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University of Graz

Atmospheric Remote Sensing and Climate System Research Group
ARSCliSys – on the art of understanding the climate system

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Final Report

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ESA study:

ACEPASS – LEO-LEO Occultation Characterisation Study

The ACE+ Phase A Scientific Support Study ACEPASS: Summary Report

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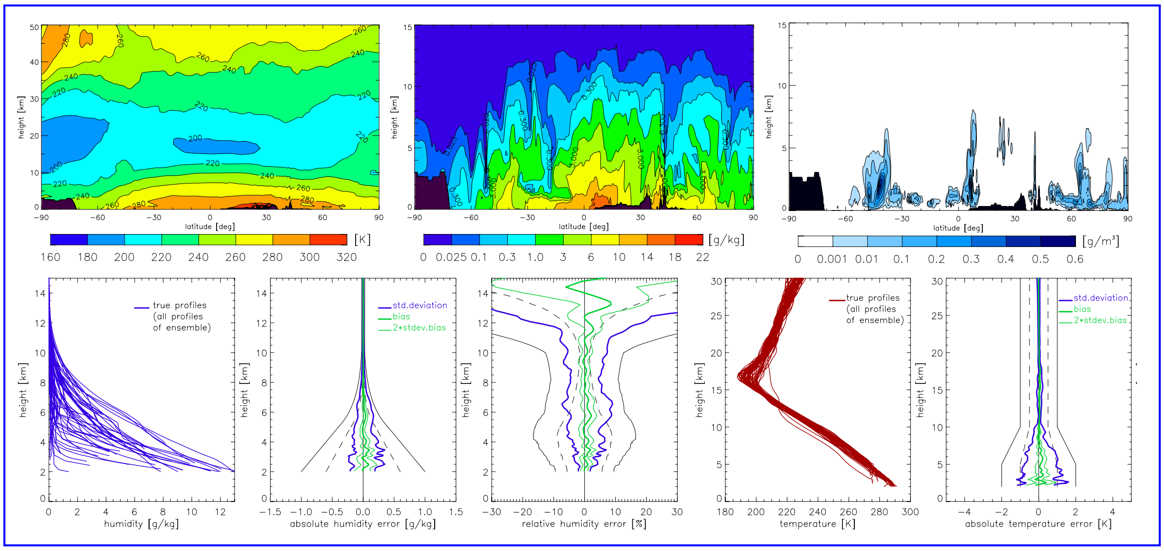

March 2005

This summary report is the main document of the final report set of documents and links with its references section to all component reports. The complete set of ACEPASS reports is included on the Final Report CD-Rom.

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Frequently Used Acronyms

GNSS	Global Navigation Satellite System (GPS and Galileo systems, also Glonass system)
GO	geometric optics (e.g., geometric optics retrieval)
LEO	Low Earth Orbit
MRD	Mission Requirements Document
RO	radio occultation
SNR	signal-to-noise ratio
WO	wave optics (e.g., wave optics bending angle and transmission retrieval)

1. Executive Summary

The objective of the ACE+ Phase A Scientific Support Study on LEO-LEO Occultation Characterisation (ACEPASS study hereafter) was a thorough evaluation and characterization of the measurement and geophysical retrieval performance achievable by sounding the atmosphere through active microwave X/K band links between Low Earth Orbiting (LEO) satellites.

This novel radio occultation concept, termed LEO-LEO RO hereafter, is the core part of the Atmosphere and Climate Explorer Mission ACE+; the complementary part is GNSS-LEO RO using Global Navigation Satellite System signals from the GPS and Galileo systems. The LEO-LEO RO measurement principle is that the radio signals, while passing the atmosphere from transmitter to receiver satellite, are refracted and absorbed in a way allowing for accurate determination of key variables of atmosphere and climate such as humidity and temperature. ACE+ can provide such data globally, with unprecedented accuracy, high vertical resolution, and long-term stability.

The ACE+ mission, of which an artistic view is provided by Figure 1, was pre-selected in May 2002 by ESA as top priority out of 25 proposed Earth Explorer Opportunity Missions. Whilst ACE+ did then not proceed towards full implementation in an ESA mission selection round in April 2004, this pre-selection allowed to undertake complete and successful Phase A studies within 2003–2004 and to prepare a mission concept ready for implementation. The ACEPASS study was the key scientific study of these ACE+ feasibility studies.

Within the ACEPASS study the geophysical processing of ACE+ data was investigated in detail and the ACE+ performance was assessed by means of comprehensive end-to-end performance modeling. To this end an advanced End-to-end Generic Occultation Performance Simulator was developed (EGOPS5), starting from heritage in form of an End-to-end GNSS Occultation Performance Simulator available from GNSS-LEO RO work (EGOPS4). EGOPS5 was complemented by the development of two more specific simulators focusing on wave optics (WO) simulations. One of these enabled explicit high-resolution turbulence simulations and careful study of the impact of turbulence on the retrieval performance.

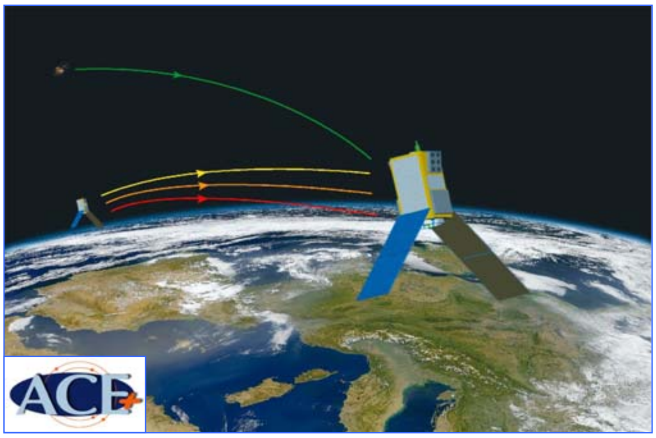

Figure 1: Illustration of the ACE+ concept, indicating both LEO-LEO and GNSS-LEO occultation.

