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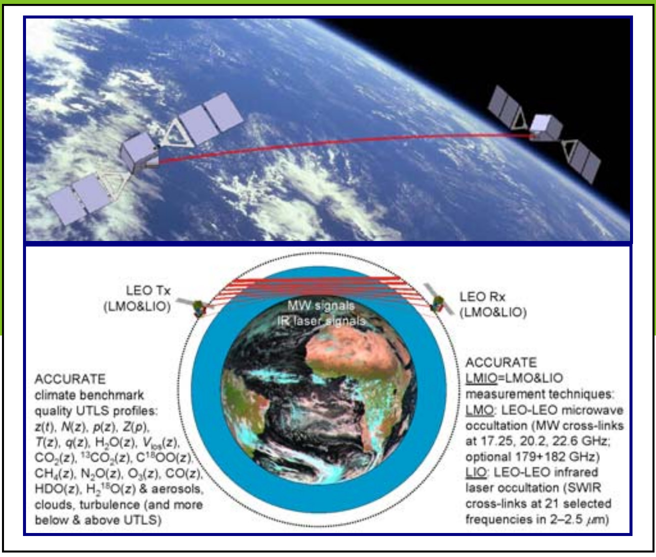


Scientific Report No. 36-2010

ACCURATE — climate benchmark profiling of greenhouse gases and thermodynamic variables and wind from space

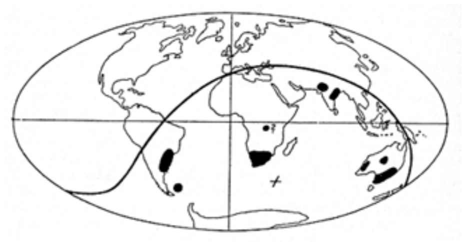
ESA Earth Explorer Opportunity Mission EE-8 Proposal

Gottfried Kirchengast
& Science Team Partners
& Industry Support Team
(details see inside report cover)

July 2010

The **Wegener Center for Climate and Global Change** combines as an interdisciplinary, internationally oriented research center the competences of the University of Graz in the research area „Climate, Environmental and Global Change“. It brings together, in a dedicated building close to the University central campus, research teams and scientists from fields such as geo- and climate physics, meteorology, economics, geography, and regional sciences. At the same time close links exist and are further developed with many cooperation partners, both nationally and internationally. The research interests extend from monitoring, analysis, modeling and prediction of climate and environmental change via climate impact research to the analysis of the human dimensions of these changes, i.e., the role of humans in causing and being effected by climate and environmental change as well as in adaptation and mitigation. The director of the center, hosting about 35 researchers, is the geophysicist Gottfried Kirchengast, the lead partner and deputy director is the economist Karl Steininger. (more information at www.wegcenter.at)

The present report includes the proposal of May 2010 (submitted 1st June 2010) of Kirchengast et al. for an Earth observation mission in the framework of a Call for Proposals of the European Space Agency (ESA) for Earth Explorer Opportunity Mission EE-8 (i.e., foreseen as eighth in the ESA Earth Explorer satellite series). All proposal partners from science and industry are gratefully acknowledged.



Alfred Wegener (1880-1930), after whom the Wegener Center is named, was founding holder of the University of Graz Geophysics Chair (1924-1930) and was in his work in the fields of geophysics, meteorology, and climatology a brilliant, interdisciplinary thinking and acting scientist and scholar, far ahead of his time with this style. The way of his ground-breaking research on continental drift is a shining role model — his sketch on the relationship of the continents based on traces of an ice age about 300 million years ago (left) as basis for the Wegener Center Logo is thus a continuous encouragement to explore equally innovative scientific ways:
paths emerge in that we walk them (Motto of the Wegener Center).

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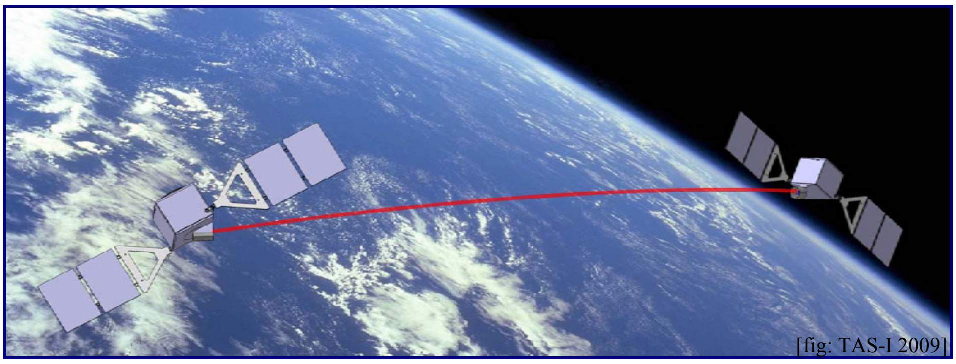
ACCURATE – climate benchmark profiling of greenhouse gases and thermodynamic variables and wind from space

A mission to initiate a novel fundamental atmospheric state dataset for climate and composition monitoring and research in the global free atmosphere using combined IR-laser and MW occultation between Low Earth Orbit satellites


[fig: TAS-I 2009]

Proposal

in response to the Call for Proposals for Earth Explorer Opportunity Mission EE-8
(ESA Doc.No. ESA/EXPLORER/COM-3/EE-8, October 2009)

by

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and an Industry Support Team (see Acknowledgments on p. viii)

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List of Acronyms

ACCURATE	(Atmospheric Climate and Chemistry in the UTLS Region and climate Trends Explorer; now used as a generic proper name for the LMIO mission concept) — climate benchmark profiling of greenhouse gases and thermodynamic variables and wind from space
ACE+	Atmosphere and Climate Explorer (occultation mission studied by ESA 2002–2004)
ACTLIMB	Performance Envelope of Active Limb Sounding of Planetary Atmospheres (ESA study 2008-10 with focus LMO and LIO sounding of Earth's atmosphere)
AGSA	ACCURATE GRAS Support Assembly, aux. support payload on both Tx and Rx
AIOS(-T, -R)	ACCURATE Infrared-laser Occultation Senor (LIO instrument), Tx and Rx payload
AMOS(-T, -R)	ACCURATE Microwave Occultation Sensor (LMO instrument), Tx and Rx payload
ALPS	ACCURATE LIO Performance Simulator
AO	Announcement of Oppurtunity
CW	Continuous Wave
Diversitas	An International Programme of Biodiversity Science (partner of ESSP)
DFB	Distributed Feed-Back (laser diode technology)
ECMWF	European Centre for Medium-Range Weather Forecasts (Reading, U.K.)
EGOPS	End-to-end Generic Occultation Performance Simulation and Processing System
ESA	European Space Agency
ESSP	Earth System Science Partnership (initiative incl. WCRP, IGBP, IHDP, Diversitas)
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FASCODE	FASt Atmospheric Signature CODE (a set of simple standard atmosphere profiles)
FOV	Field of View (remote sounding area sensed by receiver antennae or optics)
Galileo	European future global navigation satellite system
GAW	Global Atmosphere Watch
GCM	Global Circulation Models
GCOS	Global Climate Observing System
GHG(s)	Greenhouse gas(es)
GMES	Global Monitoring for Environment and Security
GNSS	Global Navigation Satellite Systems (Global Navigation System, GPS, and Galileo)
GOMOS	Global Ozone Monitoring by Occultation of Stars
GOSAT	Greenhouse Gases Observing Satellite
GPS	Global Positioning System
GRAS	GNSS Receiver for Atmospheric Sounding
HITRAN	High-resolution Transmission molecular absorption database
HT	Higher Troposphere (equals UT)
ICSU	International Council for Science
IGBP	International Geosphere Biosphere Programme (partner of ESSP)
IHDP	International Human Dimensions Programme (partner of ESSP)
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared (here specifically relevant the 2–2.5 μm region in shortwave IR, SWIR)
IRDAS	Differential Absorption Spectroscopy in the SWIR for Greenhouse Gas Monitoring using Coherent Signal Sources in a Limb Sounding Geometry (ESA study 2008-10)
l.o.s. Wind	line-of-sight wind (denoting the wind speed along occultation rays)
LEO	Low Earth Orbit (or satellite in Low Earth Orbit)
LEOP	Launch and Early Orbit (or Operations) Phase
LIO	LEO-LEO IR-laser Occultation (here IR-laser crosslink signals within 2–2.5 μm)
LMO	LEO-LEO MW Occultation (here MW crosslink signals within 17–23 GHz)
LMIO	Combined LMO and LIO technique (in fact the ACCURATE concept)

LODM	Assessment of a Laser-based Occultation Demonstration Mission (ESA study 2009)
LS	Lower Stratosphere (WMO: 100–10 hPa / ~15–35 km)
LT	Lower Troposphere (WMO: 1000–500 hPa / ~0–5 km)
MACC	Monitoring Atmospheric Composition and Climate (EU project GMES atm.service)
MetOp	Meteorological Operational satellite (of EUMETSAT)
MW	Microwave (here specifically relevant the 17–23 GHz region in K band)
NEP	Noise Equivalent Power
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
RAAN	Right Ascension of Ascending Node
RF	Radio Frequency
RH	Relative humidity
RMS(E), rms(e)	Root Mean Square (Error) (average spread measure for statistical or total error)
SI	Système Internationale (International system of fundamental physical units)
SNR	Signal-to-noise ratio
SWIR	Short wave infrared spectral region (1.5-3 μm; here referring to the 2–2.5 μm region)
TBL	Top of atmospheric boundary layer
TOA	Top of the Atmosphere (here referring to heights of 40 to 80 km, context-depending)
Tx, Rx	Transmitter (Tx) resp. Receiver (Rx); also Transmitter resp. Receiver satellite
US	Upper Stratosphere (WMO: 10–1 hPa / ~35–50 km)
UT	Upper Troposphere (WMO: 500–100 hPa / ~5–15 km)
UTC	Universal Time Coordinated (worldwide standard time)
UTLS	Upper Troposphere & Lower Stratosphere region (WMO: 500–10 hPa / ~5–35 km)
WCRP	World Climate Research Programme (partner of ESSP)
WMO	World Meteorological Organization
H_2O, CO_2, CH_4	water vapor, carbon dioxide, methane (ACCURATE target species)
N_2O, O_3, CO	nitrous oxide, ozone, carbon monoxide (ACCURATE target species)
$^{13}CO_2$, $C^{18}OO$	“heavy-carbon” and “heavy-oxygen” carbon dioxide main isotopes (ACCURATE target isotope species for carbon dioxide)
HDO, $H_2{}^{18}O$	“heavy-hydrogen” and “heavy-oxygen” water vapor main isotopes (ACCURATE target isotope species for water vapor)
V_{los}	Line-of-sight wind (speed)

Selected References

[*Note:* all references cited here are for convenience available to ESA and evaluators also as pdfs via a single spot access: ftp://wegc203115.uni-graz.at, usern: ee8-accu, passw: accu2pa In case of access problems Wim.De-Geeter@uni-graz.at (system administrator) can be contacted]

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The selected references mainly include documents related to the initial ACCU (2005) mission concept, and subsequent relevant studies based on the ESAC (2006) recommendations, as well as to the predecessor ACE+ mission concept. These are key references (all available also, e.g., via ESA/ESTEC Future Missions Division), since the present ACCURATE mission proposal builds on this previous ACCURATE and ACE+ work as main ESA related heritage.
Literature referencing has otherwise mostly been omitted in this proposal, given the limited space and detailed referencing being readily accessible via the selected references given. Furthermore, web links such as to the IPCC and its Assessment Reports (www.ipcc.ch) or to the Earth System Science Partnership and its related international programmes WCRP, IGBP, IHDP, and Diversitas (www.essp.org) provide convenient entry points to the full body of relevant scientific literature.

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- ThalesAleniaSpace, Torino, Italy (L. Bonino, S. Cesare); overall design advice; TAS-I - www.thalesaleniaspace.com
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- RUAG Space AB, Gothenburg, Sweden (M. Bonnedal, H. Fritz); AMOS payload (LMO) and AGSA payload advice; RUAG - www.ruag.com
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1. Cover Page

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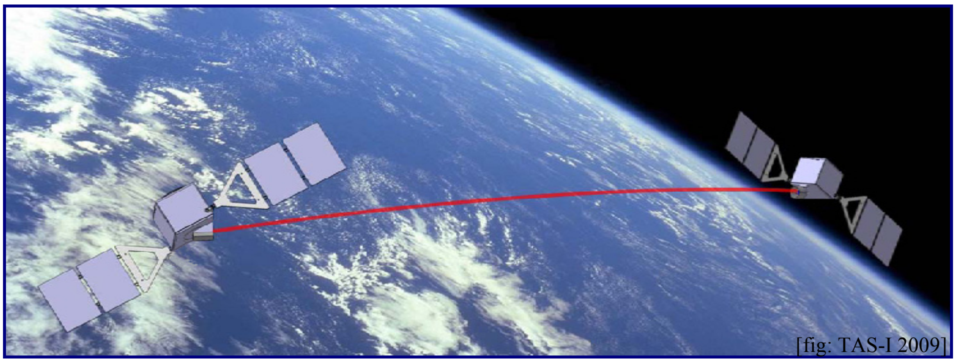

Proposal – May 2010

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2. Executive Summary

The Mission

The mission of **ACCURATE—climate benchmark profiling of greenhouse gases and thermodynamic variables and wind from space** is to initiate a novel fundamental atmospheric state dataset for climate and composition monitoring and research in the global free atmosphere using combined infrared-laser and microwave occultation between Low Earth Orbit (LEO) satellites.

