detailed knowledge and understanding of the ionosphere to enable corrections to be made which are required for many ionosphere-dependent applications. These include (among others) geodesy and navigation, satellite communications and orbit maintenance, and also neutral atmospheric profiling by the radio occultation technique.

It is clear that ionospheric research is relevant to both geophysical research and applications, the common thread being the ionosphere's 'radio feeling'. The scientific issues grouped below are relevant to both aspects. All of them would be enormously enhanced by exploiting the radio occultation technique.

Global 4-dimensional Monitoring and Modelling of Electron Density Climatology:
Ionospheric structure varies up to orders of magnitudes in electron density, mainly in response to radio and particle energy input of solar origin. There are pronounced climatological dependencies in density profiles with local time, latitude, season, solar cycle and magnetic activity. This climatology is, although much needed as a fundamental data product, still not adequately modeled since present data coverage is insufficient. The number of (non-GNSS) ionosphere observing stations is actually declining.

Employing the radio occultation technique for ionospheric profiling, imaging and tomography (on this terminology see section 2.3.3 below) would drastically improve global monitoring and empirical modelling (e.g., Hajj et al., 1994). Also, the modelling of mesoscale climatological structures such as the ionospheric trough could be performed. At present this is impossible. As a specific application example, the correction of small residual ionospheric errors in upper stratospheric profiling could be aided as necessary by ionospheric monitoring.

Travelling Ionospheric Disturbances and Ionospheric Storm Effects:
Travelling Ionospheric Disturbances (TIDs) are ionospheric signatures of atmospheric gravity waves which play an important role for the transport and distribution of energy and momentum within the global neutral atmosphere. Monitoring TID activity in the ionosphere is a key method for observing routinely global atmospheric gravity wave climatology in the thermosphere (e.g., Kirchengast et al., 1995). It can help to clarify atmospheric gravity wave generation and propagation characteristics and to quantify atmospheric gravity wave-related energy and momentum inputs to the atmosphere. They can also help further understanding and to quantify the effects of TID activity on radio propagation. While present observations are insufficient for these purposes, the radio occultation technique would be a unique tool for such monitoring.

The ionospheric response to magnetic storms, providing a large, sudden, impulsive input of energy in form of energetic particles and electrical currents into the ionosphere, is also still incompletely understood. Monitoring 'ionosphere weather' by the radio occultation technique can significantly contribute to clarifying the processes involved in storm evolution and to predicting storm effects on radio propagation.

Ionospheric Currents and Geomagnetic Field Analysis:
High-resolution electron density data in the ionospheric 'E-region' permit the mapping of ionospheric conductivity and thus of ionospheric currents. Conductivity is also a key parameter for the calculation of energy input. Radio occultation measurements could contribute to such ionisation data and be used together with magnetic field data to provide

high-quality separation of internal (solid Earth) and external (current system) magnetic field contributions in near-Earth space (Hajj et al., 1994).

Ionospheric Irregularities and Scintillations:
Scintillations created by scattering of radio waves through small-scale ionospheric irregularities affect the reliability of trans-ionospheric radio links. Presently, experience with satellite-to-satellite links is very sparse. The radio occultation technique would provide scintillation data for globally analyzing the statistical properties of the irregular/turbulent behaviour of the ionospheric plasma under occultation conditions, e.g., for obtaining irregularity spectra and drift speeds.

2.3. Use of Data

2.3.1. Climate Monitoring and Prediction

Expected anthropogenic changes may be of smaller amplitude than the weekly to decadal natural variability. The natural variability needs to be carefully evaluated before any attempt is made to estimate trends. To be useful for climate monitoring, radio occultation measurements must be performed over long period (more than 10 years) with good temporal and geographical coverage. This also requires the control of any systematic biases in the data that could arise from instrumental errors or from poor corrections for atmospheric or ionospheric effects.

Data to be used for temperature monitoring will consist of all available profiles from their lowest altitude (which depends on the water vapour content) up to the stratopause. For water vapour monitoring, climate studies will be limited to areas where the water vapour content is high enough to allow accurate retrieval, i.e. mainly in the lower troposphere at low latitudes. The geographical coverage obtained using the radio occultation technique will allow to perform regional climate studies, including studies of the seasonal behaviour.

Due to the fact that the instrument does not have to be calibrated, it is possible to improve the accuracy of climate monitoring by using data received by several independent receivers on LEO satellites in operation at the same time or separated in time by many years.

High vertical resolution temperature data in the upper troposphere and stratosphere could be used for the development of physical processes such as gravity wave drag paramerisation which is crucial for a realistic representation of dynamical processes in the stratosphere. The high vertical resolution around the tropopause will allow insight into dynamical effects responsible for tropospheric folding and rapid vertical movements of the tropopause and the associated mass exchange between troposphere and stratosphere.

The improved determination of water vapour in the lower troposphere will provide information on the hydrological cycle in a part of the atmosphere where other methods have distinct difficulties.

For climate analysis and modelling, similar procedures to those used in NWP, atmospheric analysis and modelling could be used (cf. section 2.3.2 below), but without the constraint of near real-time availability. The data/products should be made available for integration into appropriate climate data bases.

Table 2.1 summarises the objectives for climate research.

- Mass exchange between troposphere and stratosphere
- Gravity wave drag parameterisation
- Quasi-biannual oscillation
- Stratospheric dynamics
- Stratospheric interannual variations
- Parameterisation of clouds and precipitation
- The hydrological cycle

Table 2.1. *Summary of Climate Research Objectives*

2.3.2. Atmospheric Analysis and Modelling

Meteorological observations are used in atmospheric analysis through the process of data assimilation into forecast models. Observations of many different types are used together to improve estimates of the state of the atmosphere. For forecasting (by providing the initial state) and in many aspects of atmospheric and climate research (including model improvement) an accurate and dynamically consistent description of the atmospheric state is needed.

Raw radio occultation measurements would be pre-processed to produce profiles of refracted angle. Standard retrieval methods already exist to convert such data into profiles of refractivity and then to temperature and/or humidity. Such methods are expected to work well in most conditions though several problems such as multi-path propagation or refraction require further research. Retrieved profiles could then be passed to data assimilation systems for use along with (and in a similar way to) other observations. In areas where horizontal gradients of temperature/humidity are strong, alternative methods involving direct assimilation of refracted angle may be preferred (see Eyre, 1994). Such cases represent a small minority of profiles but they occur in some of the most meteorologically sensitive areas. Therefore the refracted angle data may also be required at data assimilation centres.

For optimal use of the data, it is also important to ensure that expected error characteristics are carefully assessed and that this information is made available to users.

2.3.3. Ionospheric Research

The radio occultation technique yields total electron content, TEC, along the occultation rays as a basic data product. Using GNSS code and carrier phase measurements at both available frequencies enable the accurate derivation of TEC data. In regimes with large electron density gradients (e.g., E-region) also the ionospheric bending angle is a useful basic parameter. Scintillation research would make use of the basic amplitude and phase data.

The further processing of the TEC (or bending angle) occultation data is performed as follows.

Ionospheric Profiling – electron density profiles ('height profiles') attributable to the ray perigee location can be obtained by an inversion of the TEC (or bending angle) data.

Ionospheric Imaging – density profiles from profiling can be combined with information from vertical TEC (gradient) data from ground-to-satellite measurements. High-resolution vertical data can be processed jointly with occultation data, but even coarse ground-to-satellite data enhance the usefulness of the profiling data.

Ionospheric Tomography – occultation rays can be part of a nearly co-planar ray system – a combination of near-horizontal occultation rays with slant/near-vertical ground-to-satellite rays. The TEC data derived can be uniquely converted to produce a 2-dimensional picture of electron density (e.g., latitude-height slice).

Imaging and tomography products can be synthesised to yield 4-dimensional electron density distributions, the space-time resolution being determined by basic TEC data coverage.

After having been processed to various levels as outlined above, the data form the basis for ionospheric research according to the scientific issues posed in section 2.2.3 and the research objectives given in section 3.3.

2.4. Links to the Global Climate Observing System

Weather analysis and forecast models require regular and homogeneous measurements of temperature, moisture, pressure and wind. In addition, information on surface conditions and cloud features is needed for many weather and climate models. These data are used as input to four-dimensional data-assimilation systems, whereby different observations and model information are combined to create a dataset consistent in time and space. Although the data assimilation can often reconstitute missing information surprisingly well, such data restoration is only feasible to a limited degree and generally not in areas where rapid changes are taking place. Accurate observations of wind or temperature in the troposphere are particularly important since they provide an essential basis for the assimilation of other observations.

A Global Climate Observing System (GCOS) is presently being established (JSTC, 1995). GCOS addresses the climate system at large including physical, chemical and biological aspects and incorporates specific atmospheric, oceanographic and terrestrial components. The key scientific issues are detection of climate change and climate prediction on different timescales including as a specific element El Niño – Southern Oscillation prediction. Requirements for atmospheric observations for weather and for climate are to a large extent common. Atmospheric data sets, systematically controlled and analysed, constitute key information for many climate studies. In addition to such data, analysed atmospheric fields, for example from ECMWF´s data assimilation system, are also used by climate groups worldwide.