Detailed LEO-LEO RO performance analyses were conducted, which heavily used the simulator tools developed, addressing the following main aspects: effects of instrumental errors on retrieval performance; retrieval performance for different algorithm combinations and algorithmic parameter settings in the retrieval processing chain; effects of clouds, rain, and turbulence on the retrieval performance, including study by statistical performance analyses based on ensembles of profiles under quasi-realistic atmospheric conditions (ECMWF analysis fields); retrieval performance analyses including explicit turbulence modeling based on high-resolution WO signal propagation modeling; effects of upper boundary initialization and potential ionospheric influences; humidity retrieval performance for a differential spectral attenuation concept using closely spaced “twin frequencies”.

The major practical aim of the performance analyses was to support the definition and refinement of the ACE+ observational requirements and system requirements. Furthermore, ACEPASS results contributed substantially to the formulation of the ACE+ documents for the Earth Explorers User Consultation Meeting for mission selection in April 2004 at ESRIN, Frascati, Italy.

Building on the findings and conclusions of the ACEPASS study, recommendations have been formulated that address the most needed further developments regarding LEO-LEO RO performance evaluation and retrieval tools and algorithms, some suggested performance studies for further advancing our scientific understanding and the exploitation of future data, and desirable LEO-LEO RO experimental preparations.

A more detailed summary, and the detailed conclusions and recommendations reached are provided in Sections 2 to 4 below. Section 5 completes the summary by listing all relevant ACEPASS documents (Section 5.1), further ACE+ mission key documents substantially supported by the ACEPASS results (Section 5.2), and a few other references needed (Section 5.3). All documents of Sections 5.1 and 5.2 are available electronically on the ACEPASS Final Report CD-Rom (.pdf files).

2. Summary

The objective of the ACE+ Phase A Scientific Support Study on LEO-LEO Occultation Characterisation (ACEPASS study hereafter) was a thorough evaluation and characterization of the measurement and geophysical retrieval performance achievable by sounding the atmosphere through active microwave (X/K band) links between Low Earth Orbiting (LEO) satellites.

This novel radio occultation (RO) concept, termed LEO-LEO RO hereafter, is the core part of the ACE+ Atmosphere and Climate Explorer Mission of which an up-to-date overview description was provided by Kirchengast and Hoeg (2004). The LEO-LEO RO measurement principle is that the radio signals, while passing the atmosphere from transmitter to receiver satellite, are refracted and absorbed in a way allowing accurate determination of key variables of atmosphere and climate such as humidity and temperature. ACE+ can provide such data globally, with unprecedented accuracy, high vertical resolution, and long-term stability.

Besides demonstrating LEO-LEO RO, ACE+ also utilizes Global Navigation Satellite System (GNSS) signals from the GPS and Galileo systems for "classical" GNSS-LEO RO sounding. However, whilst GNSS-LEO RO cannot separate temperature and water vapor based on the refraction-only information available from the GNSS L band signals, LEO-LEO RO enables to independently derive humidity and temperature thanks to the strong water vapor absorption information in the X/K band (23 GHz water vapor line).

The ACE+ mission was pre-selected in May 2002 by ESA as top priority out of 25 proposed Earth Explorer Opportunity Missions. Whilst ACE+ was then not proceeded towards full implementation in an ESA mission selection round in April 2004, this pre-selection allowed to undertake Phase A studies within 2003–2004 and to prepare a mission concept ready for implementation (ESA, 2004a,b,c,d). The ACEPASS study was the key scientific study as part of these ACE+ feasibility studies.

Within the ACEPASS study the geophysical processing of ACE+ data, starting from the LEO-LEO RO amplitude and phase measurements, was investigated in detail and the ACE+ performance was assessed by means of comprehensive end-to-end performance modeling from transmission of the X/K band signals by a LEO transmitter to geophysical products such as temperature, humidity, and liquid water profiles. To this end, an advanced End-to-end Generic Occultation Performance Simulator was developed (EGOPS5; Kirchengast et al., 2004d), starting from heritage in form of an End-to-end GNSS Occultation Performance Simulator available from GNSS-LEO RO work (EGOPS4; Kirchengast et al., 2002). This simulator was complemented by another independent end-to-end simulator focusing on wave optics (WO) simulations (Benzon et al., 2004a,b) and a special advanced WO based simulator enabling explicit high-resolution turbulence simulations and careful study of impact of turbulence on the retrieval performance (Gorbunov and Kirchengast, 2005).

Many new or extended modeling components needed to be developed in the context of these simulators, such as atmospheric clouds and rain modeling, geometric-optics (GO) and WO signal propagation modeling in X/K band accounting for absorption, turbulence and signal scintillation modeling, LEO transmitter and LEO receiver antennae pattern modeling, instrumental error modeling, and GO and WO retrieval processing exploiting refraction and absorption data.

