The ACE+ Mission: An Atmosphere and Climate Explorer based on GPS, GALILEO, and LEO-LEO Radio Occultation

G. Kirchengast [1] and P. Hoeg [2]

(1) Institute for Geophysics, Astrophysics, and Meteorology (IGAM),
University of Graz, Graz, Austria
gottfried.kirchengast@uni-graz.at
(2) Danish Meteorological Institute (DMI), Copenhagen, Denmark

Abstract. The European Space Agency (ESA) has recently, in May 2002, selected the Atmosphere and Climate Explorer (ACE+) radio occultation (RO) mission as the top priority mission out of 25 proposed Earth Explorer Opportunity Missions, which had addressed all areas of Earth system science. The ACE+ constellation of 4 Low Earth Orbit (LEO) satellites utilizes GPS, GALILEO, and LEO-LEO signals for RO sounding of fundamental atmospheric variables such as humidity and temperature. ACE+ will acquire near 5000 GPS/GALILEO RO soundings per day and demonstrate the novel LEO-LEO concept collecting about 230 LEO-crosslink soundings per day. Following confirmation after the ongoing phase A study, expected before mid 2004, the ACE+ development is scheduled to last until 2007, with launches in 2007/08 followed by a 5 years operational phase. The primary ACE+ mission goals are focused on climate and include, based on precise monitoring of climatic variations and trends in temperature, humidity, and geopotential heights, improved climate change detection and attribution, improved understanding of climatic feedbacks, validation of the simulated mean climate and its variability in global climate models, improvement – via data assimilation – of process parameterizations in climate models, and detection of variations in external forcings of climate. Additional important goals relate to numerical weather prediction, atmospheric processes research, and space weather. The key innovation compared to similar (earlier) missions (e.g., COSMIC) is the novel use of GALILEO and LEO-LEO signals. Especially the LEO-LEO signals placed at 3 frequencies within 9–23 GHz, from center to wing of the 22 GHz water vapor absorption line, will for the first time allow for RO measurements of humidity in the troposphere without temperature-humidity ambiguity. For example, the LEO-LEO data have the potential to furnish much needed upper troposphere humidity profiles with an unprecedented accuracy of better than 5% in specific humidity. The paper provides an introduction to the ACE+ mission along the above lines, with emphasis on the scientific rationale and the novel LEO-LEO capability, including first humidity and temperature retrieval performance results.

1 Introduction

The ACE+ mission (Atmosphere and Climate Explorer based on GPS, GALILEO, and LEO-LEO radio occultation; Hoeg and Kirchengast 2002), of which an artistic view is provided in Figure 1, is a next-generation RO mission currently under phase A development by ESA. It draws from a strong heritage in Global Navigation Satellite System (GNSS) RO science and technology built up over now more than a decade both in the European and other communities, in particular in the U.S.A. and Russia. Lee et al. (2001), especially Yunck et al. (2001) therein, include a good account on the pioneering contributions of the latter, here we limit ourselves for brevity to tracing back the European roots of ACE+.

Concerning the GNSS-LEO occultation part, the ACE+ mission concept and objectives are mainly based on scientific and technical work for the ACE mission proposal (Atmosphere Climate Experiment; Hoeg and Leppelmeier 2000) as well as experience with the instrument development of the GNSS Receiver for Atmospheric Sounding (GRAS) for the upcoming METOP operational weather satellites of ESA/EUMETSAT (Edwards and Pawlak 2000; Silvestrin et al. 2000). The ACE mission proposal was highly ranked ("hot standby") in the first selection round in 1999 for Opportunity Missions in the ESA Living Planet Programme (ESA 1998), together with the ACLISCOPE mission proposal (Atmosphere and Climate Sensors Constellation Performance Explorer; Kirchengast et al. 1998), which joined the ACE proposal by end of the selection round. ACE and ACLISCOPE enjoyed, in turn, already considerable heritage from the APM mission proposal (Atmospheric Profiling Mission; ESA 1996), which achieved excellent marks, but no final selection, within the first round in 1996 of ESA Earth Explorer Core Missions. This first ESA mission proposal was encouraged by the promise of both initial European GNSS RO work about a decade ago (e.g., Bauer 1992; Hoeg et al. 1995) and initial non-European (U.S. and Russian) work, which had started in the 1980s already (see, e.g., Melbourne et al. 1994; Yunck et al. 2001).

Concerning the novel LEO-LEO occultation part, and the use of future GNSS signals from the European GALILEO system in addition to those from the U.S. GPS system, the ACE+ concept roots in the WATS mission proposal (Water Vapour and Temperature in the Troposphere and Stratosphere; ESA 2001), which ranked among the top-five missions in the second round in 2001 of ESA Earth Explorer Core Missions, and was the first European mission proposal to extend RO capabilities by LEO-LEO inter-satellite observations for enabling unique tropospheric water vapor measurements. The WATS concept could, in turn, already benefit from first U.S.-led proposals with LEO-LEO components in the late 1990s (see, e.g., Herman et al. 2004). The original suggestion for a LEO-LEO RO concept dates back to Lusignan et al. (1969).

For the ACE+ mission, the best elements from all this previous work, and the experience so acquired, have been carefully gathered and distilled, and ACE+ is now on a good track to being implemented. A considerable international team of scientists supports the mission, an indication of which is found in the Annex of Hoeg and Kirchengast (2002). Upon mission confirmation by ESA, scheduled in late spring 2004, a more formal international science team will be convened.

