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ACE+

Atmosphere and Climate Explorer

By

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ACE+

Atmosphere and Climate Explorer

Based on GPS, GALILEO, and LEO-LEO Radio Occultation

Proposal to ESA in Response to the
Second Call for Proposals for Earth Explorer Opportunity Missions

by

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Executive Summary

The ACE+ mission will contribute in a significant manner to Science Theme 2 – *Physical Climate* – and Science Theme 4 – *Atmosphere and Marine Environment* – of the ESA Living Planet Programme.

ACE+ will considerably advance our knowledge about atmosphere physics and climate change processes. The mission will demonstrate a highly innovative approach using radio occultations for globally measuring profiles of humidity and temperature throughout the troposphere and stratosphere. The mission will provide data of remarkably high accuracy, density and resolution, leading to new methods for testing and improving global climate models and predictions within the planned mission lifetime of 5 years.

A constellation of 4 small satellites, tracking L-band GPS/GALILEO signals and X/K-band LEO-LEO cross-link signals, will map the detailed refractivity profile and structure of the global atmosphere from the Earth's surface to the top of the stratosphere. Detecting predicted climate change trends of the troposphere within a decade requires refractivity accuracies corresponding to around a tenth of a Kelvin. We propose to test the predictive capability of global climate models by using atmospheric profiling occultation observations from the ACE+ constellation of satellites to search for and quantify forced climate signals, predicted by existing climate models. An important asset of utilising the radio occultation technique is its "all-weather" capability due to the long wavelengths involved (centimetre and decimetre waves). Furthermore, the measurements feature exceptional long-term stability due to their self-calibrating nature, a feature that is of key importance for climate change monitoring.

The ACE+ mission is very timely. It complies with the objectives and requirements for a wide range of international programmes and conventions, including: UN Kyoto Protocol, IPCC, WCRP CLIVAR and GEWEX programme, WMO GCOS (Global Climate Observing System), WMO satellite requirements, SPARC recommendations, EU GMES Programme, and several EU COST Actions.

The proposed mission will be highly complementary to other ESA missions and to other planned European observation systems with participation from EUMETSAT and EU. Moreover, it will place Europe in a leading role internationally, since other planned occultation-based observation systems will only provide additional temperature coverage if they eventually get approved. The LEO-LEO part would be a genuinely novel demonstration.

Finally, the ACE+ mission is based on comprehensive scientific and technical ESA studies since 1995, especially on the ACE (Atmosphere Climate Experiment) and related small satellite constellation missions, supplemented with results from recent ESA studies including on the proposed WATS Earth Explorer Core Mission. The ACE+ implementation is based on a strong heritage from previous satellite designs and foresees extensive use of commercial components. A European scientific core team of more than 10 institutions and a worldwide science user team of a dozen institutions support the proposal and are keen to realize its promise. Furthermore, an industrial consortium composed of leading companies from a range of ESA's smaller and larger member states and with substantial experience and success in implementing small satellite missions has been instrumental in preparing the proposal. Hence the overall risk of the project is considered to be low.

A concise summary of the scientific background, research objectives, observational requirements, mission elements, and system concept is given in the following summary sheet.

ACE+ — Atmosphere and Climate Explorer

Based on GPS, GALILEO, and LEO-LEO Radio Occultation

Scientific Background

Accurate observations of humidity and temperature in the troposphere and stratosphere - including their variability - are highly important in climate change research (IPCC, 2001). ACE+ serves this need with the mission goals:

- To **monitor** climatic variations and trends at different vertical levels and for each season. This to improve our understanding of the climate system as well as to detect the different fingerprints of global warming;
- To **improve the understanding** of climatic feedbacks defining the magnitude of climate changes in response to given forcings;
- To **validate** the simulated mean climate and its variability in global climate models;
- To **improve** and tune - via data assimilation - the **parameterisation** of unresolved processes in climate models and to detect interannual variations in external forcing of climate.

Research Objectives

Main objectives:

- to establish a **highly accurate** and **vertically resolved climatology of humidity** in the troposphere with global all-weather measurements of its concentration,
- to establish a **highly accurate** and **vertically resolved climatology of temperature** in the troposphere and stratosphere with global all-weather measurements of its vertical structure,
- to support **research on climate** variability and climate change and on **validation and improvement of atmospheric models**,
- to support **advancements on NWP** (Numerical Weather Prediction),
- to support **analysis and validation of** data from **other space missions**,
- to **demonstrate a novel active** self-calibrating atmospheric **sounding method**.

Spin-off objectives:

- ionospheric climate & weather and space weather investigations,
- assessing and improving present water vapour attenuation models.

Mission Elements

Space segment:

Small constellation of micro-satellites each of them carrying two instruments:

- a precision L-band receiver and related antennae for GPS/GALILEO-LEO occultations,
- a precision X/K-band transmitter (on 2 sats) and receiver (on 2 counter-rotating sats) and related antennae for LEO-LEO occultations (3 frequencies).

Ground segment:

- Satellite operation and control
- Fiducial stations for Precise Orbit Determination
- Level 1b processing and archiving centre
- Science data centres for higher level product generation and for data assimilation

Data products:

Profiles of bending angle and absorption, and retrieved profiles of refractivity, humidity, temperature, and pressure as function of height. Data products will be made available to data assimilation centres in near-real time.

Observational Requirements

Horizontal coverage	global
Horizontal sampling	< 500 km (LEO-LEO per month)
Vertical domain	surface – 15 km (humidity) surface – 50 km (temperature)
Vertical sampling	0.5–1 km
Temporal sampling	< 12 hrs
Accuracy of humidity	< 0.025–1 g/kg rms
Long-term stability humid.	< 2% RH / decade
Accuracy of temperature	< 1 K rms
Long-term stability temp.	< 0.1 K / decade
Spatial distribution	homogeneous over each day
Local time distribution	homogen. over a few months
Mission duration	> 5 years

System Concept

- 4 micro-satellites
  - – mass: ~130 kg
  - – power: ~80 W
- in a stable constellation – to optimise the quality of occultation measurements (two counter-rotating orbits with 2 satellites each),
- two altitudes (650 km and 850 km) – to optimise the spatial distribution of occultations,
- orbits drifting in local time – to optimise the temporal (local time) distribution of occultations.

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Reference Documents

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ESA, 1996: *Atmospheric Profiling Mission*, ESA SP-1196(7).

ESA, 1998: *Report of the ESA/EUMETSAT GRAS-SAG – The GRAS Instrument on METOP*, Doc.No. VR/3021/PI (ESA), EPS/MIS/TN/97805 (EUM).

Kirchengast, G., et al., 1998: *ACLISCOPE – Atmosphere and Climate Sensors Constellation Performance Explorer* (ESA Opportunity Missions proposal 1998), IGAM/UG Scientific Report, No. 4/1998.

Høeg, P., and G. Leppelmeier, 2000: *ACE – Atmosphere Climate Experiment* (ESA Opportunity Missions proposal 1998), DMI Scientific Report, 00-01.

ESA, 2001: *WATS – Water Vapour and Temperature in the Troposphere and Stratosphere*, ESA SP-1257(3).

These references are the key documents on ESA related heritage of the ACE+ mission, including lists of references to the full body of the relevant scientific literature.

1. Scientific Justification

1.1 Introduction

1.1.1 Heritage and Previous ESA Initiatives

The ACE+ proposal and objectives are, concerning GNSS-LEO occultations, based on detailed scientific and technical phase-A studies of the *Atmosphere Climate Experiment* (ACE) mission (Høeg and Leppelmeier, 2000) and experiences with the instrument development of the GRAS receiver for the EPS/METOP mission (ESA, 1998).

ACE was selected as the third Opportunity Mission ("hot standby") in ESA's first selection of missions to this element of the ESA Living Planet Programme. The team of the second occultation mission proposed in that first round – *Atmosphere and Climate Sensors Constellation Performance Explorer* (ACLISCOPE) mission (Kirchengast et al., 1998) – joined with the ACE team immediately after the evaluation process.

ACE (and ACLISCOPE) enjoyed, in turn, already considerable heritage from the *Atmospheric Profiling Mission* (ESA, 1996) proposal within the first round of Earth Explorer Core Missions, encouraged by the promise of initial ESA supported radio occultation work by Høeg et al. (1995) and other non-European (mainly U.S. and Russian) activities.

More recently, the *Water Vapour and Temperature in the Troposphere and Stratosphere* (WATS) mission (ESA, 2001) proposed in the second round of ESA Earth Explorer Core Missions – and one of the five final candidate missions – extended the capabilities of radio occultation measurements by adding the LEO-LEO inter-satellite observations for enabling unique tropospheric water vapour measurements. The LEO-LEO technique, which is new and novel with an unprecedented accuracy, has now been included in the ACE+ mission.

In summary, the best elements from all previous work, and the profound experience acquired by doing that work, have been carefully gathered and distilled for this ACE+ mission proposal.

1.2 Science Review

1.2.1 Climate Change

Observations indicate that arctic stratospheric winter temperatures are decreasing. The lowest temperatures in winter seasons occur now in combination with more stable and long-lasting arctic vortices. It is therefore important in the coming years to observe if winter temperatures continue to decrease, leading to more widespread polar stratospheric cloud formation, more stable polar vortex conditions, and stronger ozone depletion.

The atmospheric mass field, characterised by temperature, pressure and water vapour, dominates the main features of the large-scale atmospheric wind systems via the geostrophic balance. This, together with the fact that massive amounts of latent heat are transported via the atmospheric dynamics and released in areas of condensation, underlines the importance of water vapour and temperature in controlling the atmospheric circulation. The latest IPCC scientific assessment report concluded that the bulk of the observed global warming in the last century mostly was due to natural processes, like solar and internal climate variability. However, the more recent warming during the last 20 years is attributed to the increased emission of greenhouse gases, mainly caused by human activity. This conclusion originates from coupled atmosphere-ocean model simulations and re-analysis studies. Climate change predictions indicate that the surface temperature of the Earth, globally averaged, may increase from 1.4° to 5.8° over the period of the next hundred years.

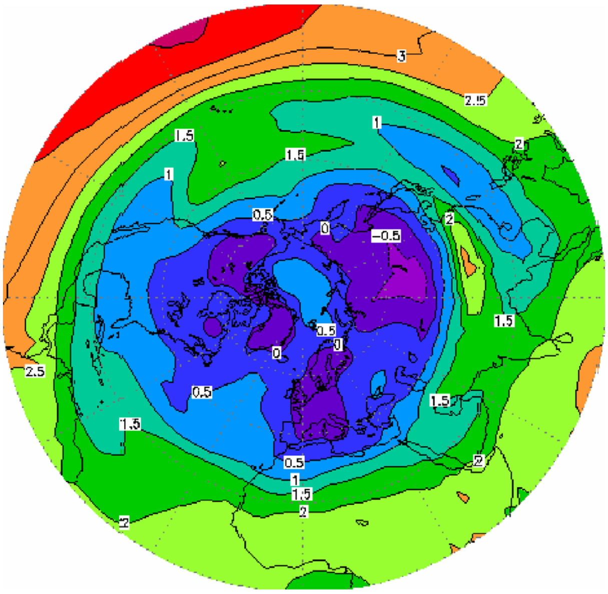


Figure 1. Mean tropopause temperature changes in the Northern Hemisphere. The plotted variations are the mean of the annual differences, when comparing the global re-analysis results covering the periods 1958-1977 and 1978-1997.

Central to most of the least understood internal feedbacks of the applied climate models are those associated with water vapour, giving rise in part to the above span in the temperature increase estimates. Mechanisms of water vapour remain poorly understood because the climatology and atmosphere processes have not been observed with the accuracy, precision, and coverage necessary to understand them. Thus accurate observations of the present temperature and humidity climate, including its variability, are highly important in climate change research as well as in weather forecasting. Establishing unbiased observations of global water vapour and temperature fields throughout the troposphere is the goal of ACE+. The extensive database from the mission will lead to improved understanding of the climatic feedbacks defining the magnitude of climate change and the inter-annual variations in external forcing.

Since chaotic processes dominate the climate system on short time scales, most of the variations in troposphere temperatures and other quantities on time scales up to decades are purely random and not related to external forcing of the climate. To identify variations in external forcing using a short data set of 5 years requires that the chaotic component can be removed. One method to achieve this is to assimilate the ACE+ profiles into an atmospheric climate model throughout the mission period. Together with data sets from other missions the occultation data will give an unprecedented long-term reliable data set for the direct detection of climate trends due to the self-calibrating nature of the occultation measurements.

1.2.2 Stratosphere and Troposphere Weather Forecast

The mission is designed mainly for research on the atmosphere and climate. But it is important to note that the data produced are highly valuable for weather forecasting, too. At present our observational information on the three-dimensional temperature and humidity over the oceans and the tropics is limited to few radiosonde stations and the relatively inaccurate and coarse vertical soundings of temperature and humidity from the orbiting NOAA satellites. This severely limits the predictability over the continent of Europe in relation to synoptic disturbances developing over the North Atlantic Ocean. There are numerous examples of forecasts missing severe extra-tropical lows, which can be ascribed to missing or incomplete upper air information over the ocean west of Europe. Therefore deficiencies in the current observing system degrade present day weather forecasting. Not only improved temperature and humidity observations are needed to improve the weather prediction skills. Mutual information on wind and mass field must be known in modelling the atmosphere state. In general, information about the wind field is relatively more important than mass field information in the tropics. However for synoptic and larger scale disturbances in the extra-tropical regions there is little doubt that high quality mass field observations over the oceans are the main factor limiting the skill of operational numerical weather prediction systems. Taking into account that data delivery from ACE+ may be achieved within a 3-hour time window makes the mission very attractive for weather forecast and atmospheric analysis.

1.2.3 Satellite Based Atmosphere Profiling

The radio occultation technique has been using signals from the Global Positioning System (GPS) to measure phase and amplitude changes caused by the atmosphere. The observations have been done from low Earth orbiting (LEO) satellites. In the ACE+ mission the GRAS+ (Advanced GRAS) instrument will provide such data for both GPS and GALILEO with unprecedented coverage. The retrieved vertical profiles of the refractive index are used to extract information on temperature, pressure, and humidity as a function of height in the troposphere and stratosphere.

In order to improve the separation of the contributions of water vapour and temperature in the lower troposphere, without using external data, ACE+ will also actively sound the atmosphere using LEO-to-LEO signal transmission at three frequencies around the 22 GHz water vapour absorption line (10, 17, and 23 GHz). Measurements of the occulted phase and amplitude of the electric field from the LEO transmitter at these frequencies will deduce independent information on both temperature and water vapour profiles, which will lead to unprecedented precise atmosphere data. This technique was also suggested in the WATS Core Mission proposal to ESA's Earth Explorer Programme (ESA, 2001).

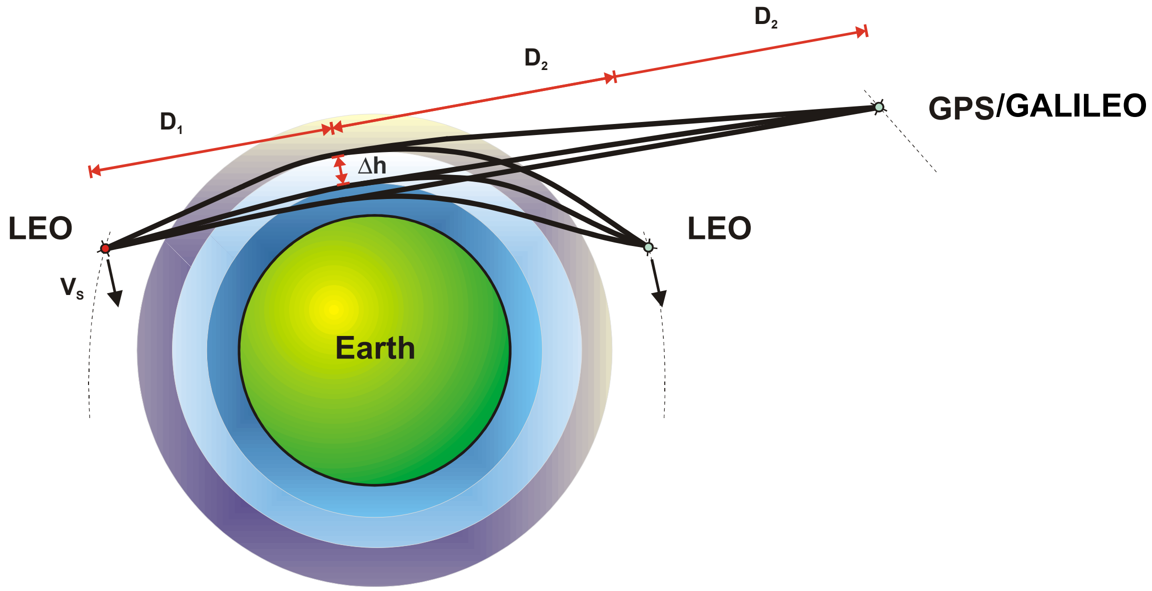


Figure 2. Schematic presentation of the geometry of observations for the retrieval based on the LEO-LEO measurements and the GRAS+ observations (GPS/GALILEO-LEO).

1.2.3.1 Humidity and Temperature Profiling using CALL

The new and novel observations performed by the CALL (Cross-Atmosphere LEO-LEO) instrument in the ACE+ mission will focus on measuring amplitude and phase at different frequencies in order to resolve the main terms for intensity changes in the received signal. Water vapour absorption as function of frequency is not symmetric around the 22 GHz absorption line and also liquid water contributes to absorption (see Figure 3). However, combining three frequencies can essentially remove the effect of liquid water droplets in clouds from the process of estimating the profile of tropospheric water vapour.

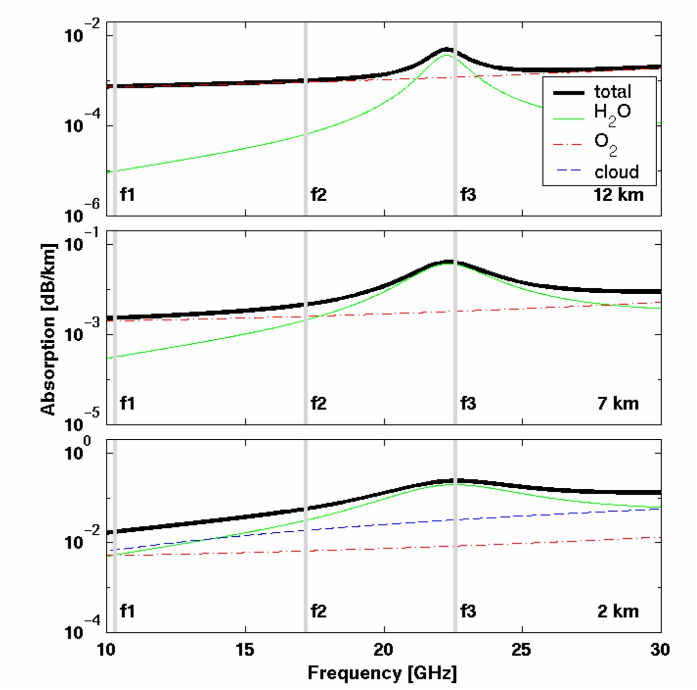


Figure 3. Absorption due to the atmosphere as function of the frequency at three different height levels (2 km, 7 km, 12 km). The suggested three X/K-band frequencies are indicated (approximately; f1 will be ~9.8 GHz in line with frequency regulations). In addition to total absorption, water vapour (H_2O), ambient air (O_2), and liquid water (cloud; lowest panel) absorption are shown.

The transmissions of coded signals, with similar signal structure as GPS, between LEOs are key observables for monitoring the global distribution of atmospheric water vapour in the future. The microwave cross-links are engineered to handle the expected water vapour absorption, while delivering the required measurement precision. In the lower troposphere, where water vapour is abundant, we employ the less strongly absorbed 10 and 17 GHz signal. Transmitted power and receiver antennae gains are sized to achieve a worst-case moisture concentration of 20 g/kg at the bottom of the troposphere in the tropics.

In the upper troposphere, where the moisture concentration can be lower by 4 orders of magnitude, the overriding consideration is detecting the relatively weak effect with sufficient precision in order to achieve accurate moisture measurements. A frequency close to the 23 GHz water absorption line maximum is therefore essential. For the baselined frequencies of ~17.2 and ~22.6 GHz it is required that the instrument can distinguish received amplitude variations of order 0.01 dB. Also, the gain shall be very stable over an occultation and drifts shall be < 0.025 dB per 15 sec (see section 3.1 for details).

Assessment of RMS Retrieval Errors.

Using realistically simulated measurements through model atmospheres with errors consistent with the CALL specifications, we have performed end-to-end retrieval performance analyses down to retrieved humidity, temperature, and liquid water profiles. The forward modelling/ inversion system employed for the purpose was the one developed by P. Eriksson, Chalmers University, and co-workers in a recently finished ESA study on LEO-LEO performance (Eriksson et al., "Assessment of uncertainties in LEO-LEO transmission observations through the troposphere/stratosphere", ESA contract report).

Figure 4 illustrates the retrieval errors obtained for humidity and temperature. The specific humidity error in the upper troposphere (between ~5 and 12 km) is < 5%, in the lower troposphere < 10%. Sub-Kelvin temperature accuracies are possible. The accuracy decreases higher up towards the stratosphere, where water vapour densities are very low and gain drift plays an increased role. Clouds decrease the accuracy only moderately. Even tropical cumulonimbus was found not to decrease it by more than about a factor of two, consistent with findings of colleagues at Univ. of Arizona (see Annex section 6.4 and their letter of support).

Horizontal variability was not accounted for in this analysis (this would be a phase A activity), but its effects on the quasi-horizontal occultation rays are basically well known from extensive studies in the GNSS-LEO context. They may decrease the humidity accuracy in the lower troposphere (< 5km) also by up to about a factor of 2 (temperature perhaps more compared to this analysis). On the other hand, we did presently use the phase/bending angle information only to correct for defocusing – only accuracy < 5-10% needed for this purpose, which is readily fulfilled. If the bending information is exploited in addition to absorption in an enhanced retrieval algorithm (planned during phase A), the humidity retrieval accuracy below 5 km is expected to again increase significantly.