A central data requirement in climate research is to minimise observational and processing biases or as a minimum requirement control changes in biases over time. While processing biases can be eliminated by reprocessing observations (as is now being done in the so called reanalysis activities, e.g. Bengtsson and Shukla, 1988), observational biases constitute a serious problem. Systematic errors in 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. In areas of clouds and precipitation the retrieved profiles contain less information from measurements and more from the background information. Therefore, in these areas any bias in the background information will tend to propagate more strongly into the retrieval bias (Eyre, 1987). The retrieved vertical profiles also have insufficient resolution in particular in the upper troposphere and stratosphere where greenhouse gas forcing has strong vertical gradients.

Radio occultation measurements will constitute an excellent contribution to the global observing system for weather and climate. They will provide basic measurements of vertical profiles of temperature and moisture (in combination with other observations). Of particular importance is the fact that this will be provided under all weather conditions and with an essentially constant accuracy. They will constitute a complement to passive satellite sounding data.

From a technical point of view, data (both in the form of refraction measurements and retrieved temperature and moisture measurements) should be made available on the World Weather Watch (WWW) network to the meteorological services and other agencies in the same way as other satellite meteorological observations. World wide coordination for retrieval, processing and dissemination of the data will have to be established. The requirement of a specially designed data-assimilation scheme for climate modelling and validation is stressed.

2.5. Unique Contributions of the Atmospheric Profiling Mission

2.5.1. Climate Monitoring and Prediction

Climate monitoring of the temperature in upper troposphere and the stratosphere is obtained at the present time by two ways, the international network of radiosondes and operational meteorological satellites. Both methods suffer from a number of limitations (e.g. low accuracies, low vertical resolution).

Temperature data obtained with the radio occultation technique have several advantages compared to existing techniques:

- Contrary to present satellite and radiosonde data, the basic measurement is a Doppler shift or time delay measurement which can be made with very high accuracy. It is possible to use data from different satellites without requiring large intercalibration efforts. As a consequence, the lifetime of each satellite is not critical and it is possible to compare two datasets separated by many years.
- The measurements have a global and evenly distributed coverage, which is not the case for radiosondes which are mainly limited to continental areas.
- The measurements have an all-weather capacity, which is not the case for passive infrared sounders which are limited by cloudiness.
- The measurements have a very high vertical resolution (1 km or better), which is not the case for the present nadir viewing sounders.

A good knowledge of the climatology of water vapour in the lower tropical atmosphere is essential for furthering understanding of the full atmospheric system. Radio occultation data will give an essential input. Spatial and temporal coverage and accuracy would be met by the requirements for meteorological analysis.

2.5.2. Atmospheric Analysis and Modelling

A series of radio occultation receivers on LEO satellites would provide observations highly complementary to those provided by present/planned observation networks. It would make an important contribution towards closing the gap between the requirements of atmospheric research and NWP for observations and the capability of present/planned systems to supply them.

Radio occultation observations would be distributed roughly uniformly over the world. They would provide soundings at higher vertical resolution (but lower horizontal resolution) than passive sounders, and thus address the main limitation of the present systems. They would be particularly valuable in cloudy areas, which will not be covered adequately by advanced infrared sounders.

They would provide observations of high quality on upper tropospheric temperature and would also provide substantially improved observations of temperature over the full depth of the stratosphere, with high vertical resolution and absolute accuracy.

For water vapour, if the expected accuracy, vertical resolution and coverage described in section 2.1 are realised, these observations would be a major new source of information, particularly valuable over data sparse regions and in cloudy areas.

2.5.3. Ionospheric Research

Ionospheric data as provided by the radio occultation technique are unique in their space/time coverage and vertical resolution for electron density measurements. Existing ground-based techniques provide, due to sparse station coverage, quite limited data coverage. With the exception of employing Incoherent-Scatter (IS), no technique yields full density profiles for both the bottomside and the topside ionosphere.

Radio occultation data are highly complementary to existing ground-based data, in particular ground-to-satellite TEC data as provided by VHF/UHF radio-beacon receivers and an increasing number of GNSS receiving stations. The ionospheric imaging and tomography potential, severely limited with ground-based techniques alone, is enormously enhanced by the radio occultation technique. The combination of a multi-LEO receiver constellation with ground-receiver networks opens an entirely new era for ionospheric remote sensing of unprecedented resolution and quality.

From the point of view of data quality and value, the electron density data from the radio occultation technique are comparable to data from the IS technique (the leading ground-based technique), if tomographic reconstruction is applied. The radio occultation data cannot replace IS data but they can greatly enhance the knowledge on electron density distributions where no IS stations exist and since IS facilities are not operated continuously for monitoring but on a project-oriented, campaign basis.

2.5.4. Summary

Table 2.2 summarises the unique contributions expected from the Earth Explorer Atmospheric Profiling Mission per application.

Climate monitoring and prediction	– high absolute accuracy – long-term stability and consistency – high vertical resolution
Atmospheric analysis and modelling	– high vertical resolution – all weather capability – high accuracy
Ionospheric research	– unique space/time coverage and resolution – enhanced ionospheric imaging potential – quality same as leading ground-based technique

Table 2.2. *The Unique Contributions from the Earth Explorer Atmospheric Profiling Mission*

3. Research Objectives

3.1. Climate Monitoring and Prediction

The main objective for climate monitoring and prediction are

- to provide a global climatology of the temperature in the upper troposphere and lower stratosphere at very high absolute accuracy (< 0.2 K) and vertical resolution (1 km);
- to support research into climate variability and change (inter-annual and intra-annual) and into the energetics of the climate system over the period of the mission, and thus to contribute to the observational input and validation of models used to predict future trends and variability;
- to monitor water vapour in the lower/mid troposphere over the period of the mission and to support research on trends and variability of the hydrological cycle.

3.2. Atmospheric Analysis and Modelling

In addition, for atmospheric analysis and modelling, the mission could provide vertical profiles of atmospheric refractivity from which profiles of temperature for the stratosphere and upper troposphere and profiles of water vapour for the troposphere could be derived. It could provide profiles of temperature and humidity with the same accuracy under all weather conditions for assimilation into NWP systems in near real-time to improve the accuracy of weather forecasts. Together with other observations and through data assimilation systems used in delayed mode, long consistent sets of atmospheric states for research and model development could be established.

3.3. Ionospheric Research

The main objectives for ionospheric research are

- to provide TEC data for diagnosing ionospheric variability and for ionospheric profiling, imaging and tomography;
- to provide bending angle data for deriving characteristics/properties of the ionospheric ‘E-layer’;
- to provide phase and amplitude data for ionospheric small-scale irregularity and radio wave scintillations research.

4. Observational Requirements

4.1. 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 possible 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 (Figure 2.7). These trends may be masked by the natural variability of the atmosphere (El Niño – Southern Oscillation, Quasi Biannual Oscillation, volcanic eruptions). The data will used by fitting them to climate models which include natural variability.

In order to have enough 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. The expected maximum systematic bias for water vapour in the lower tropical troposphere, due to biases in the temperature profile used in the retrieval, ranges from 2% near the ground to 5% at 6 km (Kursinski et al., 1995).

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 in nature 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 to 5%). Any bias caused by the diurnal cycle must be considered in the selection of orbits.

Climatological means should be derived on a regional basis. In order to be consistent with present climate models the Earth's surface should be divided into 2.5° boxes (in latitude and longitude). A network of 12 receivers on board LEO satellites would produce up to 13,200 temperature profiles per day over the globe corresponding to a mean value of 40 profiles per month in each region. Assuming a conservative value of 1 K for the individual random error in the upper troposphere/lower stratosphere (5-30 km), the expected random error for the monthly mean temperature in each individual region would be about 0.16 K, compatible with the desired accuracy of 0.2 K.

For water vapour measurements, the random error for a single profile is estimated to range from 7% at 2 km to 20% below 6 km in the tropical regions (Kursinski et al., 1995). The corresponding monthly mean random error will range from 1% at 2 km to 3% at 6 km also compatible with the expected bias of 2 to 5%. If more than 12 radio occultation satellites are available at the same time, the random error will be reduced accordingly or it will be possible to achieve the same accuracy with a higher horizontal resolution. The overall error can be reduced to the systematic error by averaging a large number of profiles. Due to the fact that the radio occultation technique is based on a time delay measurement, it is difficult to identify for temperature a single source of systematic error that is likely to be comparable with the random error.

In conclusion, the observational requirements for use of the radio occultation technique in climate monitoring are summarised in table 4.1.