The Need and the Scientific Objectives

Expanding the observational foundation for climate change studies by accurate, long-term, consistent benchmark data is a fundamental need of climate science (see, e.g., IPCC reports) and Earth observation from space is the key means to obtain such data globally (see, e.g., WMO/GCOS reports). **Current methods** of satellite remote sensing of Earth's free atmosphere (above boundary layer) do collectively enable global observations **of GCOS Essential Climate Variables**, including on thermodynamic state (temperature, pressure, humidity), dynamics (wind), and composition (ozone, carbon dioxide, methane, other greenhouse gases), but **are unable to provide them as consistent climate benchmark dataset**.

The latter requires joint sensitivity to all essential variables, measurement stability over decades and longer, high accuracy tied to international metrological standards and un-biased spatiotemporal sampling. Despite the demand and having GNSS radio occultation as a valuable starting point for refractivity, such **a fundamentally needed "full atmospheric state" method did not exist so far. ACCURATE furnishes this method** which enables to profile all variables noted above over the upper troposphere and lower stratosphere (UTLS, ~5-35 km) and beyond with ~1 km height resolution as consistent benchmark dataset. It combines LEO-to-LEO microwave occultation (LMO) for thermodynamic state profiling with LEO-to-LEO infrared-laser occultation (LIO) for greenhouse gas and line-of-sight wind profiling, jointly **referred to as LMIO method**, conceived late 2004 and pioneered in Europe.

Employing this unique method the **ACCURATE Scientific Objectives** aim at science contributions and demonstration in particular in the following fields (main ones listed, there are additional ones such as related to atmospheric composition forecasting and NWP):

- Pioneering **demonstration of the science value of the novel LMIO method** by providing ground-breaking contributions to:
- **Monitoring of climate variability and trends** in thermodynamic variables (T, p, q), greenhouse gases (H_2O, CO_2, CH_4, N_2O, O_3, CO; including CO_2, H_2O isotopes), and the wind field (meridional wind), and **diagnostics of UTLS** thermal, chemical, radiative, and dynamical **changes**, as initial part of long-term benchmark observations of climate in the atmosphere.
- **Testing of global climate, composition, and weather models**, and improvement of their physics and other processes parameterizations, such as related to energy balance or chemistry, to enhance their predictive skill for simulating future climate, composition, and weather.
- **Analysis of atmospheric processes in the UTLS** at high vertical resolution, in the context of atmospheric physics and chemistry research, and **provision of authoritative reference data for calibration and validation** of data from other space/airborne/ground observing systems.

The Mission Requirements

The basis for reaching the scientific objectives is the **accurate LMIO profiling of the "full atmospheric state" X** = (z, T, p/Z, q/H_2O, V_{los}, CO_2, $^{13}CO_2$, $C^{18}OO$, CH_4, N_2O, O_3, CO, HDO, $H_2{}^{18}O$), complemented by profiling of aerosol, cloud layering, and turbulence characteristics, where the symbols denoting the targeted fundamental atmospheric variables have their common meteorological and chemical meaning and where V_{los} is line-of-sight wind.

This atmospheric state needs to be profiled over the UTLS (and at best effort beyond) with **physical consistency** amongst all variables and essentially **independent of prior information** as well as with an **accuracy** (absolute, not just precision) of better than 0.1–1 % at 1–2 km height resolution for monthly-mean values of the variables. Individual profiles have to be of adequate accuracy (typically better than 1–10 %) to achieve this, including that they come with accurate **height knowledge** (in absolute WGS84 frame) of better than 10–20 m.

In terms of horizontal resolution, this performance is required for large-scale regions (~3000 km scale for monthly means from this first pioneering LMIO mission), with **regular global coverage** and full **local time coverage within single seasons** as well as preferably with a fixed coverage repeat pattern to facilitate validation and reference data provision.

Furthermore, establishing and maintaining **traceability of the data to fundamental metrological (SI) standards** – essentially time and frequency standards – is a key requirement to ensure that the above demanding accuracy requirements are demonstrably met. Based on this the data can then serve as **authoritative reference** standard for the large-scale evolution of the above "full atmospheric state" **X** in the global free atmosphere, **for the benefit of all** other atmospheric data, and of atmospheric climate, composition and weather models, **which can "anchor" to this reference state** like so far only to special ground station networks.

The Mission Implementation Concept

In order to fulfill the mission requirements the main elements of the mission include:

Observation Techniques.
The **LMIO** method = combined microwave (MW) and infrared-laser (IR laser) occultation between LEO satellites **= LMO+LIO**: Carefully chosen and simultaneously transmitted MW signals and IR laser signals, used in LEO transmitter (Tx) to LEO receiver (Rx) cross-link mode, powerfully join to collect atmospheric information from refraction and absorption along closely aligned MW and IR signal travel paths to yield state **X** with required quality.

Instrument Concepts.
LMO: MW transmitter and receiver for **3 signals in K-band/17-23 GHz** (17.25, 20.2, 22.6 GHz; 22 GHz water vapor absorption line), phase and amplitude profiles for thermodyn. state.

LIO: IR laser transmitter and receiver for **21 signals in SWIR/2-2.5 μm** (frequencies at GHG and "off" reference lines), pulse and background intensity profiles for GHGs and wind.
Plus complementary **GPS NAV** receiver for timing, navigation, and POD for Tx and Rx.

Architecture and Elements.
Tx and Rx spacecraft in counter-rotating ~80°-inclination orbits (local time drifting) at 500–600 km with 15-day repeat pattern, carrying the **LMO+LIO Tx resp. Rx and NAV payload**; single **dual launch (Vega)** with 1-yr drifting phase to final orbits; S-band downlink to **GS Kiruna**; mission operations and control **ESOC**; processing and archiving **ESRIN**; **Science Centers** value-added products; **Science Team/AO** addressing all science objectives.

3. Scientific Objectives, Requirements and Justification

3.1 Mission Objectives and Scientific Rationale

The objectives of the proposed ACCURATE Earth Explorer Opportunity Mission EE-8 are based on two main existing pillars of formulating and justifying them: 1) on the original ACCURATE proposal for an Earth Explorer Core Mission, ACCU (2005), which received very positive evaluation in 2006 and was shortlisted but at that time somewhat immature and thus recommended for further initial studies and developments (ESAC, 2006; also attached as Annex A), and 2) on the results of the subsequent studies and developments on ACCURATE since 2006 that matured the concept, where in particular ACCU (2009) and ACCU (2010) summarize science objectives and impacts and where ACTLIMB (2009) and ACCUPHD (2010) include detailed reviews and justification.

The fundamental range of objectives and their rationale is thus still as proposed in ACCU (2005) and evaluated in ESAC (2006) but several advancements and consolidations were achieved since then. These include the new account for the fact that also line-of-sight wind profiles are available simultaneously with the thermodynamic and trace species profiles but also that the present ACCURATE EE-8 proposal focuses on a first demonstration of this novel and unique occultation measurements concept, with smaller total number of profiles from a two-satellite constellation compatible with the strict EE-8 boundary conditions but still with full fledged capabilities from each occultation event and decent overall coverage.

Based on successful demonstration by this first and pioneering mission, any follow-on readily and cost-effectively could expand to beyond 500 “full atmospheric state” profiles per day operationally, like the current MetOp/GRAS GPS radio occultation mission delivers for refractivity-only sounding. ACCURATE strongly fulfills both science *and* demonstration objectives as formulated in ESACALL (2009): “These missions are intended to be used to conduct research in the field of Earth Observation and/or to demonstrate the potential of new innovative Earth Observation techniques of relevance to both the scientific and the application communities.” It is thus genuinely fitting for EE-8 as the following sections describe.

3.1.1 The Need and Science and Demonstration Objectives Overview

Expanding the observational foundation for climate change studies by accurate, long-term, consistent benchmark data is a fundamental need of climate science (see, e.g., IPCC reports) and Earth observation from space is the key means to obtain such data globally (see, e.g., WMO/GCOS reports). Current methods of satellite remote sensing of Earth’s free atmosphere (above boundary layer) do collectively enable the global observation of GCOS Essential Climate Variables (ACCU, 2009), including on thermodynamic state (temperature, pressure, humidity), dynamics (wind), and composition (ozone, carbon dioxide, methane, other greenhouse gases), but are unable to provide them as consistent climate benchmark dataset.

The latter requires joint sensitivity to all essential variables, measurement stability over decades and longer, high accuracy tied to international metrological standards and un-biased spatiotemporal sampling. Despite the demand and having GNSS radio occultation as a valuable starting point for refractivity sounding, such a fundamentally needed “full atmospheric state” method did not exist so far. ACCURATE furnishes this method and profiles all variables noted above over the upper troposphere and lower stratosphere (~5-35 km) and beyond with ~1 km height resolution as consistent benchmark dataset.

Section 4 describes the method that is founded on the occultation measurement principle (OPAC, 2004a), applied between satellites in low Earth orbit (LEO), and combines LEO-to-LEO microwave occultation (LMO) for thermodynamic state profiling (heritage from ACE+; e.g., OPAC, 2004b), with LEO-to-LEO IR laser occultation (LIO) for greenhouse gas and line-of-sight wind profiling (e.g., ACCUPHD, 2010), both jointly referred to as LMO+LIO or just LMIO technique.

Among further potential the LMIO method enables to rigorously monitor how greenhouse gas and climatic changes evolve from monthly to decadal scales and it can serve as independent observational constraint for model testing, re-analyses and forecasting, and anthropogenic change detection and attribution. Based on this the ACCURATE science and demonstration mission objectives are tailored to enable advances, new insights and demonstration in particular in the following four fields:

- Pioneering demonstration of the novel LMIO technique and of its science value to:
- monitor and diagnose climate and chemical variability and change as a benchmark
- test and validate climate models and contribute to improve their parameterizations
- analyze atmospheric processes in the UTLS and serve as reference for other data

Beyond these focus fields there are several other fields to which ACCURATE will strongly contribute, such as weather analysis and numerical weather prediction as well as analysis and prediction of atmospheric composition and chemistry.

The mission objectives are categorized into three classes: primary, secondary, and spin-off benefits, respectively, where the primary objectives 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 ACCURATE 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 explained with brief justification, in subsections 3.1.2 to 3.1.4. Subsection 3.1.5 finally provides a summary of the unique set of properties of the ACCURATE LMIO technique, on which the value of all its atmosphere and climate science contributions will rest.

3.1.2 Primary Mission Objectives and Rationale

Primary objectives of ACCURATE are:

1) Demonstration of the science value of the novel combined LEO-LEO microwave occultation and LEO-LEO infrared laser occultation technique (LMIO) by providing, via an initial multi-year set of ACCURATE atmospheric state data, essential contributions to the following objectives:

2) Monitoring of climate variability and trends in thermodynamic variables (temperature, pressure, humidity), in greenhouse gases (H_2O, CO_2, CH_4, N_2O, O_3, CO) including CO_2 and H_2O isotopes, and in the wind field (meridional wind), and diagnostics of UTLS thermal, chemical, radiative, and dynamical changes, as an initial key component of long-term benchmark observations of climate in the atmosphere;

Contribution to detection and attribution of anthropogenic and natural climate and composition changes in the atmosphere, as well as of changes in the global carbon and water cycles, and support of climate change predictions via global reference data of climate benchmark quality;

Improvement of the understanding of climate forcing variations (e.g., greenhouse gases and aerosol) and of climate feedbacks determining magnitude and characteristics of climate changes, especially related to the carbon and water cycles and to climate-chemistry interactions;

3) Testing of global climate models (GCMs) and improvement of their physics and chemistry parameterizations, such as related to radiation and energy balance, to enhance their predictive skill for simulating future climate and chemical composition;

   Validation of GCM runs, in simulated mean climate and climate variability seen in atmospheric physics/chemistry/radiation variables in the UTLS region;

4) Study of atmospheric processes in the UTLS region at high vertical resolution, in the context of atmospheric physics and chemistry research, including aerosol, cloud, and dynamical variability studies;

   Provision of reference data for the calibration, validation, and analysis of data from other space missions or airborne/ground-based observing systems.