The LEO-LEO RO performance analyses, which heavily used the simulator tools, included the following main areas of study:

- effects of instrumental errors on retrieval performance, including errors due to thermal noise, amplitude drifts, and 1/f noise (flicker noise) under a representative range of different atmospheric conditions (Schweitzer et al., 2003; Kirchengast et al., 2004a).
- investigation of the retrieval performance for different algorithm combinations and algorithmic parameter settings in the retrieval processing chain, including GO and WO algorithms, and improvement of retrieval processing by such investigations (Benzon et al., 2004a,b; Gorbunov and Kirchengast, 2005; Kirchengast et al., 2004a).
- effects of clouds (both water and ice clouds), rain, and turbulence on the retrieval performance (Gradinarsky et al., 2004; Gorbunov and Kirchengast, 2005; Kirchengast et al., 2004a,b,c; Schweitzer, 2004).
- End-to-end statistical retrieval performance analyses based on ensembles of profiles under quasi-realistic atmospheric conditions (ECMWF T511L60 analysis fields) including investigation of the effects of clouds, turbulence, and horizontal variability (Kirchengast et al., 2004b,c; Schweitzer, 2004).
- Retrieval performance analyses including explicit turbulence modeling (high-resolution random refractivity perturbation fields) based on very-high-resolution WO signal propagation modeling (~ 100 m horizontal x 1 m vertical gridding) and advanced WO retrieval (Gorbunov and Kirchengast, 2005).
- Performance assessment related to effects of upper boundary initialization (“reference height selection”) and potential ionospheric influences due to both the large-scale ionosphere and ionospheric scintillations (Kirchengast et al., 2004c).
- Investigation of the humidity retrieval performance for a differential spectral attenuation concept using closely spaced (order 100 MHz) “twin frequency” channels (Facheris and Cuccoli, 2003).

The major practical aim of the performance analyses was — besides their scientific value in terms of substantially advancing algorithm developments and the understanding of LEO-LEO RO properties — to support the definition and refinement of the observational requirements and system requirements laid down in ESA (2004a). Furthermore, the results contributed substantially to the formulation of the ACE+ documents for the Earth Explorers User Consultation Meeting for mission selection in April 2004 (ESA, 2004b,c) and the related presentation material (ESA, 2004d; Kirchengast et al., 2004c).

In representation of the wealth of significant results reported in the range of ACEPASS documents (section 5.1), which can only be summarized here, we illustrate and briefly discuss below a temperature and humidity retrieval end-to-end performance study based on high resolution ECMWF analysis data (Kirchengast et al., 2004b,c; Schweitzer, 2004) as well as a transmission retrieval performance study using the new advanced WO retrieval approach reported by Gorbunov and Kirchengast (2005).

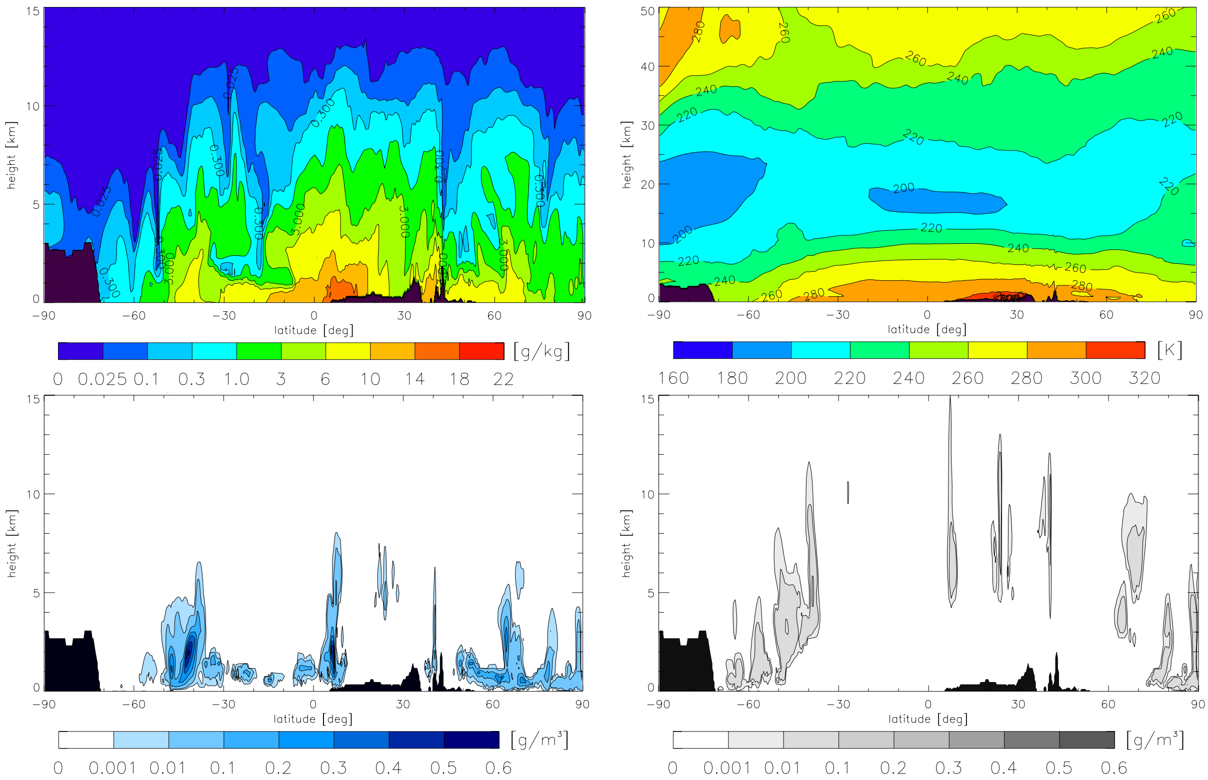

Figure 2: Specific humidity (top-left), temperature (top-right), liquid water density (bottom-left), and ice water density (bottom-right) latitude-height cross sections at 0 deg longitude through the ECMWF T511L60 analysis of Sept 15, 2002, 12 UT, used in the simulations. [from Kirchengast et al., 2004b]