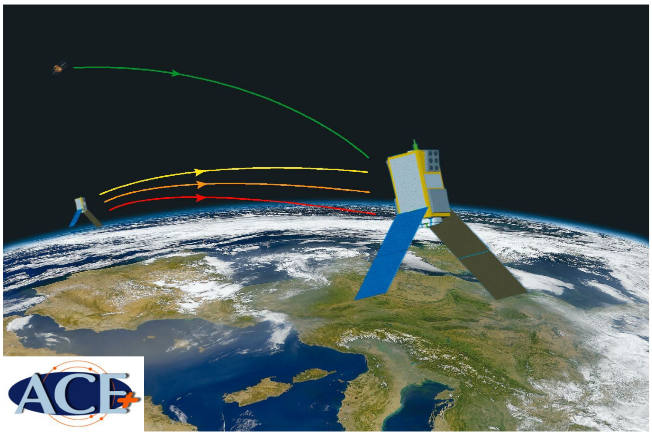


Fig. 1. Illustration of the ACE+ occultation concept, indicating both the GNSS-LEO (GPS-/GALILEO-LEO) and 3-frequency LEO-LEO occultation links.

This paper introduces the mission as follows. Section 2 describes the main scientific themes addressed and key contributions expected from ACE+. It closes with concisely listing the unique RO characteristics which enable these contributions. Section 3 summarizes the scientific mission objectives and Section 4 gives an overview on the mission concept and expected performance. Sections 2 to 4 draw partly from a draft version of the ACE+ Mission Requirements Document of the ACE+ Mission Advisory Group of ESA (ESA 2003), from parts essentially provided by the authors of this paper. Section 5, finally, provides concluding remarks.

2 Scientific Themes and Key Contributions

While below we briefly discuss several important scientific application areas of ACE+ occultation data, ranging from climate change to space weather, the coverage is clearly not exhaustive. Some further areas are touched upon in Section 3. For more detailed information on the wealth of expected scientific contributions of ACE+ see, e.g., ESA (2003), Hoeg and Kirchengast (2002), and ESA (2001). As a starting point to general information on the scientific value of occultation data for atmosphere and climate science, and other fields, see, e.g., Kirchengast (2004).

2.1 Climate Change

The latest IPCC scientific assessment report (IPCC 2001) concluded that the bulk of the observed global warming in the last century up to the 1970s mostly was due to natural processes, like solar and internal climate variability. However, the more recent warming during the last about 25 years is mostly 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 projections indicate that the surface temperature of the Earth, globally averaged, may increase by 1.4° to 5.8° over the 21st century.

Central to most of the least understood internal feedbacks of the applied climate models are those associated with water vapor, giving rise in part to the above span in the temperature increase estimates. Mechanisms of water vapor remain poorly understood because the associated climatology and atmosphere processes have not been observed with the accuracy, precision, resolution, and coverage necessary to understand them. Figure 2 serves to illustrate the high variability of water vapor even in monthly-mean vertically-averaged fields (left) as well as in the vertical (right), indicating the need for new measurement methods.

In particular there are only sparse and inaccurate humidity data available for the upper troposphere and tropopause region. 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 vapor and temperature fields throughout the free 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.

2.2 Monitoring Climate Variability and Change

ACE+ data are ideally suited to monitor variations and changes in the Earth's climate. 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 are on the other hand due to anomalous influence such as from a change in the solar constant, volcanic eruptions, or an increased greenhouse effect. ACE+ provides the capability to isolate and detect those climate variations during the mission period.

Due to the high accuracy and long-term stability of ACE+ data, the monitoring of climate variations and trends in measured parameters during the mission period is relatively straightforward and performed, depending on the scientific purpose, either independent of any model, creating authoritative reference climatologies, or by employing modern data assimilation techniques.

ACE+ climatologies can, to give one specific example, provide valuable information on stratospheric changes. Observational indications exist that arctic stratospheric winter temperatures decrease. The lowest temperatures in winter seasons occur now in combination with more stable and long-lasting arctic vortices. It is thus important to accurately monitor whether winter temperatures continue to decrease, leading to more widespread polar stratospheric cloud formation, more stable polar vortex conditions, and stronger ozone depletion. ACE+ data will well fit this purpose.

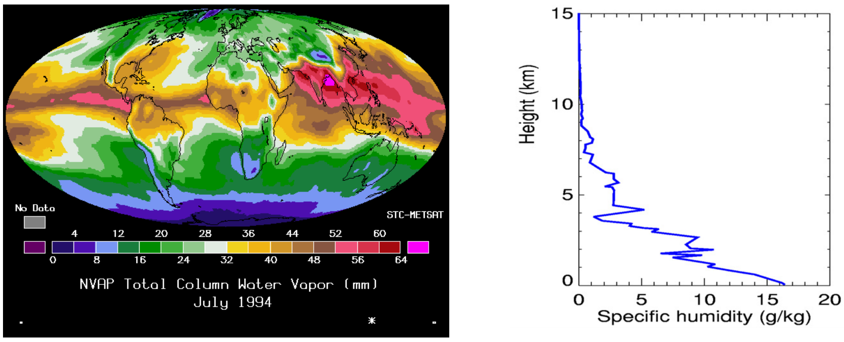


Fig. 2. Examples of global distribution of vertical-column water vapor in summer (left; July 1994 monthly mean, courtesy of NASA water vapor project 1997) and of vertical distribution of humidity (right; raob profile from Kauai, Hawaii, 1 Oct 2000, 12 UTC).

A more difficult problem, to be tackled by modern data assimilation, is the isolation of variations due to external climate forcing from those internal to the climate system, mainly because the 5-year mission period is short compared to the typical time scales of internal climate variability. Considerable variations in the global mean tropospheric temperature occur, e.g., 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 whether for example the greenhouse effect strengthens. However, by using ACE+ occultation data in a data assimilation system it is possible to monitor and identify external forcing variations via careful inspection of model's fit to observations.

Furthermore, in the context of monitoring of climate trends, ACE+ climatologies may serve as an initial cornerstone and trigger of a subsequent operational occultation-based observing system for long-term climate monitoring.