In summary we have considerable evidence and confidence that CALL as specified will be able to retrieve lower troposphere humidity to < 10% accuracy, and upper troposphere humidity to < 5%, at 1 km resolution, even under horizontally variable and cloudy conditions. We stress that we have assumed relatively conservative specifications: – End-to-end performance analysis results of Univ. of Arizona colleagues (Kursinski and Feng, priv. communications, 2001) for similar instrument quality indicate potential for three times this accuracy (see also Univ. of Arizona letter of support).

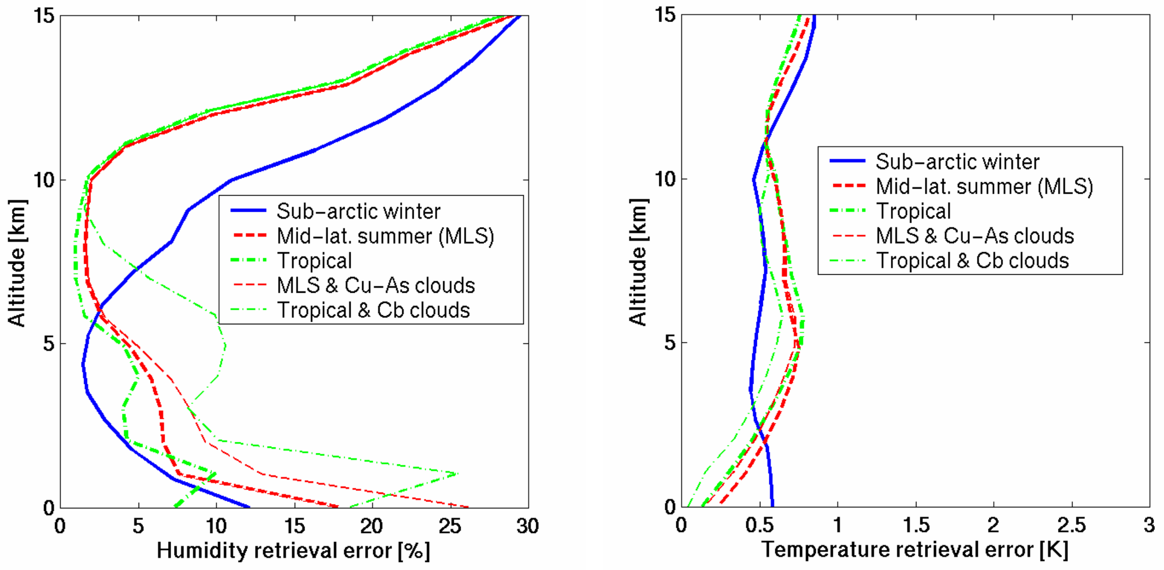


Figure 4. Specific humidity (left) and temperature (right) retrieval errors obtained for realistic simulated CALL transmission measurements (adopted measurement noise and gain drift consistent with CALL specs in section 3.1). Depicted are results for three different standard profiles in clear air (heavy lines) and for two typical cloudy cases (thin lines) (based on FASCODE transmission model clouds), a mixed mid-latitude cumulus/altocumulus case and a tropical cumulonimbus case. A spherically layered atmosphere was assumed. Vertical resolution of the profiles shown is 1 km (estimated by "averaging kernel width" and "Backus-Gilbert spread" measures).

In addition to humidity and temperature, CALL also isolates useful integrated liquid water profiles above 1 km height as the liquid-water retrieval results, Figure 5, indicate. Given that the present algorithm was optimised to isolate liquid water rather than to focus on its retrieval, this result suggests liquid water to potentially be a valuable further data product of ACE+. This potential will be explored in more detail during phase A as well.

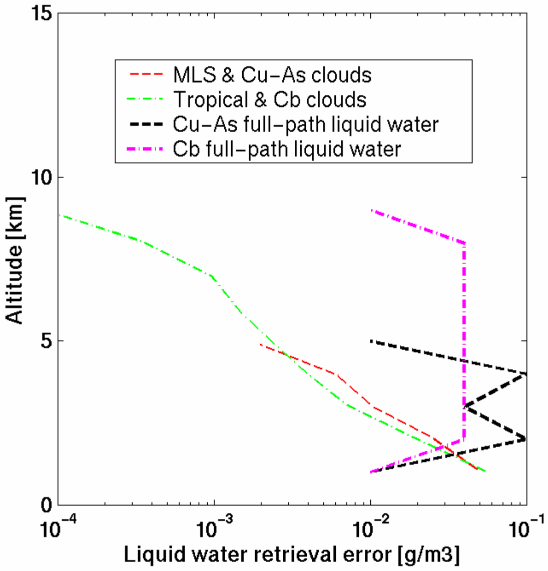


Figure 5. Full-path liquid water retrieval for the two cloud cases involved in Figure 4 above. Mid-latitude mixed Cu/As clouds (light dashed) and tropical Cb clouds (light dashed-dotted). Also indicated are the full-path liquid water abundances assumed for the two cases.

Based on a complementary and totally independent retrieval algorithm, retrieval performance analyses related to CALL where also undertaken at DMI (S. Leroy, priv. communications, 2001). Those findings are consistent with the ones discussed above, which strongly add confidence to the unique water vapour measurement potential of the LEO-LEO method.

Assessment of Residual Humidity Bias Errors.

In addition to assessing rms retrieval errors, potential residual biases have been estimated for CALL observations. The nominal absence of such biases is a key unique characteristic of the self-calibrating LEO-LEO measurements. Nevertheless, several sources may leave small residual biases. These potential residual biases can be summarized as follows:

Residual Bias[1] Source	**Estimated Residual Specific Humidity Bias[2]**
Systematics in linear gain drifts	< 1%
Non-linearities in gain drifts	< 0.5%
Time-dependent spectroscopic errors	< 1%
Systematics in horizontal variability	< 1% (>5km), < 2% (<5km)
Impact of clouds	< 2% (>5km), < 3% (<5km)

[1] *Residual Bias:* The systematic difference left in an average profile over > 40 profiles per grid box per month (cf. climate requirements in section 2.1) compared to the average profile over the corresponding > 40 true profiles.

[2] The estimate is meant as a "2-sigma" value, i.e., it is expected to be exceeded by a fraction of less than 5% of all climatological average profiles.

Gain drifts are expected to yield sub-percent biases only, due to the high stability, the shortness of the occultation and the short distance crossed from the point of view of an antenna.

Similarly, time-dependent spectroscopic biases are expected to be very small, since they mainly depend on the degree to which the temperature dependence is not modelled correctly in the spectroscopic parameters and the errors thus potentially induced by slightly misestimated climatological temperature changes. As temperatures will be accurately known simultaneously, this effect will be very small. Note that static errors in spectroscopic parameters will not degrade variability and drift estimates; current values for the 22 GHz line allow an absolute accuracy of ~5%. However, new laboratory measurements are expected to readily yield line strength accuracy of < 2% and line width accuracy of < 4%, respectively. Furthermore, the CALL precise transmission measurements themselves will allow improving spectroscopic coefficients if adequate validation data are available (e.g., from water vapour lidar campaigns).

Horizontal variability will usually not leave systematic effects > 2% even in the lower troposphere, since the errors due to horizontal structure in individual profiles are largely random from profile to profile and averaging suppresses this error (e.g., by a factor of 7 for ~50 profiles). There are small regions such as the edge of the polar vortex during high-latitude winter, which may leave higher systematic bias in monthly averages (not in annual averages) due to systematic deviation from spherical symmetry. However, these biases can be mitigated by an additional step in the climatological processing which uses the large-scale horizontal structure estimates from a first step to account for it in non-spherical re-processing in a second step.

Clouds above 5 km, mainly ice clouds, may leave some systematic error due to non-linear effects from scattering, while absorption by ice clouds will be negligible. The end-to-end error analysis system used for the results above is currently upgraded to allow simulation of scattering by ice clouds and to investigate this effect more rigorously. The effects are expected to be < 2% but may well be even smaller than 1%. Liquid clouds (below ~5 km) may have a slightly higher residual bias since the rms errors in the presence of clouds are higher and since they are more sensitive to a priori liquid water assumptions if such are involved. On the other hand, scattering is expected not to be a major problem in this context thanks to the long wavelengths involved (around 2 cm). Since the retrieval of all three, humidity, temperature, and liquid water, is a well-posed problem based on the three CALL frequencies, careful design of climatological analysis may allow reaching < 2% also for liquid clouds.

Overall, humidity biases are estimated to be < 2% in the upper troposphere, and less than 3% in the lower troposphere (in clear air even < 1% and < 2%, respectively). The cloud estimates involve several uncertainties (they may be too conservative, tentatively), which would need further investigation during phase A. Also precipitation effects are worth further investigation (large raindrops will degrade accuracy), although rain-influenced profiles will be rare.

In summary, it is certain that the LEO-LEO system allows to achieve, thanks to its self-calibration principle, an observation accuracy for humidity trends and variability, including under cloudy conditions, which is unmatched by any present system, including in-situ ones. From a climate research point of view, the particular strength to sense upper troposphere humidity so accurately is especially intriguing.

1.2.3.2 Temperature and Humidity Profiling using GRAS+

The GNSS radio occultation technique uses limb sounding to retrieve the parameters of the neutral atmosphere in the stratosphere and the troposphere. The basis of the radio occultation technique originates from the fact that radio waves of the satellite navigation system (GPS and GALILEO) get refracted along the ray path of the wave, determined by the dispersion relation of the media, as they pass through the atmosphere (either during a rise event or a setting event as seen from the receiver). Thus the refractivity profile can be derived from the observations of phase change and amplitude variations.

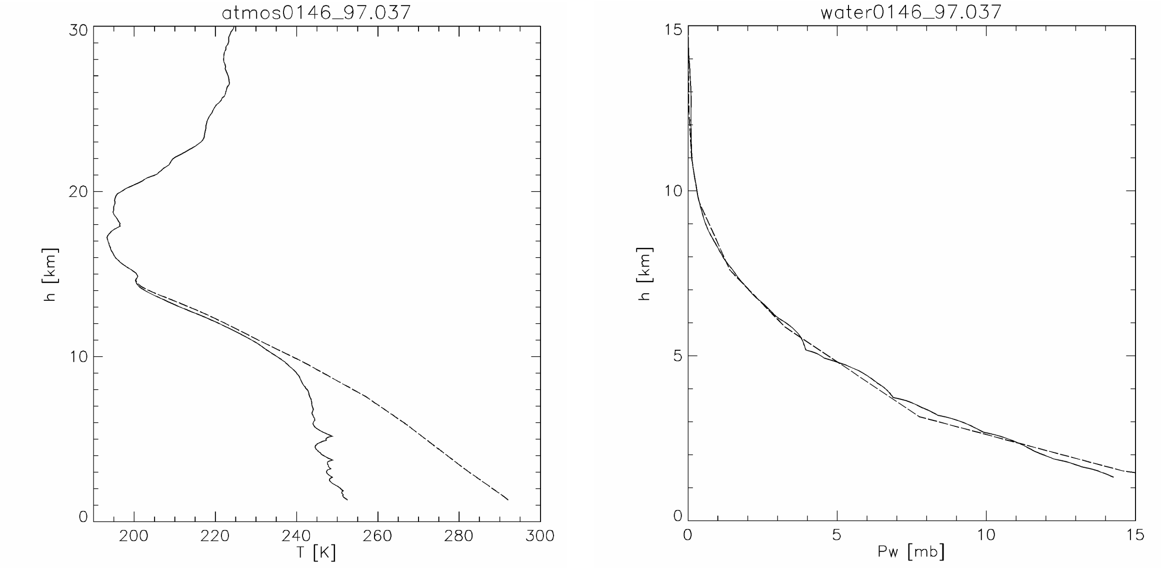


Figure 6. Left panel: Retrieved GPS/MET dry temperature profile (solid line) compared to ECMWF temperature profile (dotted) at the same location. The troposphere difference between the retrieved dry temperature and the ECMWF temperature profile indicates the presence of water vapour. Right panel: Retrieved water vapour profile (solid line) compared to ECMWF profile (dotted). The profile is situated in the tropics at a latitude and longitude of (10.2 S; 63.4 W). The time of the occultation was 5:08 UT, on 6. February 1997.

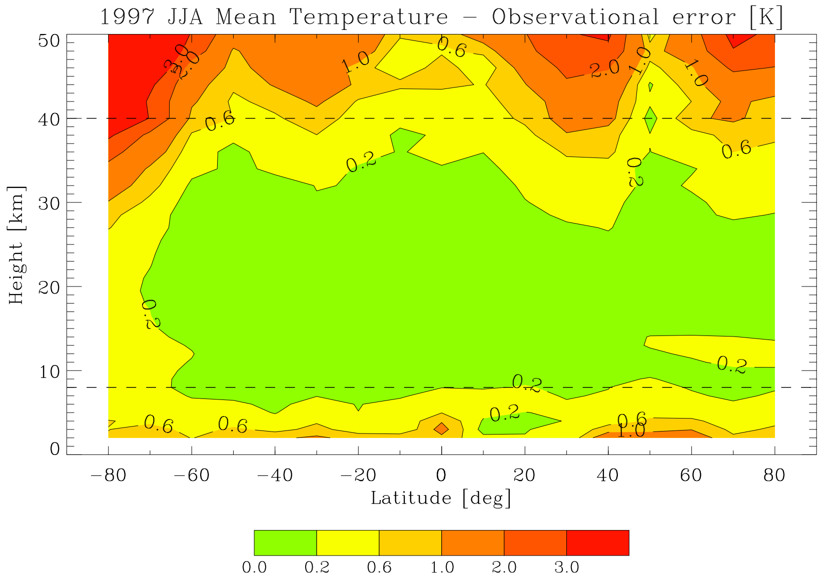


Figure 7. Latitude-height slice of climatological residual bias errors in climatological profiles of dry temperature in 17 latitude bins (every 10 deg from –80 to +80 deg). Each average profile involves ~50 individual GNSS-LEO occultation profiles realistically sampled by an ACE-type 6 satellite constellation within a full JJA (June-July-August) season.

In the stratosphere and upper troposphere, where the humidity is low, refraction is dominated by vertical temperature gradients, and the temperature profile can be retrieved accurately. In the lower troposphere, where humidity effects play the major role, water vapour profiles can be retrieved even allowing for typical uncertainties in the prior knowledge of temperature. In the tropics the typical border between the two regimes is at an altitude of ~7-8 km, while in the dry polar atmosphere accurate temperature sounding is possible down into the atmospheric boundary layer. Figure 6 shows a typical retrieved dry temperature profile and water vapour profile based on GPS/MET observations for tropical conditions. The water vapour retrieval was constrained by a global 24-hour forecast from ECMWF. The method is robust even with errors in the forecast temperature fields of up to 2 K. The error in the water vapour pressure is in average less than 1 hPa in the lower troposphere.

For climate change monitoring based on GNSS-LEO data, dry temperature and geopotential height are very promising. Figure 7 shows a result for dry temperature from a comprehensive and realistic GNSS-LEO climate observing system simulation experiment (conducted by IGAM/UG Graz, Austria, supported by MPIM Hamburg, Germany). About 50 profiles in each of 17 equal-area geographic cells of 10 deg latitudinal width are involved in the climatological average profiles shown for all bins. It is visible that in most of the latitude height-slice the residual biases are below 0.2 K (green area), the biases somewhat increasing down into the troposphere (horizontal variability) and towards the stratopause (decreasing signal-to-noise ratio).

Further details can be found in the ESA reference documents (after Table of Contents), which contain extensive detail on GNSS-LEO occultation methodology and performance as well as extensive references to the relevant scientific literature.

1.2.4 Monitoring of Climate Variability and Change

An important objective of the proposed project is to monitor variations and changes in the climate of the Earth. Such variations can be due to processes internal to the climate system as well as due to external forcing effects. No anomalous forcing is needed to initiate internal climate variability, which basically occurs because of the differential radiative heating between high and low latitudes. Externally forced variations and changes on the other hand are due to anomalous influence such as from a change in the solar constant or an increased greenhouse effect. A further objective is therefore to isolate and detect those climate variations during the mission period.

Externally forced climate variations are often split into terms related to natural and anthropogenic causes, as given in the table below.

Natural external forcings
• Stratospheric sulphate aerosols resulting from certain large volcanic eruptions. These aerosols lead to a heating of the lower stratosphere and cooling in the lower part of the troposphere. • Variations in solar activity, either directly via the energy release from the sun or possibly via solar wind induced variations in the earth's magnetic field and therefore in the cosmic ray flux, which may impact cloud formation. • Variations in the orbital motion of the Earth around the Sun, which quite generally is accepted as the main mechanism initiating the ice ages.
Anthropogenic external forcings
• Increased atmospheric concentration of radiatively active gases like CO_2, CH_4, N_2O and CFCs. These lead to an enhanced greenhouse effect with heating in most of the troposphere, and cooling in the stratosphere. • Stratospheric ozone depletion due to chemical reactions with CFCs. These lead to a cooling in the lower stratosphere and to some extend also in the troposphere. Enhanced greenhouse effects and ozone depletion are related, since a cooling in the polar stratospheric accelerates the photochemical ozone destruction. • Changes in tropospheric aerosol loading due to environmental pollution. • Changes in the land-surface conditions leading to anomalous albedo and evapo-transpiration.

Internal variations mostly occur on relatively short time scales up to a decade or so, but also slower variations involving modulations of the ocean currents, particularly the North Atlantic overturning, are non-negligible. One of the most prominent examples of internal climate variability on time-scales from 3 to 7 years is the well-known El Nino/Southern Oscillation (ENSO) phenomenon, which impacts weather and climate over large - mainly tropical and sub-tropical - regions.

Due to the extremely high accuracy of the retrieved climate data the basic monitoring of climate variations during the mission period is relatively straightforward using modern data assimilation techniques as described in the next section. It is, however, a much trickier problem to isolate those variations that are due to external forcing from those internal to the climate system, mainly because the mission period is short compared the typical time scales of internal climate variability. Considerable variations in the global mean tropospheric temperature occur as part of ENSO and other internal climatic variability mechanisms and therefore a simple global mean temperature trend during the mission period will not tell us directly if for example the greenhouse effect is increasing. However, by assimilating the observed occultation data into the atmospheric component of a climate model it is possible to monitor variations in the models fit to the observations.

Assuming perfectly observed data, such variations are directly linked to varying external forcing not build into the model. Thus a period, where anomalous heating must be added to the assimilation model in order to match the observations, must also be a period dominated by external forcing. Figure 8 shows an example of anomalous 24-hour forecast of global temperature errors relative to analyses of the temperature in the lower stratosphere (30 hPa) for the same model used for assimilating the observations. The depicted short-term forecast errors are a measure of the quality of the model fit with respect to the observations. Thus these indicators can identify periods of external climatic forcing. On top of a slow trend, two episodes around 1982 and 1991 are observed where the forecasts are too cold, meaning that positive external forcing must have been present. In this case the forcing is well known and related to two volcanic eruptions (El Chichon in Mexico and Mount Pinatubo at the Philippines).

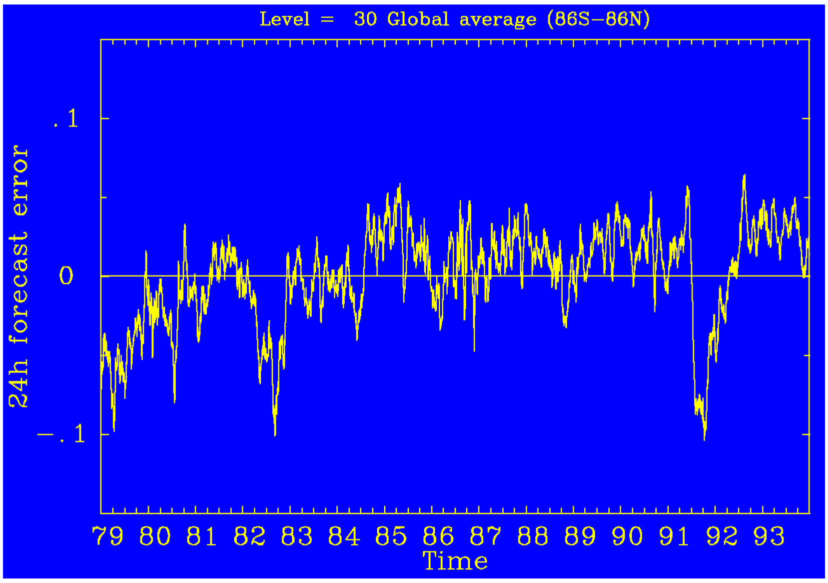


Figure 8. Daily global average temperature differences of forecast errors at the 30-hPa pressure level. The analysis covers the years 1979 – 1993 of the ECMWF 24-hour re-analysis (ERA model). The units in the plot are degrees/day.

Assimilation of atmospheric mass field data, possibly combined with wind data obtained from other data sources, into atmospheric models will be used quite generally in the project to identify variations in the external forcing of the climate. It is important to note that accurate and homogenous data are needed for applying the technique. The above results for the lower stratosphere prove that it is possible to identify signs of varying external forcing.

1.2.5 Data Assimilation Techniques

The temperature, humidity and wind fields are the most important parameter to characterise the mean state of the atmosphere and its long-term evolution. The thermal structure of the atmosphere is likely to change under the impact of anthropogenic forcing as the increase of greenhouse gases and the stratospheric ozone depletion. Both of them are expected to have an effect on the radiative budget, affecting the radiative coupling between the stratosphere and the troposphere, and thus changing the climate of the Earth. In order to reach reliable conclusions on the inferred trends, it is essential to understand the role of the natural forcing (volcanic eruptions, solar activity) as well as the internal forcing (e.g., Quasi-Biennial Oscillation, El Nino Southern Oscillation) on the observed variability.