	Temperature	Water Vapour
	high/low latitudes	high/low latitudes
Altitude range	0/8 to 50 km	0 to 6 km
Vertical resolution	1 km	0.5 km
Geographic coverage	global	40° S to 40° N
Horizontal averaging	2.5° lat. * 2.5° long.	2.5° lat. * 2.5° long.
Systematic bias	< 0.2 K	< 3%
Random accuracy (1 profile)	< 1 K below 30 km < 2 K from 30 to 50 km	< 20%
Number of profiles per grid box and month	> 40	> 40
Expected duration	> 10 years (using several satellites)	

Table 4.1. *Observational Requirements for Climate Monitoring*

Due to the large interannual variability of the atmosphere, radio occultation data obtained from the Earth Explorer Atmospheric Profiling Mission will certainly not give a definitive answer concerning the determination of long-term trends related to human activities. However, it will give a very precise fingerprint of the present state of the atmosphere and its evolution during the mission. It will furnish a database of very high value for comparison with predictions of climate models and with future global observations.

4.2. Atmospheric Analysis and Modelling

Statements of the characteristics of observations required for atmospheric analysis for use in operational meteorology and atmospheric research have been made in a number of documents, with minor variations. Most can be related to the statement of requirements endorsed by

WMO (1993) and JSTC (1995). It should be noted that the requirement represented by this statement is continually evolving as the applications evolve (e.g. the ability of atmospheric models to make use of improved observations). With this caveat, the 'requirements' of global analysis and forecasting for the next ~ 10 years are summarised in table 4.2.

	Horiz. res. (km)	Vert. res. (km)	Time res. (hrs)	Accuracy	Timeliness (hrs)
Temperature	50-100	0.5-1	1-6	1 K	2-3
Relative hum.	50-100	0.5-1	1-6	10%	2-3

Table 4.2. *Observational Requirements for Global Analysis and Forecasting.*

Additional comments:

- These represent 'maximum requirements', i.e. observations of higher specification would not add significant value. However, observations of lower specification (in one or more aspects) may still be useful (as is the case for all observing systems).
- The domain for the observations is global in the horizontal and from the surface to 30-40 km in the vertical. It is desirable but not essential for one observing system to monitor the whole domain; complementarity with other observing systems is relevant.
- Maximum requirements for local/regional analysis are similar, but more demanding in terms of horizontal resolution and timeliness.

Given the capabilities and limitations of the radio occultation technique and the realistically achievable radio occultation networks, it is reasonable to look for a radio occultation system that could meet the following requirements:

Temperature
Accuracy of 1 K at a vertical resolution of 0.5-1.0 km for a vertical range from 8 km to 30-40 km (with progressively extended coverage towards the surface at higher latitudes, and with coverage to the stratopause at lower accuracy, about 2 K).

Relative humidity
Accuracy of 10% at a vertical resolution of 0.5 km for a vertical range of 0-3 km from 50° N-50° S (with progressively extended coverage in the mid-troposphere at low latitudes).

Horizontal/time resolution
This is determined by the number of receivers (and their efficiency in yielding useable profiles). Even one receiver would provide a valuable contribution to the current observing

system, particularly in the Southern hemisphere. A network of about 50 orbiting receivers would be required to achieve a space/time resolution of 200 km every 6 hours.

The requirements for data processing are:

- Data should be pre-processed to provide refracted angle profiles corrected for ionospheric effects (level 1 products).
- Refractivity profiles (and then temperature/humidity profiles) should be retrieved (level 2 products).
- At least in the evaluation phase for these data, both level 1 and level 2 products should be made available to data assimilation centres.
- Profiles should be specified with a vertical interval that slightly over-resolves the inherent vertical resolution of the instruments (0.5-1.0 km, determined by the width of the first Fresnel zone at the tangent point). This suggest that a resolution of 0.1-0.3 km should be retained throughout the processing.
- Products should be made available in near real-time to data assimilation centres.

4.3. Ionospheric Research

Observational requirements for ionospheric research strongly depend on specific topics of interest, since the electron density in the ionosphere varies up to orders of magnitudes over a wide range of spatial and temporal scales. For this reason table 4.3 shows, as appropriate, different samples of requirements for major scientific issues/research objectives to be addressed by the radio occultation technique.

	Ionos. climatology monitoring and modelling	Ionos. weather monitoring and modelling	E-layer studies (conductivity mapping, etc.)
Horiz. resol. (km)	200-600	50-300	50-600
Horiz. domain (km)	global	regional	regional
Vert. resol. (km)	10-30	5-10	0.3-3
Vert. domain (km)	90-1000	90-800	90-150
Time resol. (hrs)	2-4	0.1-2	0.1-4
Time domain (yrs)	> 10	> 1	> 1
Accuracy. elec.dens. (%)	1-10	0.3-5	1-10
TEC (%)	0.5-5	0.1-3	0.5-5

Table 4.3. *Observational Requirements for Ionospheric Research*

The following remarks should be noted with respect to the above requirements of table 4.3:

1) These requirements are 'desired specifications': even if not all requirements are met observations would still provide an enormous advance.

2) The degree of fulfilment depends on the number of satellite receivers implemented. Even one receiver operating over one year would provide sufficient data for improving present empirical ionospheric descriptions. The satellite height provides an upper limit to the vertical domain accessible, thus altitudes above 800 km are desirable.

3) For ionospheric climatology monitoring/modelling a constellation of 12 LEO receivers operating over a decade could fulfil the requirements. Ionospheric imaging would be the primary data processing means. Over remote areas like oceans, 'fall-back' from imaging to profiling or model-assisted imaging would be necessary. Each receiver up to 12 would significantly enhance the data product, beyond that each additional 6-receiver-package up to about 50 receivers would add value.

4) The requirements for ionospheric weather monitoring/modelling could be met even by a few receivers. Tomography depends on the availability of ground-based TEC data.

5) For ionospheric research the small satellite option would be desirable since in this case the orbits can be chosen optimally. Specifically, ionospheric research would prefer orbits above 800 km and sampling across different local times.

5. Mission Elements

5.1. Introduction

The system implementing the Earth Explorer Atmospheric Profiling Mission includes four different elements:

- the radio-navigation signal transmitters, i.e. currently the GPS and GLONASS satellite constellations;
- the on-board instrumentation, i.e. the precision receivers and related antennae carried on-board LEO spacecraft;
- the ground network of reference receivers;
- the data collection and processing ground facilities.

Before describing these four elements in chapter 6, it is worth noting that the Atmospheric Profiling Mission is unique in two respects. First, its implementation is simple, since a large space infrastructure is exploited, namely the radio-navigation satellite constellation, which already exists. Preparatory work is underway in Europe and elsewhere to augment this system. For the Atmospheric Profiling Mission, these developments ensure that the active part of the radio occultation sounding will be available for several decades with progressively enhanced performance.

Secondly, this mission can be progressively implemented, starting from a minimal configuration of a few orbiting receivers flying as passengers on LEO satellites, up to a constellation of receiver-carrying micro-satellites. Even a couple of orbiting receivers would be able to provide a number of atmospheric profiles comparable to that obtained from the existing network of radiosondes. Each receiver is small and thus could be carried as a co-passenger payload on most future Earth observation satellites or other suitable space missions. The observations are well distributed over the entire Earth, provided the orbit is a highly inclined one.

5.2. Discussion of Implementation Options

A cautious consideration of the observational requirements, described in chapter 4 above for the different scientific issues to be addressed by the Atmospheric Profiling Mission, leads to several important conclusions on possible implementation options for this Mission. These are discussed below, according to increasing levels of usefulness and value, and finally summarised. The primary ingredients for adding value are increasing the size of the LEO satellite constellation and adding flexibility in orbit selection. Multiple receivers are desirable since each additional GNSS receiver, as long as the total number is small, adds substantial value to a radio occultation system. Figure 5.1 shows, as an example, the coverage with

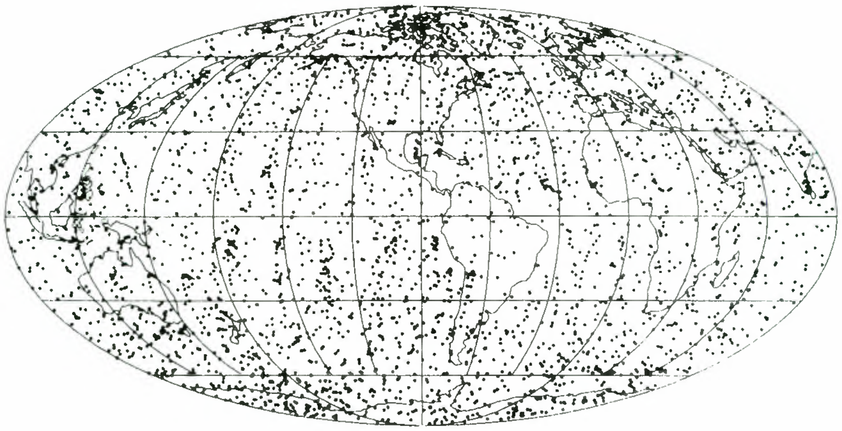

Figure 5.1. *The Figure shows a simulated global distribution of occultation events for six hours when tracking both GPS and GLONASS signals. Setting and rising events (3220 total) for twelve GNSS receivers evenly distributed in two orthogonal orbital planes at 80° inclination, assuming a typical azimuthal antennae field-of-view of 45° about the orbit plane. The map projection is an equal area (Mollweide) projection, which well shows the increase in measurement density at the mid and higher latitudes*

atmospheric profiles for a 6-hour period for 12 receivers tracking the GNSS satellites from LEOs at 800 km altitude and 80° orbital inclination. About 3200 useful occultations, which are almost equally (though irregularly) distributed over the globe are available within the 6-hour period (plus more than 2000 useful ionospheric profiles – not illustrated).