2.3 Climate Model Validation and Improvement

The accurate model-independent ACE+ climatologies will be essential means for validating climate models. In this context it is of importance that climate models are validated not only with respect to the observed mean climate, but also in their variability and against known external forcings (like volcanic eruptions) during the mission period. A simple but important example is the annual cycle of solar forcing and the associated seasons. Another example regards heating rates from release of latent heat in association with monsoons, which can be validated by invoking data assimilation methods. In such cases, the observed data must be assimilated into the relevant atmospheric model and the parameters varied in such a way that the forcing (mainly heating) errors are minimized in a global sense.

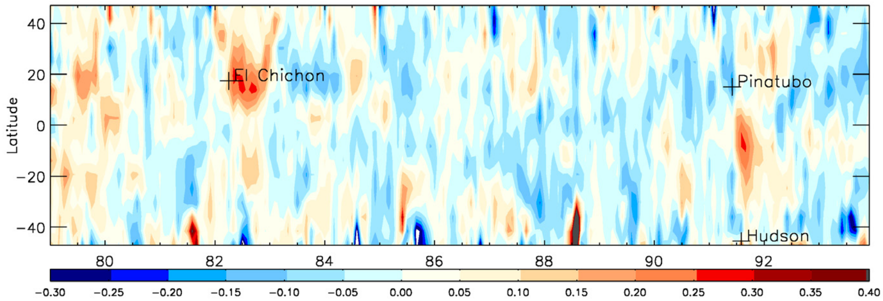


Fig. 3. Anomalies relative to the average annual cycle in the zonal mean of 24-hr temperature analysis increments (units K/day; 30 hPa level, period 1979–1993, use of ECMWF reanalysis data set "ERA15"). From Andersen et al. (2001).

The technique of minimization of forcing errors by assimilation of high quality analyses is already now used in a range of European projects. Figure 3 shows an example of using data assimilation for detecting volcanic forcing and potential long-term trends (Andersen et al. 2001). The two major volcanic eruptions, El Chichon 1982 and Pinatubo 1991, are clearly seen via anomalous heating rates of up to > 0.25 K/day. In addition, there seems to exist some long-term cooling trend, the reliability of which is hard to judge, however, due to inhomogeneities in the underlying data.

Indeed a major obstacle when using data from currently available sources, such as radiosondes and vertical profiling from present satellites, is either their coarse spatial and temporal resolution and/or lack of sufficient accuracy and/or long-term stability and vertical coverage. Thus high quality data as obtainable from ACE+ are extremely valuable for improving long-term stability and inter-calibration of other systems in providing absolute references. This will also improve atmospheric models by clearly identifying biases. In particular, additionally to standard state parameter estimation, the technique of forcing error estimation can provide valuable guidelines for constructing new and improved physics parameterization algorithms (e.g., in radiation and cloud modeling). Assimilation of ACE+ data for the purpose of model improvement is thus an important mission goal.

Identifying and validating the water vapor, cloudiness, and temperature lapse rate feedback processes is a necessary objective to narrow the range of uncertainties, which affect current model predictions of future climate. A corresponding approach to climate model validation consists in exploring the correlation between different variables, computing statistics of those correlations for given sea surface temperature (SST) or dynamical conditions. The ACE+ experiment will offer a large number of new measurements of temperature and water vapor at specified altitudes, covering in particular the upper troposphere, and will bring a unique contribution to these studies.

For applications related to cloud microphysics the important humidity parameter is relative humidity, not absolute humidity. For example, it is currently unclear how much over-saturation of humidity with respect to ice is present in the upper troposphere. In general, the use of remote sensing data for such studies is problematic, since uncertainties in the atmospheric temperature strongly propagate into uncertainties in the retrieved relative humidity. Because of the simultaneous measurement of high precision humidity and temperature, ACE+ will allow the determination of the relative humidity with adequate precision.

From an overall perspective, the potential of ACE+ to aid climate model validation and improvement is so important since it extends the mission value decades beyond its actual duration in that better models will lead to decreased uncertainty in and increased credibility of long-term climate predictions. These improved predictive capabilities are, in turn, vital for sensible climate policy, where a key issue is what actions to take consistent with uncertainties in climate predictions.

2.4 Weather Forecasting and Atmospheric Analysis

The mission is designed mainly for atmosphere and climate research. But it is important to note that the data produced may be highly valuable for weather forecasting as well, if the data are delivered in near real time. At present our observational information on the 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, for example, severely limits the predictability over continental 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. Thus 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 mass and wind field has to be known in modeling the atmospheric state.

The atmospheric mass field, characterized by temperature, pressure, and water vapor, 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 vapor and temperature in controlling the atmospheric circulation.

In the tropics, information about the wind field is, in general, relatively more important than mass field information. 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+ can be achieved within a 3-hour time window for a significant fraction of the data, the mission is very attractive for weather forecasting and atmospheric analysis.

2.5 Ionosphere and Space Weather

The Earth's ionosphere, ranging from about 90 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. Due to its capability to also yield ionization information on a global scale, ACE+ will significantly contribute, as a spin-off, to space weather services, e.g., the planned European Space Weather Programme (ESWP). Furthermore, the ionospheric data allow to improve ionospheric correction in stratospheric retrievals.

Reliable now- and forecasting of space weather phenomena need an improved understanding of the ionospheric behavior and its close coupling with the magnetosphere and thermosphere systems. Applying innovative inversion techniques, data assimilation methods, and tomographic approaches will allow to monitor and model space/time electron density structures on global and regional scales with high reliability and accuracy. Figure 4 shows an example of such a data product based on CHAMP RO data; the future datasets will allow much improved resolution. Also forecasts of the ionospheric weather up to hours ahead (ionospheric weather is much less predictable than tropospheric weather) will be possible.

Permanent growth of GPS ground station networks globally allows meanwhile to construct quite accurate global and regional total electron content maps. The results suffer from lack of knowledge on the vertical structure of the ionosphere, however. This can be improved dramatically by merging ground-based electron density data and ACE+ data. Combining all ground-based GPS/GALILEO data, available from 2008 onwards, with the large amount of ACE+ data will allow for global and continuous analyses and forecasts of ionosphere and space weather with unprecedented quality.