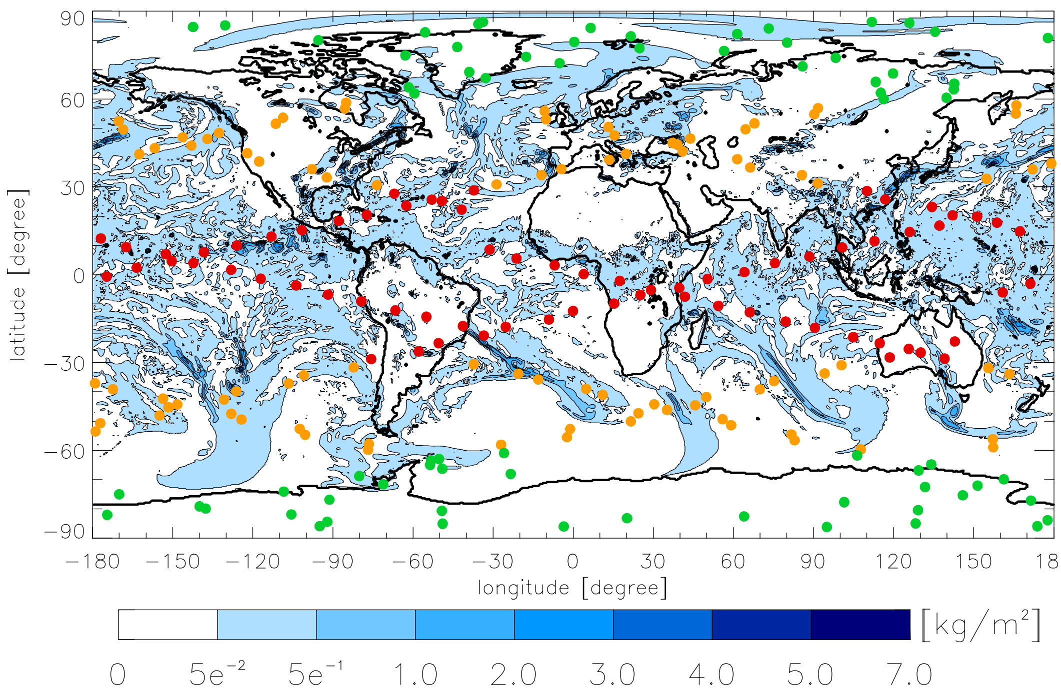

Figure 3: Coverage with 1 day of ACE+ LEO-LEO RO events, sorted into low (red dots), middle (orange dots), and high (green dots) latitude bands of 30 deg width each. The background shows the vertically integrated liquid water density (units kg/m^2), indicating cloud coverage (data from the Sept 15, 2002, 12 UT, ECMWF T511L60 analysis). [from Kirchengast et al., 2004c]

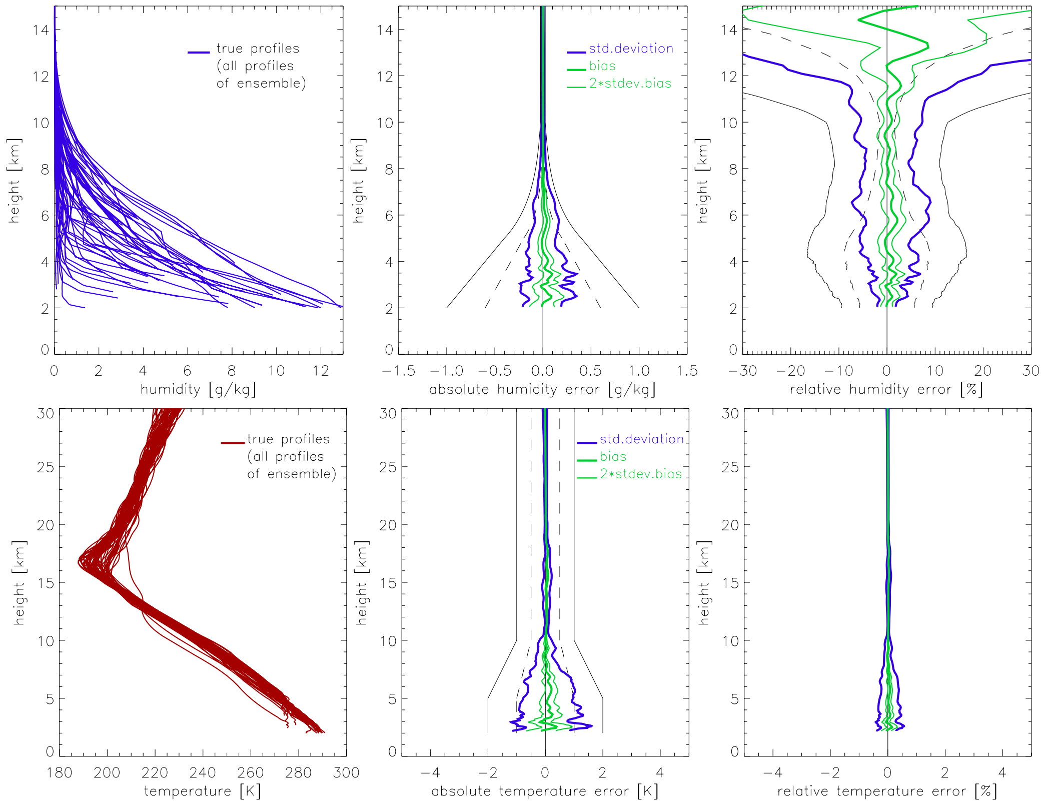

Figure 4: Humidity (top) and temperature (bottom) "true" profiles (left panels) and ACE+ retrieval error results (middle and right panels) for the ECMWF low-latitude ensemble. Statistical performance results are shown (standard deviation, bias, 2 x std.deviation of bias), with the std. deviations depicted as +/– envelopes about the bias profiles. In the upper middle, upper right, and lower middle panels the observational requirements, as laid out in ESA (2004a), are shown for reference (solid black, threshold requirements; dashed black, target requirements). [from Schweitzer, 2004]

Figures 2 to 4 illustrate end-to-end performance simulations for which a day of simulated LEO-LEO RO events (about 230 events) was used to assess the humidity and temperature retrieval performance under quasi-realistic atmospheric conditions including clouds and turbulence effects. Figures 2 and 3 illustrate the atmospheric conditions and the RO event coverage and Figure 4 depicts low latitude retrieval results (30°S to 30°N) as an example.