As the objectives show, the ACCURATE mission is primarily driven by being a pioneering demonstration of science utility for climate research, but also UTLS process studies and methodological objectives reaching beyond climate (e.g., model validation and improvement will also benefit NWP and chemistry modeling) are important.

The basis for reaching the objectives is the accurate LMIO profiling of the "full atmospheric state" vector $\mathbf{X} = (z, T, p/\mathrm{Z}, q/\mathrm{H_2O}, V_{\mathrm{los}}, \mathrm{CO_2}, {}^{13}\mathrm{CO_2}, \mathrm{C^{18}OO}, \mathrm{CH_4}, \mathrm{N_2O}, \mathrm{O_3}, \mathrm{CO}, \mathrm{HDO}, \mathrm{H_2{}^{18}O})$, where V_{los} is line-of-sight wind, together with profiling of aerosol, cloud layering, and turbulence characteristics. Amongst this rich set of observations, to highlight one favorable property as an example, humidity measurements are of special importance due to the prominent role of water vapor both in radiative processes and in the hydrological cycle (as described in detail in ESA, 2004a). It will thus be highly valuable that ACCURATE will provide both complementarity and redundancy in humidity measurements of the LMO system (measuring it in the upper troposphere up to about 12 km, including through clouds) and the LIO system (measuring it over the full UTLS domain outside clouds), respectively. The redundancy will allow cross-validation of the independent but simultaneous and co-located humidity measurements, which will also be a useful cross-check of the spectroscopy in the K band and SWIR band.

The objectives shall be achieved based on preparing, with utmost care on accuracy, consistency, and repeatability, primary profiles and aggregated climatological fields of all measured parameters and derived parameters of interest. These profiles and aggregated fields will be produced essentially independent of model information or other background data (as independent as possible), which is a core strength of the occultation measurement principle leading to an essentially well-posed inversion problem (above the lower troposphere). The ACCURATE data prepared this way as a climate benchmark dataset will serve as an unique observational basis for addressing the objectives.

ACCURATE will significantly improve our understanding of the climate system of the Earth. The data obtained from the LMIO profiling have several advantages compared to existing techniques. 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, ACCURATE measurements can improve data assimilation bias correction schemes.

The atmospheric chemistry and physics studies in the UTLS will specifically exploit the high vertical resolution and accuracy of the ACCURATE data, and the unique availability of the CO_2 and H_2O isotope profiles together with the other trace species. ACCURATE can play a vital role for example in the investigation of the interaction of chemistry and climate in the tropopause region, a region which is crucial for better understanding of the interrelation of climate changes and ozone chemistry and stratosphere-troposphere exchange of trace gases.

ACCURATE will provide the first simultaneous measurements of H_2O, CO_2, and their rare isotopes along with high-resolution thermodynamic profiles with global coverage. This combination will provide valuable insight into changing transport of water and air from the troposphere into the stratosphere. The seasonal cycle in CO_2 provides a clock measuring transport rates into the stratosphere and for example the $\delta^{18}O$ isotopic ratio from the ACCURATE CO_2 and $C^{18}OO$ data provides highly useful information on ozone chemistry. This works because O_3 isotope anomalies, carrying information on atmospheric processes, leave a clear mark in the $\delta^{18}O$ ratio of CO_2. High accuracy tropopause temperature and H_2O measurements combined with global coverage allow identification of regions where air entering the stratosphere is being actively dehydrated.

The global coverage of upper troposphere water vapor isotopic composition will be a valuable complement to the still higher-resolution but sparse in-situ observations of HDO and $H_2{}^{18}O$ that have recently become possible. Aircraft observations can provide snapshots of the processes that bring H_2O to the stratosphere, but only by observing the distribution of these processes globally can we determine their relative importance to the global water budget. The profiles provided by ACCURATE will be important constraints to understanding how H_2O is brought to the stratosphere, and how that transport may change under a future warmer climate. As another example, the ACCURATE data can contribute to our understanding of tropical UTLS water vapor and clouds and how they affect the radiation budget.

Support in calibration, validation and analysis of concurrent space missions is also an important objective and during the time of ACCURATE a series of space missions, European and non-European, can sensibly exploit this type of synergy. ACCURATE can, in particular, provide invaluable reference data for the validation of such missions, but also to airborne and ground-based systems, due to the accuracy, consistency and long-term stability of the data.

Overall ACCURATE will, in line with the priorities of ESA’s Living Planet Programme (ESALP, 2006) and with WMO/GCOS/GAW priorities (ACCU, 2009), provide cornerstone contributions to the climate and chemistry theme and also vital contributions to the global water cycle and global carbon cycle priorities.

3.1.3 Secondary Mission Objectives and Rationale

Secondary objectives of ACCURATE are:

- Contribution to improved forecasting and analysis of weather conditions, including in thermodynamic, wind and cloud/precipitation variables, by numerical weather prediction (NWP) and data assimilation systems; in particular also by testing of NWP models and improvement of their process formulations, in order to enhance their weather forecasting skill;

- Contribution to improved forecasting and analysis of atmospheric composition, including greenhouse gases and aerosols, by atmospheric constituent model and data assimilation systems; in particular also by testing of constituent models and improvement of their process formulations, in order to enhance their composition forecasting skill.

ACCURATE will provide an accurate and rich data set, with particular strength in the UTLS, which can be used in NWP data assimilation systems as well as data assimilation and forecast systems for atmospheric composition (and climate), such as currently prepared in the European Project MACC that lead-prepares the atmospheric service of the GMES programme (www.gmes-atmosphere.eu).

Also, the atmospheric model improvement work in GCMs will at the same time benefit NWP and composition forecasting models. The other way round, advances in NWP and composition forecasting will feed back to benefit climate studies, because the atmospheric analyses, a routine by-product of these prediction systems, are very valuable also for climate purposes, in particular the re-analyses (consistent analysis sequences over decades).

3.1.4 Spin-off Benefits of the Mission

Spin-off benefits of ACCURATE are:

- Assessment and improvement of spectroscopy in the SWIR and K bands;
- Studies of turbulence in the troposphere and lower stratosphere.

Improved water vapor attenuation coefficients are important pieces of fundamental spectroscopic information in the K band as is improvement of spectroscopic parameters in the shortwave infrared (SWIR). The ACCURATE mission can potentially contribute in the K band via its LMO transmission measurements near the center and along the wing of the 22 GHz water vapor line. Complementarily, the SWIR data can potentially contribute related to the absorption lines selected for the laser occultation, and indirectly via water vapor cross-calibration also to the K band improvement. For the LIO it is important to improve before launch the line parameters of utilized absorption lines. It is thus very useful that modern methods of cavity-ringdown spectroscopy, which can employ the diode lasers used for the ACCURATE target lines as seed lasers (cf. section 5), are able to provide dedicated spectroscopy of target lines with accuracy at the 0.1 % level. Based on such focused spectroscopy ACCURATE's LMIO technique can establish absolute greenhouse gas concentration standards in the global free atmosphere without needing additional ground- or other cross-calibration.

Scattering by refractivity inhomogeneities caused by atmospheric turbulence will result in scintillation phenomena in ACCURATE LMIO data which, while accurately corrected for in the differential transmission data used as basis for trace species retrieval, will be visible in the direct transmission data. From these data, estimates of height variations of the scintillation power spectrum and of the refractive structure parameter are possible, which can be interpreted in terms of power spectrum and variance of refractive index 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. Also due to the hazardous effect of turbulence on aircraft, its global monitoring via ACCURATE will be of interest.

Though not in the ACCURATE focus, this type of benefits is still of very high scientific value to the respective fields.

3.1.5 Key Contributions to Science due to Unique Properties

The ACCURATE mission can provide key contributions to the science and application areas addressed by the above mission objectives mainly due to the following unique set of properties:

- High absolute accuracy and long-term stability of all thermodynamic variable, wind, and trace species profiles due to intrinsic self-calibration of the LMIO data, which are Doppler shift (time standard) and differential transmission (spectrally differenced normalized intensity) data,
- Simultaneous LMO K band and LIO SWIR band measurements of nearly the same atmospheric volumes, including refracted signal propagation (due to close similarity of refractivity at 17–23 GHz and 2–2.5 μm), with vast synergy potential (e.g., using the LMO *T* and *p* measurements to accurately compute absorption cross sections for LIO species retrieval, and much more),
- Global and uniform coverage with LMIO profiles, over both oceans and land, with unique repeat pattern possible, facilitating validation for this first demonstration mission (cf. section 5),
- Unprecedented observational constraint on the UTLS chemistry and radiation balance from the LMIO profiling of the “full atmospheric state” vector $\mathbf{X} = (z, T, p/\mathrm{Z}, q/\mathrm{H_2O}, V_{\mathrm{los}}, \mathrm{CO_2}, {}^{13}\mathrm{CO_2}, \mathrm{C^{18}OO}, \mathrm{CH_4}, \mathrm{N_2O}, \mathrm{O_3}, \mathrm{CO}, \mathrm{HDO}, \mathrm{H_2{}^{18}O})$, and further aerosol-clouds-turbulence parameters,
- High vertical resolution (~1 km or better) of fine structures in the atmosphere such as around the tropopause and resolution of cloud layers from LIO transmission data down to order 100 m,
- Virtually all-weather capability due to long wavelengths (> 1 cm) of the LMO data, in particular also accurate humidity and temperature retrieval in presence of ice clouds in the upper troposphere by LMO, high synergy with cloud structure data and other data from LIO,
- All data coming with accurate and globally consistent geo-location intrinsic to the measurement system itself, in particular with accurate height knowledge (< 10 m uncertainty); this will, e.g., allow to locate (uppermost) cloud layer top *T* and *p* to order 10–100 m accuracy,
- Independent measurement of temperature, pressure, and humidity as function of height in the upper troposphere by the LMO, high synergy with complementary and redundant LIO data (including for validation and improvement of spectroscopy both in SWIR and K band),
- The data can be used as climate benchmark reference datasets and need not be inter-calibrated with follow-on and possibly non-overlapping LMIO missions.

A systematic assessment of scientific impacts of ACCURATE observation information to reach scientific objectives as addressed in the subsections 3.1.2 to 3.1.4 above has been done in ACCU (2010). It was concluded that ACCURATE can provide due to its unique properties an unprecedented climate benchmark dataset of the atmospheric thermodynamic, chemical, and dynamical state with high vertical resolution, accuracy, consistency, and long-term stability. However its information is also highly complementary in information content to other sources like advanced passive IR down-looking and chemistry limb-looking sounders; such aspects of synergy and complementarity are addressed in section 4.3.

3.2 Observational Requirements, Variables and Data Products

3.2.1 Observation Concept Overview

In order to set the scene for the discussion of observational requirements, targeted geophysical variables and data products in the following subsections, the overall observation concept of the ACCURATE LMIO method is illustrated in Figure 3.2-1. It provides for context a concise overview of the general characteristics and concept of the proposed ACCURATE LMIO observations.

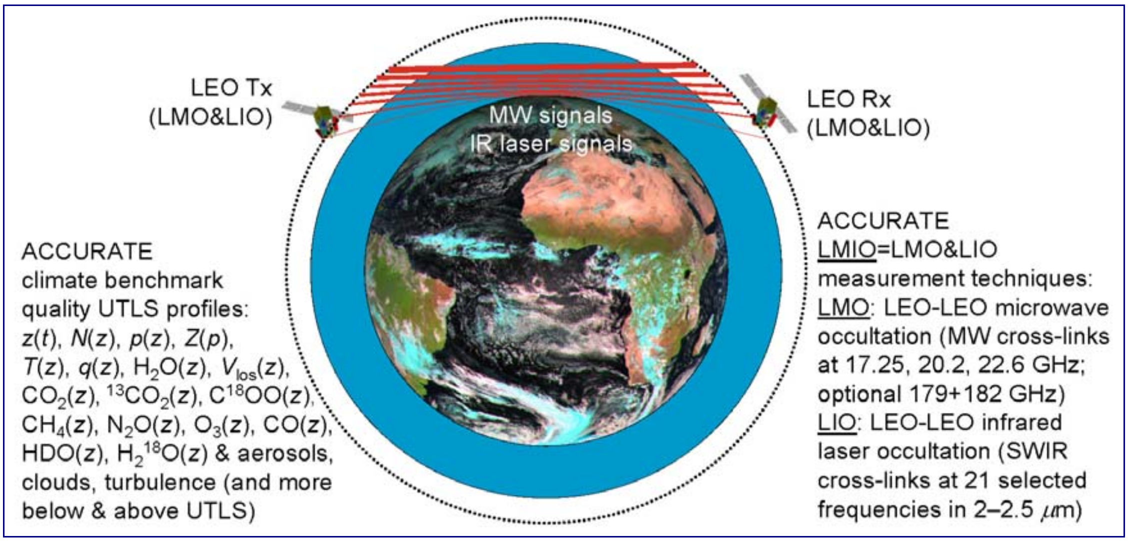

Figure 3.2-1: Schematic view of the LMIO measurement concept of ACCURATE, comprising the LMO and LIO components. The view is attached with sidebar information summarizing key information on measurement techniques and data products. Occultation events are quasi-vertical scans through the atmosphere, occurring due to the motions of the Tx and Rx satellites.