Figure 5.2 gives an illustration of the gain in average horizontal resolution due to increasing the number of receivers in LEO. This horizontal resolution is a measure of the average geographical spacing of perigee paths of single occultation events covering the entire globe, and is to be distinguished from the physical horizontal resolution of retrieved atmospheric profiles which is typically about 300 km along ray paths (Melbourne et al., 1994). For instance, the 12-receiver constellation of Figure 5.1 corresponds to an average horizontal resolution of about 400 km in 6 hours. This illustrates well the value of multi-receiver constellations which provide much better horizontal coverage than a few single receivers.

Figure 5.2 further illustrates that horizontal resolution is a function of sampling time during which global coverage is desired. For reaching a resolution of 600 km with global coverage within each 4 hr interval (as desirable for ionospheric climatology monitoring according to section 4.3 above) a 12-receiver constellation would suffice (marked by an 'x'). For reaching a resolution of 100km/6hrs/global coverage (see table 4.2) with a stand-alone atmospheric profiling system, a 192-receiver constellation would be needed (marked by a '+'). Generally,

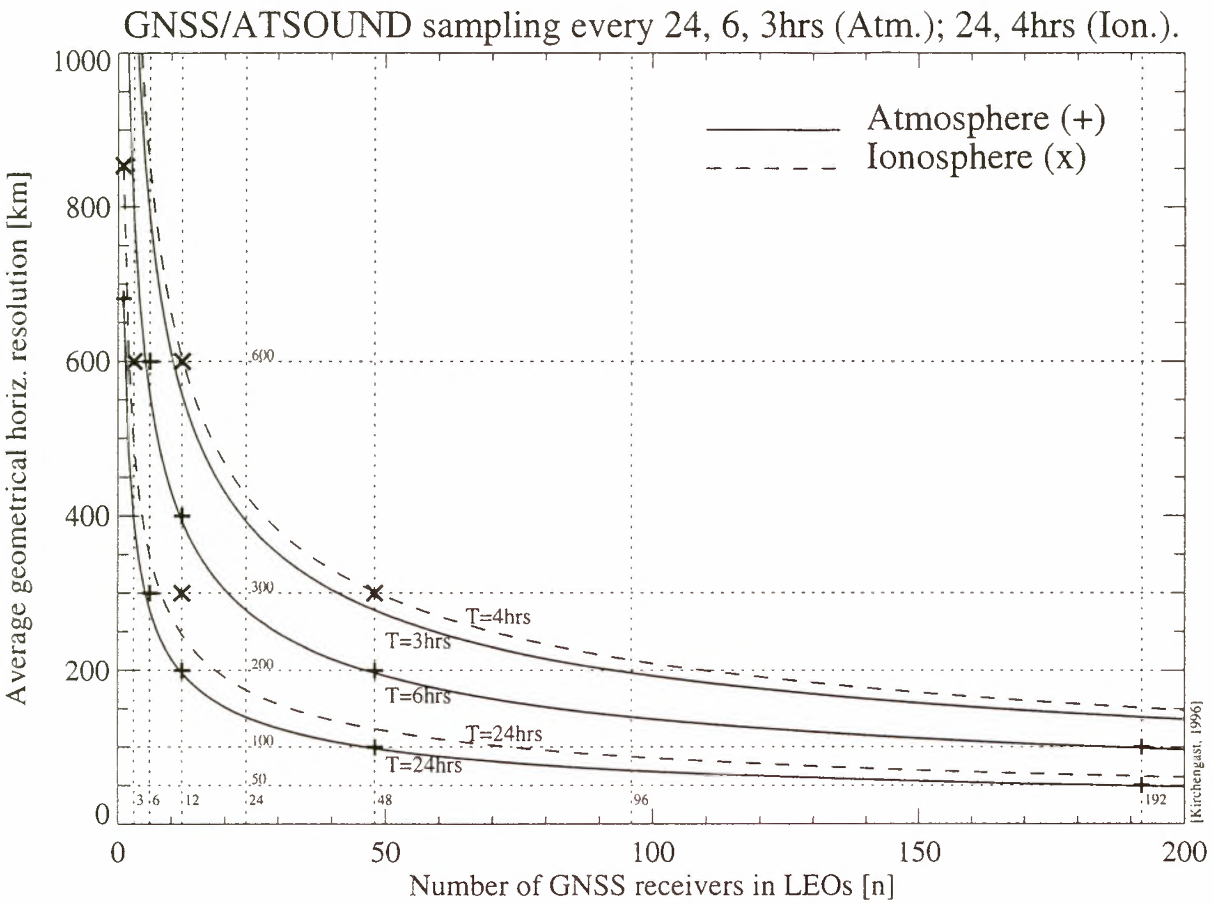

Figure 5.2. *This figure illustrates the dependence of average geometrical horizontal resolution on the size of the GNSS receiver constellation, given the time interval within which this resolution is to be globally achieved.*

the '+' and 'x' symbols mark different constellation options for some useful multi-receiver systems.

A relevant aspect besides the mere number of receivers is their distribution on LEO satellites. From this point of view a dedicated micro-satellite Atmospheric Profiling Mission is preferred over a co-passenger payload on platforms of other LEO missions. The former allows us to select orbits which best serve radio occultation requirements.

Generally, two orbit selection strategies can be considered:

1) Optimisation for balanced global and temporal coverage which globally provides the horizontal resolution according to Figure 5.2 avoiding systematically sparser regions remaining for sub-optimal co-passenger orbits. Orbits would be chosen with inclinations around 75°-80° with several receivers per orbit and with nodes longitudinally well distributed.

2) Clustering of receivers to achieve increased space resolution at the expense of global coverage within a given time interval. As an example, 12 moderately clustered receivers would, differing from Figure 5.2, achieve a horizontal resolution of better than 200 km within 6 hrs but covering only a quarter of the globe. Observations of smaller-scale atmospheric structures could benefit from such higher horizontal resolution.

In summary, considering a trade-off between what is desirable for the fulfilment of the observational requirements as:

- homogeneous global coverage,
- with adequate sampling of the diurnal cycle,

and what is a realistic perspective for the Earth Explorer Atmospheric Profiling Mission, the overall conclusion can be a ranking of implementation options as given in table 5.1 below.

An entry into both the dedicated mission and the co-passenger column (options 1 and 3) means a combined Mission employing both approaches and providing the advantages of a dedicated mission while at the same time making best use of available platform resources. The orbit selection for a dedicated mission (options 1 to 4) should be a matter of detailed constellation scenario studies clarifying the space-time distribution of radio occultation events which best addresses the research issues of concern. Comparing the value of the options in general (as indicated by the right hand column), the first option performs most effectively and would be a leading and key contribution in a global perspective.

Ranking of options	Dedicated small-sat. mission (number of receiv.)	Receivers as co-passengers on other LEO platforms	Contribution of the Atmospheric Profiling Mission to the exploitation of the radio occultation technique, compared to other radio occultation efforts worldwide
1	12	on at least 3	Leading contribution, key relevance
2	12	---	Leading contribution, very high relevance
3	6	on at least 3	Major contribution, very high relevance
4	6	---	Important contribution, high relevance
5	---	on at least 3	Worthwhile contribution, relevant

Table 5.1. *Earth Explorer Atmospheric Profiling Mission – the ranking of implementation options for meeting the observational requirements.*

5.3. Contribution to Other Missions

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

For these reason it is expected that several of the other Earth Explorer missions would benefit from the improved atmospheric profiling of temperature and water vapour:

- The Precipitation Mission (ESA, 1996 a) would benefit because of improved water vapour data which would make better determination of clouds and precipitation possible.
- The Earth Radiation Mission (ESA, 1996 b) would benefit from the improved temperature and water vapour through the depth of the atmosphere.
- The Atmospheric Chemistry Mission (ESA, 1996 c) would use the data from the Atmospheric Profiling Mission to obtain high-quality temperature data: for a better determination of stratosphere/troposphere exchange, the anthropogenic influence on the stratosphere, and the ozone budget and its possible depletion.
- The Magnetometry Mission (ESA, 1996 d) would benefit from the total electron content and electron density data supplied by this mission as these data would be an important contribution to studies of ionospheric currents and analyses of the geomagnetic field.

6. System Concept

6.1. Introduction

As already mentioned in section 5.1, the system concept for the Earth Explorer Atmospheric Profiling Mission includes four elements, namely the radio-navigation signal transmitters, the on-board instrumentation, the ground network of reference receivers and the data collection and processing ground facilities.