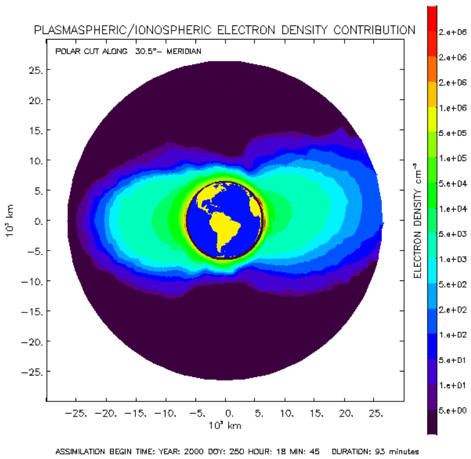


Fig. 4. Electron density distribution of the topside ionosphere and plasmasphere reconstructed by data assimilation techniques in the orbit plane of the CHAMP satellite from one day of GPS RO data (Sept. 6, 2000; courtesy of N. Jakowski, DLR Berlin, Germany).

2.6 Key Contributions Thanks to Unique Characteristics

The ACE+ mission can provide key contributions to the science and application areas discussed above thanks mainly to the following unique characteristics:

- High absolute accuracy and long-term stability of humidity, temperature, and pressure due to intrinsic self-calibration of RO data, which are Doppler shift (time standard) and transmission (normalized intensity) data,
- High vertical resolution (~1 km or better) of fine structures in the atmosphere such as around the tropopause,
- Virtually all-weather capability due to long wavelengths (> 1 cm), in particular also accurate humidity and temperature retrieval in presence of ice clouds in the upper troposphere by LEO-LEO occultations,
- Global and even coverage with globally consistent high quality profiles, over both oceans and land,
- Rigorous independent measurement of humidity, temperature, and pressure as function of height in the free troposphere by LEO-LEO occultations,
- The data can be used as reference datasets and need not necessarily be inter-calibrated with follow-on and possibly non-overlapping RO missions.

3 Scientific Mission Objectives

The ACE+ mission objectives are tailored to enable all the contributions to the scientific application areas discussed in Section 2 above. In addition to scientific goals also demonstration goals are involved, due to the fact that ACE+ is set to be the very first mission to employ LEO-LEO and GALILEO-LEO occultation in addition to GPS-LEO occultation.

The objectives fall into the three classes primary, secondary, and spin-off benefits, respectively, where the first ones are of highest priority and drive the mission. The secondary ones are important add-on objectives, which will be accounted for with as much dedication as possible within available resources. Spin-off benefits are benefits of opportunity available from ACE+ despite of its design being driven by the primary objectives, and will be accounted for on a best-effort basis. The objectives of each of the three classes are listed and briefly discussed below.

3.1 Primary Mission Objectives

Primary objectives of ACE+ are:

- Monitoring of climate variability and trends as an initial key component of long-term occultation observations of climate,

- Contribution to detection of climate changes and support of climate change predictions via high-quality global reference data,
- Validation of global circulation models (GCMs), both in simulated mean climate and variability,
- Improvement, via data assimilation methods, of physics parameterizations in GCMs, and of the characterization of external forcing variations,
- Improvement of the understanding of climate feedbacks determining magnitude and characteristics of climate changes,
- Study of structures in the troposphere and tropopause regions at high vertical resolution, in the context of atmospheric process research,
- Demonstration of the novel LEO-LEO occultation technique,
- Demonstration of the novel use of GALILEO-LEO occultation.

The climate objectives shall be achieved by monitoring, analyzing, and interpreting variations and changes in the global atmospheric temperature, water vapor, and pressure (or geopotential height) distribution in order to understand the current state and further evolution of the climate. In particular in the upper troposphere, ACE+ will be able to provide humidity data globally, with unprecedented accuracy, high vertical resolution and long-term stability.

The humidity measurements will be insensitive to ice clouds, in clear contrast to other remote sensing techniques. Furthermore, the quality of the simultaneously measured humidity and temperature profiles will be high enough to accurately determine relative humidity as well as associated moist temperature lapse rates.

In the field of climate model validation and improvement, advanced data assimilation concepts, including parameter and sensitivity estimation methods far beyond state estimation, will play a key role. Due to the high absolute accuracy ACE+ measurements can improve data assimilation bias correction schemes. The atmospheric physics studies on troposphere and tropopause structures will specifically exploit the high vertical resolution and accuracy of ACE+ occultation data.

The new LEO-LEO occultation method, which will be demonstrated by ACE+, is expected to become invaluable for climate research. The LEO-LEO demonstration will include, in addition to rigorously assessing the performance for simultaneous independent determination of humidity, temperature, and pressure (geopotential height), also the assessment of sensing at the same time cloud liquid water in cloudy situations. The utility and performance of GALILEO-LEO occultation will be thoroughly assessed, including assessment of the complementarity and of potential performance advantages over GPS-LEO occultation. Overall, ACE+ will significantly improve our understanding of the climate system.

Indicating the versatile utility of ACE+ data, the mission can help advance the understanding of many important atmospheric physics and climate change processes by addressing issues such as:

- Global warming and related changes in atmospheric water vapor 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 temperatures and atmospheric wave phenomena,
- Polar front dynamics and mass exchange together with tropospheric water vapor feedback on climate stability,
- High latitude tropospheric-stratospheric exchange processes related to polar vortex conditions,
- Climatology of Rossby waves and atmospheric internal waves.

3.2 Secondary Mission Objectives

Secondary objectives of ACE+ are:

- Contribution to improved numerical weather prediction (NWP),
- Support of analysis, validation and calibration of data from other space missions.