Based on the discussion of requirements on the observations and required variables and products (this section 3.2), and of algorithmic needs and performance (section 3.3) as well as scientific needs and relevance (sections 3.4 and 3.5) in the remainder of this section 3, detailed information on the observation techniques and technical requirements to meet these scientific requirements follows in section 4. Compared to ACCU (2005) the concept and requirements have been further substantially refined and matured, in particular in the LIO part, which becomes evident in the following description and also in section 4.

3.2.2 Observational Requirements and Relation to Other Missions

The observational requirements are given in Table 3.2-1 below. They are from ACCU (2009), which are consistent with the scientific objectives and WMO/GCOS/GAW recommendations discussed in section 3.1 above; more detailed discussion to this end is also contained in ACCU (2009). The proposed ACCURATE EE-8 is a “first demonstration” of the LMIO mission concept (cf. footnotes 1 and 3), where footnote 3 on horizontal sampling of such a pioneering demonstration has been extended from ACCU (2009) to also express the scientific user preference for fixed coverage repeat patterns clearly facilitating validation.

Table 3.2-1: ACCURATE LMIO observational requirements

		LMO				LIO				
		Temperature		Sp. Humidity		Trace Species[1]		l.o.s. Wind[2]		
Requirement		Target	Thres	Target	Thres	Target	Thres	Target	Thres	Units
Horizontal domain		global								
Horizontal sampling[3] (mean distance of adjacent profiles) to be achieved within:		900	1800	900	1800	900	1800	900	1800	[km]
time sampling[4]		12	24	12	24	12	24	12	24	[hrs]
No. of profiles per grid box per month[5]		40	30	40	30	40	30	40	30	
Vertical domain[6]		5-50	7-40	5-18[7]	7-12	5-35	7-30[8]	10-40	15-35	[km]
Vertical sampling	LT	0.5	1	0.5	1	0.5	1	0.5	1	[km]
	UT	0.5	1	0.5	1	0.5	1	0.5	1	[km]
	LS	0.5	1	0.5	1	0.5	1	0.5	1	[km]
	US	1	2.5	-	-	1	2.5	1	2.5	[km]
RMS accuracy[9]	LT	best-effort basis						-	-	Temp [K] Humi [%] Species [%] Wind [m/s]
	UT-bottom	1	2	10	20	4 (2)	10 (3)	best-effort basis		
	UT-≥10km	0.5	1	10	20	4 (2)	10 (3)	2	5	
	LS	0.5	1	10	-	4 (2)	10 (3)	2	5	
	US	1.5	3	-	-	best-effort basis		3	-	
Long-term stability (per decade)		0.1	0.15	2	3	0.5	1	0.5	1	
		[K/dec]		[%RH[10]/dec]		[%/dec]		[(m/s)/dec]		
Timeliness	Climate	7	14	7	14	7	14	7	14	[days]
	NWP[11]	1.5	3	1.5	3	1.5	3	1.5	3	[hrs]
Time domain[12]		> 3								[years]

[1] Trace species to include the ten gases H_2O, CO_2, $^{13}CO_2$, $C^{18}OO$, CH_4, N_2O, O_3, CO, HDO, $H_2{}^{18}O$; the latter up to four gases optional in a first demonstration of the novel method if only a reduced number of IR laser channels is affordable.

[2] Line-of-sight (l.o.s.) wind measurements shall focus on the meridional wind component ("Brewer-Dobson circulation").

[3] Horiz. sampling may be up to a factor of 2 coarser in a first demonstration mission if max. two satellites are affordable; in this case fixed repeat pattern of occultation event locations preferred (e.g., revisit of target locations 1-3 times per month within < 100 km (target) / < 300 km (threshold) during the mission lifetime), for facilitating ground-based/balloon-borne/airborne validation.

[4] Time sampling shall also sample over all local times within as small as possible UTC time period (e.g., within a season) or, alternatively, sample near fixed local time (in this case alignment with MetOp 9:30/21:30 orbit nodes preferred).

[5] No. of profiles to be fulfilled in global average by all grid boxes but also any individual grid box shall receive at least 80% of this number. Grid box is here defined as square of the horizontal sampling requirement (box of size Horiz. sampling [km] × Horiz. sampling [km]) or any box of equivalent size with at least 500 km length of its smaller dimension.

[6] Vertical domain to be sampled for adequate climate benchmark profiles retrieval capability with a horizontal displacement of the occultation tangent point location from 60 km to 3 km height of < 60 km (target) / < 120 km (threshold), and within an occultation event duration within 60 km to 3 km height of < 1 min (target) / < 5 min (threshold).

[7] Meeting the target upper boundary requirement implies full coverage of high-reaching convective cloud systems, up to and including the tropical tropopause (16-17 km), with LMO humidity measurements within and through such clouds.

[8] For the trace gas O_3 / CO, the concentration of which strongly decreases below / above about 15 km, the threshold lower / upper boundary requirement shall be 10 km / 20 km. Regarding the H_2O isotopes (HDO, $H_2{}^{18}O$), for which the sensitivity focus is the UT, these shall be retrieved within required accuracy over the best possible height range up to 12 km.

9) Understood to be the accuracy for an individual occultation event over the required vertical domain at a vertical resolution consistent with the required sampling (i.e., a resolution of 2 x Vertical sampling [km]). The LMO temperature accuracy requirements shall be understood to decrease linearly from the UT-bottom = 5 km value until they reach the UT-≥10km value at 10 km; above, the height dependence shall be constant over the UTLS. The LMO humidity accuracy threshold requirement shall be understood to apply to global statistics over all latitudes (i.e., data from very dry regions may exceed this fractional accuracy). The LIO trace species CO_2 and its isotopes $^{13}CO_2$ and $C^{18}OO$ shall fulfill the more stringent accuracy requirements given in parentheses. All LIO accuracy requirements apply to clear-air measurements; cloud-perturbed vertical levels shall be flagged (e.g., via a co-retrieved cloud layering profile) and accuracies at these levels shall be as good as possible on a best-effort basis.

10) For LMO humidity measurements, stability is specified in terms of relative humidity (RH), a quantity with well-defined linear range over the vertical domain. There are standard formulae to convert between RH and specific humidity as functions of temperature and pressure.

11) Supporting NWP is a secondary but still relevant objective; its requirements shall thus be fulfilled on a best effort basis for a significant fraction (> 50 %) of the data.

12) Climate monitoring and research prefer long-term observations over many years and decades; the pioneering ACCURATE mission should thus be followed by similar missions. The ACCURATE mission objectives themselves, however, can be fulfilled within the given mission duration time frame (3 years or more).

The ACCURATE mission assumptions and technical requirements in section 4 will be specified to be consistent with these observational requirements, the fulfillment of which allows to meet the scientific objectives and to achieve unique scientific impact as analyzed in ACCU (2010). As shown in ACCU (2010) the proposed mission is an excellent model for a first cost-effective demonstration of the LMIO concept, since within its factor-of-2 coarser horizontal resolution also such a pioneering Earth Explorer Opportunity Mission is already capable to fully address the scientific objectives laid out in section 3.1.

Regarding relation to respectively dependence on other missions, the ACCURATE mission has no dependence on any other mission. In this sense no mandatory timing or other relation requirements apply. There is high synergy and complementarity with many other upcoming or planned missions, however, where overlap in mission duration would be of mutual benefit. An example of operational missions with good synergy is the MetOp satellite series, which is scheduled to cover the time up to 2020 and overlap is expected. An ESA example would be the EarthCARE mission, the cloud, aerosol and radiation measurements of which would be an interesting complement to the geophysical data available from this mission.

In the view of the proposing Science Team and also of ESAC (2006) such a pioneering LMIO mission is highly timely (see also section 3.4.4) and ACCURATE should therefore be realized as soon as possible to operate within the planned EE-8 compliant period 2018-2022.

3.2.3 Targeted Geophysical Variables

The geophysical variables targeted by ACCURATE, consistent with the observational requirements of Table 3.2-1 above, are given in Table 3.2-2 below. Table 3.2-2 provides a convenient summary with focus on the list of geophysical variables together with their required altitude ranges, complementary to Table 3.2-1. The “grey box” domains symbolize the core altitude domains of interest, clearly showing that ACCURATE mainly targets the UTLS region, but extends (mostly on a best-effort basis) also beyond. As section 3.3 below shows, the LMIO method is based on exploiting the fundamental synergy between LMO and LIO in that the LMO variables retrieved first provide a strong and consistent thermodynamic state constraint for retrieving the LIO variables (and there is further synergy, see section 3.3).

Table 3.2-2: ACCURATE geophysical variables from LMO and LIO data

	Target Variables	Vertical Domain				Target [km]	Threshold [km]
		LT	UT	LS	US		
LMO	refractivity	b.e.	×	×	×	5-50	7-40
	pressure	b.e.	×	×	×	5-50	7-40
	geopotential height	b.e.	×	×	×	5-50	7-40
	temperature	b.e.	×	×	×	5-50	7-40
	humidity	b.e.	×	b.e.		5-18	7-12
	(cloud liquid water)	b.e.	×			5-10	b.e.
	(turbulence strength)	b.e.	×	b.e.		5-15	b.e.
LIO	H_2O	b.e.	×	×	b.e.	5-35	7-30
	CO_2	b.e.	×	×	b.e.	5-35	7-30
	$^{13}CO_2$	b.e.	×	×	b.e.	5-35	7-30
	$C^{18}OO$	b.e.	×	×	b.e.	5-35	7-30
	CH_4	b.e.	×	×		5-35	7-30
	N_2O	b.e.	×	×		5-35	7-30
	O_3		×	×	b.e.	5-35	10-30
	CO	b.e.	×	×		5-35	7-20
	HDO	b.e.	×			5-12	b.e.
	$H_2{}^{18}O$	b.e.	×			5-12	b.e.
	l.o.s. wind		×	×	b.e.	10-40	15-35
	(cloud layering)	b.e.	×	×		5-35	7-18
	(aerosol extinction)	b.e.	×	×		5-35	b.e.
	(turbulence strength)	b.e.	×	×	b.e.	5-35	b.e.

Following WMO definition of vertical domain (height ranges):
LT … Lower Troposphere (TBL ~2 km to 5 km)
UT … Upper Troposphere (5 km to 15 km)
LS … Lower Stratosphere (15 km to 35 km)
US … Upper Stratosphere (35 km to 50 km)

The "Target [km]" and "Threshold [km]" columns denote the target / threshold vertical domain ranges

b.e.: "best effort", i.e., retrieved on a best-effort basis in a height range

l.o.s. wind: line-of-sight wind, i.e., the wind along the occultation ray paths that should be based on polar or near-polar orbits to access in particular meridional wind (focus on Brewer-Dobson circulation)

Parameters in parentheses: By-products, not parameters of primary interest. The two water isotopes HDO and $H_2{}^{18}O$ are not in parentheses since they are core products but they are parameters of secondary interest and therefore have no explicit threshold domain specified (see also footnote 8 of Table 3.2.1 above). If only a reduced number of LIO measurement channels is affordable in a first demonstration mission, these two isotopes, and CO and O_3 if even more reduction needed, are optional (see also footnote 1 of Table 3.2-1 above).

3.2.4 Level 1 and Level 2 Data Products

The ACCURATE Level 1 and Level 2 data products are summarized in Table 3.2-3 below, where the Level 1 products are divided suitably into Level 1a and Level 1b as from ACE+ heritage (ESA, 2004a;b). The data products are categorized following the CEOS (Committee on Earth Observation Satellites; www.ceos.org) definitions, whereby at this point the focus is in line with ESACALL (2009) on the geophysical profile levels only. Levels 0 data are addressed in the technical section 5.4 (on mission ground segment incl. data processing) and higher level data (level 3 etc., such as derived two- or three-dimensional temperature or trace species fields) are discussed in section 3.3.2 (on the data evaluation and exploitation approach).