Regarding humidity, the performance was in general found within target requirements below about 6 to 10 km, while above it is not far from these and well within threshold requirements. No significant biases were found at any height and the humidity errors up to near 10 to 12 km, dependent on latitude, were found within about 10%. Above 10 to 12 km, a significant fraction of the errors can be attributed to the not yet fully optimized LEO-LEO end-to-end simulator, in particular to improvement potential in the filtering and weighting of transmission and imaginary refractivity data. Regarding temperature, the performance was found unbiased and within target requirements essentially at all heights at all latitudes. Kirchengast (2004b,c) and Schweitzer (2004) describe this type of simulations and results in detail.

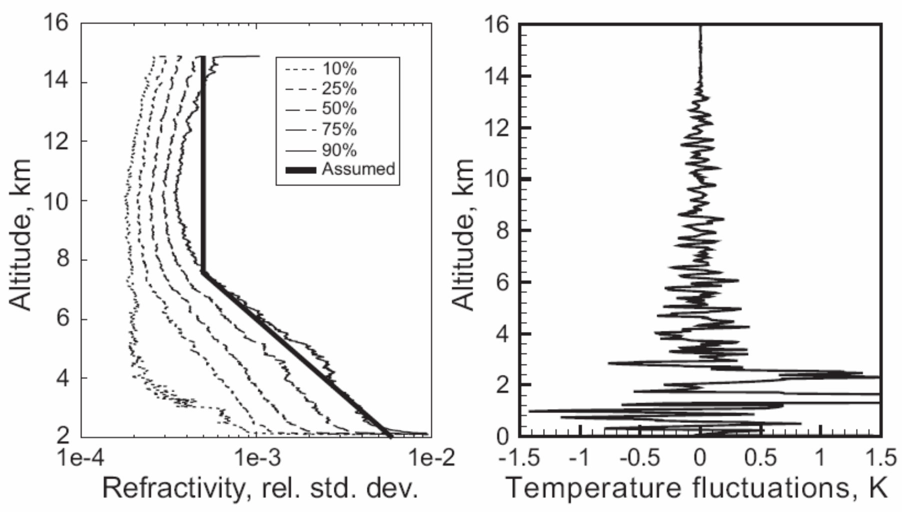

Figure 5: (left) Profiles of turbulent fluctuations (rms) on the basis of a dataset of high-resolution radiosonde profiles observed at the low latitude station St.Helena (15.6°S, 5.4°W): Median profile (50%) and different percentiles. The profile "Assumed" (heavy black line), meant roughly to reflect the upper decile (90%), is the one used for the turbulence modeling. (right) associated turbulent fluctuations in the dry temperature. [from Gorbunov and Kirchengast, 2005; adapted]

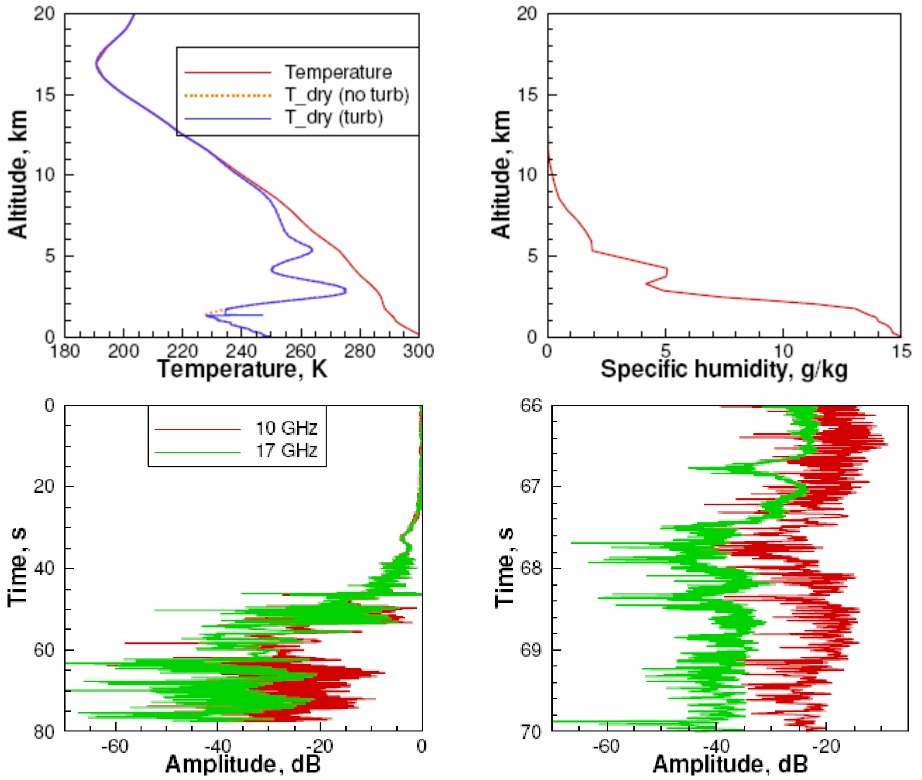

Figure 6: (upper panels) Temperature profile (incl. dry temperatures for comparison) and humidity profile near the tangent point of a LEO-LEO RO event simulated based on a 3D ECMWF analysis field (moist low latitude conditions) plus presence of strong turbulence ("Assumed" profile of Figure 5 above). (lower panels) Simulated 1 kHz rate amplitude profiles at 10 and 17 GHz, the right panel being a zoom into 4 sec of the left panel, showing the typical diffraction features in raw X/K band high-resolution amplitude data. [from Gorbunov and Kirchengast, 2005]