ACE+ data will provide a highly accurate temperature and humidity data set, with particular strength in the upper troposphere, which can be used in data assimilation systems. The atmospheric model improvement work in GCMs will at the same time benefit NWP models. The other way round, advances in NWP will benefit climate studies, because the atmospheric analyses, a routine by-product of NWP systems, are highly valuable also for climate purposes, in particular the reanalyses (consistent analysis sequences over decades).

Mutual support in analysis, calibration and validation of concurrent space missions is an important objective. Also during the time of ACE+ a series of space missions, European and non-European, can sensibly exploit this type of synergy. As one example, the close collaboration with the nominally overlapping GPS-LEO occultation mission COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) will be of particular interest.

3.3 Spin-off Benefits of the Mission

Spin-off benefits of ACE+ are:

- Ionospheric climate & weather and space weather investigations,
- Assessment and improvement of present water vapor attenuation models,
- Turbulence products in the lower troposphere.

Ionosphere and space weather investigations comprise a wide range of specific objectives from electron density monitoring and modeling via ionospheric and space weather prediction and data assimilation advancements to studies of phenomena and processes like ionospheric storms, traveling disturbances, current systems, irregularities and scintillations. The electron density data provided by ACE+ for these purposes are unique in their space/time coverage and vertical resolution.

Improved water vapor attenuation coefficients are important pieces of fundamental spectroscopic information that the ACE+ mission can potentially contribute via its LEO-LEO attenuation measurements of unprecedented accuracy near the center and along the wing of the 22 GHz water vapor line. These data, complemented by accurate water vapor validation data (e.g., from water vapor lidar campaigns), should allow to derive improved spectroscopic coefficients, including improved knowledge of their temperature dependence.

Radio scattering by refractivity inhomogeneities caused by atmospheric turbulence will enable to observe scintillation phenomena in ACE+ data, in particular in the lower troposphere. Estimates of height variations of the scintillation power spectrum and of the refractive structure parameter will be possible, which can be interpreted in terms of power spectrum and variance of temperature and humidity fluctuations. Details of the atmospheric turbulence such as its intermittency and the role of coherent structures may be studied. Of particular value for climate science, e.g., for improvement of turbulence parameterizations in climate models, will be global climatologies of kinetic energy dissipation rates, which can be deduced as well. Scientific information can furthermore be gained by joint analysis of ACE+ scintillation parameters and profile measurements with ground-based meteorological data. Due to the hazardous effect of turbulence on aircraft operations, its global monitoring via ACE+ scintillation measurements is also of great practical utility.

4 Mission Overview and Expected Performance

The RO technique has so far been using signals from the Global Positioning System (GPS). The observations have been collected from low Earth orbit (LEO) satellites. Figure 5 has embedded this "classical" RO measurement geometry. In the ACE+ mission, an advanced GNSS-LEO RO receiver will provide not only such GPS RO data but also, as a novelty, data from using signals of the currently developed European navigation satellite system GALILEO.

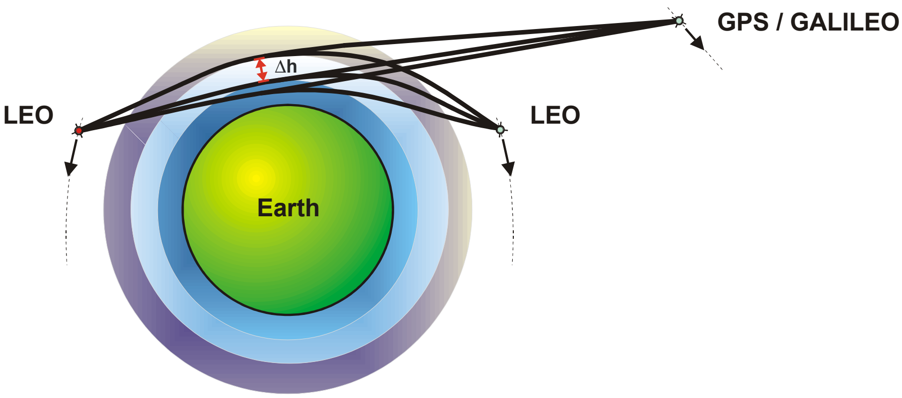
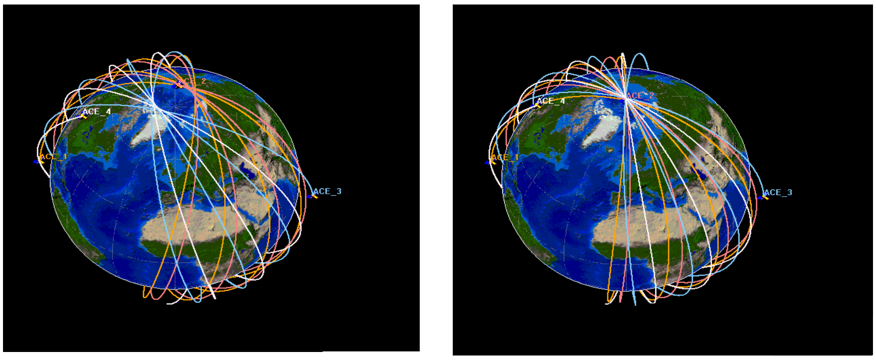


Fig. 5. Schematic view of the ACE+ measurement geometry for LEO-LEO crosslink occultation as well as "classical" GPS-LEO and GALILEO-LEO occultation. Occultation events are quasi-vertical scans through the atmosphere, occurring due to the satellite motions.

Profiles of atmospheric bending angle and refractivity are retrieved and used to extract information on temperature, pressure (or geopotential height), and humidity as a function of height in the troposphere and stratosphere. Brief further information on the GNSS-LEO part of ACE+ is provided in subsection 4.2.