Table 3.2-3: ACCURATE LMIO Level 1 and Level 2 data products

Level	**Key data and products**	
	LMO	**LIO**
Level 1a	(all profiles as function of time) • LEO Tx and LEO Rx precise orbit data (based on navigation receivers at Tx and Rx)	
	• Excess phase data (at all MW freq.) • Amplitude data (at all MW freq.)	• Tx pulse signal frequency and intensity data (at all IR freq.) • Rx pulse and background signal intensity data (at all IR freq.)
Level 1b	• Doppler shift and Raw **Transmission**(1) profiles (at all MW freq.) vs. time • Transmission profiles (at all MW freq.) vs. impact parameter • **Bending angle**(1) profiles vs. impact parameter	• Raw **Transmission**(1) profiles (at all IR freq.) vs. time • Transmission profiles (at all IR freq.) vs. impact parameter • Target species transmission profiles (at all absorption channel freq.) and Wind delta-transmission profiles (of wind channel freq. pair) vs. impact parameter
Level 2	(all profiles as function of altitude)	
	• Refractivity profiles • Differential absorption coefficient profiles (at all MW freq. pairs) • **Sp. Humidity**(2) profiles • **Temperature**(2) profiles • Pressure and Geopot. Height profiles	• Target species absorption coefficient profiles (at all absorption channel freq.) • **Trace Species**(2) profiles (of all required species according to Obs. Requirements) • **l.o.s. Wind**(2) profiles
	Error estimates and meta-data for all retrieved Level 1b and Level 2 profiles	
(by-products)	• Cloud liquid water profiles • Turbulence strength profiles (MW)	• Cloud layering profiles • Aerosol extinction profiles • Turbulence strength profiles (IR)

(1) driving parameter for main system requirements (see section 4.2.2). The "Raw Transmission" is the normalized received power ($Tr = I/I_0$) including defocusing and absorption, whilst the "Transmission" is understood to include absorption only (*Transmission* = 1 – *Absorption*).

(2) driving parameter for observational requirements (see Table 3.2-1 above). Specific humidity and temperature can also be determined within clouds (temperature in severe scintillation/cloudiness conditions by extrapolating from above cloud top into clouds), trace species and l.o.s. wind outside clouds and on a best effort basis through intermittent cloud layering (see also footnote 9 of Table 3.2-1 above).

The Level 2 data products that are driving for fulfilling the observational requirements, and the Level 1b ones driving the system requirements (which have been determined from retrieval performance analyses to be consistent with the observational requirements) are highlighted. They have been selected carefully in the way so that if they do fulfill the specified requirements all other Level 1b and Level 2 data products are of the needed quality as well to contribute to meet the science and demonstration objectives laid out in section 3.1.

Further refinement of the data products definition, as well as of the observational requirements and targeted variables may be done during Phase A.

3.3 Retrieval Algorithms and Data Evaluation Approach

3.3.1 Algorithms Development and Retrieval Performance Overview

A recent detailed description of the current status (at the time of this proposal preparation) of the ACCURATE LMIO algorithm developments, including performance estimation results, has been provided by LMOPAP (2010) on LMO and by ACCUPHD (2010) on the joint LMIO with focus LIO. The relevant work was performed since the ESAC (2006) evaluation within various ESA studies 2007-2010 (especially in projects called ACTLIMB and IRDAS) as well as several national projects 2006-2010 (especially in the Austrian Space Applications Programme, in projects called ACCURAID, EOPSCLIM, ACCU-Clouds).

Two main tools have been advanced resp. developed and used for the purpose: the End-to-end Generic Occultation Performance Simulation and Processing System EGOPS (EGOPS, 2009) for LMO+LIO and the ACCURATE LIO Performance Simulator ALPS (ALPS, 2010) as a fast and simplified complement to EGOPS for LIO, respectively.

The status of EGOPS is that this system (in its LIO-extended version xEGOPS) has meanwhile implemented end-to-end performance simulation capabilities for all target geophysical variables of Table 3.2-2 except retrieval of the by-products which received no focused attention so far. It simulates based on forward modeling and observation system modeling, including instrumental errors, quasi-realistic Level 1a profiles (see Table 3.2-3). From these, Level 1b and Level 2 profiles (see also Table 3.2-3) are then retrieved and compared to the co-located “true” profiles from the atmospheric model used in the forward modeling in order to assess the retrieval performance (typical atmospheres used range from simple FASCODE atmospheres to high-resolution ECMWF analysis and short-range forecast fields).
Regarding specifically LMIO retrieval development status, EGOPS is able to treat LMO retrieval quasi-realistic in all atmospheric conditions (basis from ACE+ heritage, further consolidated), LIO trace species retrieval quasi-realistic in all conditions except atmospheres with intermittent cloud layering (finished by end 2010), and LIO l.o.s. wind retrieval in a simplified “smooth wind conditions” way (a project proposal is currently in review aiming to upgrade this as of begin 2011 to quasi-realistic l.o.s. wind profiling).

The status of ALPS is that it can estimate performance aspects of the LIO technique in that it starts with quasi-realistic transmission profiles for all IR frequencies from the RFM/HITRAN/FASCODEAtm system (www-atm.physics.ox.ac.uk/RFM; www.harvard.edu/HITRAN) based on which it can model atmospheric losses, link budget, observation system errors, and finally signal-to-noise ratio (SNR) profiles at the receiver. From this retrieval error propagation modeling provides error estimates for trace species and l.o.s. wind profiles in a simplified yet adequate manner, as comparison to EGOPS simulations confirmed.
ALPS is scheduled to be expanded as of later in 2010 to cope with simulations and retrieval processing of a ground-based IR laser occultation demonstration experiment for H_2O, CO_2, CH_4 and l.o.s. wind retrieval at the Canary Islands (under a recently started ESA study called IRDAS-EXP and a complementary national project currently in review).

The respective LMO+LIO retrieval scheme of EGOPS is illustrated in Figure 3.3-1 below at up-to-date status. The LMO retrieval (left) is run first to provide the profiles of altitude and thermodynamic state $\mathbf{X}_{z,TD} = (z; T, p, q)$ based on which the trace species (“GHGs, Isotopes”) and l.o.s. wind profiles $\mathbf{X}_{\mathrm{GHGs,V}}$ = (H_2O, CO_2, $^{13}CO_2$, $C^{18}OO$, CH_4, N_2O, O_3, CO, HDO, $H_2{}^{18}O$; V_{los}) are retrieved from LIO data and aided by the LMO results (right).

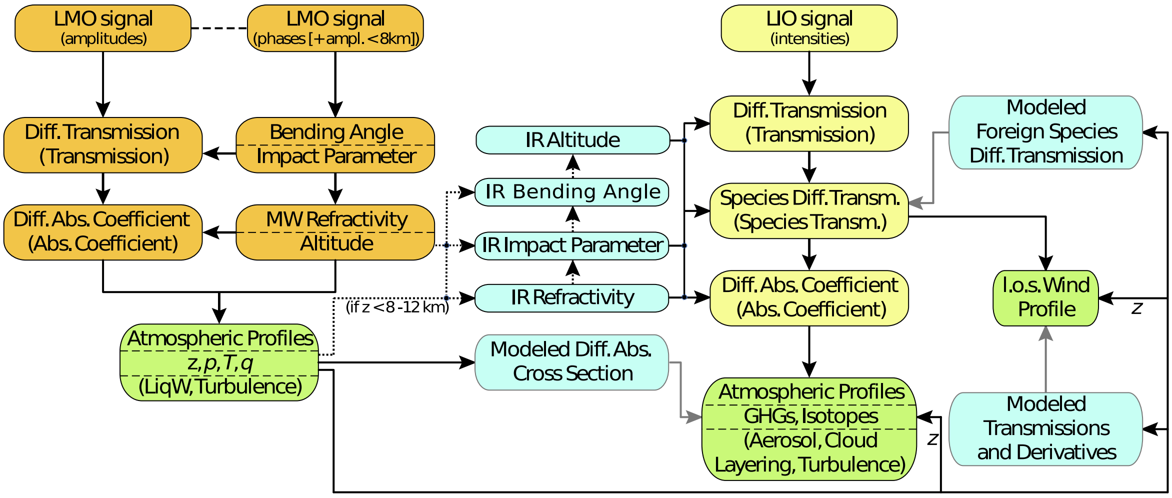

Figure 3.3-1: LMIO Level 1a to Level 2 retrieval processing chain in EGOPS.

The key that constitutes the power and uniqueness of the LMIO method and this retrieval scheme is, while it may look complicated at first glance, that it is in essence composed of fairly simple linear transforms and that there is negligible dependence of the finally retrieved profiles on any prior information other than for “upper boundary initialization” at high altitudes (where the influence quickly decays downwards, faster than for GNSS radio occultation since ionospheric errors are negligible for LMIO). Also all potential residual systematic errors like LIO foreign species effects at target species absorption frequencies are small enough to safely mitigate them by co-modeling and compensating them to negligible levels.

Figure 3.3-2 below illustrates performance estimates for all targeted geophysical variables, those for the LIO parameters derived by ALPS and those for the thermodynamic parameters by EGOPS, respectively. The estimates shown from ALPS have also been compared with EGOPS LIO retrievals and found consistent, confirming that also quasi-realistic LIO simulations lead to very similar results (so far small ensembles of EGOPS LIO retrievals only since this capability was very recently finished within the ESA ACTLIMB project, but sufficient to ensure and verify the basic adequacy of the ALPS estimates).

Figure 3.3-2 shows that ACCURATE, when fulfilling its system requirements (section 4.2) which in fact have been quantified based on such performance simulations, can deliver its atmospheric profiles well within observational requirements, in most cases within target requirements, which are set to outperform any existing instruments that target the same parameters. These encouraging results underline the potential of the ACCURATE LMIO method to provide benchmark measurements of unprecedented quality for addressing the climate, chemistry and other science objectives laid out in section 3.1.

Further advancements on retrieval algorithms and performance estimates, also to further consolidate the link quantifying the system requirements from such Level 1a/1b to Level 2 retrievals that fulfill the observational requirements, can be done during Phase A.

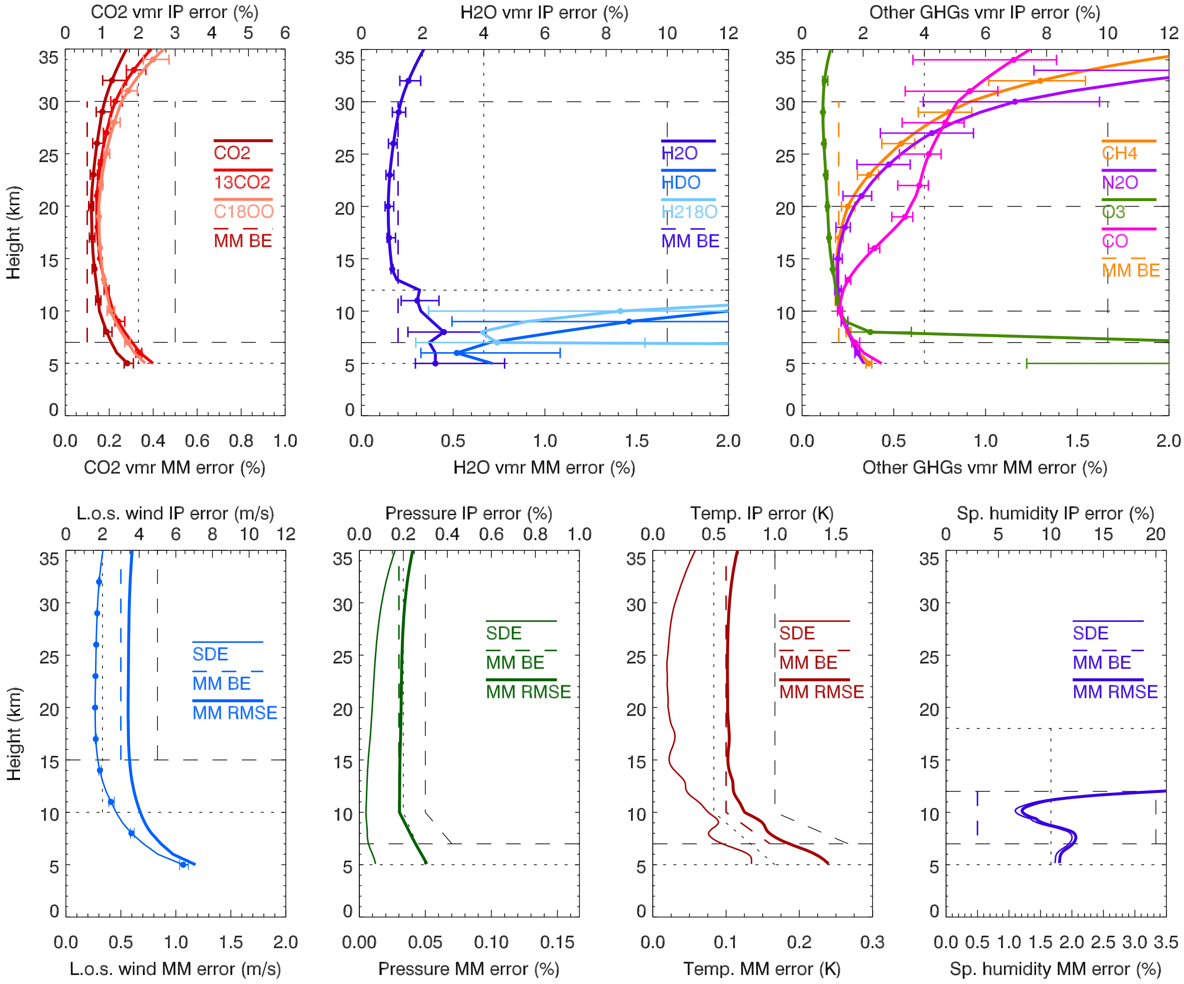

Figure 3.3-2: ACCURATE retrieval performance estimated for the trace species CO_2 and isotopes (upper left), H_2O and isotopes (upper middle), and other GHGs (upper right) as well as for l.o.s. wind (lower left) and the thermodynamic parameters pressure (lower mid-left), temperature (lower mid-right), and specific humidity (lower right). The upper axis of each panel quantifies the individual profile (IP) retrieval error, while the lower axis quantifies the monthly mean (MM) error, the latter estimated by assuming 36 profiles averaged per grid box per month, consistent with the respective observational requirements (Table 3.2-1), which reduces the statistical error by a factor of 6. That is all "MM" quantities relate to the lower axis only, while all non-MM quantities also relate to the upper axis to see the IP error there in addition to the MM error below. The vertical and horizontal dotted / dashed black lines mark the target / threshold requirements for accuracy and height domain according to Table 3.2-1 and the colored vertical dashed lines mark the monthly mean bias estimate (MM BE) upper bounds as estimated by ACCU (2010). The upper panels for the GHGs show these MM BEs in comparison with the statistical GHG retrieval error estimates while the lower panels for l.o.s. wind and the thermodynamic parameters show them together with the statistical error (standard deviation estimate, SDE) and the monthly mean RMS error (MM RMSE) combined from the MM BE and SDE.