These elements will be described in some detail in sections 6.2 to 6.6. Detailed studies on the implementation of the overall system with constellations of small satellites have not yet been carried out. However some preliminary considerations are reported in section 6.6. These are mainly based on the observation and system requirements identified in chapters 4 and 5.

6.2. The Global Navigation Satellite Systems

The two presently available satellite-based navigation systems, the USA's GPS and the Russian GLONASS, provide highly accurate continuous measurements of position, velocity, and time to users worldwide (Parkinson and Spilker, 1995). The GPS constellation is fully operational since 1994, and the GLONASS constellation has been completed since the end of 1995. The operators of both systems have pledged to maintain them for open civil use for at least a decade. To that end, formal agreements have been established between the U.S. and Russian governments and the International Civil Aviation Organisation. A large international user basis exists today, which includes scientific applications in geodesy, ionospheric monitoring, precise orbit determination and ground-based meteorology.

GPS and GLONASS are based on the same idea, namely passive one-way ranging, and have much in common. Each constellation consists of 24 satellites placed in high Earth orbits with approximate altitudes of 20000 km and periods of about 12 hours. The GPS satellites are distributed over six equally spaced orbital planes with an inclination of 55°, whereas GLONASS uses three orbital planes with an inclination of 64.8°. Each satellite continuously transmits two signals in the microwave L band, at frequencies of 1575.42 MHz and 1227.6 MHz for GPS and in the bands 1597-1617 MHz and 1240-1260 MHz for GLONASS. The signals are generated from on-board atomic oscillators and modulated with pseudo-random codes and navigation data. Frequency generation and modulation are performed coherently, so that very precise timing signals are produced.

A user receiver can detect the signals and measure their transit time, as well as decipher the navigation data. From the travel time measurements from four or more satellites, the receiver position, velocity and time can be derived. In addition, the receiver can provide measurements of the phase of the received signals at the two frequencies to a high precision (sub-mm noise).

These measurements represent the integrated contribution of the frequency shift due to the Doppler effect caused by the orbital geometry and to the propagation effects in the atmosphere and ionosphere and are the primary observations which need to be collected for the Atmospheric Profiling Mission. Signal amplitude can also be measured, which may be useful for spectral analysis of the carrier signal.

6.3. The On-Board Instrumentation

The on-board instrumentation consists of a GNSS Receiver for Atmospheric Sounding (GRAS), possibly in a redundant configuration, with antennae mounted on the spacecraft aft side (anti-velocity direction) for observing set (descending) occultations and on the front side (velocity direction) for observing rise (ascending) occultations. An additional zenith-pointed antenna of small dimensions provides the hemispherical field-of-view needed for precise orbit determination.

Receiver technology has much advanced in recent years, in particular thanks to developments in very-large scale integration (VLSI) electronic circuitry, so that the development of a combined GPS/ GLONASS (GNSS) receiver with the accuracy required for atmospheric profiling and low mass, volume and power consumption is now feasible.

A receiver capable of collecting precise radio occultation measurements has the following main characteristics:

- multiple antenna inputs;
- dual-frequency operation with both GPS and GLONASS systems;
- precise measurement of the phase of the (L-band) carrier signals at both frequencies at a minimum sampling rate of 10 Hz;
- simultaneous reception of several signals (multiple parallel channels).

The multiple antenna inputs are required to accommodate both rise and set occultations, as well as reception of signals for precise orbit determination. Dual-frequency operation is mandatory to remove ionospheric effects (Ladreiter and Kirchengast, 1996).

A receiver with the characteristics outlined above has been designed and prototyped for ESA. The main specifications of GRAS are indicated in table 6.1. It features 12 parallel channels, which would be adequate for collecting radio occultation measurements with both transmitting systems.

The receiver operation is autonomous, requiring no ground intervention, and is outlined in section 6.5. It basically consists of a radio-frequency stage, a high-speed digital signal processing section implemented with VLSI technology, and a computer for overall receiver management. Sufficient computing power would be available to determine the receiver position, the position of GNSS satellites in full visibility or occultation and to perform other tasks using a 32-bit floating-point processor. The phase of the carrier signals constitutes the main observable and can be sampled at rates up to 100 Hz.

To measure the carrier phase of the GPS signal at 1.2 GHz the problem of the unknown modulation code imposed on such signal must be overcome. To this end, a high-performance codeless tracking scheme is used in the receiver signal processing. It results in a slight noise increase with respect to the measurement at the upper frequency, but it is still compatible with the use of these measurements for correcting ionospheric effects. This problem does not exist with GLONASS, which makes no use of encrypted modulations.

Number of parallel dual-frequency channels	12
Channel assignment to GPS or GLONASS	arbitrary
Carrier phase noise at 10 Hz tracking bandwidth	< 1 mm r.m.s.
Code phase (pseudo-range) noise at 1 Hz bandwidth	< 25 cm r.m.s. (GPS) < 50 cm r.m.s. (GLONASS)
Mass	< 3 kg
Volume	< 3 litres
Power Consumption	< 15 W
Data Rate	< 10 kbit/s
Nominal Dimensions	30 cm, 18 cm, 6 cm

Table 6.1. *Main GRAS Specifications (excluding antennae)*

The physical and data rate characteristics are also shown in table 6.1. The accommodation requirements in terms of mass, power and data rate are very modest.

An antenna pointed towards the Earth's limb along the satellite anti-velocity direction is required for collecting (set) radio occultation measurements. A second one pointed towards the Earth's limb along the satellite velocity direction is needed to observe also rise occultations. Signal acquisition during rise occultations needs also on-board prediction of the initial Doppler parameters of the signal crossing the lower troposphere. The antennae should be directional and provide sufficient gain to compensate for the signal attenuation which occurs at the crossing of the tropopause and in the lower troposphere, as well as to improve overall measurement performance.

An antenna array has been developed for ESA which provides sufficient gain in a field-of-view of +/- 45° in the azimuth direction (i.e., +/- 45° from the orbital plane for front or aft-mounted antennae). The array consists of a flat panel with a number of antenna elements. Three elements are used in the azimuth direction to obtain the required coverage.

The expected gain is in the range 6 dB to 10 dB, depending on the number of elements in elevation. The array is based on a suspended microstrip technology. Electrical beam steering by proper phasing of the elements can be used to avoid mechanically pointing the antenna towards the Earth's limb. The total mass for the largest configuration (5 by 3 elements) is conservatively estimated at 3 kg. This array has been prototyped and a demonstration model is planned to fly on the CHAMP satellite in 1999.

The antennae should have an unobstructed view of the Earth's limb from the front and aft spacecraft sides, with adequate margins in order to minimise the perturbing effect of signals reflected, diffracted or scattered by other spacecraft surfaces or appendages. This constraint has to be accounted for in the spacecraft configuration design. The antenna pointing requirements are easy to meet, since a pointing error of a few degrees will not affect the refracted angle estimates significantly. Since the fundamental measurement is that of an excess Doppler shift, the spacecraft angular rate around the vertical axis (yaw axis) has to be known to better than 1 mrad/s from the satellite attitude determination system in order not to introduce residual errors. This is easily achieved on most attitude-stabilised satellites.

6.4. The Ground Receiver Network

Separating the effect of the Doppler shift caused by the orbital motion of both transmitter and receiver from the propagation effects caused by the atmosphere requires the precise knowledge of the positions and velocities of both transmitter and receiver. This can be achieved using the measurements collected by the orbiting receiver and by a network of ground receivers.

Precise orbit determination is usually achieved by combining (differencing) measurements from different receivers (an orbiting one and a reference ground receiver) to different transmitters. This technique has the advantage of removing the effect of transmitter oscillator instabilities, which is particularly important with GPS. This system is affected by an intentional accuracy degradation implemented, among other means, as a pseudo-random oscillator instability. This degradation is entirely removed with the differential technique.

Ground networks of precision receivers are already in place for geodetic research and ionospheric monitoring. The foremost example is constituted by the International GPS Service for Geodynamics (IGS), established in 1994 by the International Association of Geodesy, with the objective of providing GPS data and data products to support geodetic and geophysical research activities. It includes more than 100 globally distributed permanent tracking stations and several operational, data and analysis centres. Upgrades at a number of tracking stations to collect also GLONASS measurements are expected to take place in the near future as geodetic-quality GPS/GLONASS receivers become commercially available.

In fact only a few stations are needed for the purpose of implementing differential techniques in support of the Atmospheric Profiling Mission. Six stations evenly distributed around the globe would provide sufficient coverage for this application. ESA participates in the IGS by providing ground stations equipped with precision receivers and by processing the data. Six stations are operational, at Maspalomas (E), Kourou (F), Kiruna (S), Perth (AU), Villafranca (E), and Malindi (Kenia). Further stations are planned. These stations will be available for the Atmospheric Profiling Mission. Because they are set up within operational ground stations, they offer adequate availability. They could also be operated in a near real-time scenario, as required for a pre-operational demonstration of the use of atmospheric profiling data for numerical weather prediction.