In order to improve the separation of the contributions of humidity and temperature in the troposphere, without using external auxiliary data, and to provide humidity measurements also in the upper troposphere, ACE+ will furthermore sound the atmosphere in an active limb sounding mode using novel LEO-to-LEO signals. Figure 5 illustrates also this LEO-LEO geometry. ACE+ will use three frequency channels near the center and at the wing of the 22 GHz water vapor absorption line, nominally placed at 9.7 GHz, 17.25 GHz, and 22.6 GHz. An alternative using a 20.2-20.6 GHz frequency pair instead of the 9.7 GHz frequency, for extended data processing flexibility when using differential absorption modes, is also considered. Measurements of the phase and amplitude of the occulted signals at the chosen frequencies are expected to deliver independent information on humidity and temperature in the troposphere of unprecedented quality. More information on the LEO-LEO part of ACE+ is provided in subsection 4.1.

In order to realize the LEO-LEO cross-links and to obtain adequate global coverage, an innovative constellation concept will be used for ACE+, with two pairs of satellites flying in counter-rotating orbits at different altitudes. Figure 6 illustrates the baseline primary and alternative concepts and summarizes the associated constellation definitions.



Primary concept:	*Alternative concept:*
2 orbit planes, counter-rotating Rx vs Tx sats	2 orbit planes, also counter-rotating satellites
2 satellites/plane, sun-synchronous (i ~ 98°)	2 satellites/plane, polar inclination (i = 90°)
2 orbit heights (Rx's ~650 km, Tx's ~800 km)	2 orbit heights (Rx's~650 km, Tx's~850 km)
Rx's in-orbit spacing 80°, Tx's spacing 180°	Rx's in-orbit spacing 90°, Tx's spacing 180°
Antenna FOV < 10° azimuth (active pointing)	Antenna FOV < 10° azimuth (fixed possible)

Fig. 6. ACE+ sun-synchronous (left) and polar (right) 4-satellite constellation concepts comprising 2 LEO-LEO transmitters (Tx) and 2 counter-rotating LEO-LEO receivers (Rx). Constellation details such as exact orbit heights and in-orbit spacings may be further optimized during mission development. (Figure courtesy of Alcatel Space, France; adapted)

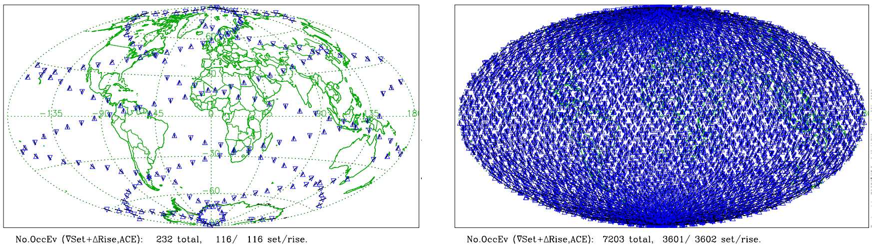


Fig. 7. Daily (left) and monthly (right) global geographic coverage by ACE+ LEO-LEO occultation events, based on the sun-synchronous constellation.

Figure 7 shows the geographic coverage obtained with the sun-synchronous constellation, which is planned to be aligned in the local time of its orbit nodes with the orbit of the European METOP satellite series for synergy reasons. About 230 LEO-LEO events are available per day (similar to the CHAMP/GPS RO experiment, the first mission providing a multi-year dataset of GPS RO data) and about 7000 events per month.

4.1 LEO-LEO-based Humidity and Temperature Profiling

The novel LEO-LEO observations will focus on measuring precise amplitudes and phases at the three ACE+ frequencies noted above in order to enable accurate retrieval of the key atmospheric parameters causing the intensity and phase changes in the received signals. Figure 8 shows that the 22 GHz water vapor line, as is desired, is a prominent feature in the absorption at the frequencies of interest.

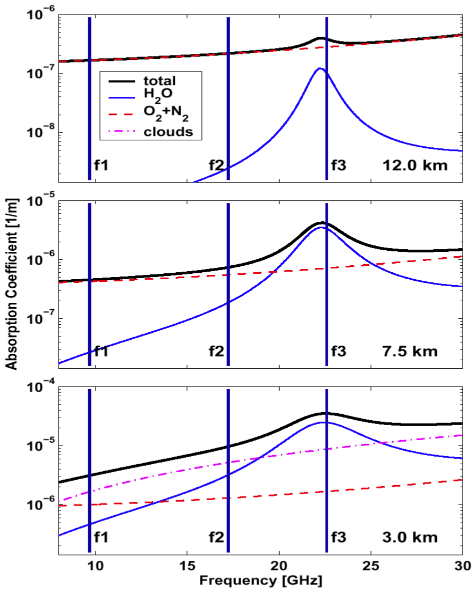


Fig. 8. Absorption due to the atmosphere as function of the frequency at three different height levels (3 km, 7.5 km, 12 km) for a mid-latitude summer atmosphere. The three ACE+ baseline frequencies (9.7 GHz, 17.25 GHz, 22.6 GHz) used in the performance simulations discussed below are indicated. In addition to total absorption, water vapor (H_2O), bulk air (O_2), and liquid water (cloud; lowest panel) absorption are shown.

Combined exploitation of the intensity change (raw transmission) data available at the three frequencies and of the phase change (Doppler shift) data allows to accurately retrieve humidity, temperature, and pressure (or geopotential height) as a function of height in the troposphere, with liquid water profiles as a by product. Compared to GNSS RO, the retrieval process involves, in addition to bending angle and refractivity profiles derived essentially from Doppler shift data, also absorption loss and absorption coefficient (or imaginary refractivity) profiles derived from raw transmission data.