3.3.2 Data Evaluation and Exploitation Approach

Data Evaluation – Validation and SI Traceability

ACCURATE data evaluation is here understood as objectively evaluating, establishing and maintaining the quality of the data within requirements and is foreseen in the 3-fold way of

1) the validation by independent ground-, balloon-, air-, and space-borne observational data of suitable quality that collectively measure the same parameters,
2) the validation by atmospheric analysis and short-range forecast data such as ECMWF atmospheric analyses (www.ecmwf.int/products) for the thermodynamic state and wind and MACC composition analyses (www.gmes-atmosphere.eu) for the greenhouse gas trace species, respectively, and
3) the use of the traceability to fundamental metrological (SI) standards – essentially time and frequency standards – in order to ensure with an unbroken trace-back chain to such standards knowledge of data quality independent of the "classical" validation approaches 1) and 2).

The first validation approach will be prepared for and applied to data evaluation in intensive limited periods, especially during commissioning phase of the mission, but also based on dedicated primary high-equipment level sites (such as the Lindenberg Observatory in Germany; www.dwd.de/mol). The implementation option of ACCURATE fixed repeat pattern coverage, so that occultation events revisit twice per month the same target location within about 100 km distance (see section 5.5), strongly facilitates such validation. In addition the fixed repeat pattern can be readily shifted by satellite control (for example after collecting a year or so at several primary sites for one fixed pattern) to another fixed pattern to serve other primary sites if so desired. As far as independent space-borne data are concerned GNSS radio occultation data will be one key source for validating the thermodynamic state but also other limb sounding data play a role.
Dedicated LEO-Tx to ground or to airplane LMIO measurements are possible during the first-year drifting phase of the orbits (section 5.5), where data evaluation can already start.

The second validation approach will be prepared for routine validation and quality monitoring of the data, with ECWMF and MACC (GMES atmospheric service) analyses and short-term forecasts as baseline reference fields, since this approach provides good spatial and temporal co-location for every ACCURATE occultation event independent of its location and time.

The third "non-classical" evaluation approach is vital due to the primary aim of ACCURATE to supply data of climate benchmark quality in order to meet its objectives (see section 3.1). A benchmark fulfilling the accuracy and stability requirements as defined for ACCURATE (see Table 3.2-1) is unprecedented and will therefore within its expected small error bounds find no independent data source of sufficient quality to serve as validation reference to really constrain the ACCURATE data within their unique small bounds (GNSS radio occultation reaching closest for refractivity and, in its "dry air" domain, for temperature and pressure).
Establishing and maintaining SI traceability for the ACCURATE data is thus *the* key to make them the authoritative reference standard for the large-scale evolution of the "full atmospheric state" $\mathbf{X} = (z, T, p/Z, q/H_2O, V_{los}, CO_2, {}^{13}CO_2, C^{18}OO, CH_4, N_2O, O_3, CO, HDO, H_2{}^{18}O)$ in the global free atmosphere, for the benefit of all other atmospheric data, and of atmospheric climate, composition and weather models, which can "anchor" to this reference state like so far only to special limited ground station networks that supply climate benchmark data.

Data Exploitation Approach – from Main Lines of Use to Announcement of Opportunity

The exploitation approach of the ACCURATE Level 1b and Level 2 science data (see Table 3.2-3) will depend on the user or user group and on the scientific or demonstration objective addressed, where the *main lines of use* will be along three paths as follows,

1) *direct use of Level 2 profiles*, or profiles of other dependent parameters derived at the location of the profile from the available state information $\mathbf{X} = (z, T, p/Z, q/H_2O, V_{los}, CO_2, {}^{13}CO_2, C^{18}OO, CH_4, N_2O, O_3, CO, HDO, H_2{}^{18}O)$, for scientific aims such as atmospheric physics and chemistry process studies in the UTLS region,
2) use of the Level 2 profiles, or derived profiles in the sense of point 1 or sometimes also of Level 1b profiles, to derive *value-added higher level products* such as gridded 2D and 3D climatologies of essential climate variables and any other parameter of interest to support an objective, and work with these value-added products,
3) use of Level 1b or Level 2 profiles in *data assimilation schemes*, for various purposes and in different modes, ranging from climate model testing and validation via observationally constrained climate forcing/pattern/trends detection and attribution to classical assimilation for initialization of NWP or composition forecasts.

These three main paths of data exploitation reflect the diversity of needs for the range of science and demonstration objectives laid out in section 3.1 and can be seen as framing also the user needs for value-added data products and software tools beyond those provided by the Level 1 and Level 2 processors of the ground segment (section 5.4).

A key of the preparation of data exploitation already over the years before launch will thus be that the proposing Science Team, together with their groups/institutes and complemented by further interested scientists and groups, will form an *ACCURATE International Science Team* that together defines a science and data exploitation plan making sure that collectively dedicated *operational and science centers* are prepared to provide all needed value-added products and software tools as well as address all targeted mission objectives.
As just one example, fundamental Level 3 and Level 4 climatology products, i.e., aggregated climatological fields of all Level 2 products and other (derived) parameters of interest, will be prepared by the Wegener Center/University of Graz, which is foreseen, attached to the ground segment in ESRIN, as a science center dedicated to climate data products and occultation-based climate validation service, and will itself scientifically exploit the data for climate monitoring, diagnostics, and evaluation of models and other climate data, in line with the heritage expertise from similar activities based on GNSS radio occultation data. Likewise other Science Team institutes will act in their fields of expertise.

Furthermore, as is good practice for Earth Explorer missions and other ESA missions or ESA-related missions so far, an *Announcement of Opportunity (AO)* for use of the ACCURATE data to the international scientific and other user community shall be issued. This will ensure broad exploitation of the data over the mission operations time and beyond, not least since all members of the ACCURATE International Science Team as an open broad platform will already be well aware of the possibilities and options so that a strong response to the ACCURATE AO is granted. Data validation activities for the early mission phase shall be part of the AO.

3.4 Relevance to ESA Programme and Evaluation Criteria

The ESAC (2006) evaluation of the ACCU (2005) proposal, attached for convenient access as Annex A to this proposal, has in the individual assessment report by the Joint Assessment Panel(s) commented on the ACCURATE LMIO concept along the seven criteria for the evaluation of candidate Earth Explorer missions, into which also this section is structured.

The evaluation comments have been very positive throughout and on some criteria recommendations were included, mainly related to the LIO part that was very new and somewhat immature at that time (see in Annex A on pages 67-69, section “4. Assessment and Boundary Conditions”, of that assessment report).

Given that the fundamental merits and unique potential of the ACCURATE LMIO concept have in no way degraded since ACCU (2005) — they were rather further enhanced in that now also line-of-sight wind is simultaneously accessible and that LIO is much more mature — it is found not meaningful to repeat here all “convincing pro arguments” that have already been positively acknowledged in the ESAC (2006) evaluation (despite these arguments are as valid as ever). Rather we shall focus to comment on what has improved or otherwise changed in relation to these seven evaluation criteria from ACCU (2005) to the present ACCURATE EE-8 proposal.

We thus just refer in the subsections below for the unchanged arguments to ACCU (2005), section “4. Relevance to Evaluation Criteria” p. 17-19, attached for convenient access as Annex B to this proposal, and to the related Annex A assessment report section “4. Assessment and Boundary Conditions” p. 67-69 cited above.

3.4.1 Relevance to ESA Living Planet Programme/Research Objectives for Earth Observation

See Annex B, section “4. Relevance to Evaluation Criteria” p. 17 of ACCU (2005), and the related evaluation in Annex A, section “4. Assessment and Boundary Conditions” p. 67.

The high and broad-ranging relevance is still fully valid for the present ACCURATE mission as can also be seen from the science and demonstration objectives in section 3.1.

3.4.2 Need, Usefulness and Excellence; Uniqueness and Complementarity

Need, Usefulness and Excellence

See Annex B, section “4. Relevance to Evaluation Criteria” p. 17 of ACCU (2005), and the related evaluation in Annex A, section “4. Assessment and Boundary Conditions” p. 67.

The needs for the type of climate benchmark data and their utility and excellence are still fully valid for the present ACCURATE mission as can also be seen from section 3.1. The usefulness has further improved due to the additional availability of line-of-sight wind which in combination with the near-polar orbits in particular enables to probe meridional winds in the UTLS (“Brewer-Dobson Circulation”).

A main difference by ansatz is that under the resource conditions of this Earth Explorer Opportunity Mission Call the present ACCURATE mission is proposed as a dedicated first demonstration mission based on two satellites only while ACCU (2005) was an Earth Explorer Core Mission proposal for four satellites with optional GNSS radio occultation payload.

However, while this implies a factor-of-2 coarser horizontal resolution and focus on the LMIO technique (also GNSS radio occultation is no longer that new and innovative in the Earth Explorer sense and, e.g., meanwhile operationally foreseen as part of the PostEPS with using both GPS and Galileo signals), this has the advantage that it is a very cost-effective but still truly pioneering mission able to fully demonstrate the LMIO science utility.

Uniqueness and Complementarity

See Annex B, sect. "4. Relevance to Evaluation Criteria" p. 18-19 of ACCU (2005), and the related evaluation in Annex A, section "4. Assessment and Boundary Conditions" p. 67-68.

The uniqueness and complementarity is still fully valid for the present ACCURATE mission as can also be seen from section 3.1, especially subsection 3.1.5 and also from section 4.3. A more detailed assessment to this end has been recently given by ACCU (2010).

3.4.3 Degree of Innovation and Contribution to the Advancement of European EO Capabilities

See Annex B, section "4. Relevance to Evaluation Criteria" p. 18 of ACCU (2005), and the related evaluation in Annex A, section "4. Assessment and Boundary Conditions" p. 68.

Also the arguments related to innovation and contribution to European EO are still fully valid for the present ACCURATE mission; it strongly fulfills both innovation in science and demonstration of new techniques as well as reinforces the European lead in occultations.

3.4.4 Feasibility and Level of Maturity; Timeliness; Programmatics

Feasibility and Level of Maturity

See Annex B, sect. "4. Relevance to Evaluation Criteria" p. 18-19 of ACCU (2005), and the related evaluation in Annex A, section "4. Assessment and Boundary Conditions" p. 68.

The arguments on the LMO part are still basically valid, the maturity of which is scientifically and technically very high. But there was further progress also on LMO, for example by further consolidation of algorithms in Europe (e.g., LMOPAP, 2010) and by the preparation of an airplane-to-airplane LMO demonstration experiment in the U.S. (led by Science Team member R. Kursinsiki, Univ. of Arizona, Tucson, AZ, USA).

Truly substantial advances have been made in the LIO part, where a range of science and technology studies, both by ESA and in national projects, have significantly matured the concept. This is well visible starting from sections 3.2 and 3.3 on observational requirements and retrieval algorithms via section 4 on the techniques and system requirements to sections 5 and 6 with the mission architecture, incl. payloads, and programmatics. Also the selected references in this proposal from the work since the ESAC (2006) evaluation witness the progress.

Overall in the view of the proposing Science Team and the Industrial Support Team the current ACCURATE concept is thus perfectly prepared to move into Phase A studies and subsequently into full implementation.