The determination of the three-dimensional temperature fields in the upper troposphere and in the stratosphere with a high vertical resolution and in absolute values will allow for the estimation of the natural variability. The radio occultation technique will give absolute values of atmosphere temperatures and facilitate long-term trend studies. This will offer the opportunity to study more local phenomena as well. For example, the anti-correlation between the mean temperatures in Scandinavia and Greenland, sudden stratospheric warmings in polar regions, and the breakdown of the polar vortex in conjunction with the injection of particles in the stratosphere, leading to a modification of the radiative budget of the stratosphere.

The ideal model for describing the atmosphere radiative and dynamical relations would essentially only need observations once to initialise all parameters of the model. But due to the complexity of the physics of the atmosphere, existing models have to rely strongly on a range of meteorological observations to be able to come up with any results on the future state of the atmosphere. In order to study and understand the interplay between the model and the observations, it is necessary to perform observation system studies of the climate and weather results. Such verifications-against-reality indicate that the atmospheric profiling observations from data-sparse areas of the Earth will have a large impact on the total error of the atmosphere state description for much larger regions than covered by the observations. Comparative studies of long-term weather analysis results can further strengthen this, when more observations are assimilated into analysis runs and matched with original analysis estimates.

The assimilation of remotely sensed observations, particularly from satellites, into the present atmosphere models gives rise to several difficulties related to the non-linear characteristics of the problem and the method applied. The most frequently used theory in present weather prediction models is the Optimal Interpolation method (OI). This assimilation technique calculates for each geographical region a statistical least square estimation of the meteorological parameter by weighting the preliminary fields (first-guess fields) and observations, utilising their specific error characteristics. Thus observations with good quality characteristics are favoured in the estimates compared to model calculations, while the preliminary fields are given the highest weight, when observations are scarce or show larger error variances. A difficulty in OI schemes, which does not favour most observations from satellites, is the fact that all observations in a predefined interval (e.g., 6 hours) are assumed to be valid at the same time with a high vertical resolution, thereby omitting any temporal variations in the observables.

The variational data analysis technique provides an effective and consistent method to overcome some of the above mentioned limitations. Through the formulation of the statistical cost function for each parameter covering the observations, the background fields and the physical constraints, it is possible to optimise the combined cost function in space and time (in the four-dimensional variational assimilation method, 4DVAR). The concept of an 'observation operator' for each data type makes it possible to assimilate more raw observations, asynoptic in nature, such as satellite observations, which generally are not made for fixed regions at regular times. So in all, the 4DVAR technique will lead to better estimates of the state of the atmosphere, since available observations are assimilated by searching the best fit to sets of observational time series. Time series, which will also take into account the temporal evolution of the past of each parameter. The 4DVAR-assimilation scheme greatly facilitates the incorporation of remotely sensed information into the weather and climate models due the above-mentioned mathematical method.

1.2.6 Climate Model Development and Validation

One of the most critical uncertainties in future climate projections is the magnitude of climatic sensitivity. Therefore it is of importance that climate models are verified not only with respect to the observed mean climate, but also verified against known external forcings during the ACE+ mission period. The most simple and important example is the annual cycle of solar forcing and the associated seasons. Therefore the annual cycle in climate model simulations with prescribed sea surface temperatures during the mission period will be compared to details in the annual cycle of the retrieved data. This also regards heating rates from release of latent heat in association with monsoons, which can be verified by the method described above.

The most important tool for estimating climatic sensitivity is modern climate models, where atmosphere, ocean, sea ice and land surface models are physically coupled. Concerning the atmospheric component, which is relevant in the ACE+ project, observed data are only included indirectly for determining relatively few (but important) parameters, which at a certain level closes sub-models describing individual processes like convection, cloud formation, turbulence, etc. So far, these parameters have mostly been determined *a posteriori* after a long simulation run. As the quality and accuracy of observed data increases it becomes more and more relevant to use the observations for a more direct calculation of the closure parameters in the models. Such a calculation must be done *a priori*, i.e., before a long free model simulation is performed, in order to minimise the problem of error compensations between the different sub-models (parameterisations). To do this, the observed data must be assimilated into the relevant atmospheric model and the parameters defined in such a way that the forcing (mainly heating) errors are minimised in a global sense. Figure 9 shows as an example proxy heating errors in spring, estimated from average errors in 24-hour forecasts compared to verifying analyses (ERA). Error analyses like these provide valuable information to the possible problems in the assimilation model. In this example, a candidate like wrong albedo input, related to snow cover and vegetation seems likely. But also mountain induced gravity wave drag can be the error source, which after 24 hours is also observed as an error in the mass field.

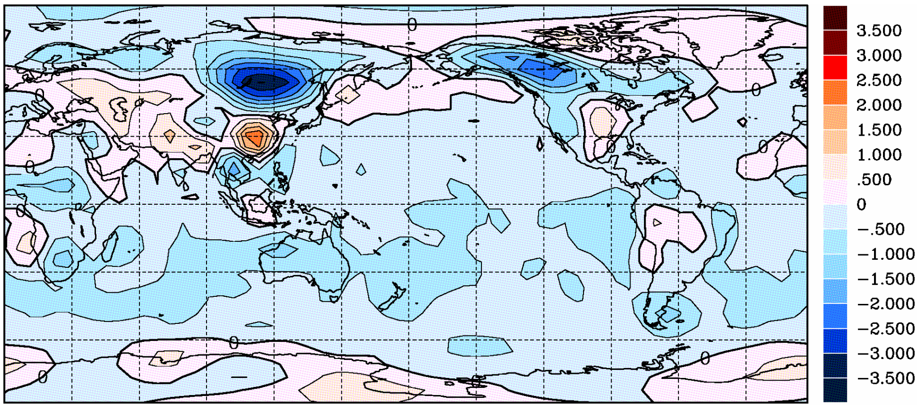


Figure 9. Averaged 24-hour forecast errors in the temperature fields for the years 1979 – 1993. The contours represent the conditions at a pressure surface of 850 hPa in the middle of the month of March. The results are based on ECMWF re-analysis model (ERA). The units are degrees/day.

The technique of minimisation of forcing errors by assimilation of high quality analyses is currently used in a range of European projects. However, a major obstacle when using data from traditional sources, such as radiosondes and vertical profiling from present satellites, are their coarse spatial and temporal resolution and/or lack of sufficient accuracy. Therefore, high quality data as obtained in the ACE+ project are extremely valuable for improving the performance of climate models. Furthermore, and additionally to the simple parameter optimisation, the technique of forcing error estimation can provide valuable guidelines for construction of new parameterisation algorithms (sub-models).

Assimilation – with the purpose of model improvement – of data obtained during the period of the ACE+ mission constitutes an important element of the project. As the data obtained from radio occultations are atmospheric density data, they provide direct information on the atmospheric mass field. Together with wind field information from other data sources during the assimilation, these observations might turn out to be vital for further improvements in climate models.

1.2.7 Space Weather

Since radio occultation measurements performed onboard ACE+ satellites include the capability to yield unique information about the ionosphere on global scale, ACE+ will essentially contribute, as a spin-off, also to space weather services planned in the frame of the European Space Weather Programme (ESWP) during the next decade. Furthermore, the intrinsic ionosphere information shall be used to improve ionospheric correction algorithms applied in neutral gas retrieving procedures to derive excellent upper stratosphere data.

The Earth's ionosphere, ranging from about 60 km up to the bottom of the plasmasphere at about 1000 km, is strongly subjected to space weather phenomena characterized by highly variable solar driven forces such as solar radiation, solar wind, electric fields and currents, thermospheric winds, and particle precipitation. On the one hand, a permanent monitoring of the ionospheric ionisation can provide key information about the underlying physics of space weather to get a better understanding of space weather phenomena and to improve corresponding models and predictions. On the other hand, this information itself shall feed application services to be established within the ESWP to reduce damages or degradation of ground- and space-based technological systems. In particular space based systems using trans-ionospheric radio waves below 10 GHz such as GPS and the future European navigation system GALILEO are vulnerable to space weather effects due to the electromagnetic interaction of L-band radio waves with the ionospheric plasma, whose density and energy is highly variable in time and space.

Reliable now- and forecasting of space weather phenomena need an improved understanding of the ionospheric behaviour and its close coupling in particular with magnetosphere and thermosphere systems. Applying innovative inversion techniques, tomographic approaches and multi sensor data assimilation methods will allow to,

- monitor and model spatial and temporal electron density structures on global scale with high reliability and accuracy
- forecast the ionospheric behaviour up to hours ahead.

In general, the GNSS-LEO radio occultation technique yields the integrated electron density (TEC- total electron content) along the occultation ray path as a basic data product. TEC can precisely be derived from the differential phases of the coherent transmitted L-band signals of GPS and GALILEO satellites, with the latter planned to be operational in 2008, just at the beginning of the ACE+ mission. The ACE+ satellites, receiving both GPS and GALILEO satellites, will provide about 5000 well-distributed and conditioned data sets per day on global scale.
It should be mentioned that the applied concept of measuring differential phases instead of the small refraction angle (as applied for neutral gas measurements) is robust against inaccuracies of orbit information of GPS/GALILEO and ACE+ satellites and attitude information of the latter as well. So the availability of two-line elements of all satellites involved would be sufficient to derive electron density profiles that agree within 10-20% with comparable vertical sounding data.

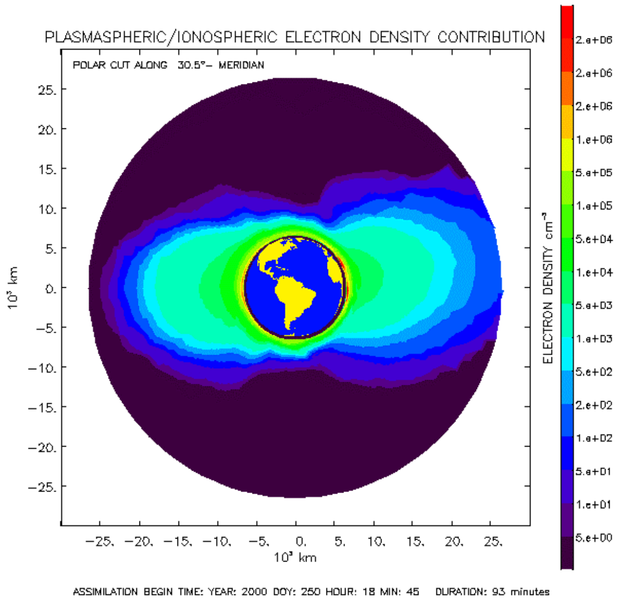


Figure 10. Electron density distribution of the topside ionosphere and plasmasphere in the CHAMP orbit plane (30.5°E) on September 6, 2000. The image is reconstructed applying data assimilation techniques based on one complete revolution of CHAMP starting at 18: 45 UT and ending 20:18 UT (Jakowski et al., 2001; Heise et al., 2001).

Permanent growing GPS ground station networks on global scale have led to progress in ionosphere sounding by constructing quite accurate regional and global TEC maps. But the results are based on lack of the vertical structure of the ionosphere. This can be improved dramatically by merging ground-based electron density data and ACE+ data to construct three-dimensional electron density distributions of the ionosphere. Combining all ground-based GPS and GALILEO data, available in 2008 and years after, with the large amount of ACE+ data, will lead to a global and continuous reconstruction of the 3D-electron density distribution of the ionosphere with unprecedented resolution and quality.

Figure 10 shows a corresponding data product. The satellite measurements are from the German CHAMP satellite, which carries a similar (though less advanced) receiver as the GRAS+ instrument. Images of this type from each of the ACE+ satellites can be generated every 45 minutes, providing actual information about shape and dynamics of the plasmasphere. This will open an entirely new era for ionospheric research and space weather monitoring. The knowledge of the complete electron density structure from the bottom of the ionosphere to GPS/GALILEO heights will furthermore allow for accurate correction of ionosphere residuals in the neutral gas retrieval procedures.

1.3 Relevance to the Living Planet Programme

The ACE+ mission will contribute significantly to science themes 2 (Physical Climate) and 4 (Atmosphere and Marine Environment) of the Programme, as noted in the Executive Summary, and its scientific objectives address many of the Programme's objectives. The following subsection 1.3.1 highlights this contribution via a concise summary of objectives.

1.3.1 Scientific Objectives

The major goal of the ACE+ mission is:

- To monitor and describe variations and changes in the global atmospheric temperature and water vapour distribution in order to assess climate changes caused by mass field changes and atmosphere dynamics. The observations from the constellation of satellites will reveal important information for weather prediction and contribute to the advanced research in atmosphere physics and climate change.

The main objectives are:

- To establish highly accurate (< 0.003 g/kg and < 3 % in specific humidity) and vertically resolved (< 1 km) global climatology of water vapour in the troposphere;
- To establish a highly accurate (< 0.2 K) and vertically resolved (~1 km) global climatology of temperature in the troposphere and the stratosphere;
- To perform research on climate variability and climate change together with research in improved atmospheric models as well as advancements in NWP;
- To study troposphere structures in polar and equatorial regions;
- To support analysis and validation of data from other space missions;
- To demonstrate a new and novel active atmospheric sounding technique with the CALL instrument;
- To enhance the European observational capability for improved contribution to the international GCOS initiative.

ACE+ seeks to advance our knowledge about atmosphere physics and climate change processes by addressing issues such as:

- Global climate warming and increased averaged atmospheric water vapour levels;
- Tropical heat and mass exchange with extra-tropical regions;
- Transport across subtropical mixing barriers, relevant for information on the lifetime of greenhouse gases;
- Stratospheric winds and temperatures and atmospheric wave phenomena;

- Polar front dynamics and mass exchange together with tropospheric water vapour feedback on climate stability;
- High latitude tropospheric-stratospheric exchange processes related to polar vortex conditions;
- Climatology of Rossby waves and atmospheric internal waves.

1.4 Relevance to Other Programmes

1.4.1 Other ESA Missions

The ESA METOP mission includes a GRAS receiver on each of the satellites to monitor temperature, pressure and humidity profiles of the stratosphere/troposphere. The main objective for these observations is to supply operational data for the European National Meteorological Centres (NMCs). The CALL and GRAS+ instruments in ACE+ will enhance the METOP observations with more precise and detailed profile measurements of tropospheric water vapour together with many more occultation data, thereby improving the coverage in time and space. The GRAS+ instrument has additionally the capability of monitoring the GALILEO satellite signals, too.

1.4.2 World Meteorological Organisation

The CBS Working Group of WMO (WG-SAT) has been assessing satellite capabilities for NWP and climate monitoring purposes. The GNSS atmosphere profiling performed in ACE and ACE+ has been evaluated to be one of the potential improvements for future monitoring of temperature, pressure and humidity profiles of the stratosphere and troposphere. WMO sees these activities very much related to the projects in the Global Climate Observing System (GCOS) Programme.

1.4.3 EUMETSAT

As part of the ground segment for the EPS/METOP mission EUMETSAT has decided to develop the higher-level data products (level 2 and above) at distributed Satellite Application Facilities (SAFs), placed at specific chosen NMCs. These SAFs will also facilitate the production and the delivery of the data products from the EPS/METOP mission. Three SAFs have direct relation to the ACE+ mission, since the data could enhance the products from these SAFs. They are:

EUMETSAT Satellite Application Facility	**Objectives and Tasks**
GRAS Meteorology SAF	The SAF will produce the algorithms for the delivery of the level 2 data products and higher to European NMCs and other operational user groups within meteorology and climate change monitoring. The observations will originate from the GRAS receiver on the satellites and result in profiles of bending angles, refractivity, temperature, pressure and humidity. DMI is leading the SAF in cooperation with UKMO and IEEC.
Climate Monitoring SAF	The SAF will generate data from a range of observational platforms to support the climate change studies and monitoring at European centres for climate change prediction and research. The data products are cloud cover, sea surface temperature, sea ice cover and radiation parameters. The SAF will also perform a statistical evaluation of global vertical profiles of temperature and humidity. DWD is hosting the SAF.
NWP SAF	UKMO is hosting this SAF, which will prepare data processing modules for NWP products and the assimilation of EPS/METOP observations into weather prediction models. The GRAS measurements will also be available at this SAF for NWP purposes.

1.4.4 European Union

The EU's future Framework Programme encompasses a thematic programme on the conservation of the Eco-system. One particular part of this programme focuses on global changes in climate and biodiversity. ACE+ will provide a data set, which will be useful to support projects to be implemented in this context.

1.4.4.1 Previous Studies in 5th Framework Programme

In the EU 5th Framework Programme the following major projects have been treating ground-based and satellite observations of the atmosphere using GPS signals, along the lines given in this proposal: WAVEFRONT, MAGIC, CLIMAP, and COSY (a new proposal put forward in 2001).

1.4.4.2 GMES

The EU GMES programme (Global Monitoring for Environment and Security) will address the monitoring of the atmosphere applying satellite measurements. The ACE+ mission would fit naturally into this European capability to assess changes in the environment and the managing of risk for the European populations and nations.

1.4.4.3 COST

The EU COST actions 716 and 723 have and will be treating radio occultation measurements and their capability for the European monitoring of the troposphere. ACE+ would follow these activities in the coming GMES initiatives.

1.4.5 Other International Programmes

The ACE+ mission complies with the requirements and descriptions in the below mentioned programmes and complements satellite observations from the EPS/METOP mission (EUMETSAT/ESA), the ADM and EarthCARE (ESA), the GCOM satellites (NASDA) and the NPOESS satellite programme (NOAA/DOD/NASA).

- UN Kyoto Protocol
- IPCC recommendations
- WCRP CLIVAR and GEWEX programmes
- WMO conclusions on GCOS (Global Climate Observing System)
- WMO satellite requirements for climate monitoring and NWP (Numerical Weather Prediction)
- SPARC recommendations for monitoring stratospheric processes

1.5 Science Summary

1.5.1 Need and Usefulness

The role of water vapour in the atmosphere is mainly associated with two processes: condensation/evaporation and radiation. The role of condensation/evaporation is very important, since it constitutes the main diabatic heat source within the troposphere. This heating is generally very strong in the inter-tropical convergence zone and in the monsoon areas. Thus it is a key player in the maintenance of the Hadley cells and the monsoons. Furthermore, the overall poleward and vertical transports of water vapour (i.e., latent heat) via the atmospheric dynamics is highly crucial in maintaining the general circulation of the atmosphere - including the high latitude wind systems. Thus the release of latent heat associated with condensation is the main mechanism driving several regional and local atmospheric circulation phenomena like tropical storms, hurricanes and severe thunderstorms.

From a radiative point of view, water vapour is the dominant greenhouse gas in the atmosphere due to its high concentration and variability relative to the other well-mixed greenhouse gases like CO_2, CH_4, N_2O and CFC's. It plays a dominant indirect radiative role via clouds and precipitation, and thus is a key parameter of the whole climate system. This regards both the maintenance of the present climate and its internal variability as well as the changes in the climatic feedback mechanisms, which determine the sensitivity of the climate through the response to variations in the external forcing.

Water vapour participates in most important atmospheric processes, but remains relatively poorly understood in climate change. The atmospheric mass field, characterised by temperature, pressure and water vapour, dominates the main features of the large-scale atmospheric wind systems via the geostrophic balance. This, together with the fact that massive amounts of latent heat is transported via the atmospheric dynamics and released in areas of condensation, underlines the importance of water vapour in controlling the atmospheric circulation.

The latest IPCC scientific assessment report concluded that the bulk of the observed global warming in the last century mostly was due to natural processes, like solar and internal climate variability. However, the more recent warming is in the report attributed to the increased emission of greenhouse gases. Central to most of the least understood internal feedbacks of the applied climate models are those associated with water vapour, giving rise in part to the span in the temperature increase estimates. Mechanisms of water vapour remain poorly understood because the climatology and atmosphere processes have not been observed with the accuracy, precision, and coverage necessary to understand them. Thus accurate observations of the present temperature and humidity climate, including its variability, are highly important in climate change research. Establishing unbiased observations of global water vapour and temperature fields throughout the troposphere is the goal of ACE+.

All the different stages of water (vapour, clouds, rain, ice crystals) in the hydrosphere are observed in the hydrological cycle of the atmosphere. The amount of water in the atmosphere is small compared to the total amount of water in oceans, lakes, rivers, groundwater and polar ice caps. But the time scales regarding changes in atmospheric water vapour are short, requiring a highly dense set of observations to estimate energy fluxes and density variations. ACE+ is the only mission able to deliver detailed temporal observations for monitoring these phenomena with a good spatial coverage over a longer time period.

1.5.2 Uniqueness and Complementarity

ACE+ is unique among planned and developing missions in that it profiles water vapour throughout the upper and lower troposphere regardless of weather conditions. No other space agency in the world is for the moment considering a similar mission. Thus ACE+ is unique and the state-of-the-art in monitoring atmospheric water vapour together with the physical and the dynamical processes controlling and regulating the mass and energy exchange in the atmosphere of the Earth.

ACE+ offers a key complement to the planned nadir-sounding spectral high-resolution infrared instruments in that clouds are largely transparent to ACE+. It also offers a fundamentally different alternative to the traditional sounding techniques, thus providing an invaluable source for validation where data products are similar in nature.

The ACE+ mission is primarily driven by climate research with applications to weather, whereas conventional water vapour sounders are instruments for weather applications. ACE+ is designed to obtain the climatology of tropospheric water vapour with unprecedented precision on global scales. The self-calibration nature of the observations allows an accurate tracking of secular changes in atmospheric water vapour content on short and long time scales.

The current operational systems of satellite sounding radiometers (passive infrared and microwave) provide information on tropospheric and stratospheric temperature and on tropospheric humidity with global coverage at high horizontal resolution. But the systems are deficient in vertical resolution since individual spectral channels have weighting functions of width 7–10 km. So the combined vertical resolution of the system is only 2-3 km in cloud-free areas and worse in cloudy areas, with humidity accuracies of 20 %. Future microwave sounders will have similar performance. The sounders on geostationary satellites, such as SEVIRI on MSG (Meteosat Second Generation), will equally not improve on vertical resolution or accuracy, but will improve on coverage and repeat rate of the observations. So all the mentioned systems do not fulfil the requirements for climate research and daily meteorological applications. ACE+ derived profiles of temperature and humidity are making a significant contribution beyond present knowledge of water vapour structures in the troposphere and temperature profiles in the stratosphere.