The ACE+ LEO-LEO cross-links are designed to furnish a high signal-to-noise ratio (SNR) for providing adequate measurement precision and dynamic range for accurate humidity retrievals. In the lower troposphere, where water vapor can be abundant, the less strongly absorbed 9.7 and 17.25 GHz signals are important and the SNR needs to ensure sufficient received signal also in humid and cloudy conditions. In the upper troposphere, where water vapor concentrations can be very small, the overriding consideration is detecting the weak absorption effect with sufficient precision so that here the 22.6 GHz signal is essential. In the upper stratosphere, the high SNR and the use of frequencies about an order of magnitude higher than in GNSS RO lead to very small ionospheric residual noise and very accurate temperature measurements up to the stratopause.

Overall, it is required that received amplitude variations of ~0.05% can be distinguished and that dynamic range for about 30 dB signal attenuation is provided, which leads to a required (un-attenuated) carrier-to-noise power spectral density above the atmosphere of about 67 dBHz.

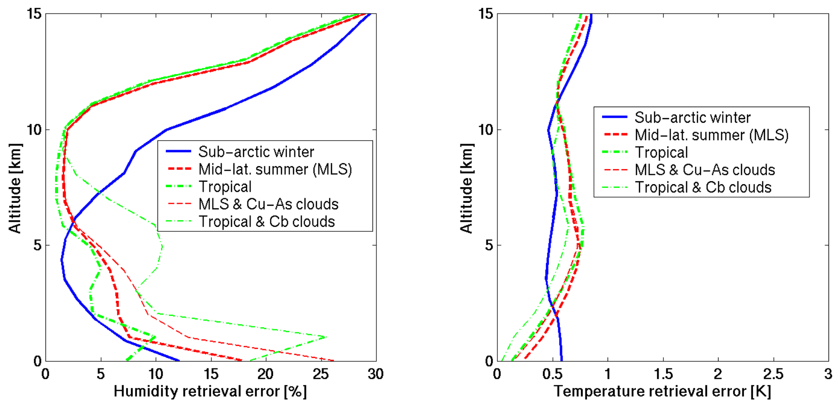


Fig. 9. Specific humidity (left) and temperature (right) retrieval errors obtained in an error analysis using optimal estimation based on simulated ACE+ LEO-LEO transmission measurements including thermal noise and amplitude drifts consistent with system specifications. Depicted are results for three 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).

The amplitude measurement system needs to be very stable during an occultation and amplitude drifts need to be smaller than ~0.2% over about 15 sec while scanning the upper troposphere. More detailed information on the LEO-LEO technique and related retrieval processing are found, e.g., in ESA (2001), Hoeg and Kirchengast (2002), Herman et al. (2004), and Kursinski et al. (2004).

Figures 9 and 10 show example results on the retrieval performance expected from ACE+ LEO-LEO data, where especially Figure 10 was obtained within a rigorous performance analysis being part of the ACE+ phase A. For Figure 10, instrumental errors (thermal noise, 1/f noise, and amplitude drifts) were modeled consistent with system specifications, clouds represented mid-latitude altostratus cloudiness at ~4–5 km height, and scintillation noise was simulated consistent with median mid-latitude turbulence conditions. The small temperature residual bias of up to 0.1 K visible below 15 km is a small technical weakness of the present not fully optimized simulation tools as is a significant fraction of the 'error oscillation' above about 12 km in the relative humidity error.

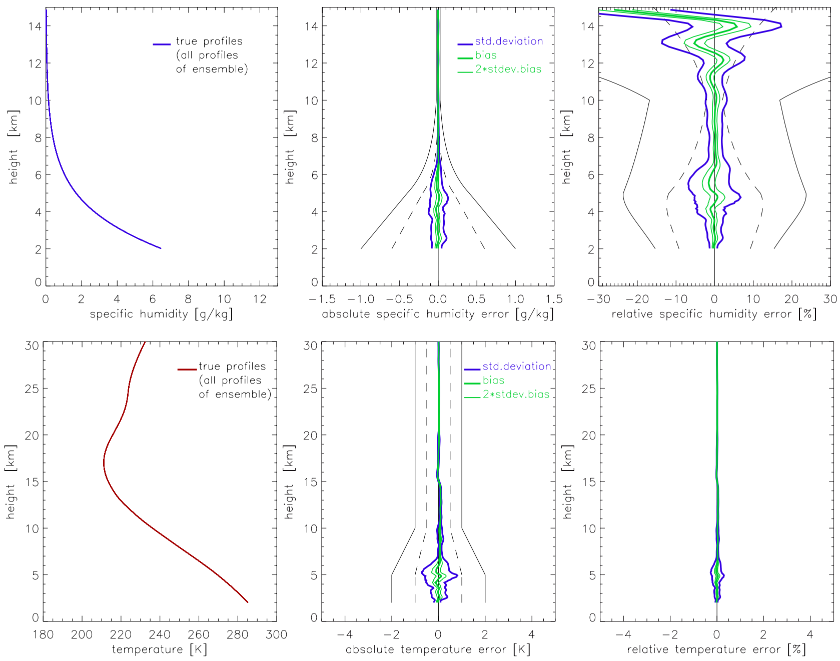


Fig. 10. Specific humidity (top panels) and temperature (bottom panels) retrieval performance results obtained in an end-to-end simulation of an ACE+ LEO-LEO occultation event under mid-latitude summer conditions (CIRA86aQ, July, 40°N, profiles; left panels). Statistical performance results from an ensemble of 40 profile realizations are shown (standard deviation, bias, 2 x std.deviation of bias; middle and right panels), with the std. deviations depicted as +/– envelopes about the bias profiles. The solid/dashed "error envelope" lines in the top middle, top right, and bottom middle panels mark the threshold/target accuracy requirements defined for ACE+. The vertical resolution of the profiles involved is ~1 km.

From the point of view of the primary climate science objectives, the evident strength to be able to sense upper tropospheric humidity in an unbiased manner and to < 5% rms accuracy is particularly intriguing. Overall, the performance results obtained so far, including under cloudy and turbulent conditions in the lower-to-mid troposphere, indicate that the ACE+ mission will be able to fully meet its scientific objectives as summarized in Section 3.