Timeliness

See Annex B, section "4. Relevance to Evaluation Criteria" p. 19 of ACCU (2005), and the related evaluation in Annex A, section "4. Assessment and Boundary Conditions" p. 68.

The high timeliness and the independence from schedules of other missions are still fully valid for the present ACCURATE mission. This pioneering LMIO mission is thus considered highly timely and ACCURATE should therefore be realized as soon as possible to operate within the planned EE-8 compliant period 2018-2022.

Programmatics

See Annex B, section "4. Relevance to Evaluation Criteria" p. 19 of ACCU (2005), and the related evaluation in Annex A, section "4. Assessment and Boundary Conditions" p. 69.

The positive view on programmatic issues is meanwhile considered even more applicable for the present ACCURATE mission. The maturity of the LMO is very high and also LIO has thanks to substantial advances from 2006-2010 reached a maturity level that it without undue risk could move to Phase A study. Moreover section 6 shows that also the subsequent implementation planning and the related cost estimates suggest no programmatic problems, thanks also due to the innovative and cost-effective mission architecture detailed in section 5. Also that it is a very clear cut end-to-end ESA mission, under full ESA programmatic control and with all technologies well mastered in Europe, minimizes programmatic risks.

Thus overall ACCURATE is considered a quite perfect fit for EE-8, a truly pioneering small Earth Explorer mission with clear and low-risk programmatics that strongly fulfills both science *and* demonstration objectives formulated in ESACALL (2009): "These missions are intended to be used to conduct research in the field of Earth Observation and/or to demonstrate the potential of new innovative Earth Observation techniques of relevance to both the scientific and the application communities."

The proposing Science Team and the Industry Support Team would thus look forward to support working out and demonstrating in a Phase A the full feasibility of the mission and to subsequently support its implementation.

3.5 Relevance to Other Programmes

As summarized in ACCU (2009), ACCURATE can provide comprehensive and unique contributions for the implementation of both the climate and atmospheric chemistry recommendations put forward for the international community by the GCOS (co-sponsored by WMO, IOC, UNEP and ICSU) and GAW (WMO) initiatives, respectively.

Based on its unique properties to supply many GCOS Essential Climate Variables in the free atmosphere, and its scientific objectives collected in section 3.1, ACCURATE will thus contribute to a range of international programmes, especially to those under the WCRP umbrella addressing questions of atmospheric chemistry and climate as well as the global water and carbon cycles, but also to IGBP and even IHDP topics given its strong greenhouse gas monitoring component.

Due to its capability to demonstrate an authoritative reference standard for greenhouse gas and climate change monitoring in the global free atmosphere ACCURATE will also be of high interest for monitoring fulfillments of international and national climate policy goals.

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4. Mission Assumptions and Technical Requirements

4.1 Observation Techniques

4.1.1 Observation and Constellation Design Overview

The overall observation design is illustrated in Figure 4.1-1, which allows to concisely discuss the general characteristics and concept of the proposed ACCURATE mission and also to note the modifications relative to the ACCU (2005) proposal evaluated by ESAC (2006).

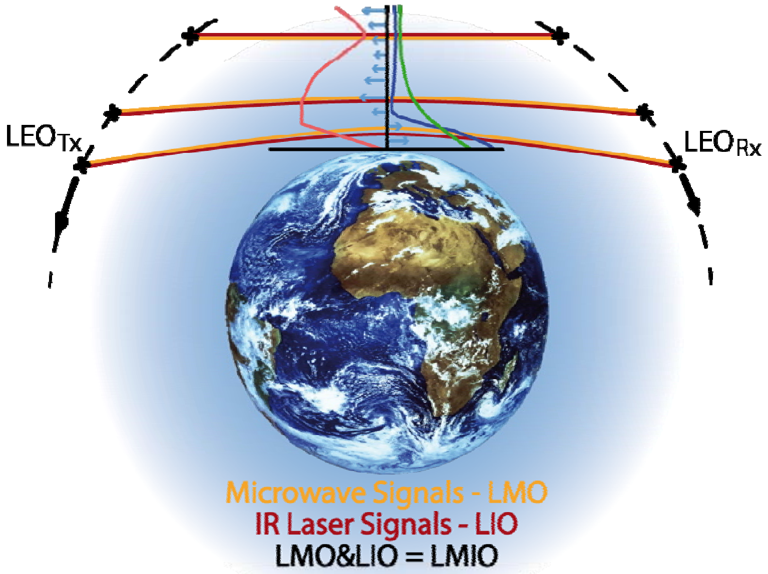


Figure 4.1-1: Overview of the ACCURATE LMIO observation design.

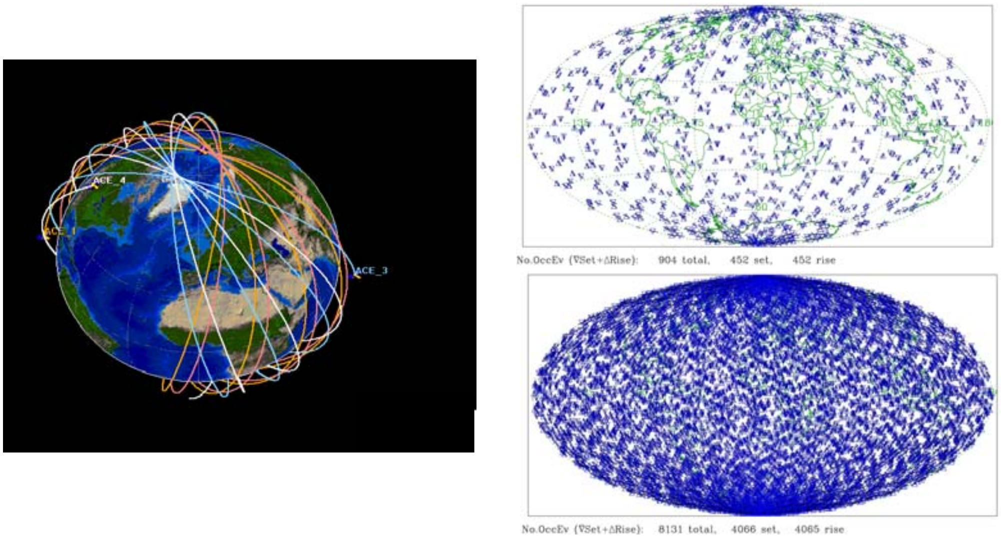
The ACCURATE mission consists of a LEO-to-LEO microwave occultation (LMO) component combined with a LEO-to-LEO infrared laser occultation (LIO) component, together referred to as LMIO concept. Carefully chosen and simultaneously transmitted MW signals and IR laser signals used in occultation measurement mode between LEO satellites powerfully join, collecting atmospheric information from refraction and absorption along closely aligned signal travel paths, to yield consistent profiles of thermodynamic variables, greenhouse gases, and line-of-sight wind over the upper troposphere and lower stratosphere (UTLS) and beyond (as symbolized in Figure 4.1-1). The "full atmospheric state" vector of profiles quantified this way by each occultation event is $\mathbf{X} = (z, T, p/Z, q/H_2O, V_{los}, CO_2, {}^{13}CO_2, C^{18}OO, CH_4, N_2O, O_3, CO, HDO, H_2{}^{18}O)$.

If technically implemented properly, including accounting for SI traceability of the measurements, this full state vector, and in particular state averages over horizontal regions ("grid boxes"; e.g., averaging the number of profiles per grid box per month in the terminology of the observational requirements, Table 3.2-1 in section 3.2), qualify as climate benchmark observations that provide an authoritative reference standard in the global free atmosphere for the state represented by **X**.

Comparing this design to the ACCU (2005) proposal it is the same plus that as a valuable addition observation of line-of-sight wind speed was added, completing the thermodynamic and composition state measurements with a direct dynamical measurement. On the other hand the GNSS radio occultation (GRO) measurements optionally foreseen in ACCU (2005) are no longer included here both due to the more limited resource conditions of an EE-8 opportunity mission but also since GRO is no longer that new and innovative in the Earth Explorer sense and, e.g., meanwhile operationally foreseen as part of the operational PostEPS with using both GPS and Galileo signals.

While Figure 4.1-1 illustrates the design per individual occultation event, i.e., the “vertical situation”, Figure 4.1-2 below illustrates how the characteristics of global coverage by LMIO events look like, i.e., the “horizontal situation”, whereby also sufficient verticality of the profiling scans is to be considered. This coverage has to be consistent with the observational requirements on horizontal and time sampling as well as regarding the number of profiles per grid box per month (see Table 3.2-1, section 3.2; regarding the verticality see its footnote 6).

Based on these requirements LEO transmitter (Tx) and LEO receiver (Rx) in counter-rotating orbits are required (left panel), as inherited from ACE+ (ESA, 2004a;b) and ACCU (2005). Given the additional preference for a fixed coverage repeat pattern for a cost-effective first demonstration as proposed here (see footnote 3 of Table 3.2-1), a further innovation in form of carefully chosen orbits is desired, however, which provide such a fixed repeat pattern, e.g., twice per month, over the mission lifetime.



Baseline constellation design/first demonstration:
2 orbit planes, counter-rotating Rx sat vs Tx sat
1 sat/plane, drifting through all local times (*i* ~ 80°)
2 orbit heights (Tx ~595 km, Rx ~512 km)

LMIO coverage twice per month (15 days repeat)
- about 900 occultation event locations visited
- about 1800 occultation events per month
- 9 times the coverage by later 3 Tx + 3 Rx satellites

Figure 4.1-2: Baseline constellation design for ACCURATE and illustration of coverage.

Figure 4.1-2 illustrates a suitable two-satellite baseline constellation (left panel) and the coverage achieved with about 900 globally well distributed locations that are revisited about twice per month (15-day repeat pattern; upper right panel), and where the “anchoring” of the pattern to some reference location can be user-defined and also change a few times during the mission if so desired for validation purposes or, after benchmark quality is established (see section 3.3.2), for the primary mission objective of better providing “reference data for the calibration, validation, and analysis of data from other space missions or airborne/ground-based observing systems” (see section 3.1.2).

The detailed implementation of orbits and operations that meet the requirements described here needs to come from dedicated mission analysis, which has been done as part of defining the mission architecture and is described in sections 5.2 and 5.5.

Compared to ACCU (2005) the major difference is the use of two instead of four satellites for this EE-8 Opportunity Mission Call, as discussed in section 3.4.2. We note though that the two-satellite constellation with one Tx resp. Rx per orbit for this pioneering demonstration is later readily and cost-effectively operationalized to, e.g., 3 Tx resp. 3 Rx into the same orbits (based on two triple launches) which then increases the number of occultation events by about an order of magnitude (illustrated for context in the lower right panel of Figure 4.1-2).

4.1.2 LEO-LEO Microwave Occultation (LMO)

This observation technique is proposed here unchanged from the ACCU (2005) proposal. For this reason and due to the strong heritage from ACE+, where a very similar LMO observation design already successfully proved feasibility in a Phase A study (ESA, 2004a;b) we restrict here to a brief description and a summary only of the modifications relative to ACE+ and ACCU (2005).

The baseline for ACCURATE LMO is to employ three K band signals (17.25, 20.2, and 22.6 GHz) that provide profiling of altitude and thermodynamic state $\mathbf{X}_{z,TD} = (z; T, p, q)$ as summarized in section 3.3.1 and described in detail, e.g., in OPAC (2004b) and LMOPAP (2010). For this design based on exploiting absorption by the 22 GHz water vapor line, adequate LMO humidity sounding reaches up to about 12 km, in line with the vertical domain upper boundary threshold observational requirements (see Table 3.2-1). Figure 4.1-3 below illustrates the underlying absorption spectrum conditions at a representative height of 7 km (left panel). LMO humidity up to about 8-12 km is needed (i.e., T, p, q separately) to aid the LIO retrieval (see Figure 3.3-1 in section 3.3.1), and at the same time sufficient for this purpose. Also the ACCURATE LMO can measure humidity within (upper tropospheric) clouds while LIO is blocked by clouds except for intermittent layering or very thin ones.