6.5. Mission Operation, Data Receiving and Processing System

Operation of the on-board receiver will be autonomous, requiring no ground intervention except at receiver switch-on for initialisation. The receiver software will perform the following functions:

- it initially sets the signal processing hardware for acquisition and tracking of the signals via the zenith-pointing antenna;
- it controls acquisition and demodulation of the signals, from which the receiver and transmitter positions are used to establish which signals are about to set or rise through the Earth's atmosphere;
- it sets the parameters of a few dedicated receiver channels (up to four) for reception of the occulting signals at a relatively high sample rate and through the appropriate directional antenna (located aft or front of the spacecraft);
- it automatically resets the channel when the occulting signal is finally lost, because of the strong tropospheric attenuation or because the signal is eclipsed by the Earth (set occultations) or outside the antenna field-of-view (rise occultations). The channel is then re-initialised to track the next occulting signal.

On average, there are no more than two occultations occurring with each system, GPS or GLONASS. Four channels are then reserved for collecting radio occultation measurements, namely amplitude and carrier phase data, which leaves a sufficient number of additional channels (8 in the case of GRAS) to track signals not eclipsed by the Earth's atmosphere. These data are needed to support the precise orbit determination. All the data collected are grouped into packets with the appropriate auxiliary information and stored in the on-board mass memory storage for transmission to ground during contacts with the ground station(s).

For a single receiver on a near-polar LEO satellite the average data rate does not exceed 10 kbit/s, resulting in an on-board data storage requirement of some 35 Mbytes if all the data is to be transmitted to a single high-latitude ground station. At least two high-latitude ground stations would be required to avoid transmission of data older than a few hours. The level 0 data will consist of time-tagged measurements of carrier and code phases and amplitudes of the occulted signals, as well as time-tagged carrier and code phases from non-occulted satellite signals. Auxiliary information from the spacecraft will be limited to attitude and angular rate data from the attitude determination system.

These data will be automatically decoded, quality checked and used together with the data collected from the network of reference ground receivers for determining the orbit of the receiver carrier spacecraft and for removing geometric effects (orbital Doppler) and the effect of transmitter oscillator instabilities. The pre-processed level 1a data will thus consist of validated phase and amplitude measurements and the related datation and location information. These data will be sent to the scientific data centre for further elaboration and archiving. Further data products may consist of:

- level 1b: phases, amplitudes, bending angles, impact parameters and related datation and location information (for both transmitter and receiver);
- level 2a: profiles of refractivity, obtained by inversion of the bending angle profiles, total electron content and related datation and location information;
- level 2b: profiles of atmospheric parameters (e.g. temperature, pressure, specific humidity) retrieved from the refractivity profiles and ionospheric parameters (e.g. electron density), and related datation and location information.

Error estimates and prior information will be included in each data set for all physical quantities. The overall data flow from the generation at the receiver on the satellite to the dissemination to the user community is depicted in Figure 6.1. The facilities required for processing the data from level 1a up to level 2b are not complex and could be easily set up within existing infrastructure.

6.6. Micro-Satellite Constellation Concepts

Although the mission implementation with co-passenger receivers is attractive from a cost standpoint, a system based on the use of dedicated satellites will provide the best solution in terms of performance, not only because of the larger number of orbiting receivers achievable, but also because it would avoid the disadvantages of a co-passenger solution, such as the use of non-optimal orbits and potential accommodation problems, e.g. local multipath interference.

The very modest instrument accommodation requirements lead naturally to a dedicated system based on the use of micro-satellites. These are spacecraft characterised by low mass and power (typically less than 50 kg and 100 W, respectively), high autonomy, and a streamlined manufacturing approach, thereby ensuring low system costs. Micro-satellites usually carry low data rate instruments with simple operational modes, which helps to contain the ground segment implementation and operation costs. Many developers of micro-satellites exist, several of them in Europe where substantial expertise can be found both in industry and in research institutions.

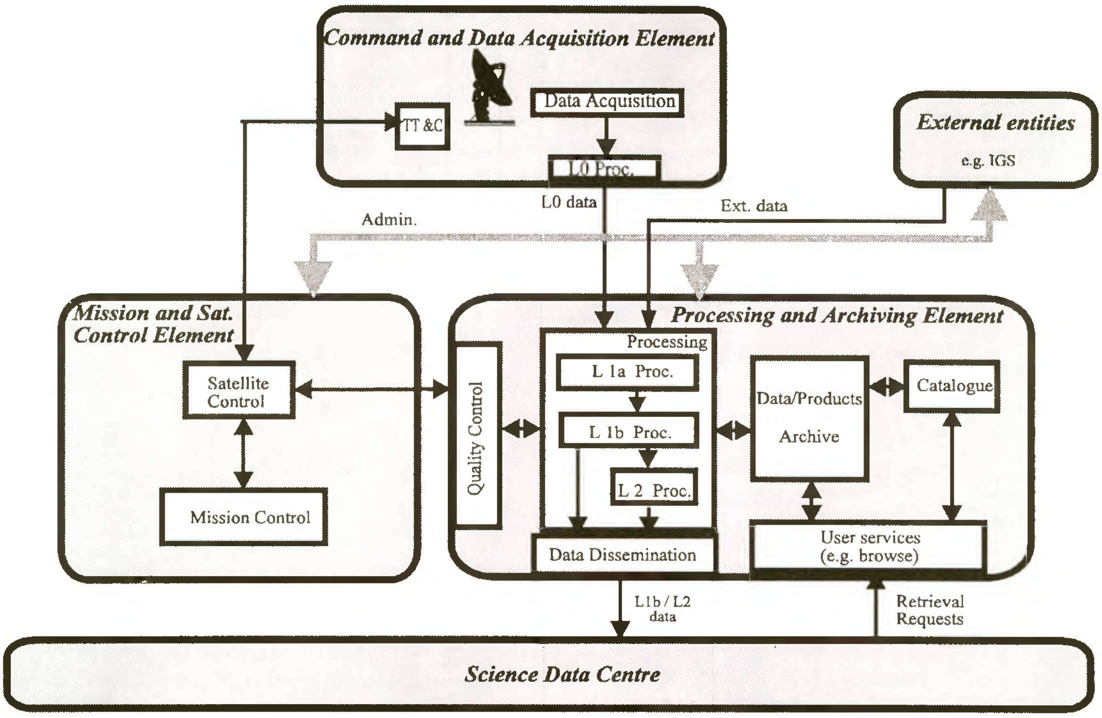

Figure 6.1. *Earth Explorer Atmospheric Profiling Mission Ground Segment*

The main system requirements for a constellation of micro-satellites for Atmospheric Profiling can be summarised as follows:

- twelve orbiting receivers with the capability to observe both rise and set occultations;
- highly inclined orbits, possibly in combination with a few LEO satellites in equatorial orbit.

An orbital altitude around 800 km would have advantages for ionospheric research. Several approaches which meet these criteria are conceivable, but not all of them result in acceptable overall costs. For instance, the number of orbital planes used has a direct bearing on the cost since it determines the number of launches. Constellations which minimise the number of orbital planes can be deployed with a smaller number of launches. Depending on the launcher characteristics, this number can be equal to the number of orbital planes.

As a first mission concept which meets the observation requirements and is highly cost-effective, a constellation of twelve micro-satellites distributed over two orthogonal orbital planes is an attractive one. Only two launches would be required, with six micro-satellites being injected into their orbit at each launch. The total mass of the six micro-satellites could be less than 200 kg, which is compatible with the performance of the available low-cost launch vehicles, such as the Eurockot, Pegasus XL, Taurus and LLV-2 launchers. The satellites would be equally spaced in each orbital plane, resulting in passes over the same ground point separated by approximately 16 minutes. For a near-polar orbit this scenario is compatible with the use of a single high-latitude ground station, possibly equipped with two antennae to communicate with two micro-satellites simultaneously in view of the station.

The choice of the orbital inclination is a compromise between operational aspects and observation capabilities. With respect to the latter, highly inclined orbits are mandatory to reach a good global distribution of the measurements, with a preference given to inclinations around 70 to 80°. From an operational standpoint, orbits of such high inclination offer the advantage that they are in visibility of a high-latitude ground station on 10 orbits out of 14 in one day. This would make a single ground station together with a small on-board mass memory sufficient for receiving all the data from the LEO satellites. Prograde orbits are preferred to sun-synchronous orbits because the latter give a constant 'temporal clustering' of the observations around the local solar times corresponding to the specific orbit plane. The low latitude regions would be mostly affected by this local time sampling, which is a disadvantage for data exploitation. Orbits at lower inclinations, e.g. at approximately 60°, suffer from a loss of ground visibility and from a reduction of the number of observations in the high latitude areas, where on the contrary a higher density of radio occultation measurements is desirable because of the large atmospheric variability.