4.2 GNSS-LEO-based Temperature and Humidity Profiling

Starting with the successful GPS/MET "proof-of-concept" measurements within 1995–1997 (e.g., Rocken et al. 1997), the GNSS-LEO RO technique is now well established and detailed descriptions of the method and its scientific potential and applications are available from rich literature (e.g., Kursinski et al. 1997; Lee et al. 2001; Steiner et al. 2001; and references therein). A very brief account only is thus given here. GNSS-LEO RO uses active limb sounding to retrieve fundamental atmospheric parameters, in particular temperature and humidity, in the stratosphere and troposphere. The physical basis is that GNSS radio signals get refracted along their ray paths, determined by the refractivity field, as they pass through the atmosphere. Refractivity profiles can thus be derived, via bending angle profiles, from the observation of mainly phase change (Doppler shift) profiles during occultation events scanning the atmosphere (Figure 5). In turn, atmospheric profiles such as of temperature and humidity can be retrieved from refractivity.

In the stratosphere and upper troposphere, where the humidity is low, refraction is dominated by vertical temperature gradients, and temperature profiles can be accurately retrieved.

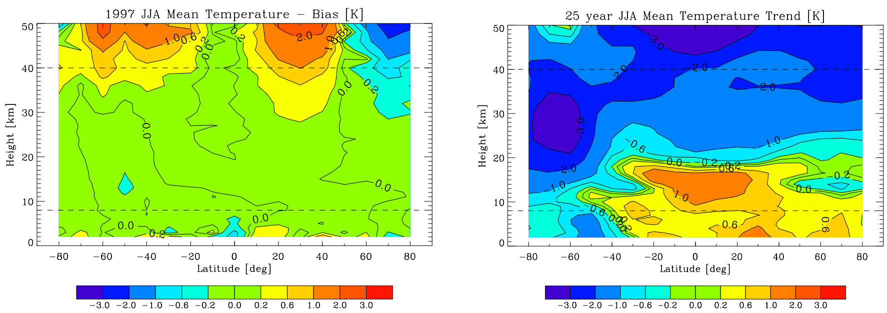


Fig. 11. Lat-Height slice of climatological residual bias errors in average profiles of dry temperature in 17 latitude bins of 10° width from 80°S to 80°N (left panel) compared to 25-yr summer temperature trends from 2001–2025 in the same bins (right panel). Each average profile in the left panel involves ~50 realistically simulated individual GNSS-LEO occultation profiles sampled by an ACE+-type satellite constellation within a full summer season (June-July-August). The trends in the right panel are derived from a recent climate model simulation with the Hamburg ECHAM5 model at T42L39 resolution (top at 0.01 hPa).

In the lower troposphere, where humidity effects play a major role, humidity profiles can be retrieved with good accuracy even allowing for typical uncertainties in the prior knowledge of temperature needed in this case. In the tropics, the typical border between the two regimes is at a height of ~7-8 km, while in the cold and dry polar atmosphere temperature sounding can reach down to the atmospheric boundary layer.

For climate change monitoring based on GNSS-LEO data, refractivity, dry temperature, and geopotential height are very promising. As an example, Figure 11 illustrates the dry temperature accuracy (left panel; for more information see Gobiet and Kirchengast 2004) and indicates that climate trends expected over the coming decades (right panel) will be reliably detectable by RO data thanks to their long-term stability and accuracy.

5 Concluding Remarks

The ACE+ mission, a next-generation RO mission set to use for the first time the concept of LEO-LEO occultations and to exploit GALILEO signals in addition to GPS signals, is on good track to realization with a 5-year operations phase planned 2008–2012. If confirmed by mid 2004 and then implemented, as nominally foreseen due to its ranking as top priority future ESA Earth Explorer Opportunity Mission, ACE+ will be another landmark achievement in RO sounding of the Earth's atmosphere, which has seen impressive advances since the launch of the GPS RO "proof-of-concept" mission GPS/MET in 1995.

With the CHAMP mission, there is now a first GPS RO experiment delivering RO data on a continuous multi-year basis. Other missions like SAC-C, GRACE, GRAS on METOP, EQUARS, and in particular the COSMIC constellation, will heavily extend this dataset in the coming years towards and into the scheduled ACE+ observation period. The start of also exploiting LEO-LEO and GALILEO-LEO RO sounding with ACE+ will thus come in very timely as an initial milestone of a next generation of missions, which will lead RO sounding beyond the classical GPS RO era.

The importance and long-term relevance of the science themes and objectives addressed by ACE+, as summarized in this paper, clearly raise hopes that this mission and the GPS RO missions of the present decade will be directly followed by a long-term operational RO observing system with worldwide stakeholders, which will serve as a leading backbone of the Global Climate Observing System (GCOS) for atmospheric climate change monitoring over the coming decades.

Acknowledgments. The authors (ACE+ Lead Investigators) thank all colleagues and collaborators within the ACE+ stakeholder community, from IGAM/Univ. of Graz, DMI Copenhagen, ESA/ESTEC Noordwijk, and from the many international partner institutions, for their dedication to the ACE+ mission and all the relevant contributions and support so far. In representation of all, the fellow members of the ACE+ Mission Advisory Group S. Buehler, K. Craig, G. Elgered, L. Kornblueh, and H. Le Treut, as well as the close collaborators in ESA P. Silvestrin and T. Wehr shall be named explicitly. All institutions funding ACE+ science and development work are thanked as well, in representation of which the European Space Agency (ESA), the lead developer of the ACE+ mission, shall be named explicitly. Furthermore, the help of U. Foelsche, A. Gobiet, M. Schwärz, S. Schweitzer, J. Fritzer, J. Ramsauer (all IGAM), and P. Eriksson (Chalmers Univ. of Technology, Gothenburg) in the preparation of several figures of the paper is gratefully acknowledged.

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