1.5.3 Contribution to European Earth Observation Capabilities

ACE+ complements satellite observations from the missions EPS/METOP (EUMETSAT/ESA), GOCE, ADM and EarthCARE (ESA). The mission will be of the first of its kind in LEO-LEO water vapour profiling, which will strengthen and enhance Europe’s leading role and capability in monitoring the changing climate and the environment of the Earth.

ACE+ will benefit several other missions planned in the timeframe of the next ESA Core Mission Earth Explorers. It will widely extend the measurements made by GRAS on METOP and GPSOS on NPOESS. It will add complementary mass field measurements to the wind field measurements performed by the ESA ADM mission. ACE+ will also enhance and complement other missions aimed at observing atmospheric processes, as the US-Taiwan mission COSMIC. ACE+ will provide precise water vapour and temperature profiles that can support the modelling of atmospheric processes, as suggested in the EarthCARE proposal to the ESA Core Explorer Programme. ACE+ will additionally answer critical issues in the international programmes and enhance our understanding of the changes in the climate of the Earth.

1.5.4 Timeliness

Calculations of climate warming indicate that the amount of water vapour in the atmosphere may increase as much as 5 % over the next 20 years. The strong indications of climate changes call for a mission like ACE+ to enhance and substantiate the observational database for the predictions. The ACE+ mission will further extend the international community efforts in quantifying the changes outlined in the UN Kyoto Protocol, the IPCC recommendations, the WCRP CLIVAR and GEWEX programme, the WMO GCOS programme, the SPARC recommendations for monitoring stratospheric processes, the EU GMES Programme, and the EU COST Actions 716 and 723.

The amount of GNSS observations in the ACE+ constellation is more than 5000 daily atmosphere profiles, globally homogeneously distributed over the Earth with a horizontal resolution of about 300 km. The number of LEO-LEO occultations obtained per day is around 230, with similar horizontal resolution as GNSS-LEO. An important feature of the radio occultation technique is its "all-weather" capability. The measurements also have a high long-term stability, with no significant calibration problems, a feature particularly important for climate change monitoring. Another key strength of the radio occultation measurements is their high vertical resolution, which well matches the physical scales of the atmosphere. The vertical resolution is limited only by diffraction effects and becomes less than 1 km for most of the vertical profile.

2. Mission Characteristics

2.1 Scientific and Technical Requirements

2.1.1 Atmospheric Monitoring

The GRAS Science Advisory Group of ESA/EUMETSAT has in their User Requirements Document (ESA, 1998) formulated requirements for GRAS climate monitoring and NWP applications. The requirements shown in the tables below reflect these findings and are taken as guidelines for the ACE+ mission.

The WATS Mission Assessment Report (ESA, 2001) for the ESA Earth Explorer Core Mission Programme gave detailed descriptions of the observational requirements for a mission similar in many respects to ACE+, including on LEO-LEO observations. These are also integrated in the below summarized requirements with the definitions of the troposphere and stratosphere regions based on the WMO specifications.

Atmosphere Region	Abbreviation	Pressure levels	Altitudes
Lower Troposphere	LT	1000 hPa - 500 hPa	Surface - 5 km
Higher Troposphere	HT	500 hPa - 100 hPa	5 km - 15 km
Lower Stratosphere	LS	100 hPa - 10 hPa	15 km - 35 km
Higher Stratosphere	HS	10 hPa - 1 hPa	35 km - 50 km

Table 2-1: Height domain definitions according to WMO.

2.1.2 Temperature and Humidity Profiling of GRAS+

Parameter		Temperature	Humidity
Horizontal domain		Global	Global
Horizontal sampling		1.0°x1.0° - 2.5°x2.5°	1.0°x1.0° - 2.5°x2.5°
Vertical domain		Surface - 1 hPa (0 - 50 km)	Surface - 300 hPa (0 - 10 km)
Vertical Resolution	Troposphere	0.5 km	0.5 km
	Stratosphere	1 km	–
Time domain		> 5 years	> 5 years
Time resolution		1 - 10 years	1 - 10 years
Long-term stability		< 0.1 K/decade	< 2% RH/decade
Number of profiles per grid box per month		> 40	> 40
Accuracy	Troposphere	< 1 K	< 10%
	Stratosphere	< 1 K	–
Timeliness (NWP)		3 hrs	3 hrs
Timeliness (Climate)		30–60 days	30–60 days

Table 2-2: Requirements for GNSS-LEO observations.

2.1.3 Humidity and Temperature Profiling of CALL

Parameter		Specific Humidity	Temperature
Horizontal Domain		Global	Global
Horizontal Sampling		100–500 km	100–500 km
Vertical Domain		Surface to 10 hPa	Surface to 100 hPa
Vertical Sampling	LT	0.4–2 km	0.3–3 km
	HT	0.5–2 km	1–3 km
	LS	–	1–3 km
	HS	–	5–10 km
Time Sampling		3–24 hrs	3–24 hrs
RMS Accuracy	LT	0.25–1 g/kg	0.5–3 K
	HT	0.025–0.1 g/kg	0.5–3 K
	LS	–	0.5–3 K
	HS	–	1–3K
Timeliness (NWP)		1–3 hrs	1–3 hrs
Timeliness (Climate)		30–60 days	30–60 days
Time Domain (Climate)		> 5 years	> 5 years
Long-term Stability		< 2% RH/decade	< 0.1 K/decade
No. of profiles/ grid box/month		> 40	> 40

Table 2-3: Requirements for LEO-LEO observations.

2.1.4 Electron Density Profiling and Space Weather

Observational requirements for ionospheric research strongly depend on specific topics of interest, since the electron density in the ionosphere varies up to several orders of magnitudes over a wide range of spatial and temporal scales. For this reason requirements depend on the major scientific issues/research that need to be addressed. Table 2-4 gives requirements, which all can be fulfilled if the troposphere/stratosphere requirements above are met.

Parameter	Climatology	Storms and TIDs	Space Weather Monitoring
Horizontal resolution (km)	1000 – 2000	50 – 500	100 – 1000
Horizontal domain (km)	Global	Regional/Global	Global
Vertical resolution (km)	2 – 30	0.1 – 15	5 – 30
Vertical domain (km)	90 – 20000	60 – 20000	90 – 20000
Time resolution (hrs)	1 – 3	0.01 – 1.5	0.1 – 3
Time domain (yrs)	> 5	> 1	> 1
Accuracy (day-time, %):			
Electron density	< 10	< 10	< 15
TEC	< 5	< 5	< 10

Table 2-4: Requirements for ionosphere and space weather observations.

2.2 Mission Specific Characteristics

2.2.1 Mission Duration

The purpose of both the GRAS+ and the CALL instrument is to extract data over extended periods, in fact the longer the better. This concerns both major objectives of the mission in providing data in support for deriving atmospheric parameters:

- Climate change observations require data over a long period to extract trends under similar yearly conditions.
- Weather prediction. The use of data from occultations for NWP assimilation has been prototyped and proven to be useful in case of GPS occultations (GPS/MET and ØRSTED

data with CLIMAP) but large amounts of data from over an extended period have never been available. The continuous provision of such data for assimilation under different and repeated weather conditions serves very well the needs of NWP. Furthermore the real time production of products serves the proof of operational aspects.

A five years mission life is planned taking into account the non-redundant architectures of the satellites as dictated by satellite and launch expenses.

2.2.2 Mission Timing and Potential

There is no current mission flying or planned that matches the combined GRAS+ and CALL measurements of the ACE+ mission in terms of simultaneous global geographic coverage and revisit plus vertical resolution in providing atmospheric parameters with special emphasis on water vapour.

The present CHAMP and SAC-C missions and the future GRACE and METOP missions are all examples of single satellite missions that will supply GPS occultation measurements, but only METOP will certainly range into 2008 and beyond. The GRAS instrument for METOP is the basis for the GRAS+ instrument of the proposed ACE+ mission. The measurements of these missions are leading to the direct and absolute extraction of temperature and dry atmosphere pressure without calibrations except at low elevations where the independent measurement of ('wet') temperature is needed by e.g. balloons in order to derive the water vapour pressure. The measurements of these missions are not synchronised to optimise the coverage and revisit. The COSMIC mission - presently planned for about year 2005, but still uncertain - may optimise coverage and revisit with six satellites measuring GPS occultations.

The proposed ACE + mission will complement and hugely enhance the missions, which are still operating beyond year 2007. The additions of GALILEO based occultation measurements will optionally double the amount of GNSS occultation measurements. Presently no other mission is, however, in addition foreseen to provide CALL type of measurements with the associated extraction of absolute water vapour contents through measuring the attenuation. These measurements are performed globally in the same region as the GNSS measurements thus supporting also these measurements.

2.2.3 Other Dependencies

ACE+ does not depend on any data from other satellites or data sources needing special synchronisation of development and operational availability. The sufficient ground segment data collection of GNSS measurements in support of orbit determination and GNSS clock extraction is already available for GPS and similar data servers will be available for GALILEO when available. The use of multiple satellite measurements of the same GNSS from the proposed constellation may further complement the auxiliary data provisions.

2.3 Products and Algorithms

The first table below present for the GRAS+ and the CALL instrument the key data and products: Input data (level 0) from instruments data download from satellites and from data acquisition from ground based servers, intermediately calculated data (level 1) and final products (level 2 and level 3).

Level	Key Data and Products	
	GRAS+	**CALL**
Level 0	LEO-GNSS received tracking data including occultations: L1 and L2 carrier phase and pseudorange.	LEO-LEO tracking data: Received carrier phase and amplitude at three frequencies (about 10, 17 and 23 GHz). In addition pseudo-range/coded phase signals at the three frequencies.
		LEO transmitter data: Amplitude at the three frequencies (for gain corrections, phase or clock extracted as LEO clock at level 1for clock corrections)
	• GNSS Ephemeris data (from IGS) • GNSS health data • (Ground) Fiducial station GNSS tracking data • Earth orientation data • LEO/Instrument housekeeping data • LEO attitude/pointing data	
Level 1	• Determined LEO ephemeris data • GNSS ephemeris data (IGS delivery) • Extracted GNSS clocks • Extracted LEO clocks • Residual phase observations extracted	
	Bending angle profiles calculated	Bending and absorption profiles calculated
	(Real) Refractivity profiles calculated	Complex (real and imaginary) refractivity calculated
Level 2	• Temperature profiles • Pressure profiles (and geopotential height profiles) • Humidity profiles • Error profile estimates • Vertical integrated water vapour (all profiles as a function of height)	
Level 3	• Global field maps: Temperature, pressure, humidity • Global trend maps: Temperature, pressure, humidity	

Table 2-5: GRAS+ and CALL Ground Processing: Key data and products

The products produced can be characterised as follows:

Temperature

One GRAS+ LEO instrument will produce 80 – 90 temperature profiles per orbit covering the troposphere and the stratosphere (GPS and GALILEO assumed). The accuracy of the observations are 1 Kelvin or better at altitudes ranging from 2 km to 40 km. Given approximately 14.5 orbits per day, the 4 ACE+ satellites will produce about 5000 high-quality temperature profiles per day.

Pressure

For GRAS+ the uncertainty in the pressure profile is less than 0.3 % in the range from 10 – 1100 hPa. The coverage equals the temperature profile data since they originate from the same observables as the temperatures.

Humidity

The GRAS+ tropospheric humidity profile is retrieved from solutions constrained by external wet temperature information. The accuracy of the latter need not be better than 2 Kelvin. This method gives an uncertainty in the water vapour profile that is less than 20 %, in the range from 1 hPa to 45 hPa. The level 1 and 2 algorithms for occultation products have all been defined implemented, tested and verified. Testing and verification have partly been done on the basis of GPS/MET data and ØRSTED data, partly by end-to-end simulations. The central level 1b and level 2 Abel transform algorithms for refraction have been tested and verified considering a wide range of conditions pertaining to global ionospheric and tropospheric behaviour.

For CALL water vapour is determined absolutely within the range of < 0.003 g/kg or < 3%, whatever is higher. The CALL algorithms have been prototyped and sensitivity and accuracy analyses have been performed (see section 1.2).

The vertical resolution in all the above results is < 1 km.

The Table below presents the principal related algorithms at each of the same levels.

<table>
<tr><th rowspan="2">Level</th><th colspan="2">Key Algorithms</th></tr>
<tr><th>GRAS+</th><th>CALL</th></tr>
<tr><td>Level 0</td><td colspan="2">• Frame quality and sequence check plus clean up
• Format Conversions</td></tr>
<tr><td rowspan="6">Level 1</td><td colspan="2">• POD calculation and correction
• Relativistic effect correction
• Phase slip detection /correction
• Instrument corrections (e.g. antenna gain vs. temp and pointing for CALL)
• GNSS and LEO Clock extraction and correction (including effects of different resolution for L1 and L2 for GRAS, etc.)</td></tr>
<tr><td>Signal conditioning for Ionospheric corrections</td><td></td></tr>
<tr><td></td><td>Liquid water correction (e.g., using freq1 vs. freq2 results and freq2 vs. freq3 results)</td></tr>
<tr><td>Doppler extraction/Multipath corrected inversion (Back Propagation/Canonical Transform)</td><td>Complex (amplitude and phase) residual extraction/Multipath corrected inversion (Back Propagation/ Canonical Transform)</td></tr>
<tr><td>Bending angle determination with frequency bias correction</td><td>Extracting Complex Profile with Bending Angle Profile and Attenuation Profile</td></tr>
<tr><td>Ionospheric correction</td><td>ionospheric correction (optional)</td></tr>
<tr><td rowspan="2">Level 2</td><td colspan="2">• Ideal gas equation
• Hydrostatic equilibrium</td></tr>
<tr><td>• TEC calculation
• Electron density calculations
• F2 and E layer peak detection
• Scintillation calculations</td><td></td></tr>
<tr><td>Level 3</td><td colspan="2">• Assimilation
• Field maps
• Trend analysis</td></tr>
</table>

Table 2-6: GRAS+ and CALL Ground Processing: Key Algorithms

2.4 Observation Requirements

Two occultation applications shall be supported

- LEO-LEO occultations, called CALL
- GPS and GALILEO occultations received at LEO, called GRAS+

The number of satellites and the number of launches allowed in the below considerations are determined by cost constrains. 4 satellites are the present limit and maximum 2 launches of the Rockot type and expense.

At least two counter rotating orbits are essential for the execution of the CALL application. The counter rotation is necessary to establish the satellite-to-satellite signal links with atmospheric traces of ascending or descending vertical profiles. The obits shall preferably be parallel. This is important to achieve the optimal satellite-to-satellite link quality through the antenna beam angle. Separation of the orbits would result in dramatic changes to the necessary antenna gain or the need to execute quite complex antenna steering. Taking into account the need for the same drift of the two parallel orbits the solution is 90 degrees inclination. Orbits with this inclination further provide for excellent coverage for the GRAS+ application with some preference for the polar regions. With 2 launches we place 2 satellites in each orbit. One orbit will contain satellites with GRAS+ and CALL receivers and the other orbit satellites with GRAS+ receivers and CALL transmitters.

4 satellites are launched two at a time in separate 90 degree inclination orbits which are 180 degrees separated along equator, i.e., counter-rotating orbits. The altitude of the two orbits are different, one at about 650 Km, the other at about 850 Km, the minimum 200 Km altitude difference being essential for the CALL application to support the daily global movement of the CALL occultation points along all latitudes.

During a period (one month or more) after launch the two satellites of each orbit are separated slowly to an about 90 degrees separation in the circular orbits. A 180 degrees separation that may seem reasonable for good global coverage will result in characteristic coverage pattern where some regions are not well covered per day, since all events would sit along lines.

The GRAS+ application is impacted by the need for parallel counter rotating orbits that in praxis is limiting the coverage to the one achievable by 4 satellites in one orbit and even a bit worse since the satellites are not always evenly dispersed in the orbit. The satellites are changing positions relatively to each other due to the counter rotation. Furthermore, the orbits have not the same altitude. The number of occultations is not impacted and the geographical coverage is good over a day. However, the overall revisit is less good than the one normally achievable with 4 satellites in one orbit. The GALILEO will double the number of occultations and complement the somewhat reduced coverage for the equator regions achievable with the given orbits and GPS alone.

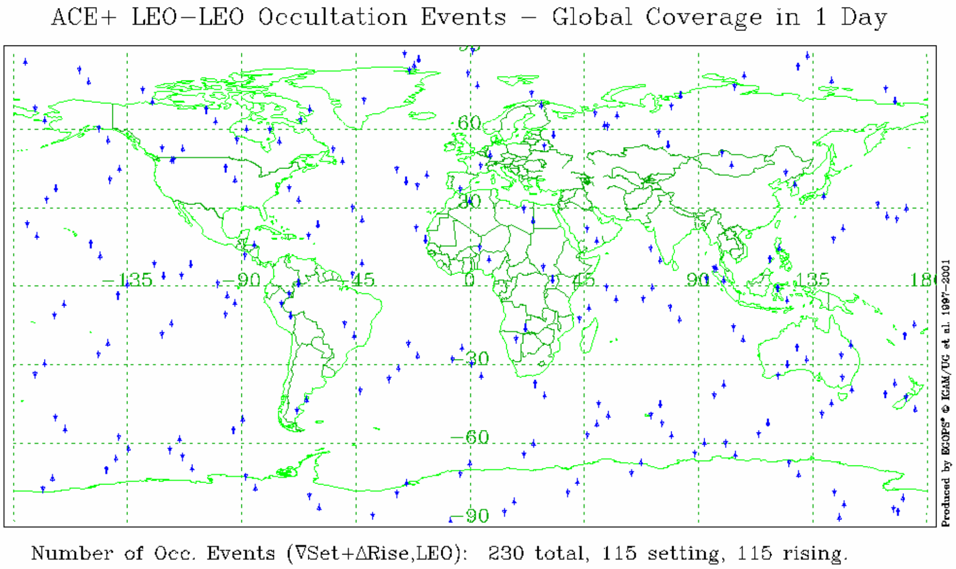


Figure 2-1: Global Daily Distribution of CALL Occultation Events

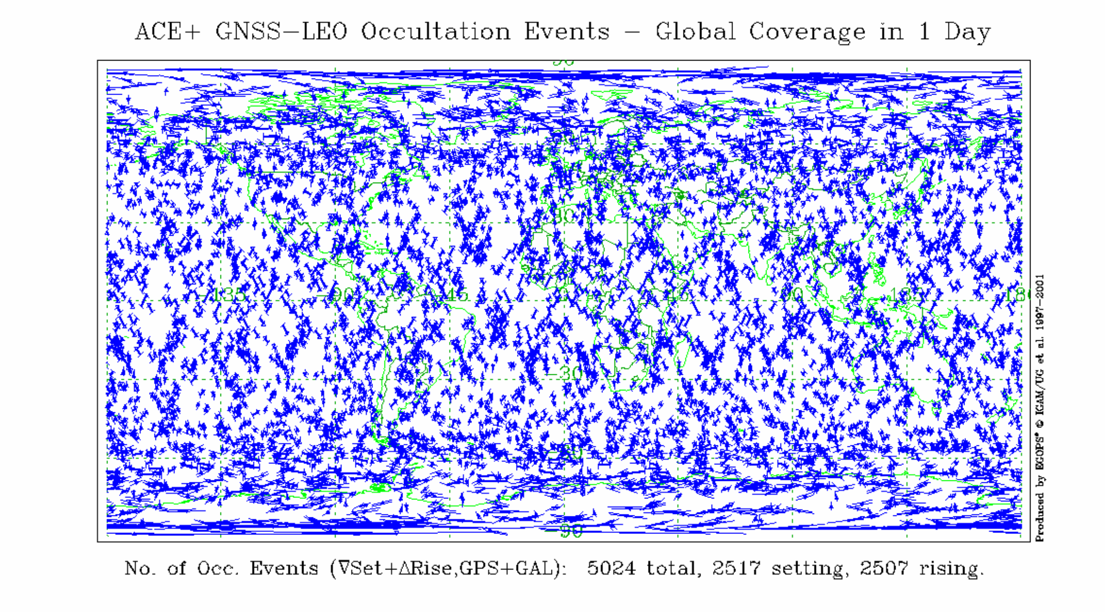


Figure 2-2: Global Daily Distribution of GRAS+ Occultation Events

Figures 2-1 and 2-2 show the resulting coverage diagrams for CALL and GRAS+ (GNSS = GPS and GALILEO) coverage over one day. For CALL it is seen that the non-antipodal satellite positions avoid the otherwise characteristic “diamond” pattern (cf. ESA, 2001). Computations for a full month confirmed that CALL provides about 7000 very well distributed events per month; already a highly valuable humidity dataset for climate.

3. Technical Concept

3.1 Payload Instrumentation

3.1.1 Architecture

The ACE+ satellites carry instruments with two main functions:

- a precision L-band receiver and related antennas for GNSS occultations, denoted GRAS+ (Advanced GRAS) for the next generation GNSS receiver. This is foreseen to include some of the evolution identified within the present ACE study. The capability will also be enhanced to support the CALL function of the instrument.
- a precision X/Ku/Ka-band transmitter or receiver and related antennas for LEO–LEO occultations, denoted as Cross-Atmosphere LEO-LEO Sounder (CALL).

GRAS+ and CALL constitute functionally two instruments. However, CALL relies on GRAS+ in order to navigate and time stamp data. With the envisaged coding scheme, the final down-conversion and despreading will be identical to those for GRAS. Several functions and operating modes are also identical, such as frequency generation, acquisition and tracking. There is therefore a great advantage to build the CALL instrument as an add-on unit to the GRAS+ electronics unit, see below.