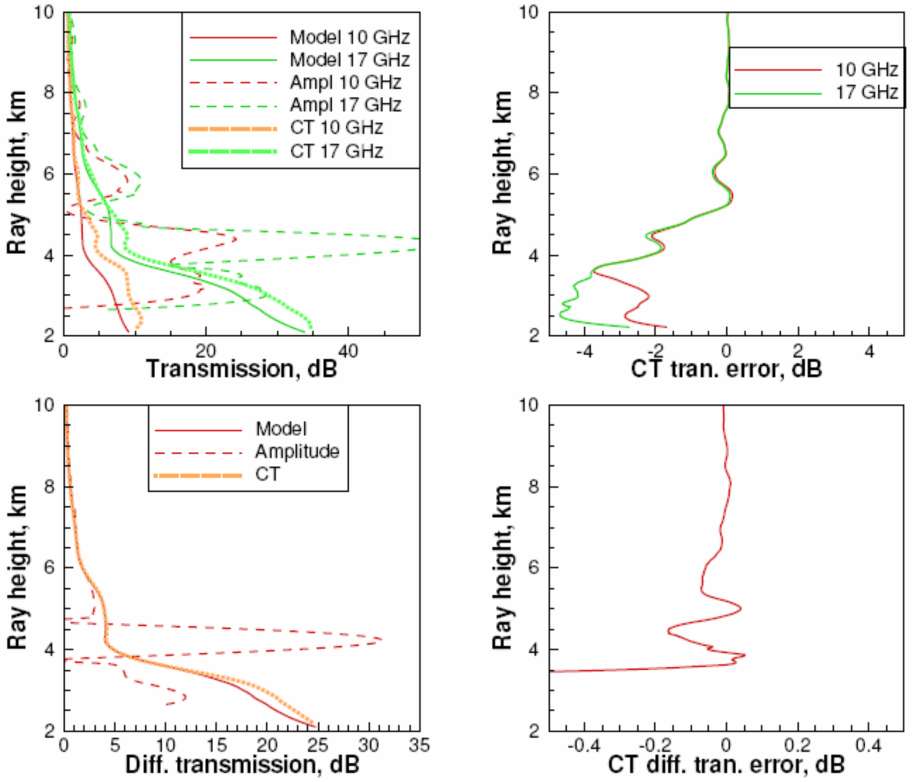

Figure 7: (upper panels) retrieved transmission profiles and Canonical Transform (CT) transmission retrieval error at 10 and 17 GHz for an ACE+ receiver with C/N_0 = 67 dBHz. The retrievals have been performed either without CT (light dashed) or with CT (heavy dashed). (lower panels) retrieved differential transmission profiles (log-transmission difference between 10 and 17 GHz) and CT differential transmission error. Either the transmissions directly have been differenced (light dashed) or the CT transmissions (heavy dashed). [from Gorbunov and Kirchengast, 2005]

Figures 5 to 7 illustrate an example case of simulations investigating advanced wave optics processing of LEO-LEO RO data in presence of turbulence, which was the most recent development within the final phase of the ACEPASS study. Very high resolution forward modeling (~200 m horizontally, ~ 1 m vertically), including explicit modeling of turbulence as 2D random field perturbations in the occultation plane, was combined with a new retrieval method (CT differential transmission retrieval).

As illustrated by Figure 7, the new method has the favorable capability to effectively correct for scintillations in the differential transmission even under moist tropical conditions, down towards the boundary layer as long as the signal is not too much defocused and absorbed. In the example case shown, the top of the boundary layer is reached with a CT differential transmission error of < 0.15 dB (< 3.5%); note that a ray height of ~3.5 km (see the error increase in the lower right panel of Figure 7) corresponds to an altitude of near 2 km, which is the altitude of the boundary layer in the given case (see the steep humidity decay in the upper right panel of Figure 6). Gorbunov and Kirchengast (2005) describe this type of simulations and results in detail.

The ACEPASS performance analyses were preceded by a comprehensive review and general characterization of the LEO-LEO RO technique by Nielsen et al. (2005), including detailed background information on the various physical phenomena in the atmosphere influencing LEO-LEO RO measurements as well as on inversion/retrieval strategies and the modeling of random and systematic errors.

Important auxiliary work to the review and the performance analyses was provided by Kuhn (2003a,b) on atmospheric scintillations and their modeling and by Buehler (2004) regarding the modeling of the turbulent structure constant based on high-resolution radiosonde profiles.

Regarding the end-to-end simulation and algorithm developments, the EGOPS5 software package, together with its documentation, was transferred to ESA as a product of the ACEPASS study in addition to all ACEPASS reports (References Section 5.1). Also the other simulator developments (Benzon et al., 2004a,b; Gorbunov and Kirchengast, 2005) will be of help for future LEO-LEO RO studies and will be maintained for this purpose.

3. Conclusions

The main conclusions from the ACEPASS work, drawn from the various ACEPASS reports summarized above, can be collected as follows (selected references are included below to ease finding detailed background on specific conclusions from the most suitable reports):

Algorithms development:

- The end-to-end performance simulation systems and the scientific algorithms in their versions developed during the ACEPASS study proved to be suitable for LEO-LEO performance analyses under fairly realistic conditions, including the use of ECMWF high-resolution operational analysis fields and accounting for cloudy and turbulent conditions. (Kirchengast et al., 2004a,b,d; Kuhn, 2003b; Benzon et al., 2004a,b; Gorbunov and Kirchengast, 2005)
- Building on this good status, still a series of further algorithm extensions, improvements, and optimizations should be tackled in the future, however. Relevant avenues and needs are summarized in Section 4 (Recommendations) below.