Figures 6.2 to 6.5 provide an illustration of the coverage characteristics achieved with two different options. Both set and rise occultations with GPS and GLONASS are considered over a six hours period. The coverage for the antennae is restricted to +/- 45° from the orbital plane. Figure 6.2 shows the average number of profiles in a day for each 200 by 200 km^2 area as a function of the latitude for a constellation of 12 satellites distributed in two orthogonal orbital planes at an inclination of 80° (constellation concept A). The higher measurement density in the high latitude regions as compared to the low latitude ones is quite apparent. This can be compared with Figure 6.3, which shows the same quantity for a constellation with 8 satellites evenly spaced in a single orbital plane at an inclination of 80° and 4 satellites at 30° inclination (constellation concept B). The measurement distribution with respect to latitude is evidently improved in the latter case.

Figure 6.4 and 6.5 show the profile distribution as a function of the local time over a six hours period for the two constellation concepts A and B.

The selection of the constellation orbital parameters and the related ground segment concept will need further detailed studies accounting for observational and operational constraints.

Implicit in the concept of a constellation are two notable aspects: the intrinsically high availability, which is an important point for a pre-operational demonstration, and the reduction in costs achieved by the production of a large series of identical spacecraft. The high availability stems from the fact that a micro-satellite outage has only a minor impact on the observational capability. Development cost savings will accrue not only from the diminished relative weight of the non-recurring costs (design, qualification, etc.), but also because of the

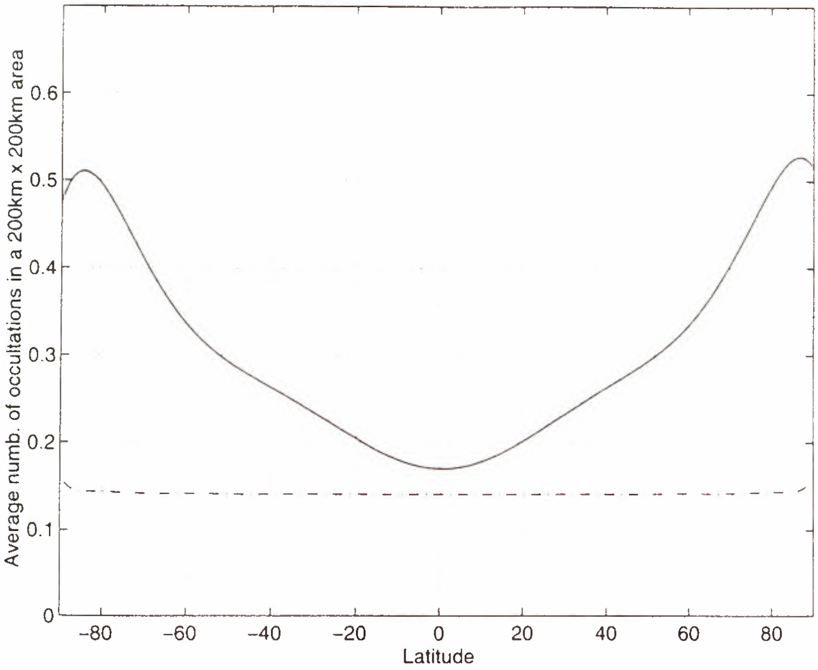

__Figure 6.2.__ Average number of profiles over a six hours period in a 200 by 200 km2 area as a function of latitude for a constellation of 12 satellites distributed in two orthogonal orbital planes at 80° Inclination. The average altitude is 800 km.

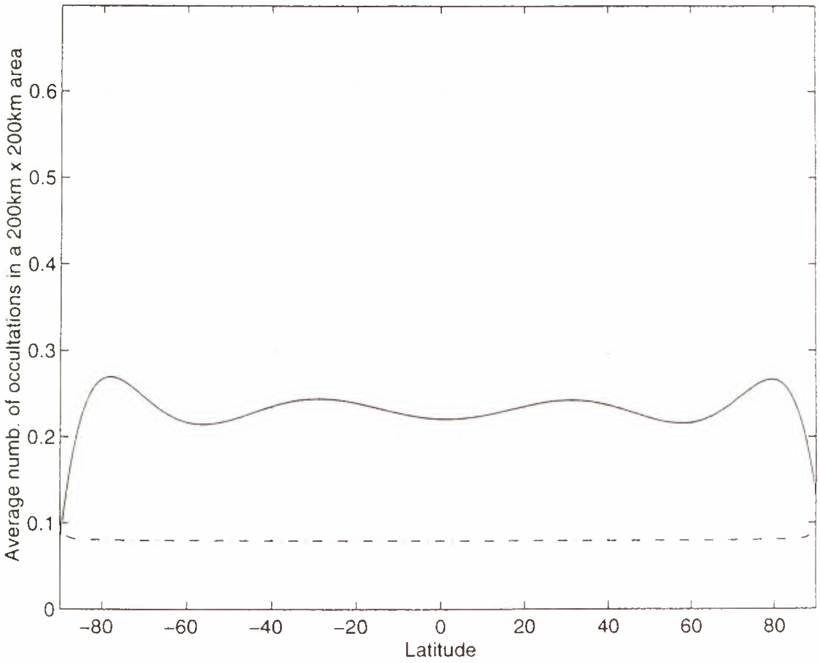

__Figure 6.3.__ Average number of profiles over a six hours period in a 200 by 200 km2 area as a function of latitude for a constellation of 12 satellites distributed in two planes, one at an inclination I = 80° and the other at I = 30°. The plane at higher inclination contains 8 equally spaced satellites. In both cases the average altitude is 800 km.

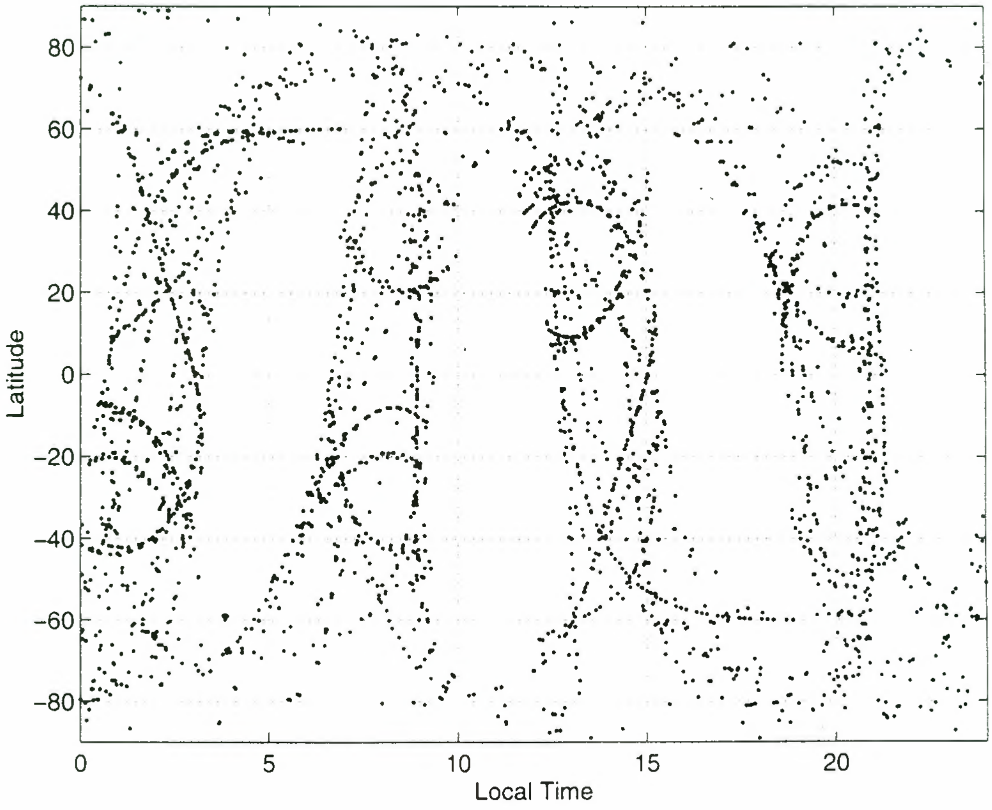

Figure 6.4. *Profiles distribution for constellation concept A in a six hours period.*