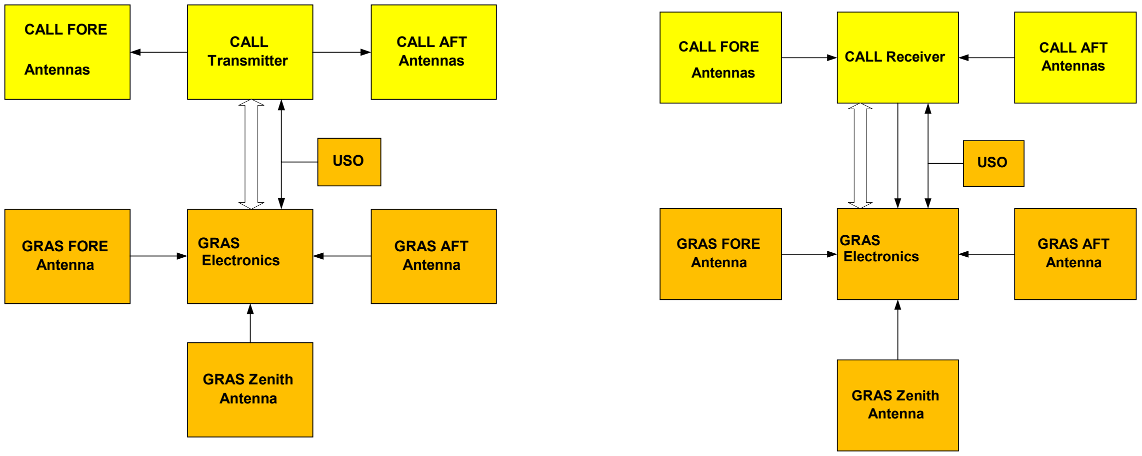


Figure 3-1: Instrument block diagrams for transmitter and receiver

3.1.2 GRAS+

Development of a miniaturised GRAS+ instrument is ongoing at SES within the ACE study, ESA contract 14397/00/NL/DC, and is based on the existing METOP GRAS instrument. The GRAS+ instrument consists of three antennas, one electronics unit, and a separate reference oscillator. GNSS signals are received through the antennas and are filtered and amplified in the Low Noise Amplifiers (LNAs) located in the GRAS+ electronics unit. Following amplification, the signals are down-converted, despread and correlated using locally generated GNSS replicas.

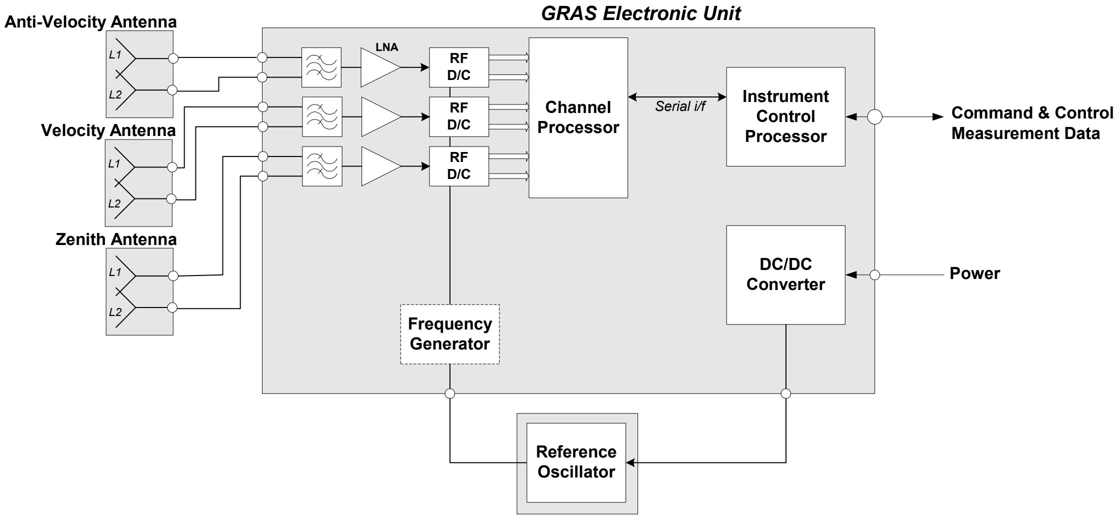


Figure 3-2: GRAS+ instrument functional block diagram

The occultation antennas are considerably smaller than their METOP counterparts. The antenna baseline 1 x 4 antenna elements and zenith antenna contains a single L1 and L2 element.

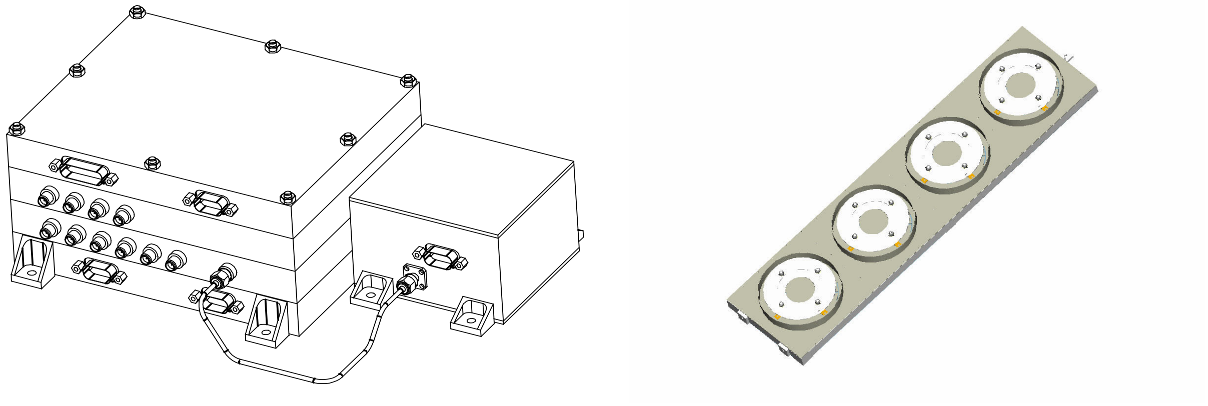


Figure 3-3: GRAS+ electronics unit, reference oscillator and occultation antenna

3.1.3 CALL

The CALL instrument has been analysed by SES in the WATS study for the Earth Explorer Core Mission. The receiver will amplify and down convert the signal to a suitable IF, which enables GRAS receiver technology to be reused. The carrier phase of the signal is detected and tracked in the same way as for GNSS occultations. Both the transmitter and the receiver should be phase locked to the GRAS+ reference oscillator. For transmission, the CALL signals are modulated digitally at IF. This frequency is generated from the GRAS+ oscillator. The signals are foreseen to be up-converted in two stages to the transmission frequencies.

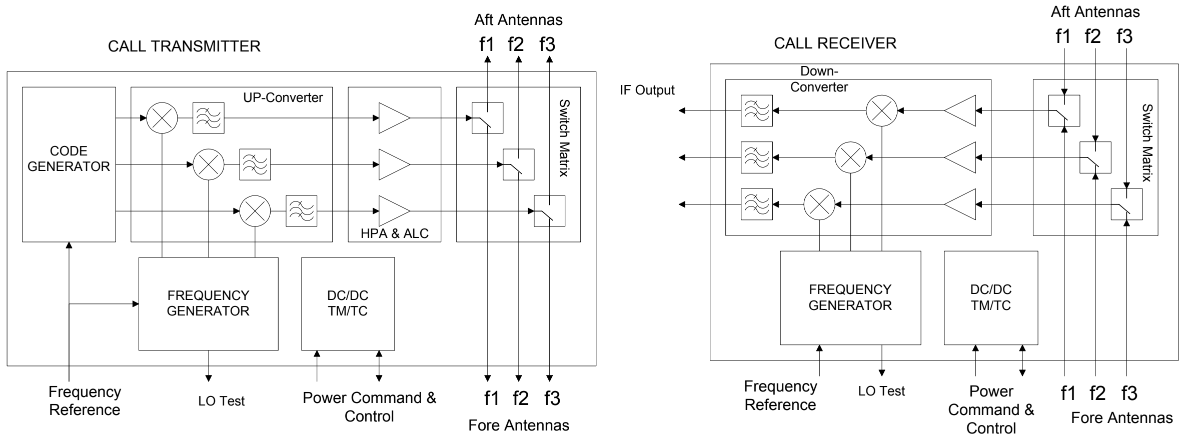


Figure 3-4: CALL transmitter and receiver functional block diagram.

Note that the IF output signal is fed into the GRAS+ instrument.

The antennas shall serve in either receive or transmit mode. Three frequency bands in the regions 10 GHz, 17 GHz and 23 GHz shall be served, with individual feed ports. Linearly polarised horn antennas are envisaged, one for the 10 GHz band and one combined antenna for the 17/23 GHz bands, the latter with orthogonal polarisations. A tentative design for conical circular horns is given in the table below. Alternative solutions can be considered, key requirement is the antenna peak gain.

Frequency	10	17	23	GHz
Wavelength	30	18	13	mm
Diameter	7.0	8.5	11.5	wl
	210	150	150	mm
Length	18	31	42	wl
	550	550	550	mm
Directivity	24.4	26.5	28.1	dBi

Table 3-1: CALL horn antenna parameters.

3.1.4 Instrument Budgets

A tentative CALL link budget is presented in the table below, based on the merged results from the two parallel WATS studies. The C/No figures are valid above the atmosphere i.e. without atmospheric attenuation or defocusing.

The expected stability of the receiver/transmitter is estimated to 0.01 dB/K each, in total 0.015 dB/K. This is based on in-house experience of receivers, and converters with and without thermal stability compensation. The temperature variation is estimated to 0.3 K/min maximum, rms <0.2 dB/min. This gives for 30 s occultation 0.002 dB, including some margin and indicating that we can reduce the requirement on S/C and Instrument thermal design and control.

Antenna gain can be controlled to an accuracy of 0.01 dB/antenna, total 0.015 dB/occultation, but can be improved e.g. by using S/C attitude control to track the transmitter/received beam at the peak of the antenna beam.

In total the Instrument can meet a total amplitude stability of 0.015 dB during one 30 second occultation. The major part of the amplitude variation will be linear, the non-linear part should be a magnitude smaller.

Frequency		10	17	23	GHz
Wavelength		29	18	13	mm
Free space att		-188.7	-193.1	-195.6	dB
TX Power [W]	2.0	33.0	33.0	33.0	dBm
TX gain		24.0	26.5	28.0	dBi
RX gain		24.0	26.5	28.0	dBi
Pre LNA losses		1.0	1.0	1.0	dB
Received power		-106.7	-106.1	-105.6	dBm
System noise temp		270	311	368	K
System noise temp		24.3	24.9	25.7	dBK
Bolzmann's const		-198.6	-198.6	-198.6	dBm/Hz/K
Noise power density		-174.3	-173.7	-172.9	dBHz
Implementation loss		-1.0	-1.0	-1.0	dB
C/No @ high altitude		66.6	66.6	66.3	dBHz

Table 3-2: Link budget for the LEO/LEO occultation link above the atmosphere

The instrument power and mass budgets are summarised in the Tables 3-3 and 3-4.

Unit / sub-unit	GRAS+ CALL Receiver Value [W]	GRAS+ CALL Transmitter Value [W]	Remark
GRAS+ Part	**27.0**	**21.2**	
CALL Part	**12.0**	**28.8**	Transmitter continuously operating
Total	**39.0**	**50.0**	

Table 3-3: Power budget for the instrument (GRAS+ and CALL) No redundancy included.

Unit / sub-unit	GRAS+ CALL Receiver Value [kg]	GRAS+ CALL Transmitter Value [kg]	Remark
GRAS+ Part	**8.3**	**7.8**	4 x 1 array for occultations
CALL Part	**9.2**	**9.1**	2 x 2 conical horns
Total	**17.5**	**16.9**	

Table 3-4: Mass budget for the instrument (GRAS+ and CALL). No redundancy included.

3.2 System Concept

3.2.1 Spacecraft

Several aspects drive the spacecraft design. First of all it is a platform for a payload with relatively high power consumption. Secondly, the pointing and stability requirements require a fully capable 3-axis attitude control system. Finally the mission should fit the cost envelope of the Earth Explorer Opportunity missions. It should therefore be a simple design and also fit a low cost launch vehicle.

This last aspect proved vital during the first design iterations. Taking the earlier studied ACE spacecraft with a baseline START-1 launch as starting point, it appeared that launch mass increased to the extent that the START-1 launch vehicle cannot launch into the high 900 km orbit. Cost considerations indicate to go for a mix of a START-1 launch for the low orbit and a Rockot for the high orbit. However, a complete Rockot launch would remove the need to optimise mass and volume. Increased cost of the two Rockot launches could be balanced against cost gains due to simplified design.

The following sections will first present the designs optimised for the START-1 launch and the Rockot launch. It then will proceed to give an overview of the general design, including the subsystems that are common to both options.

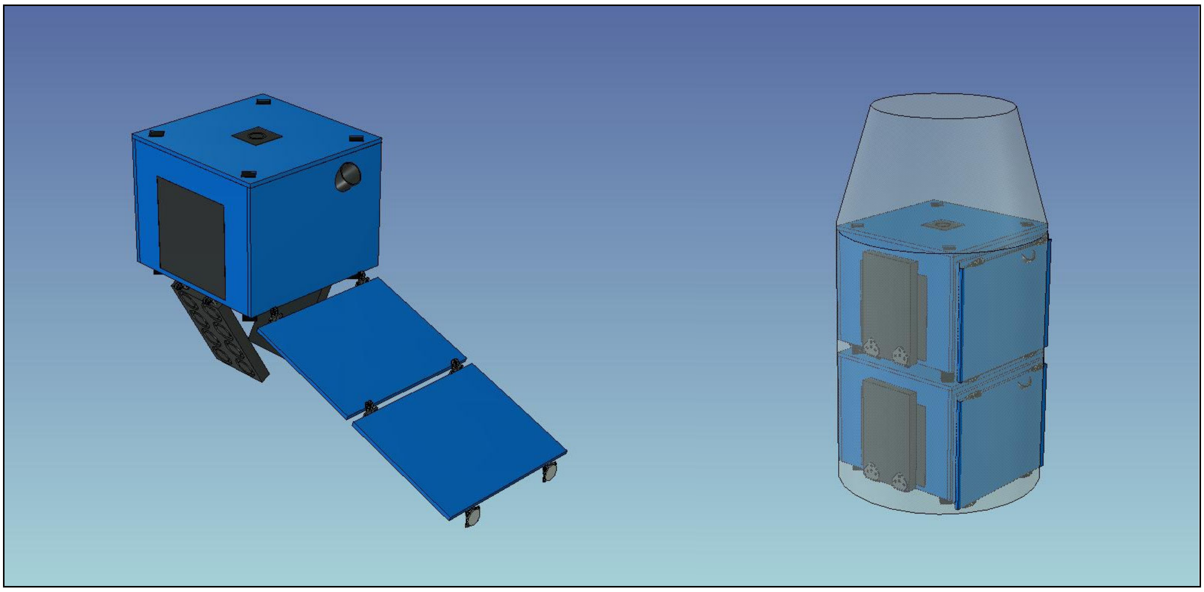


Figure 3-5: Configuration optimised for START

3.2.1.1 START-1 optimised configuration

The design problem focuses on fitting two spacecraft in available space and mass. For this solution a number of alternatives have been defined. The alternative based on the ACE configuration features stacking of the spacecraft during launch, and this facilitates launching one satellite (see option 1 in the launch vehicle description) because the centre of mass will stay on the launch vehicle centreline. A drawback is that both the solar panel and GRAS+ antennas have to be deployable. Other alternatives feature is a side-by-side launch, which offers less deployables, and thus a simpler system.

The table below shows a typical mass breakdown for the spacecraft, which meets the START-1 performance to launch in a 600 km orbit at 90° inclination.

The deployable solar panel at one side of the body needs a180° yaw manoeuvre each time the sun passes the orbit plane to keep the sun on the panel. The AOCS system is fully capable of performing this slew in a limited time frame.

Subsystem	Nominal mass [kg]	Average Contingency	Max. Mass [kg]
Power	13.8	18%	16.2
Radio	3.2	5%	3.4
Data handling	7.5	15%	8.6
Attitude Control	19.4	5%	20.3
Orbit Control	7.7	14%	8.8
Structure & Mechanisms	31.4	20%	37.6
Thermal Control	2.0	20%	2.4
Harness	10.0	35%	13.5
Platform mass	**122.0**	**17%**	**145**
GRAS+ payload	**14.1**	**20%**	**16.9**
Total S/C mass	**109.1**	**17%**	**127.7**

Table 3-5: Mass budget for the START-1 optimised spacecraft

3.2.1.2 Rockot optimised configuration

The figure below shows the configuration optimised for Rockot. It makes use of the volume available to have large, body-mounted Si solar panels, and also to have the GRAS+ antennas fixed to the body. This configuration should offer savings in terms of solar cell cost, mechanisms, and simplified AIV. A drawback is its size, which will make shipping and testing more difficult. The mass of one spacecraft is about 175 kg, well within the Rockot launch performance.

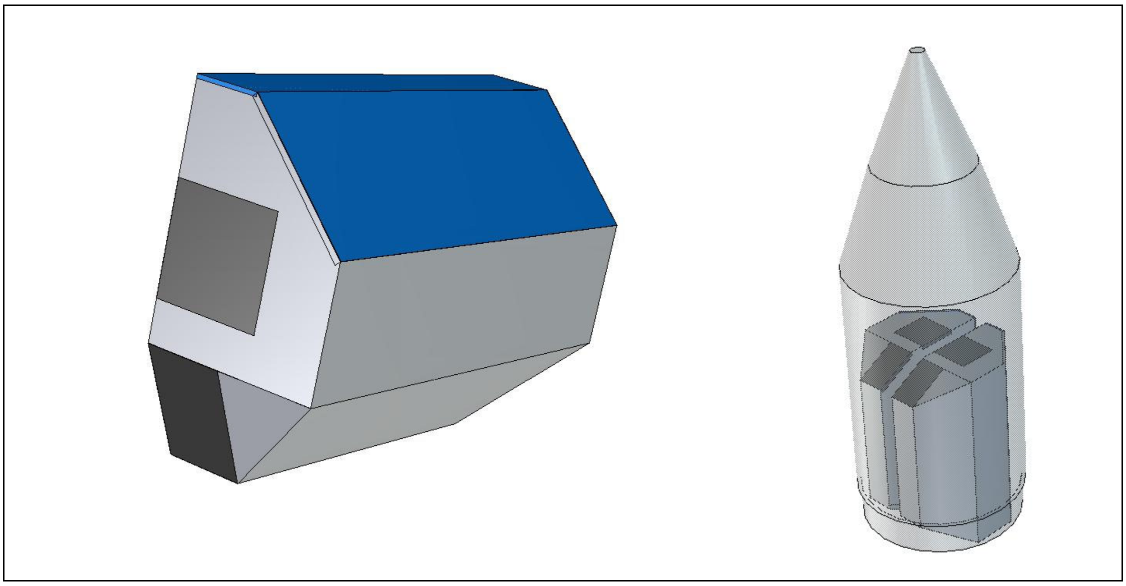


Figure 3-6: Configuration optimised for Rockot

3.2.1.3 General system layout and avionics

The figure below shows the general system concept for the spacecraft. A central role is played by avionics, which is called System Unit (SU) at SSC. The SU is based on SSC's Microsat Avionics Architecture (MAA) that was used for the ACE platform. This off-the-shelf concept has a strong heritage of the SMART-1 SU. The MAA consists of a number of loosely coupled boards (via the CAN bus) for processor, mass memory, TM/TC and interfaces to the other subsystems. This loose coupling of the boards is a strong advantage because it facilitates the early testing of board and interfaces. Simply plug in the CAN bus to a PC and start testing.

The spacecraft will basically be single string spacecraft, i.e. redundancy is only included for components and units that are less reliable. Two areas identified for redundancy are the reaction wheels and the separation command system. Although reaction wheels are not prone to fail, three reaction wheel have an increased chance of failing, and therefore a fourth wheel is an efficient means of increasing the reliability.

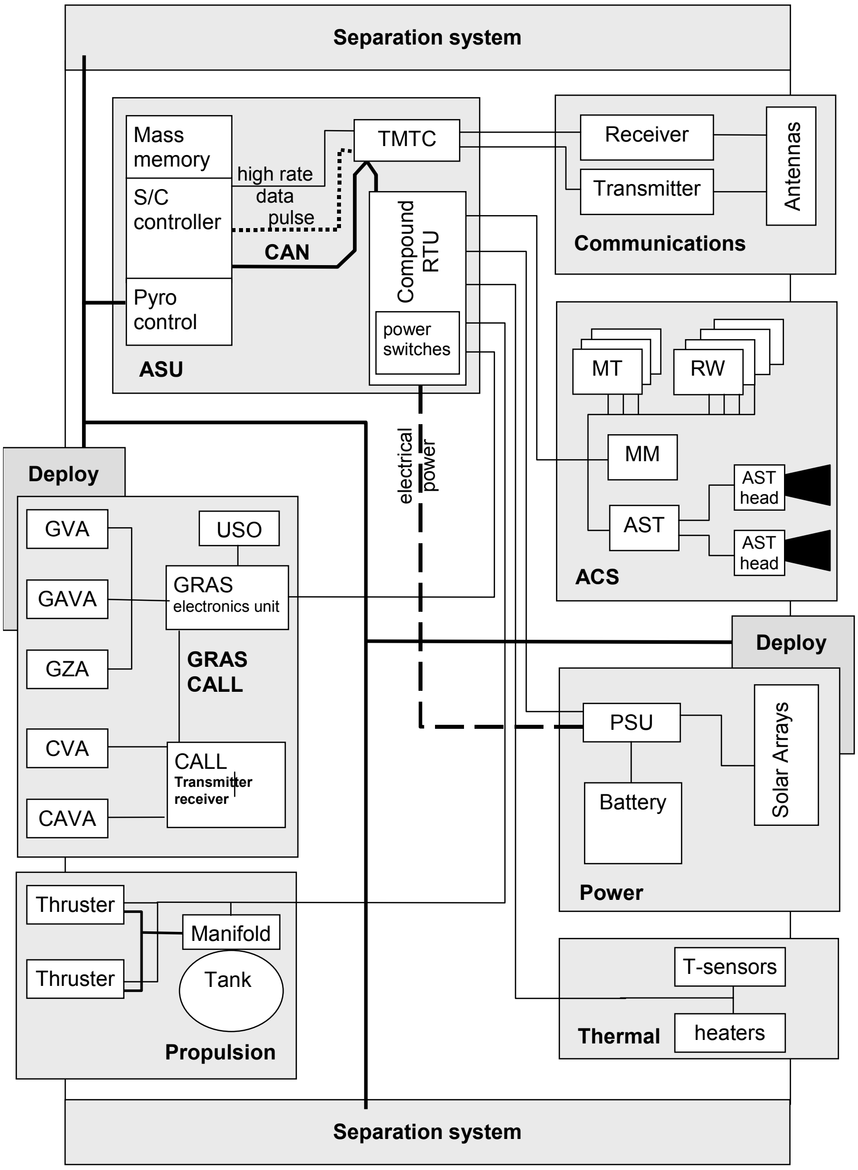


Figure 3-7: ACE+ system layout

3.2.1.4 Power system

The power system is designed for an orbit average power demand of about 77 W as specified below. The system for the START-1 alternatives is aimed at maximising power output and minimising mass. It employs triple/junction GaAs solar cells with a total of 2.2 m^2 installed, and a TBD Wh Li-Ion batteries. The power conditioning system uses the S^{3}R technique with constant solar panel bias voltage. This means that the full power is left on the panels. The power system for the Rockot configuration employs Si solar cells, and the other components will be optimised for cost.