Retrieval performance:

- The LEO-LEO retrieval performance was found compliant with the observational requirements given in ESA (2004a,b), when using the respective system requirements (ESA, 2004a,c) as basis. In most cases compliance was found with the target requirements, including under the adverse conditions of severe atmospheric turbulence below about 3 to 6 km. (Kirchengast et al., 2004b)

  Specific retrieval performance aspects worth noting include:

  - the essentially bias-free character of the retrieval products such as temperature and humidity, including under cloudy and turbulent conditions, which roots in the self-calibrating nature of the ACE+ RO data and was found conserved throughout the retrieval chain from phases and amplitudes to humidity and temperature profiles. (Kirchengast et al., 2004a,b; Schweitzer, 2004)

  - the ability of simultaneous retrieval of accurate humidity, temperature, and pressure as function of height from LEO-LEO, which is a particularly valuable property compared to GNSS-LEO with its tropospheric temperature–humidity ambiguity. (Nielsen et al., 2005; Kirchengast et al., 2004b)

- the retrieval of upper troposphere humidity with an rms accuracy of ~5–10% (absolute errors < 0.01 g/kg), including through ice clouds to which the retrieval is virtually insensitive due to the long wavelengths employed (> 1 cm). The latter insensitivity holds also for ice water concentrations prevailing in tropical cumulonimbus anvils. (Gradinarsky et al., 2004; Kirchengast et al., 2004a)

- the presence of liquid water clouds does not significantly degrade the retrieval performance due to the liquid water attenuation, since the amplitude data at the different X/K band frequencies allow to isolate the liquid water effect; the increased turbulence in cloudy areas will thus be the major effect of clouds on retrievals. (Gradinarsky et al., 2004; Kirchengast et al., 2004a,b; Schweitzer, 2004)

- rain of sufficient strength (e.g., from nimbostratus or cumulonimbus clouds) will strongly attenuate the signal and thereby in general inhibit the use of amplitude data for humidity-temperature retrieval during rain; this effect will be limited to below about 3 km, however, where sufficient rain rates and droplet sizes can occur. (Nielsen et al., 2005; Gradinarsky et al., 2004)

- the ionospheric degradation of performance, both from large-scale ionization and small-scale irregularities leading to scintillation, is negligible thanks to the high frequencies used (~10 GHz and higher). This implies, together with the low thermal noise due to the high SNR of LEO-LEO measurements, that upper stratospheric temperature accuracy is substantially improved over GNSS-LEO accuracy and that LEO-LEO temperature profiles will thus be of high utility up towards the stratopause. (Kirchengast et al., 2004c; Nielsen et al., 2005; Kirchengast et al., 2004a)

Amplitude normalization, Processing in presence of turbulence:

- Altitudes of 25–30 km are found sufficiently high up for normalization of the amplitude profiles. Thus any stability requirement during a LEO-LEO RO event is sufficiently fulfilled if holding for ~20 sec over the time of scanning below 25 km. Capability to measure amplitudes over the range 30–50 km in addition will allow to observe, over ~6–10 sec, the essentially un-attenuated amplitude stability characteristics as a baseline, which may serve as a useful quality control in a first-time demonstration as done by ACE+ (e.g., regarding residual amplitude drifts). (Kirchengast et al., 2004c; Kirchengast et al., 2004a; Nielsen et al., 2005)
- In conditions of strong turbulence, which typically occur below about 3 to 6 km and which may affect up to every 2nd RO event in average, two measures were found to ensure robust retrieval within requirements down to the boundary layer: 1) use of differential transmissions derived by advanced WO retrieval based on a canonical transform differential transmission approach (Gorbunov and Kirchengast, 2005); 2) use of background temperature profiles from a short-term (e.g., 1 day) weather forecast within a best-fit temperature extrapolation approach (Kirchengast et al., 2004b,c; Schweitzer, 2004).
- The differential spectral attenuation concept is an attractive complementary approach to measure tropospheric humidity profiles, especially in presence of turbulence, provided sufficient signal-to-noise (SNR) ratio is available at signal reception. The SNR associated with the present ACE+ system specifications (ESA, 2004a,c) is

somewhat small for a demonstration of this concept in the ACE+ context. (Facheris and Cuccoli, 2003)

For detailed conclusions per specific study see the summary and conclusions sections of the specific reports in the ACEPASS Bibliography (Section 5.1).

4. Recommendations

Building on the findings and conclusions of the ACEPASS study, the following recommendations for further study can be given, which will help to further advance the understanding and characterization of the LEO-LEO RO concept. The recommendations in each group are listed in order of priority, whereby the tasks listed under "First Priority" are those considered most relevant and recommendable for immediate follow-on study.

1. LEO-LEO RO performance evaluation and retrieval tools and algorithms:

First Priority:

1.a advance the WO forward modeling and retrieval simulation tools in order to allow for quasi-realistic end-to-end simulations to systematically explore the full potential of the Canonical Transform (CT) differential transmission algorithm and of advanced Full Spectrum Inversion (FSI) algorithms for bending angle and transmission retrieval in presence of turbulence. In the forward modeling, advance WO signal propagation to allow explicit turbulence simulations down to an inner scale of turbulence of 10 m and to an-isotropy coefficients as small as 5.

1.b in support of the WO retrievals, advance the turbulent random refractivity field modeling to allow simulations of refractivity fluctuations fully consistent with those derived from high-resolution radiosonde profiles or other high-resolution refractivity records. Advance also algorithms for the reliable estimation of the rms of small-scale turbulent refractivity fluctuations from such records.

1.c advance the present retrieval processing tools based on bending angles and single-channel transmissions by exploiting also — as an alternative or in combination with single-channel transmissions —differential transmission profiles, i.e., by retrieving differential imaginary refractivities and subsequently atmospheric profiles making use of differential transmissions.

1.d refine the atmospheric profiles retrieval processing in terms of its height-dependent weighting of the real refractivity and (differential) imaginary refractivity profiles in the optimal atmospheric state estimation process. Related to this, improve also the filtering processes associated with all elements of the LEO-LEO retrieval chain as well as the upper boundary treatment of the atmospheric profiles retrieval.