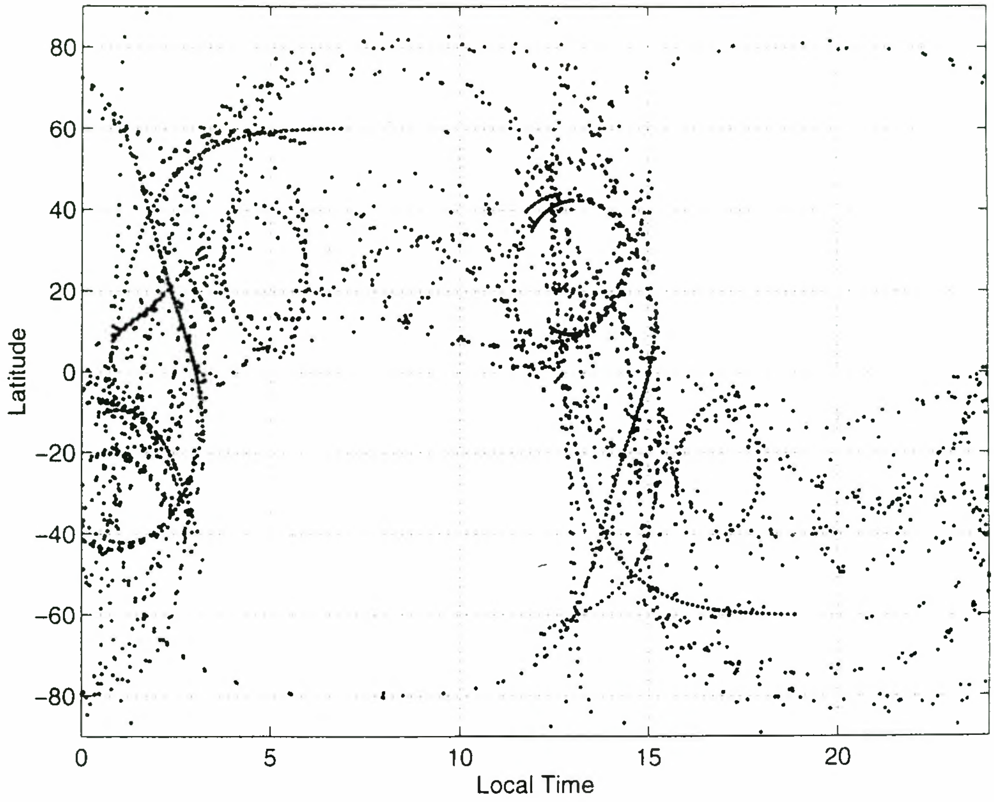

Figure 6.5. *Profiles distribution for constellation concept B in a six hours period.*

new and efficient production techniques being introduced for manufacturing large series of satellites for telecommunication constellations.

Because of the 'graceful degradation' achieved by the constellation of satellites when some fail, there would be no need for implementing full redundancy in either the payload or in the satellite subsystems. This will help to keep the microsatellite mass and power to low values, certainly less than 50 kg and 100 W, respectively. Concerning the satellite subsystems, the receiver could be adapted to provide also attitude determination data by an optimised multi-antenna scheme. This new function has already been taken into account in the development of GRAS. Attitude control can be performed by a combination of gravity gradient stabilisation and actuation with magnetic torquers, provided that the loss of control and the consequent data loss around the magnetic poles can be tolerated.

By designing the satellite with no large appendages it would be characterised by a relatively high ballistic coefficient, hence a slow orbital decay. An initial altitude of 800 km results in an orbital decay of less than 100 m per year and is compatible with a long lifetime without any on-board propulsion system. With no on-board consumables, the lifetime will depend only on the rate of degradation of the solar cells and other electronic devices caused by the in-orbit radiation environment. GaAs solar cells for electrical power generation have already been used extensively in past micro-satellites. Their high efficiency will help avoiding the use of deployed solar panels, which would otherwise create a difficult multipath environment for the occultation antennae.

At 800 km altitude a ground station pass will last about 10 minutes. An S-band communication link will provide a data downlink rate of up to 1 Mb/s, which is sufficient to receive on ground the contents of the on-board mass memory in a single pass. Up-link telecommands will be rather infrequent because of the autonomy and simplicity of the spacecraft subsystems.

6.7. Data Analysis Techniques

Through experience with GPS/MET data, analysis procedures already exist for pre-processing and processing radio occultation data to provide temperature profiles of useful accuracy. Further work is required (and is planned in the short term) to make similar demonstrations of processing for water vapour and electron density profiles. Plans are also in place to build appropriate interfaces between radio occultation data/products and NWP systems, in order to study assimilation techniques and forecast impacts. Further studies are required to demonstrate more advanced applications and the control of different errors in the refractivity measurements from a number of sources including:

1) Reference oscillator frequency drifts in the LEO satellite, GNSS satellite, or ground based GNSS tracking receivers;
2) Errors in receiver tracking;

3) Precision orbit determination;
4) Ionospheric effects that are not corrected by the dual-frequency phase measurements;
5) Tracking errors due to multipath effects in the lower troposphere; and
6) Departures from the atmospheric spherical symmetry assumed in the inversion algorithms.

Effort is required to solve these problems but no significant difficulties are foreseen.

7. Programmatics

7.1. General

The Earth Explorer Atmospheric Profiling Mission would be implemented in the frame of an ESA Earth Explorer Programme of research missions if selected after phase A studies carried out within the frame of the Agency's Earth Observation Preparatory Programme.

In analysing the programmatic aspects of the mission, its operational potential has been kept in mind, also because operational systems are a means for reliable provision of data for research. In this respect, the steps being taken to fly the GRAS instrument as part of the METOP payload are very valuable.

7.2. Critical Areas and Open Issues

The instrumentation for this mission, namely the specialised GNSS receiver, GRAS, and its antennae, are already being developed. Breadboard models have been tested and no special problems are expected in the continuing development of these items.

Although the initial results of simulation studies and experimental data reductions are promising, a number of technical and data analysis issues remain to be addressed in future activities. These include for instance the performance under various ionospheric conditions, the definition of optimised inversion methods, and, probably most important, the development of data assimilation methods which enable the data users to blend the radio occultation data with other observations in an optimal way. Ground segment aspects will have to be analysed in greater detail, especially if the radio occultation technique is to become part of the observation network for operational meteorology.

The implementation options identified in a preliminary way in the course of the preparations for this report will have to be evaluated to a proper depth.

7.3. Related Missions and Timeliness

The science data products of the Earth Explorer Atmospheric Profiling Mission are of direct relevance for several of the Explorer Missions: the Atmospheric Chemistry Mission, the Earth Radiation Mission, the Precipitation Mission and the Magnetometry Mission. The rationale for this is provided in section 5.3.

The U.S. GPS/MET experiment has provided the first set of experimental data. Other missions which will contribute to develop data exploitation techniques are the German mission CHAMP, planned to be flown in 1999, and, to a reduced extent because of payload limitations, the Danish mission Oersted. In addition, if the flight of the GRAS instrument within the METOP payload is confirmed, it guarantees the provision of some data in an operational context for several years from 2002.

The technical maturity of the payload development and the short development cycle typical of small satellites make it realistic to consider a constellation deployment early in the next century.

7.4. International Cooperation

In a co-passenger implementation scenario, one should consider also the possibility for providing instrument units to national European and non-European projects.

A dedicated constellation could also be developed in an international cooperation context. For instance, NASA is understood to be analyzing options very similar to those described in this report, though at present no firm plans exist. In all cases, any future constellation should be developed in cooperation with the relevant operational entities (e.g. Eumetsat) so as to ease a future transition to a monitoring system.

7.5. Enhancement of European Capabilities and Applications Potential

The research areas discussed in chapters 2 and 3, in particular the possibility to obtain improved climate models and a deeper understanding of atmospheric and ionospheric physics, have an important application potential for many human activities. The perspectives for an operational exploitation of the radio occultation technique are obvious, considering the opportunity offered to greatly improve the monitoring of the atmosphere and ionosphere for weather forecasting and other applications.

From a technological standpoint, it is worth noting that no space-qualified instrumentation has been developed so far. All the planned small missions previously mentioned use a modified commercial GPS receiver to gather their radio occultation data. The development activities initiated in Europe could result in the first space-qualified GNSS receiver, so providing European industry with a new technological capability.

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List of Acronyms

AIRS	Advanced Infrared Sounder
AMSU	Advanced MSU
ATOVS	Advanced TOVS
CHAMP	Catastrophe and Hazard Monitoring and Prediction
ECMWF	European Centre for Medium-range Weather Forecasts
GCOS	Global Climate Observing System
GLONASS	(Russian) Global Navigation Satellite System
GNSS	Global Navigation Satellite System (generic term)
GPS	Global Positioning System
GPS/MET	GPS Meteorology
GRAS	GNSS Receiver for Atmospheric Sounding
GSFC	Goddard Space Flight Center
HF	High Frequency
HIRS	High-resolution Infrared Radiation Sounder
IASI	Infrared Atmospheric Sounding Interferometer
IGS	International GPS Service for Geodynamics
IPCC	Intergovernmental Panel on Climate Change
IS	Incoherent Scatter
JPL	Jet Propulsion Laboratory
JSTC	Joint Scientific and Technical Committee (of GCOS)
LEO	Low Earth Orbiting
MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Administration
NCEP	National Center for Environmental Prediction (of NOAA)
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
SSU	Stratospheric Sounding Unit
TEC	Total Electron Content
TID	Travelling Ionospheric Disturbance

TIROS	Television and Infrared Observation Satellite
TOVS	TIROS Operational Vertical Sounder
UHF	Ultra HF
UV	Ultraviolet
VHF	Very HF
VLSI	Very-large Scale Integration
WMO	World Meteorological Organisation
WWW	World Weather Watch

European Space Agency
Agence spatiale européenne

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