	Power Nominal (W)	contingency	Maximum Power (W)	Orb. average Power (W)
Platform			56.4	**37.4**
Radio	16.9	5%	17.7	5.3
Datahandling	11.5	10%	12.7	12.7
Attitude control	11.4	14%	13.0	13.0
Thermal control	10	30%	13	6.5
Transmitting payload			52.2	**37.6**
Total transmitting			108.6	**75.1**
Receiving payload			39.7	**39.7**
Total receiving			96.2	**77.2**

Table 3-6: Power demand of the ACE+ spacecraft

3.2.1.5 Attitude and Orbit Control system

The AOCS is based on zero momentum system with four reaction wheels and an autonomous Star Tracker with dual optical head. This configuration meets the pointing and stability requirements of the payload with ease. Initial attitude acquisition and momentum dumping is done using three magnetic torquers and a magnetometer. A simple safe mode based on sun sensors, magnetometer, and magneto torquers is envisaged.

The orbit control system is used for initial phasing of the spacecraft in one orbit, and to synchronise the two orbit planes. The ACE study showed that a delta-V of 12 m/s is sufficient and therefore a simple cold gas system can be employed.

3.2.1.6 Communications

The communication subsystem is based on off-the-shelf S-band transmitters and receivers already identified during the ACE study. Furthermore it employs a straightforward switching scheme to low cost patch antennas.

3.2.1.7 Thermal control

Thermal control is aimed to be passive. However, experience from the ACE study, and the requirements for the GRAS/CALL instrument indicate that this area needs special attention during the coming phase. One advantage of the ACE+ spacecraft over the ACE spacecraft is increased mass and thus increased thermal inertia of the design.

3.2.2 Launch Vehicles

The ACE+ plus mission needs at least two launches, and therefore the launch is a driving force in the total system cost. Three options are defined that couple launch cost to system complexity. System complexity includes amongst others the complexity of the spacecraft (i.e. optimised or not) and the complexity of the launch vehicle interface. Increased system complexity will lead to increased system cost.

The launcher baseline consists of the START-1 launch vehicle marketed by Puskovie Uslugi, and recently used for the launch of SSC’s Odin satellite, and the Rockot launch vehicle marketed by Eurockot. Both are low cost alternatives, but with very different performance. The START-1 launch vehicle can launch 260 kg in a circular 600 km, 90° inclination orbit. Rocket can launch over 1000 kg in a 900 km, 90° inclination orbit.

Finally a possibility exists to launch with the Long March 2C launch vehicle, which has a performance of 1500 kg in a 900 km, 90° inclination circular orbit.

3.2.2.1 Option 1 – START-1 launch

This option requires three launches, one for the injection of two satellites in the low (600 km) orbit, and two launches to inject two spacecraft, one at a time, in the high orbit. This option has the advantage that a common interface exists between the spacecraft and the launch vehicle, and that the spacecraft can be optimised for the launch vehicle. A drawback is the need for three launch campaigns, although a second launch campaign could contain the two single launches.

3.2.2.2 Option 2 – combined START-1 and Rockot launch

The START-1 injects the two spacecraft in the low orbit, and the Rockot the two in the high orbit. Drawback of this combination is increased complexity of having to work with two launch authorities, doubling some work. Impact on the mechanical interface is judged to be minor, because Rockot is flexible and can adapt to the START-1 interface. The spacecraft are optimised for START-1, which means Rockot has a huge over-performance. Offering piggy-back opportunities on the Rockot launch could decrease launch cost.

3.2.2.3 Option 3 – Rockot launch

Two launches will inject the spacecraft in the low and high orbits. This option has again the advantage of a common interface, but has the drawback of increased cost. Because Rockot offers so much mass and volume to the spacecraft, design can be optimised to cost, which means constructing it as simple as possible, i.e., fixed Si solar panels, fixed GRAS+ antennas, etc. The option of a Long March launch is similar to the all Rockot launch.

The table below compares the three options. All have their specific advantages and drawbacks, which should be the basis for a trade-off in the first phase of phase A.

	Option 1	Option 2	Option 3
L/V	START-1	START-1 + Rockot	Rockot Long March 2C
Number of launches	3	2	2
Advantages	Common interface Contingency capability (in case of launch failure)	Cost	Common interface Allows simple spacecraft design
Disadvantages	Optimised satellite (increased complexity) Increased launch campaign cost	Optimised satellite (increased complexity) Two launch vehicle interfaces	Higher launch cost (No launch cost in case of LM 2C)

Table 3-7: Launch option comparison for the ACE+ mission

3.2.3 Ground Segment

The ground segment is composed of two main facilities:

- Satellite Data Acquisition and Control network (SDAC)
- Data Processing and Mission Control Centre (DPMCC)

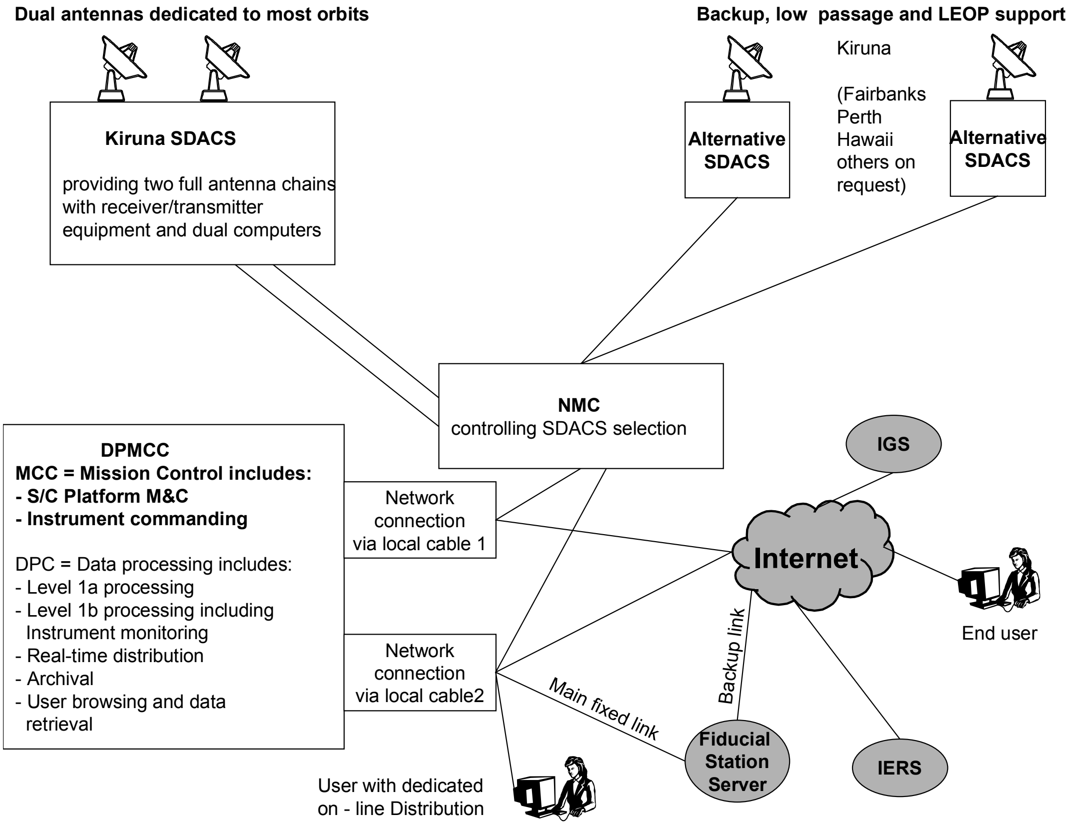


Figure 3-8: Ground Segment Overview

The SDAC consists of the main Satellite Data Acquisition and Control Station (main SDACS) and the Network Management Centre (NMC). All satellite commands and telemetry data are routed through the NMC that monitors and controls the telemetry and telecommand distribution network. All orbit data are forwarded from the MCC through the NMC that converts these to tracking co-ordinates. The NMC will manage the selection of alternative SDACS in case the main SDACS fails its mission. Alternative SDACS and/or backup antennas on the main SDACS are of particular importance during the LEOP where the tracking and control of closely positioned satellites may require additional antenna tracking and communication resources. There are 2 launches with 2 satellites launched, the two satellites in each launch having different S-band communication frequencies thus supporting the separation.

The baseline main SDACS is at Kiruna. Two 5 m S-band antennas are dedicated to the mission with one antenna providing backup and supporting simultaneous tracking and communication when necessary. With 90 degrees inclination of the orbits all orbits are visible from the Kiruna site but 3 orbits have a very low passage. These orbits are supported by additional 9 m antennas positioned in elevated positions thus providing for at least 4 minutes of tacking above one degree of horizon. As an alternative to the use of the 9 m antennas no efficient SDACS seems to be available presently at high latitude positions and separated about 90 degrees in longitude from Kiruna. An alternative main SDACS replacing Kiruna could, however, be Svalbard with the associated difficulties for high rate communication.

A maximum of 40 Mbytes of data dump per orbit from each of the 4 satellites leads to a dump rate of 1.3 Mbps over 4 minutes and an overall telemetry downlink rate of about 220 Kbps over 100 minutes (orbit time). This kind of telemetry downlink rate means storage of data at the SDACS or NMC to accommodate for temporally uneven arrival of satellites at the

SDACS. In order to speed up the downlink transfer rate and to allow backlog transfer at link switchover after failures we have selected a redundant 512 Kbps link. Thus in the worst case of simultaneous dump from two satellites the last telemetry arrives at the DPMCC no later than about 15 minutes after the beginning of the dump. 64 Kbps redundant uplinks are sufficient for the telecommanding.

The DPMCC is located in Copenhagen as a baseline. Alternatively the MCC may be placed at ESOC, Darmstadt. In the latter case the non-instrument related telemetry is stripped off at the NMC and forwarded to ESOC over existing links from Kiruna and the telecommand uplinks are likewise connecting ESOC over existing links to Kiruna. The same model will also apply if using Svalbard or any other facility as SDACS, the NMC still being at Kiruna. The DPC that is evaluating the instrument status will inform the MCC of any needs for commands through the internet with a dial up link as backup.

The DPMCC is characterised by an implementation whereby the processing platforms for the three main functional groups are kept separated. This allows for a simple and robust management of the adaptation to processing needs, of system availability, access safety, maintenance and even location as applicable. These three groups are:

- Mission Control (MC)
- Application Data Acquisition and Processing (ADAP)
- Data Distribution and Archiving (DDA)

The MC is based on SCOS 2000, a generic product developed - partly by Terma - through ESA. The MC will be configured to automated execution of satellite and ground segment commanding and the partly automated evaluation of the satellite housekeeping telemetry and the ground segment monitor information. The operator interface is highly configurable for tool-supported analysis of data. Standardised interfaces are provided to support mission planning and flight dynamics through command entry including uploading of new satellite software if necessary. SCOS 2000 supports operator manipulation of loaded commands and their execution.

Level 0 processing, i.e. check of telemetry frame quality and sequence consistency plus associated annotations, is performed at the SDACS.

Level 1a (data entry, validation and reformatting and storage for further processing) and level 1b data processing (GRAS+ bending angle profiles and CALL bending angle and absorption profiles, with associated supporting data) are performed by the ADAP. Instrument status monitoring as extracted from the telemetry or deduced from the further processing is performed as part of the level 1b handling and the MC is informed of any needs for commands.

The GRAS+ ADAP level 1 processing requires in addition to satellite data handling also the availability of data from ground based sources. Data are retrieved from the following sources:

- Servers providing continuous 1 Hz resolution GPS tracking data from fiducial tracking stations. These data are used for clock variation correction in occultation processing
- IGS servers providing GPS orbits plus 30 sec resolution continuous clock data from fiducial tracking stations for Precise Orbit Determination (POD) of the six LEO satellites
- Other servers providing infrequently updates of earth rotation data, etc.

The GRAS+ 1b occultation data processing consists of several steps. This includes corrections for satellite movement, cycle-slips, instrument and clock variations, multipath (in the lower troposphere) and ionospheric delay.

The GRAS+ near real time processing has been the subject of extended studies especially in the period since the ACE mission was selected as a standby mission during the first Earth Explorer Opportunity Mission selection. Important parts of the processing have thus been prototyped and the accuracy and processing speed mentioned below has been proven.

The POD is a prerequisite for the correction of satellite movement and has to be done with an accuracy of at least 0.1 mm/sec within the duration of an occultation (about 2 minutes). In view of the needs for fast processing this requires careful selection of POD methods (clock correction, dynamic orbit modelling and orbit integration). A dedicated LEO POD tool has been prototyped and tested for ACE based on the Bernese tool from AIUB in Bern.

Correction for LEO and GPS clock variation over the GRAS+ occultation duration is very critical. A unique clock extraction procedure has been developed. It exploits all the available tracking information - ground station and LEO GPS tracking at different data collection frequencies - and in addition provides an operational quality figure associated to the derived results as dependent on the quality of the tracking network available for the individual occultation.

The GRAS+ data processing system is designed to support the processing load associated with a satellite dump at least every 25 minutes in average. By implementing the system so that all processing associated to product generation resulting from one satellite data dump is performed within 25 minutes the required delivery times to end users (less than 2.5 hours from recording the data on board) may easily be supported. This allows as well for quite fair data transfer rates in the acquisition and delivery network. Flexibility must be provided to secure processing if data acquisition is delayed. All processing is controlled via a central database keeping track of the data availability and quality as a prerequisite for each new processing step.

Level 1b bending angle data are delivered on-line to users with operational needs, e.g. meteorologists for generation of level 2 data (temperature and pressure profiles), which may then be assimilated with NWP and Climate models.

Intermediate level 1a data from satellites and ground sources, orbit data and level 1b bending angle data are stored in archives with Web based near real time and off-line (one year or older data needing media insertion to jukeboxes) access via catalogues.

The satellite telemetry data associated to the CALL application will likewise be near real time processed at level 1a and level 1b. Instrument status monitoring is performed as part of the level 1b handling and the MC is informed of any needs for commands. Also the distribution and archiving is similar to the GRAS+ processing. The CALL processing algorithms are defined and have been subject to prototyping. Further optimisation is required in Phase A.

The ground segment has built-in redundancy and a high degree of automation based on local and system level failure contingency actions. This will secure an overall availability of system monitor and control, data acquisition, data processing and data delivery functions beyond 99.5 %, and loss of two consecutive satellite data dumps will never occur.

3.2.4 Operations

In the context of operations it is important to notice that the payload instruments are highly autonomous with on-board software controlling the operational modes, which apart from some initial power up sequences and failure mode procedures are closely associated to the individual occultation. The satellite platforms are autonomously three-axis stabilised. Orbit positioning correction activities are infrequent and primarily limited to the LEOP.

Monitor and control activities of the ground segment are highly automated, the degree of operator and specialist intervention, however, strongly dependent on the operational phase.

- *Normal operations*: 24 hours operator assistance is only required at the NMC and then normally only as a backup precaution (2 people) outside normal working hours. The operators may be shared with other missions served by the NMC. The SDACS are fully automated. At the DPMCC operator assistance is required only during daytime. Built-in redundancy results in the need for maintenance personnel only during daytimes at any part of the system.
- *LEOP*: There are two LEOP phases separated by a few months. The satellites are launched two in a bundle, then separated and slowly separated over some month using propulsion firing procedures which are not at all critical. During the first days of the LEOP there will be 24 hours operator assistance at the DPMCC.
- *Commissioning phase*: This is a long phase starting with the first launch and finalised some time after the second launch and LEOP. Basically the instruments need closer monitoring and may be associated with control involving science/instrument specialists available at the DP the first days after each LEOP. The final positioning of the satellites for best coverage is a long process over months with no need for specialists to be available on site normally, but rather at agreed meetings and on call at special events. The CALL application cannot be fully evaluated before the second launch has been executed. There is no need for 24 hours operator assistance throughout the commissioning phase, but the availability of an operator on call should be considered. The orbits can be observed quite well by the NMC operators that can, for example, assist in preparing emergency tracking co-ordinates in case of failures of the network connection to the MCC.

Ground segment platforms and network redundancy switching is automated, with maintenance personnel repairing faults during normal working hours only. Backlog processing in the context of redundancy switching – e.g., preventive storage plus repeated transmission after switching – is automated.

System platform (h/w and operating system plus network s/w) failures and degradation problems plus application s/w degradation problems (lack of resources, etc.) are flagged in the system log, on local terminals and remote terminals. In addition summary alarms may be issued that may be remotely available (e.g., SMS) in case of on call operators and maintenance personnel.

Monitor and control activities of the various parts of the ground segment are described below.

The tracking of spacecrafts, the handling of command uplink and telemetry dump is automatically controlled from the SDACS based on data forwarded well in time from the MCC and routed to the selected SDACS and antennas via the NMC. Orbital data from the MCC are in this process converted to tracking co-ordinates. The NMC operators may assist in the backup selection of alternative SDACS and in preparation of tracking co-ordinates based on known passages and radar information. The NMC will forward tracking reports, SDACS selection reports and distribution link status reports to the MCC. The NMC monitors and controls all links to SDACS and DPMCC.

The MCC will perform the automated monitoring of the satellite platform status, orbit positions, the instruments status and the ground segment overall status.

- Orbit positions are received from the DPC as Precise Orbit Prediction is an integral part of the DPC level 1b processing
- Platform status is derived by the MCC from the telemetry
- Instrument status data are received from the DPC as derived here for tuning of processing parameters and data quality estimation
- The ground segment status data are based on data from the DPMCC processes and platform monitoring (operating system and network log) plus NMC reporting (tracking reports, SDACS selection reports and distribution link status reports).

The evaluation of monitored parameters is partly automated to the extent that critical parameters are checked and warnings are raised. Otherwise the operator is assisted by MCC provided evaluation tools.

The MCC provides tools for orbit prediction and commands preparation. Instrument commands may normally not be formulated - unless of routine nature - by MCC operators and must be co-ordinated with DPC specialists. Forwarding of commands and orbit data to the NMC is normally automatic.

The DPC performs automatically the Data processing, archiving and distribution for the standard data sets.

Evaluation of processing quality may require operator intervention through inspection of the log and (system assisted) display of selected data.

Operator assistance is required for removal and insertion of tapes in the archive jukebox, i.e., insertion of new tapes and transfer of tapes between off-line and near-online archive. The total amount of data to be archived will grow in the order of 5 TB per year.

Obviously collocation of MCC and DPC in a DPMCC may save operating personnel during normal operations.

3.3 Technological Complexity

3.3.1 Feasibility

The proposed mission is highly feasible. Not only is the scientific relevance well established, but also the technical approach is based on elements which all have a very sound technical basis.

The GRAS+ instrument is mature and application data processing well established.

The CALL instrument is based on known techniques: The receiver is closely related to the GRAS+ receiver (receiving a GNSS type of signals), some heritage exists from WATS pre-phase A studies (ESA, 2001), and high frequency transmitters have been produced before. The instrument and application processing algorithms have been studied and elaborated within the WATS study for Earth Explorer Core Missions. Phase A activities shall expand the instrument and algorithmic basis needed.

3.3.2 Subsystem Maturity

The various constituents of the system are based on previous developments as illustrated in the description of section 3.4.

The GRAS+ instrument will be the instrument configuration currently under development for the METOP mission based on previous development within the EOPP framework. Acquisition of the GRAS+ scientific data will be made with observation techniques and instruments for which the underlying principles have already worked out, and for which preliminary experimental evidence have already been obtained in experiments done on European (ØRSTED, CHAMP) and American satellites (GPS/MET).

Processing of the GRAS+ data will be handled through the use of algorithms that are already developed, so that the scientific data will be useable from the very beginning of the operation of the satellites.

The prototyping of the CALL instrument and maturing of the processing algorithms for proper performance will be performed during phase A.

The technical implementation of the satellite platform and the ground segment is in general not particularly complex and critical.

The satellite weight, power and volume budgets are not critical for the launchers available and affordable. None of the various platform subsystems will be required to go beyond the present state-of-the-art in order to fulfil the scientific requirements for the mission.

For the ground segment performance tuning for GRAS+ application data has been already achieved.

The ground segment is planned implemented based on the SCOS 2000 control facilities that have already been demonstrated at ESOC for small scientific and meteorological missions. The extensions needed in order to monitor and control a constellation of satellites are not foreseen to be too complicated as the orbital monitor and control requirements are not particularly demanding and rather a question of separating the monitor and control database of the individual satellites.

3.3.3 Reuse of Elements

A considerable reuse of components, design and technology is foreseen. A more detailed review of the heritage of the various system elements is presented below.