Further Priorities:

2. in support to end-to-end simulations for different purposes as recommended below, advance the current observation error modeling as needed. Also, related to the forward modeling, advance the 3D atmospheric state modeling by expanding the current ECMWF-based atmospheric modeling by precipitation (rain rate) fields.
3. prepare algorithms for time series analysis of the LEO-LEO phase and amplitude data, extended as needed to the analysis of bending angle, transmission, and real and

imaginary refractivity data, for purposes such as height-dependent turbulence detection and estimation of turbulence strength and other turbulence parameters, and cloud and rain detection and (rough) liquid water and rain rate magnitude estimation. These "data mining algorithms" shall support tasks like intrinsic quality control and decisions on algorithmic choices and parameter settings depending on data properties and quality.

4. Extend the current retrieval processing and analysis algorithms by tools enabling to perform a complete error analysis and characterization of all retrieval products, both theoretically (optimal estimation methodology; Rodgers, 2000) and empirically (ensemble-based error analyses based on end-to-end simulations).
5. Develop observation operators for 1D variational (1D-VAR) assimilation of single-channel and differential imaginary refractivity profiles into NWP systems, for use in a 1D-VAR assimilation impact study based on LEO-LEO refractivity data.

2. LEO-LEO RO performance studies:

First Priority:

1.a Extending the current retrieval performance results based on single-channel transmission profiles, carry out a statistical humidity and temperature retrieval performance study for ACE+ including use of CT differential transmissions and similar advanced-FSI based retrievals. Assess by how much in presence of strong turbulence this complementary processing approach improves performance and allows to lower the height limits below which auxiliary temperature information is needed compared to the 3 to 6 km limits reported in Kirchengast et al. (2004b) and Schweitzer (2004).

1.b Perform a quantitative check of previous findings that residual transmission retrieval errors from turbulence will become smaller when approaching from an-isotropic, horizontally layered turbulence to isotropic turbulence (Gorbunov and Kirchengast, 2005, and references therein). Use a systematic end-to-end simulation study including explicit turbulence modeling for this purpose. Prepare also, as a testbed, an ensemble of refractivity turbulence rms profiles and associated C_n^2 profiles for different geographical locations in this context.

1.c Assess, in the context of using both single-channel and differential transmissions, the relative scientific performance, and the relative cost and cost-benefit ratio, of LEO-LEO RO systems using slightly different frequency setups. Use as reference 9.7-17.25-22.6 GHz (ACE+) and assess, against this reference, 17.25-20.2-22.6 GHz (single-antenna setup emphasizing heights > 5 km, i.e., upper troposphere/lower stratosphere) and 9.7-13.5-17.25-22.6 GHz (setup with enhanced lower troposphere emphasis < 5 km), respectively.

Further Priorities:

2. Statistically assess the improvement of upper stratosphere temperature retrieval from LEO-LEO phase delay data compared to GNSS-LEO data, in view of the much higher SNR and much lower ionospheric vulnerability of the X/K band signals used in LEO-LEO RO. Quantify the dominant error source limiting the accuracy, currently expected to be clock instabilities.

3. Using a representative ensemble of simulated ACE+ observations, including cloudy, rainy, and turbulent cases, explore the value of the "data mining algorithms" referred to above for robust and accurate retrieval under the wide range of possible atmospheric conditions. The basis for the atmospheric conditions can, for example, be ECMWF analysis fields complemented by turbulence modeling.
4. Perform, expanding on the relevant ACEPASS analyses, a complete error analysis and characterization of the LEO-LEO retrieval processing chain from phase and amplitude to temperature and humidity, both by theoretical (optimal estimation) and empirical (ensemble simulations) approaches. These studies shall beyond biases and standard deviations of errors at least also quantify error correlation characteristics and vertical resolution properties. They shall also provide error and resolution characteristics of liquid water profiles.
5. Perform a simulation study on 1D-VAR assimilation of real and imaginary refractivity profiles into suitable "background fields" to assess the analysis increments available from assimilating LEO-LEO RO profiles, in particular from assimilating (differential) imaginary refractivity profiles in addition to real refractivity profiles. The basic fields for this study can, for example, be ECMWF analyses serving as "truth" and for simulating the observations (via end-to-end simulation to reasonably capture their error characteristics) as well as ECMWF short-term forecasts serving as background fields.

3. LEO-LEO RO experimental preparations:

First Priority:

1. Using ACE+ breadboards, test the LEO-LEO crosslink in an airborne campaign, e.g., by transmitter and receiver mounted at the rear of two airplanes flying in opposite directions at a flight level > 10 km and accumulating the RO event in the troposphere in between.

Further Priorities:

2. Perform a spectroscopic study to refine the spectroscopic knowledge on the absorption lines of all relevant atmospheric species in the 1 GHz – 30 GHz range, in particular of water vapor, molecular oxygen, and molecular nitrogen.
3. Complementary to refining the relevant gas spectroscopy, also refine the knowledge on absorption and scattering cross sections of liquid water and ice typical of water and ice clouds in the atmosphere. Given the usually limited resources, keep in mind that the five frequencies of main interest lie near 9.7, 13.5, 17.25, 20.2, and 22.6 GHz.

A follow-on study on at least the First Priority tasks is strongly recommended. Such a study would allow to check and consolidate the few issues left under discussion by the end of the ACEPASS study regarding the measurement performance of the ACE+ LEO-LEO crosslink concept.

5. References

5.1. ACEPASS Bibliography

All reports referenced here are included on the ACEPASS Final Report CD-Rom; the names of the respective .pdf files are given below. For those also available on-line, the web links are given as well. [This summary report itself is also on-line: www.uni-graz.at/igam-arsclisys > Publications]

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5.2. ACE+ Mission Key References

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