3.3.4 System and Instrument Heritage

The present section provides an overview of the way in which each of the mission elements derives its design or implementation from previous developments, either through heritage from design/concept or (assumed in addition) through COTS/Implemented availability (with assumed need for configuration).

Mission Element	**New dev.**	**Design/ Concept**	**COTS/ Impl.**	**Company (Project/product)**
Instruments				
CALL Subsystem	X			SES, Alcatel (WATS study)
CALL : Receiver after down conversion		X		SES (Metop/GRAS receiver)
CALL Antennas		X		Alcatel, SES
CALL Transmitters		X		Alcatel
GRAS+ receiver/subsystem		X X	X	SES (EOPP developments/studies, incl. ACE studies) SES (GPSOS Design specifications) SES (Metop development)
Platform				
Data Handling System		X		SSC (Smart-1)
AOCS				SSC (Smart-1, Odin), Alcatel
Reaction wheels,			X	Teldix, Stork, IAI Tamam, Ithaco
Magnetic torquers			X	Zarm, Fokker Space, SSTL
Magnetometer			X	SSTL, IAI Tamam, Ithaco
Autonomous star tracker			X	Terma, DTU, Officine Galileo,
Sun sensors			X	TNO-TPD
Propulsion system		X	X	Bradford Engineering, Aerospatiale, IAI Rafael
Power system		X		Fokker Space
Solar panels			X	Fokker Space
Battery			X	AEA, SAFT
Power conditioning and distribution			X	Patria Finavitec
Communication		X		SSC
S-band transmitter/receiver			X	SSTL, QinetiQ, Alcatel, Alenia, Spacedev
RF antennas			X	SSTL, FFV
RF switches			X	DowKey
Structure and mechanisms			X	Fokker Space
Structure	X	X		Apco, Fokker Space
Mechanisms		X	X	Fokker Space
Separation system		X	X	Saab Ericsson Space, PyroAlliance
Thermal subsystem	X	X		Fokker Space
Ground Segment				
Ground Stations			X	SSC, ESOC (equipment commercially available, tracking networks available)
GRAS+ related Data Processing		X X	X X X	Terma (Developments for the ESA EOPP, study for ACE/POD, Clock extraction, processing framework) Terma, DMI, MetOffice (EU CLIMAP project/ using GPS/MET & ØRSTED occ. data) IGAM/UG, GFZ Potzdam, other European Institutes (using GPS/MET & CHAMP occ. data)

Mission Element	**New dev.**	**Design/ Concept**	**COTS/ Impl.**	**Company (Project/product)**
Instruments				
Mission Control Centre			X X X	Terma, ESOC (/SCOS2000) Terma/AIUB (/Precise Orbit Determination Tool) ESOC (/Flight dynamic support at ESOC)
CALL algorithms		X		Chalmers, DMI (WATS Study)
Satellite/Instrument & Ground Segment Testing				
EGSE		X	 X	SSC (SMART1) Terma/ESOC (/SCOS2000 with EGSE extensions)
AIV/AIT facilities				ESTEC, IABG, etc. (/Test facilities)
AIT Procedures				SSC, Terma, Fokker, SES, Alcatel (Science satellite projects)

Table 3-8: Subsystem, component and procedures heritage

3.4 Data Exploitation

The end users of the data and products will come from a variety of fields including public services, environmental protection, industrial users and International User Community interest groups, - although the initial focus will be scientific institutions.

Core users will exploit the Level 1b products delivered from the data processing centre in order to produce level 2 products and assimilate these with other data for climate change processing and NWP. The core users essentially are the participating partners and users.

'Direct' users may receive level 1b, but most likely level 2 or higher level products for their monitoring and information services.

'Peripheral' users will in their protective strategies use results concerning long-term trends as derived by level 2 assimilation and trend analysis mainly performed by other institutes.

User Group	Core	Direct	Peripheral
Public Services			
Meteorological Institutes	X		
Climate Monitoring Institutes	X		
Natural Hazard Warning Services		X	X
Environmental Protection			
National Environmental Institutes		X	X
International User Community Groups			
WCRP	X	X	
GCOS	X	X	
IPCC			X

Table 3-9: User Group data Exploitation

The data policy tentatively adopted for the project would include:

- Free access to all data and products for the participating scientific partners
- Free access to generated products for the associated user institutes
- Free access to officially released products for other users via the Internet

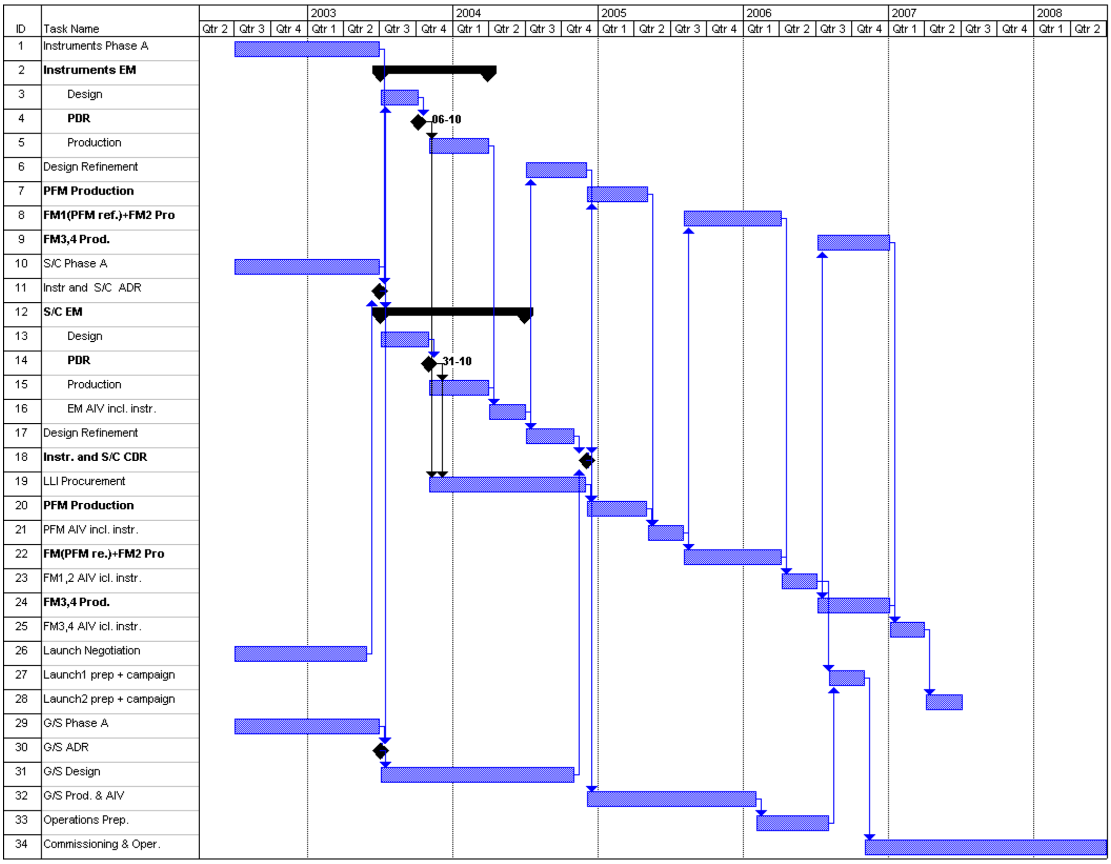
4. Implementation

4.1 Planning

4.1.1 Schedule

Below is inserted the pert diagram covering the phase A and the phase B/C/D/E work: Instrument, platform and ground segment development, launches and operational phases including commissioning.

Phase A is scheduled to last 1year. Phase B/C/D is planned to last 4 years: 1 year for EM, 1 year for PFM, 0.8 year for FM1 (refurbished PFM) and FM2, and 1.2 years for FM3 and FM4 (parallel to the first launch at start and including the second launch).



4.1.2 Critical Items and Activities

There are no severely critical items and activities.

The mission has a high level of redundancy as part of its basic concept, even though the individual instruments and platforms have little or no redundancy per se. There are two launches planned. There are 4 GRAS+ receivers planned to be in orbit at the same time, which will still generate a large volume data should one instrument or satellite fail to operate. There are two CALL receivers and two CALL transmitters in orbit at the same time, where just one receiver and transmitter would be sufficient to generate data of high scientific value.

A large set of COTS components has been included. Chapter 3.3 presents the feasibility, maturity and availability of the components and approach. Timely development of the instruments is a prerequisite. The GRAS+ is not foreseen to be a problem as being an extension for the GRAS instrument presently being developed for the Metop. The CALL has been studied in the WATS study (Earth Explorer Core Mission study). The instrument partly includes GRAS components and the front-end receiver, transmitter and antennas are based on well-known concepts and implementation experience. Considering the launchers available within the budget and the associated relatively low constraints on power, weight and volume there is no need for heavy optimisation to achieve transmitter stability, EMC immunity and other weight, volume and power demanding functions.

Implementation of the instruments, the platform and the various subsystems will follow a strategy of implementing an EM model, then a prototype flight model followed by the appropriate flight models. The prototype flight model will be refurbished to flight model one. A system simulator will be built based on the EM and an EGSE that is including the Mission Control Prototype system. Implementing the constellation in two steps will allow some last minute modifications to take place, should the in-flight evaluation of the first two satellites show a need to introduce some corrections.

The financial envelope is not foreseen to constitute a severe risk. Concerning cost versus quality the model philosophy is adapted to work allocation of the consortium partners to minimise interfaces and experience transfer (the EM and PFM manufacturers hands over FM production work to other partners together with a full EGSE and a simulator). The subsystem work including full AIV is distributed to teams monitored by a small and efficient consortium level engineering team.

4.2 Work Breakdown Structure

4.2.1 Project Phases and Interfaces

Phase A will terminate with a draft specification of the system and all subsystems. Considering the well-defined state of the mission, the Phase B is proposed included in the following Phase B/C/D/E. The consortium proposed for phase A is designed to be able to continue seamlessly to Phase B/C/D/E.

4.2.2 Model Approach

The model philosophy is selected so as to minimise project risk but at the same time make optimal use of the models established.

Phase B/C/D/E includes establishment and usage of the following models and equipment:

- Engineering Model (EM) for instruments, platform and ground segment, undergoing functional and EMC test
- Electrical Ground Support Equipment (EGSE) based on the prototype Mission Control Centre plus extensions
- System simulator based on the EM with s/w extensions
- Fitting model that allows trials on the mechanical fitting of subsystems and components
- Structure model
- Satellite Prototype flight Model (PFM) undergoing maximum vibration and maximum environment tests plus EMC test. It will be refurbished to a Flight Model (FM)
- Satellite FM's undergoing nominal vibration and environment tests

4.2.3 Phase-A Focal Activities

Following activities are in focus for the different segments of the mission.

Mission Segment	Focal Activities for Phase A
Overall Mission	• Satellite constellations for optimising coverage and revisit • Orbit LEOP and maintenance requirements • Overall planning for development, AIV, launch, commissioning and operations
Instruments	• Extend the CALL design, establish interfaces • GRAS+ update, establish interfaces • Budgets establishment (power, weight, volume) • Establish Draft Specifications • Planning the development and AIV for next phases • Check cost
Platforms	• Consolidate satellite design, subsystem and component selection • Budgets establishment (power, weight, volume) • Thermal analysis • Structural analysis • Establish Draft Specifications • Planning the development and AIV for next phases • Check costs
Launchers	• Checking launcher characteristics versus orbit and satellite weight • Checking integration of satellite (vibration, volume, fixation) • Contracting with launch company • Planning the launch, logistics
Ground Segment	• Develop CALL processing • Improve GRAS open loop processing • Define mission control and monitor requirements • Refurbish architecture from present • Establish performance and availability figures • Establish Draft Specifications • Planning the development and AIV for next phases • Check cost

Table 4-1: Focal Activities for Phase A

4.3 Scientific Organisational Structure

4.3.1 Participating Institutions

The institutions and members of the science team, led by the proposers, are listed below.

Name	Institute	E-mail
Per Høeg **(Lead Investigator)**	AIR Division Danish Meteorological Institute (DMI)	hoeg@dmi.dk
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Table 4-2: Institutes and representatives of the scientific organisation

Annex A provides a detailed description of the science team as well as of the worldwide science user team assembled. The background information given there briefly addresses, for each institution, the interest in and foreseen contribution to the mission as well as experience and expertise.

4.4 Project Management

The project management is distributed to three groups reflecting the responsibilities of the customer (ESA), the instrument developer and the overall system development.

Development Management Group	Functional Responsibility	Affiliation
Project Management (at ESTEC)	Project Scientist	UG (Note 1)
Instrument Management	Principal Investigator (PI)	DMI (Note 2,3)
	Technical Manager (TM)	SES (Note 3)
	Data Processing Manager (DPM)	DMI
System Management	Project Manager (PM)	TERMA (Note 3)
	Spacecraft Manager (SCM)	SSC (Note 3)
	Ground Segment Manager (GSM)	TERMA

Note 1: The University of Graz. Candidate proposed is G. Kirchengast

Note 2: The Danish Meteorological Institute. Candidate proposed is P. Høeg

Note 3: The PM, SCM's, instrument TM and PI are members of the industrial consortium Project Management Board

Table 4-3: Assignment of responsibilities for Project management

5. Annex

Annex Table of Contents

5.1 Science Team

5.1.1 Proposers of the Mission

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5.1.2 Science Team Overview

The structure of the scientific team behind the ACE+ mission consists of:

- A *Science Team*, which comprises the scientific partners forming the core scientific team of the ACE+ mission. They are prepared to play an active role in the detailed formulation of scientific requirements and science plans, in preparatory studies, in developing scientific algorithms, in providing value-added products, in validation, and so on.
- A *Science User Team*, which comprises the scientific partners forming the core scientific user community for ACE+ data. These partners have expressed dedicated interest in ACE+ and are prepared to exploit the data in a variety of ways. Several of them are also interested in actively contributing to the preparatory work.

5.1.3 Science Team Members

The ACE+ Science Team is led by P. Høeg (DMI, Denmark) and G. Kirchengast (IGAM/UG, Austria). Besides DMI and IGAM/UG, the research institutions include: KNMI, Netherlands, IEP/UB, Germany, Chalmers, Sweden, IAP, Russia, SA/CNRS, France, IKN/DLR and MPIM, Germany, UKMO, U.K., and IEEC, Spain. The Science Team members all bring in broad and internationally recognized expertise in different areas of radio occultation methodology and in different fields of the ACE+ data exploitation.

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Table 6.1: ACE+ Science Team Composition — Team Members and Coordinates

5.2 Science User Team

5.2.1 Science User Team Overview

The scientific team behind the ACE+ mission has been organized into a structure consisting of a *Science Team* and a *Science User Team*, respectively.

As in the Science Team, the ACE+ Science User Team is led by P. Høeg (DMI) and G. Kirchengast (IGAM/UG). The team is composed of many international partners including the institutions: Harvard Univ., USA, Univ. of Florence, Italy, Purdue Univ., USA, CRL, Japan, NRL Washington, USA, FMI, Finland, Polytechnico di Torino, Italy, UCAR Boulder, USA, Univ. of Arizona, USA, Kyoto Univ., Japan, Space Research Centre, Warsaw, Poland, and Inst. of Engineering and Electronics, Moscow, Russia.

The Science User Team members – involving most leading non-European institutions known for excellence in radio occultation research and/or application – represent wide and diverse expertise in many different fields of ACE+ data exploitation, from NWP and climate research interests via atmospheric dynamics, physics, and chemistry interests to ionosphere, space weather, and geodesy interests. In each institution there is not only a single Science User Team member but rather complete local teams have been formed. Usually these teams involve several associated team members, with the full team being interested in data exploitation.

One partner - University of Arizona, Tuscon, backed up by Jet Propulsion Lab, Pasadena - offers the option of a complete LEO-LEO add-on instrumentation (183 GHz stratospheric water vapour capability; 195 GHz ozone capability) based on NASA funds.

5.2.2 Science User Team Members

This section provides background information for each Science User Team institution. It shows the strong support received for ACE+ from many excellent scientists and institutions worldwide and thus highlights its extreme relevance and timeliness.

The information briefly addresses, for each institution, the interest in ACE+ and plans for data exploitation as well as relevant experience and expertise.

5.2.2.1 Harvard University, U.S.A. (HU)

Interest in the Mission and Plans for Data Exploitation:

Accurate monitoring of climate parameters is crucial to society's goal of accurately predicting climate change. We hope to exploit data from the ACE+ Earth Explorer mission to test and improve GCM physics and dynamics.

Aerosols affect the climate by scattering and absorbing solar radiation (direct effect), and also by altering cloud microphysical properties (indirect effect). Despite their importance to radiative forcing, the level of scientific understanding of aerosols is low to very low according to the latest IPCC report. Accurate water vapour information is important to describe aerosol phase and evolution. To test our understanding of the hygroscopic properties of different tropospheric aerosols and their radiative forcing effects it is essential to have accurate global scale measurements of water vapour. This proposed mission represents the opportunity for such a dataset. The high vertical resolution and all-weather properties of these data will also be key to this proposed research.

Scientific Expertise at HU:

HU is a world-class centre for research in atmospheric dynamics and chemistry. There are several faculty members and over 90 graduate students, post-doctoral fellows, engineers and scientists working in the atmospheric sciences. Particular areas of expertise include: tropospheric transport, stratospheric chemistry, climate dynamics, paleoclimate modelling, and atmospheric physics.

5.2.2.2 Dipartimento di Elettronica e Telecomunicazioni, Università di Firenze, Italy (DET/UF)

Interest in the Mission and Plans for Data Exploitation:

DET/UF is particularly interested in investigating the possibility offered by the project to profitably apply tomographic data processing in the reconstruction of the spatial distribution of the tropospheric water vapour. This is primarily related to the fact that the LEO-LEO configuration in occultation mode yields measurements in K band that are directly depending on the water vapour content along the propagation path. A time sequence of these measurements is a set of input parameters for tomographic data processing. The attenuation time series obtained during the relative LEO-LEO motion gives the possibility to “cover” a vertical section of the troposphere and to get, through tomographic procedures and by possibly involving slant integral water vapour data, the two-dimensional distribution of water vapour in that section.
Furthermore, DET/UF could contribute to LEO-LEO performance studies, for example, already during Phase A of the ACE+ mission.

Scientific Expertise at DET/UF:

The DET/UF group has provided original contributions to the development of tomographic systems (and related data processing procedures) for cases characterized by low spatial resolution (e.g., due to the low number of attenuation measurements). More specifically, DET/UF carried out feasibility studies in a number of different applications involving the exploitation of attenuation measurements made along point-to-point transmitter-receiver (or transmitter-retroreflector-receiver) links in stand-alone mode or inserted in a tomographic network, at both single and multifrequency, in the microwaves and infrared region. Such applications span from the reconstruction and tracking of rainfall fields and of atmospheric component concentration to the estimate of tropospheric water vapour.

5.2.2.3 Purdue University, U.S.A. (PURDUE)

Interest in the Mission and Plans for Data Exploitation:

The ACE+ mission is important in that it will provide high-resolution vertical profiles of water vapour in the upper troposphere where detection of small changes in the concentrations may have significant implications for climate change. The additional sensors in the 10, 17, and 23 GHz bands are key features that greatly enhance the mission over previous GNSS-only occultation missions. We anticipate being able to use the different types of occultation data sets to analyze the ability of a combined observation system to separate the effects of water vapour and temperature fields in order to reduce the error bars on detecting climate change.

Scientific Expertise at PURDUE:

Dr. Haase has worked on simulation studies of GNSS radio occultation from spaceborne and airborne platforms. She led the MAGIC European Community project that developed the methodology for ground-based GPS integrated water vapour retrieval, tested assimilation techniques, and investigated the use of this data in climate studies, which she worked on with Prof. Eric Calais. They are currently working with Prof. Wen-Yih Sun on assimilation of GNSS refractive delay measurements into NWP models. Through active collaborations with the ENVISAT team at ACRI-ST, France, they pursue opportunities for intercalibration of GNSS derived measurements with water vapour and temperature measurements from GOMOS and MERIS instruments.

5.2.2.4 Communications Research Laboratory, Japan (CRL)

Interest in the Mission and Plans for Data Exploitation:

CRL is conducting an Arctic atmosphere observation program, called “CRL Alaska Project”, in cooperation with University of Alaska. It involves nine kinds of atmospheric instruments covering dynamics, chemistry, and aurora/plasma processes, such as Rayleigh (+Doppler)/Mie lidars, MF/HF radars, microwave/infrared/visible spectrometers, etc. As part of such activity, CRL is starting development of a new radio occultation data analysis system in collaboration with Kyoto University. Retrieved humidity, temperature, and electron density will be used for cross-validation and comparative studies together with the Alaska atmospheric data as well as with the CRL space weather products.

Our experiments in Alaska also work as part of Arctic and global middle atmosphere observation network. The ACE+ mission and the ground-based experiments will provide excellent complementary data for larger horizontal coverage and more homogeneous spatial distribution of data for studies of dynamics (atmospheric waves and larger structures) and climatology of the whole middle atmosphere, as well as for studying effects of solar influences onto middle-lower atmospheric variation. We are convinced that unique ideas of the ACE+ project, including LEO-LEO and use of GALILEO in addition to GPS signals, will contribute importantly to weather prediction and atmosphere/climate sciences all over the world.

Scientific Expertise at CRL:

Since it was founded in 1952 as the Radio Research Laboratory of the Ministry of Posts and Telecommunications (MPT), CRL has promoted comprehensive R&D in the fields of Info-Communications based on Radio and Photonic Research. In April 2001, CRL became independent of the Ministry of Public Management, Home Afairs, Posts and Telecommunications (formerly MPT) and was newly inaugurated as an independent institution designated the (new) CRL.

CRL's diversified research themes, including the core subject of communications, are conducted in the following four divisions: Information and Network System Division, Wireless Communications Division, Applied Research and Standards Division, and Basic and Advanced Research Division. In the Applied Research and Standards Division, many studies on remote sensing technology and atmospheric science are conducted, among them radio occultation research. We are glad about the possibility to become ACE+ team members.

For more information on CRL please visit http://www.crl.go.jp/overview/index.html.

5.2.2.5 Naval Research Laboratory, U.S.A. (NRL)

Interest in the Mission and Plans for Data Exploitation:

We are currently developing a program to assimilate GPS occultation data into the Naval Operational Global Atmospheric Prediction System (NOGAPS) and the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). The assimilation tool will work within the NRL Atmospheric Variational Data Assimilation System (NAVDAS). Although initial tests of this assimilation system will be done with simulated data, we hope to eventually integrate real satellite data. Data from the ACE+ mission would provide a highly valuable dataset, which would allow us to test the value of both GPS-LEO and LEO-LEO occultation measurements on the NOGAPS and COAMPS forecasts.

Scientific Expertise at NRL:

The Naval Research Laboratory has expertise in radiative transfer, data assimilation, and weather prediction. Dr. Axel von Engeln has been working with the University of Graz EGOPS S/W system, which calculates a 3D ray tracing, and performed a statistical study of errors introduced by using a 1D (vertical) scheme to assimilate bending angles.

5.2.2.6 Geophysical Research Division, Finnish Meteorological Institute, Finland (GEO/FMI)

Interest in the Mission and Plans for Data Exploitation:

Space Weather research at FMI/GEO has been focused on the following three main issues: (1) monitoring network of space weather phenomena, (2) numerical simulation model of the magnetosphere-ionosphere system, and (3) studies of ground effects of space weather.
All these areas belong to basic research but they may also be applied to practical space weather studies. An important topic of GEO/FMI's interests directly related to the ACE+ mission are investigations of the relation of space weather with the atmosphere and with meteorological weather and climate. But ACE+ data would be of value for all areas.

Scientific Expertise at GEO/FMI:

FMI belongs to the leading European meteorological-geophysical centres, and GEO/FMI is leading or involved in many international research endeavours. A few projects shall be noted just as examples. Ground effects of space weather, i.e. geomagnetically induced currents in power systems and pipelines have been studied since the seventies together with Finnish industry. GEO/FMI has made preparatory studies for ESA in order to resolve the European capabilities in fields related to space weather. Currently studies focus on particular events in which data from the whole space weather chain from the sun to the ground are investigated.

5.2.2.7 Electronics Dept., Politecnico of Turin, Italy (ELN/POLITO)

Interest in the Mission and Plans for Data Exploitation:

We are very interested in all tasks of the ACE+ mission, especially in the LEO-LEO and GALILEO-LEO radio occultation features. In particular, we are interested to exploit data for the characterization of the lower atmospheric layers, in the form of inverted or even just integrated data to be assimilated in numerical weather prediction models.

Scientific Expertise at ELN/POLITO:

Our group has scientific experience on radio wave propagation, remote sensing, radar meteorology and development of numerical simulations. In particular we are involved in various national projects regarding past and future GPS-LEO occultation missions. Moreover, we are working on the retrievals of refractivity profiles from Earth-based GPS measurements.

5.2.2.8 University Corporation for Atmospheric Research, U.S.A. (UCAR)

Interest in the Mission and Plans for Data Exploitation:

UCAR has been involved in radio occultation science and missions since 1993 and led the pioneering proof-of-concept mission GPS/MET. We have a key interest in the methodology of the technique, the data inversion and the application of the data to numerical weather, climate, and space weather models. Improving our knowledge of the global distribution of atmospheric water vapour is of key importance to UCAR/NCAR scientists and the universities that we support. Realization of the ACE+ mission would provide, not least due to demonstrating LEO cross-link occultations, an innovative new dataset on water vapour.

The COSMIC program office at UCAR is establishing a data analysis centre for radio occultation data. This is designed as a multi-mission centre and we have a keen interest in obtaining the data from multiple radio occultation missions for near-real time and post-processed analysis. ACE+ measurements would represent a highly valuable data source for this centre.

Scientific Expertise at UCAR:

Our team has experience in managing radio occultation missions, in orbit determination, in occultation data inversion, and data assimilation into numerical models (i.e., the MM5 model). While our expertise is focussed on radio occultation from GPS transmissions, UCAR and Jet Propulsion Laboratory (JPL) submitted a joint proposal to NASA in 1998 for a combined occultation/cross-link mission called COSMIC/AMORE.

5.2.2.9 Institute of Atmospheric Physics, Univ. of Arizona, U.S.A. (IAP/UA)

Interest in the Mission and Plans for Data Exploitation:

ACE+ is a promising concept that potentially can improve on our knowledge about the state of the atmosphere, and contribute to the improvement of weather forecasts in the future. The very high vertical resolution of radio occultation data products is not matched by any other remote sensing technique. The global distribution of tropospheric water vapour from the LEO–LEO measurements would also be very important for the study and understanding of the global water and energy cycles.

At IAP/UA we are interested in the retrieval algorithm developments and error analyses as well as using the data products in various areas of research: boundary layer; data assimilation; global water vapour; climate change; ionosphere.

Scientific Expertise at IAP/UA:

The team at IAP/UA has a broad expertise in remote sensing techniques. Dr. Herman was one of the leaders of the proof-of-concept GPS/MET experiment in 1995, and Dr. Kursinski has been one of the leading scientists worldwide in the radio occultation technique since 1990. Individually, the team members have developed several inversion and retrieval codes for remote sensing problems. The team is currently leading the pre-developments of the NASA ATOMS (Active Tropospheric Ozone and Moisture Sounder) instrument and related data retrieval algorithms in co-operation with scientists at the Jet Propulsion Laboratory.

5.2.2.10 Radio Science Centre for Space and Atmosphere, Kyoto University, Japan (RASC)

Interest in the Mission and Plans for Data Exploitation:

We have been studying various characteristics of the Earth's atmosphere and ionosphere using datasets with GPS occultation measurements provided from the GPS/MET, CHAMP and SAC-C projects. We are also promoting a future project on application of GPS occultation techniques in collaboration with scientists within Japan as well as the Brazilian space agency (INPE). In particular, we are planning to clarify the behaviour of equatorial atmosphere dynamics. As radio occultation measurements provide accurate profiles of water vapour, temperature and electron density with good height resolution, they are essentially important in our study. The ACE+ mission has the potential to provide an unique dataset to this end.

Scientific Expertise at RASC:

RASC has been operating an integrated atmosphere observatory in Shigaraki, Japan (35N, 136E) by using various in-situ and remote sensing techniques. Especially, since 1984 the MU (middle and upper atmosphere) radar at 50 MHz has been measuring profiles of wind velocity, temperature and ionospheric parameters at 1 to 400 km. In addition, Rayleigh, resonance, and Raman lidars are employed. We have also established remote observatories in Indonesia, installing a number of radio and optical instruments.

5.2.2.11 Space Research Centre, Polish Acad. of Sciences, Poland (SRC)

Interest in the Mission and Plans for Data Exploitation:

The scintillation measurements in the radio occultation experiment will provide an unique opportunity to study atmospheric and ionospheric turbulence. Multi-frequency amplitude measurements (L- and X/K-band) are of particular interest. Unlike the ground-based scintillation measurements, the ACE+ experiment will let us study the vertical distribution of the turbulence parameters. The experiment will enable us to test for the importance of interactions between the atmospheric and ionospheric turbulence. We also expect to study acoustic-gravity waves in the atmosphere and their role in the generation of turbulence.

Scientific Expertise at SRC:

For over 30 years the SRC team has been involved in radio wave scintillation studies. Over 30 original papers and reviews have been published. The team is also experienced in the data analysis, including advanced methods (wavelet transform, higher order statistics, and nonlinear dynamics). The interest in the interactions between atmospheric gravity waves and ionospheric plasma resulted in 4 papers.

5.2.2.12 Inst. of Radio Engineering and Electronics, Russ. Acad. of Sciences, Russia (IRE/RAS)

Interest in the Mission and Plans for Data Exploitation:

We are very interested in the proposal for an "Atmosphere and Climate Explorer based on GPS, GALILEO, and LEO-LEO radio occultation." Active radio sounding of the atmosphere and ionosphere are among the most promising techniques that emerged in Earth remote sensing. System concept and mission elements of the proposed mission (4 micro-satellites for providing radio occultation experiments in L-band (two frequencies) and X/K band (3 frequencies)) allow to yield global measurements, with unprecedented accuracy and vertical resolution of such quantities as atmospheric refractivity, absorption, density, pressure, temperature, moisture, and geopotential height. Global observations of these parameters, including humidity and temperature in the troposphere and stratosphere, are important for monitoring climatic variations and trends at different vertical levels and for each season, and for revealing characteristics of natural processes in the atmosphere. In summary, we fully support the objectives of the ACE+ mission and are glad to join the Science User Team.

We are interesting in joint analysis of radio occultation signals in decimeter and centimeter bands for retrieving vertical gradients of temperature, humidity and (if possible) electron density in lower ionosphere and in recovering connections between natural processes in the troposphere and stratosphere using the following data products of the ACE+ mission: profiles of refractivity, absorption, temperature, and pressure as function of height.

Scientific Expertise at IRE/RAS:

Since many years our team further develops the radio occultation method as applied to monitoring of the atmosphere and ionosphere of the Earth using radio links satellite-to-satellite. We carried out pioneering experiments using radio links orbital station MIR-geostationary satellites at 32 cm and 2 cm, respectively. We derived and verified with our German and Japanese colleagues the radio holographic approach for achieving extreme resolution and accuracy of vertical profiles of atmospheric and ionospheric parameters using GPS/MET radio occultation data.

5.3 Letters of Support

In this section formal support letters received for the ACE+ mission are summarized. Except for the ESA/EUMETSAT GRAS-SAG expression of support, which is contained below, all letters have been sent under separate cover to ESTEC (by DMI and IGAM/UG).
While time constraints did not permit to collect a large number of formal letters of support, the informal feedbacks we got from within many further leading entities (e.g., World Climate Research Programme, European Commission/Environmental Research) ensure that a series of further formal endorsements by leading authorities could be obtained if desired.

5.3.1 Brief Summaries on Letters of Support

5.3.1.1 World Meteorological Organization (WMO)

The WMO letter has been sent to ESTEC under separate cover by DMI. The WMO expressed its strong support already for the ACE mission proposed 1998 and confirmed its view of considering radio occultation measurements of key importance for atmosphere and climate.

5.3.1.2 Stratospheric Processes and their Role in Climate (SPARC)

The SPARC letter has been sent to ESTEC under separate cover by DMI. The SPARC Committee expressed its strong support already for the ACE mission proposed 1998 and re-confirmed it for ACE+.

5.3.1.3 ESA/EUMETSAT GRAS-SAG (12th Meeting, Nov 28–29, 2001)

The GRAS-SAG discussed the ACE+ proposal at its Twefth Meeting in November 2001 and – as summarized in the Minutes of Meeting – noted that this would be scientifically a very interesting mission, which the group would find highly worthwhile to realize. That it would exploit both GNSS-LEO and LEO-LEO radio occultations, the latter with no ambiguities on temperature and water vapour in the troposphere, was noted to be particularly valuable.

5.3.1.4 Inst. of Atmospheric Physics, Univ. of Arizona (IAP/UA) USA

The IAP/UA letter has been sent to ESTEC under separate cover by IGAM/UG. In summary, IAP/UA considers ACE+ an unique and key atmosphere and climate mission for the future. IAP/UA even offers to contribute, based on NASA funds, add-on LEO-LEO instrumentation for extending the mission scope even further (183 GHz stratospheric water vapour capability and optionally also 195 GHz ozone capability).

5.3.1.5 Communications Research Laboratory (CRL), Japan

The CRL letter has been sent to ESTEC under separate cover by IGAM/UG. In summary, the President of CRL, a world-renowed Japanese center of excellence in radio science, sees the ACE+ mission a mission of pivotal importance for fundamentally advancing radio occultation (by demonstrating the novel LEO-LEO concept) and for aiding weather prediction and atmosphere/climate sciences worldwide.

5.3.1.6 Institute of Communications and Navigation/DLR, Germany

The DLR letter has been sent to ESTEC under separate cover by IGAM/UG. The Director of the Inst. of Communications and Navigation of DLR especially stressed the enormous importance the ACE+ mission would have for ionosphere and space weather applications. He emphasises that his Institute would be fully prepared to contribute in a leading way to the exploitation of this great spin-off capability.

6. DMI Scientific Reports

Scientific reports from the Danish Meteorological Institute cover a variety of geophysical fields, i.e. meteorology (including climatology), oceanography, subjects on air and sea pollution, geomagnetism, solar-terrestrial physics, and physics of the middle and upper atmosphere.

Reports in the series within the last five years:

No. 97-1
E. Friis Christensen og C. Skøtt: Contributions from the International Science Team. The Ørsted Mission - a pre-launch compendium

No. 97-2
Alix Rasmussen, Sissi Kiilsholm, Jens Havskov Sørensen, Ib Steen Mikkelsen: Analysis of tropospheric ozone measurements in Greenland: Contract No. EV5V-CT93-0318 (DG 12 DTEE):
DMI's contribution to CEC Final Report Arctic Trophospheric Ozone Chemistry ARCTOC

No. 97-3
Peter Thejll: A search for effects of external events on terrestrial atmospheric pressure: cosmic rays

No. 97-4
Peter Thejll: A search for effects of external events on terrestrial atmospheric pressure: sector boundary crossings

No. 97-5
Knud Lassen: Twentieth century retreat of sea-ice in the Greenland Sea

No. 98-1
Niels Woetman Nielsen, Bjarne Amstrup, Jess U. Jørgensen:
HIRLAM 2.5 parallel tests at DMI: sensitivity to type of schemes for turbulence, moist processes and advection

No. 98-2
Per Høeg, Georg Bergeton Larsen, Hans-Henrik Benzon, Stig Syndergaard, Mette Dahl Mortensen: The GPSOS project
Algorithm functional design and analysis of ionosphere, stratosphere and troposphere observations

No. 98-3
Mette Dahl Mortensen, Per Høeg:
Satellite atmosphere profiling retrieval in a nonlinear troposphere
Previously entitled: Limitations induced by Multipath

No. 98-4
Mette Dahl Mortensen, Per Høeg:
Resolution properties in atmospheric profiling with GPS

No. 98-5
R.S. Gill and M. K. Rosengren
Evaluation of the Radarsat imagery for the operational mapping of sea ice around Greenland in 1997

No. 98-6
R.S. Gill, H.H. Valeur, P. Nielsen and K.Q. Hansen: Using ERS SAR images in the operational mapping of sea ice in the Greenland waters: final report for ESA-ESRIN's: pilot projekt no. PP2.PP2.DK2 and 2nd announcement of opportunity for the exploitation of ERS data projekt No. AO2..DK 102

No. 98-7
Per Høeg et al.: GPS Atmosphere profiling methods and error assessments

No. 98-8
H. Svensmark, N. Woetmann Nielsen and A.M.
Sempreviva: Large scale soft and hard turbulent states of the atmosphere

No. 98-9
Philippe Lopez, Eigil Kaas and Annette Guldberg: The full particle-in-cell advection scheme in spherical geometry

No. 98-10
H. Svensmark: Influence of cosmic rays on earth's climate

No. 98-11
Peter Thejll and Henrik Svensmark: Notes on the method of normalized multivariate regression

No. 98-12
K. Lassen: Extent of sea ice in the Greenland Sea 1877-1997: an extension of DMI Scientific Report
97-5

No. 98-13
Niels Larsen, Alberto Adriani and Guido DiDonfrancesco: Microphysical analysis of polar stratospheric clouds observed by lidar at McMurdo, Antarctica

No.98-14
Mette Dahl Mortensen: The back-propagation method for inversion of radio occultation data

No. 98-15
Xiang-Yu Huang: Variational analysis using spatial filters

No. 99-1
Henrik Feddersen: Project on prediction of climate variations on seasonel to interannual timescales (PROVOST) EU contract ENVA4-CT95-0109: DMI contribution to the final report:Statistical analysis and post-processing of uncoupled PROVOST simulations

No. 99-2
Wilhelm May: A time-slice experiment with the ECHAM4 A-GCM at high resolution: the experimental design and the assessment of climate change as compared to a greenhouse gas experiment with ECHAM4/OPYC at low resolution

No. 99-3
Niels Larsen et al.: European stratospheric monitoring stations in the Artic II: CEC Environment and Climate Programme Contract ENV4-CT95-0136. DMI Contributions to the project

No. 99-4
Alexander Baklanov: Parameterisation of the deposition processes and radioactive decay: a review and some preliminary results with the DERMA model

No. 99-5
Mette Dahl Mortensen: Non-linear high resolution inversion of radio occultation data

No. 99-6
Stig Syndergaard: Retrieval analysis and methodologies in atmospheric limb sounding using the GNSS radio occultation technique

No. 99-7
Jun She, Jacob Woge Nielsen: Operational wave forecasts over the Baltic and North Sea

No. 99-8
Henrik Feddersen: Monthly temperature forecasts for Denmark - statistical or dynamical?

No. 99-9
P. Thejll, K. Lassen: Solar forcing of the Northern hemisphere air temperature: new data

No. 99-10
Torben Stockflet Jørgensen, Aksel Walløe Hansen: Comment on “Variation of cosmic ray flux and global coverage - a missing link in solar-climate relationships” by Henrik Svensmark and Eigil Friis-Christensen

No. 99-11
Mette Dahl Meincke: Inversion methods for atmospheric profiling with GPS occultations

No. 99-12
Hans-Henrik Benzon; Laust Olsen; Per Høeg: Simulations of current density measurements with a Faraday Current Meter and a magnetometer

No. 00-01
Per Høeg; G. Leppelmeier: ACE - Atmosphere Climate Experiment

No. 00-02
Per Høeg: FACE-IT: Field-Aligned Current Experiment in the Ionosphere and Thermosphere

No. 00-03
Allan Gross: Surface ozone and tropospheric chemistry with applications to regional air quality modeling. PhD thesis

No. 00-04
Henrik Vedel: Conversion of WGS84 geometric heights to NWP model HIRLAM geopotential heights

No. 00-05
Jérôme Chenevez: Advection experiments with DMI-Hirlam-Tracer

No. 00-06
Niels Larsen: Polar stratospheric clouds micro-physical and optical models

No. 00-07
Alix Rasmussen: "Uncertainty of meteorological parameters from DMI-HIRLAM"

No. 00-08
A.L. Morozova: Solar activity and Earth's weather. Effect of the forced atmospheric transparency changes on the troposphere temperature profile studied with atmospheric models

No. 00-09
Niels Larsen, Bjørn M. Knudsen, Michael Gauss, Giovanni Pitari: Effects from high-speed civil traffic aircraft emissions on polar stratospheric clouds

No. 00-10
Søren Andersen: Evaluation of SSM/I sea ice algorithms for use in the SAF on ocean and sea ice, July 2000

No. 00-11
Claus Petersen, Niels Woetmann Nielsen: Diagnosis of visibility in DMI-HIRLAM

No. 00-12
Erik Buch: A monograph on the physical oceanography of the Greenland waters

No. 00-13
M. Steffensen: Stability indices as indicators of lightning and thunder

No. 00-14
Bjarne Amstrup, Kristian S. Mogensen, Xiang-Yu Huang: Use of GPS observations in an optimum interpolation based data assimilation system

No. 00-15
Mads Hvid Nielsen: Dynamisk beskrivelse og hydrografisk klassifikation af den jyske kyststrøm

No. 00-16
Kristian S. Mogensen, Jess U. Jørgensen, Bjarne Amstrup, Xiaohua Yang and Xiang-Yu Huang: Towards an operational implementation of HIRLAM 3D-VAR at DMI

No. 00-17
Sattler, Kai; Huang, Xiang-Yu: Structure function characteristics for 2 meter temperature and relative humidity in different horizontal resolutions

No. 00-18
Niels Larsen, Ib Steen Mikkelsen, Bjørn M. Knudsen m.fl.: In-situ analysis of aerosols and gases in the polar stratosphere. A contribution to THESEO. Environment and climate research programme. Contract no. ENV4-CT97-0523. Final report

No. 00-19
Amstrup, Bjarne: EUCOS observing system experiments with the DMI HIRLAM optimum interpolation analysis and forecasting system

No. 01-01
V.O. Papitashvili, L.I. Gromova, V.A. Popov and O. Rasmussen: Northern polar cap magnetic activity index PCN: Effective area, universal time, seasonal, and solar cycle variations

No. 01-02
M.E. Gorbunov: Radioholographic methods for processing radio occultation data in multipath regions

No. 01-03
Niels Woetmann Nielsen; Claus Petersen: Calculation of wind gusts in DMI-HIRLAM

No. 01-04
Vladimir Penenko; Alexander Baklanov: Methods of sensitivity theory and inverse modeling for estimation of source parameter and risk/vulnerability areas

No. 01-05
Sergej Zilitinkevich; Alexander Baklanov; Jutta Rost; Ann-Sofi Smedman, Vasiliy Lykosov and Pierluigi Calanca: Diagnostic and prognostic equations for the depth of the stably stratified Ekman boundary layer

No. 01-06
Bjarne Amstrup: Impact of ATOVS AMSU-A radiance data in the DMI-HIRLAM 3D-Var analysis and forecasting system

No. 01-07
Sergej Zilitinkevich; Alexander Baklanov: Calculation of the height of stable boundary layers in operational models

No. 01-08
Vibeke Huess: Sea level variations in the North Sea – from tide gauges, altimetry and modelling

No. 01-09
Alexander Baklanov and Alexander Mahura: Atmospheric transport pathways, vulnerability and possible accidental conse-

quences from nuclear risk sites: methodology for probabilistic atmospheric studies

No. 02-01
Bent Hansen Sass and Claus Petersen: Short range atmospheric forecasts using a nudging procedure to combine analyses of cloud and precipitation with a numerical forecast model

No. 02-02
Erik Buch: Present oceanographic conditions in Greenland waters

No. 02-03
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