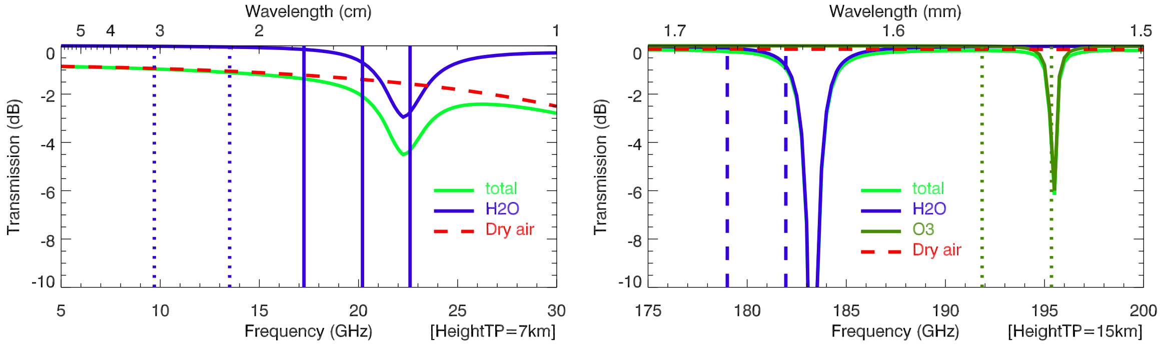


Figure 4.1-3: Spectral ranges for ACCURATE LMO illustrating the major absorption features and the mandatory K band channels (blue solid, left panel) and the optional 183 GHz channels (blue dashed, right panel). The dotted channels (X band, left; 195 GHz, right) are further best-effort channels (ACCU, 2009) that might play a role in extended LMO designs but are not relevant here.

It would be advantageous to add two further channels near the 183 GHz water vapor line (right panel of Figure 4.1-3; 179.0 and 181.95 GHz, compliant with international frequency regulation reserving 182.0-185.0 GHz for passive sounding only). This would allow LMO water vapor sensitivity beyond 12 km up to about 18 km (LMOPAP, 2010), including in high reaching (tropical) cirrus clouds, while LIO water vapor will not measure the 12-18 km range within clouds (though outside clouds with higher accuracy, see Figure 3.3-2). Since there is an interest by a U.S. team led by proposing Science Team member R. Kursinski (Univ. of Arizona, Tucson, AZ, USA) to potentially supply such an optional 183 GHz capability, though details uncertain at the current point in time, we keep this noted as an option here in section 4 (on a best-effort basis) but disregard it in the current mission architecture planning (section 5). The option may be revisited during Phase A dependent on European and U.S. programmatic and resource conditions.

Compared to ACE+, the present design means that the frequency near 10 GHz (X band) was shifted to 20.2 GHz, due to the focus of ACCURATE on the upper troposphere; altitudes < 5 km down into the lower troposphere will be covered on a best-effort basis. Also a separate X band antenna is thus not required for the present LMO approach. Otherwise the technical requirements are the same. On the side of LMO processing, this clearly has also been further improved and consolidated since ACE+ and ACCU (2005) as discussed in section 3.3.

4.1.3 LEO-LEO IR-laser Occultation (LIO)

The LIO observation technique has received significant further development and consolidation from the time of the ACCU (2005) proposal and ESAC (2006) evaluation, but the basic technical concept and design of the technique, and its tight synergy with LMO in the LMIO method, are unchanged and still fully valid. We thus do not repeat here the relatively extensive description and lines of argument on LIO in ACCU (2005), where the need was the basic introduction of a freshly conceived technique, but focus to summarize the main aspects of current status and new results, providing the basis for the significantly consolidated system requirements in the next section, as compared to ACCU (2005). A detailed description of the complete technique and related performance estimates is found in ACCUPHD (2010).

The baseline for ACCURATE LIO is to employ 21 carefully chosen IR laser signals in the short-wave infrared (SWIR) within the 2–2.5 μm band (4000–5000 cm^{-1}) that provide profiling of greenhouse gas trace species and l.o.s. wind, i.e., the state $\mathbf{X}_{\mathrm{GHGs,V}}$ = (H_2O, CO_2, $^{13}CO_2$, $C^{18}OO$, CH_4, N_2O, O_3, CO, HDO, $H_2{}^{18}O$; V_{los}) based on differential transmission measurements as described in section 3.3.1. Complementary to this species and l.o.s. wind profiling, aerosol, cloud layering, and turbulence profiling are important tasks, which will use the measured transmission data without the log-transmission frequency differencing.

At the core of the LIO technique as part of the LMIO method is the recognition that dedicated IR laser signals within 2–2.5 μm are near-ideal for occultation sounding due to:

- the 2–2.5 μm refractivity (Edlen-type formula in the ‘near-non-dispersive range’ > 2 μm) being nearly identical (< 0.1 % difference) to K band refractivity (Smith-Weintraub-type formula), implying closely similar signal travel paths of LMO and LIO signals (except for the “wet term” due to orientation polarization of water molecules in K band refractivity; thus LMO thermodynamic data aid LIO in moist air < 8-12 km, see sections 3.3.1 and 4.1.2).
- the solar radiation scattered into the LEO Rx telescope being minimal and the received atmospheric thermal radiation being negligible (“hole between the two Planck spectra”), leaving comfortable SNR also in full daylight and providing independence of atmospheric emission characteristics.
- suitable spectral (vibration-rotation) absorption lines being available for sensing of all ten targeted greenhouse gas trace species in the UTLS domain, with the sensitivity in limb sounding

being two orders of magnitude higher than in nadir, also allowing sensing of the main CO_2 and H_2O isotopes.

- the spectral characteristics being well suited to allow pairs of channels for differential transmission profiles have both high transmission contrast and closely-spaced frequency ratios $|f_2–f_1|/f_1 < 0.5$ %, very effectively suppressing scintillations and all other broadband effects.
- laser signals being point sources leading to Fresnel diameters within 2–2.5 µm of < 5 m (~3 m in LEO-LEO geometry) and allowing single-shot SNRs of ~500 (in vacuum above TOA) with Tx laser pulse powers of max. 1 W only; such SNRs in 2–2.5 µm are far out of range of natural point sources such as stars and, on the other hand, active laser sounders working on backscatter would need about two orders of magnitude more laser power.
- highly accurate and stable semiconductor lasers (Distributed Feed-Back, DFB, Lasers) and highly sensitive infrared detectors (Extended InGaAs) being available in the SWIR in 2–2.5 µm, which fulfill LIO system requirements (see section 4.2) and secure the feasibility.

The differential transmission measurements require both IR laser absorption and reference signals, where the former serve as “on-wavelengths” λ_{abs}, and the latter as “off-wavelengths” λ_{ref}, respectively. The absorption signals for trace species need sensible choice at line centers of suitable absorption lines of the target species and for l.o.s. wind at the points of inflection of the wings of a suitable highly symmetric absorption line. The reference signals are required at frequencies where the atmosphere is fully transparent except for at most very small scattering and background absorption effects. The wavelength separation $|\lambda_{abs}–\lambda_{ref}|/\lambda_{ref}$ is required to be small to within ~0.5%, in order to ensure that the differential transmission effectively corrects for all broadband effects (defocusing, residual scattering, absorption background, aerosol extinction, scintillation) and leaves the target species absorption only, except for small residual differential background absorption that is readily co-estimated in the retrieval without creating *a priori* dependences above noise level (cf. section 3.3).

Table 4.1-1 shows the selected set of laser frequencies for observing all geophysical variables targeted by LIO (Table 3.2-2 in section 3.2.3) and Figure 4.1-4 illustrates them spectrally.

Table 4.1-1: Selected set of LIO absorption and reference frequencies

Target Variable	**Absorption frequency**		**Reference frequency**		**Wavelength Separat.**
	$\bar{\nu}_{abs}$ [cm^{-1}]	λ_{abs} [µm]	$\bar{\nu}_{ref}$ [cm^{-1}]	λ_{ref} [µm]	$100\cdot(\lambda_{abs}–\lambda_{ref})/\lambda_{ref}$ [%]
H_2O (1)	4204.840	2.378212	4227.07	2.36571	+0.5259
(2)	4775.803	2.093889	4770.15	2.09637	–0.1185
(3)	4747.055	2.106569	4731.03	2.11371	–0.3387
(4)	4733.045	2.112805	4731.03	2.11371	–0.0426
CO_2	4771.621	2.095724	4770.15	2.09637	–0.0308
$^{13}CO_2$	4723.415	2.117112	4731.03	2.11371	+0.1610
$C^{18}OO$	4767.041	2.097737	4770.15	2.09637	+0.0652
CH_4	4344.164	2.301939	4322.93	2.31325	–0.4912
N_2O	4710.341	2.122989	4731.03	2.11371	+0.4373
O_3	4029.110	2.481938	4037.21	2.47696	+0.2006
CO	4248.318	2.353873	4227.07	2.36571	–0.5027
HDO	4237.016	2.360151	4227.07	2.36571	–0.2353
$H_2{}^{18}O$	4090.872	2.444467	4098.56	2.43988	+0.1876
l.o.s. (1)	4767.037	2.097739	4770.15	2.09637	+0.0653
wind (2)	4767.045	2.097735	4770.15	2.09637	+0.0651

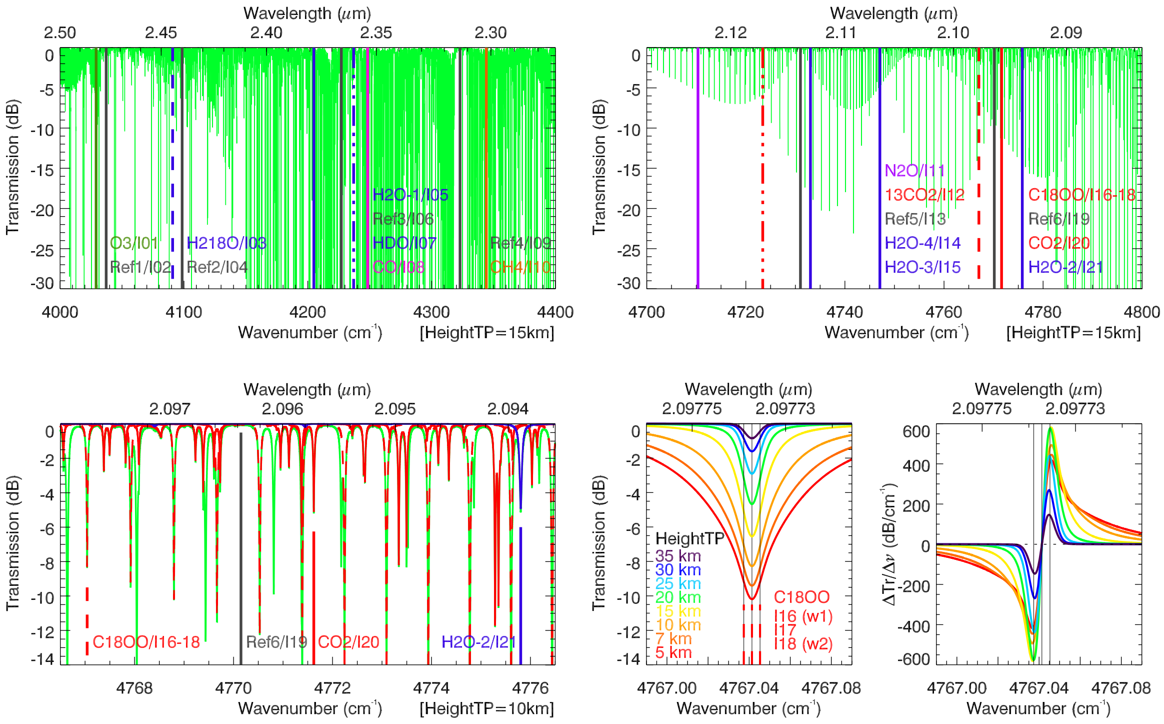


Figure 4.1-4: Spectral ranges for ACCURATE LIO illustrating the selected laser frequencies in the 2.3–2.5 µm “SWIR B” band (upper left) and the ~2.1 µm “SWIR A” band (upper right). A zoom into a narrow sub-range of the SWIR A band highlights a special “demo” band of only ~4 nm (10 cm^{-1}) width (lower left) suitable to probe the key variables CO_2 (incl. isotopes), H_2O, and l.o.s. wind within the mode-hop free tuning range of single DFB lasers. A further zoom in this band highlights a small “wind line” band of only ~0.4 nm (1 cm^{-1}) width (lower right) where the selected two wind measurement frequencies sit at the points of inflection of the highly symmetric and stable $C^{18}OO$ line (left sub-panel) and where also the spectral derivative of the transmission is shown (right sub-panel), confirming that the wind frequencies sit at maximum gradient providing highest sensitivity to wind-induced Doppler shift of the line exploited for the l.o.s. wind measurements.

The selection of these frequencies was performed by a sophisticated search over the entire 2–2.5 µm range for obtaining those frequencies with optimal sensitivities to the respective target species over the UTLS region and at the same time minimal sensitivity to any foreign species (ACCUPHD, 2010). As Table 4.1-1 shows, also adequate reference frequencies within ~0.5% wavelength separation were found for all absorption frequencies.

These consolidated selections have also undergone fine-tuning in a recent ESA study (ACCU, 2009) as well as validation based on real high-resolution spectra from balloon-borne solar occultation measurements that spanned the 4000–5000 cm^{-1} range with < 0.01 cm^{-1} resolution (MkIV experiment flights, G. Toon, JPL Pasadena, CA, USA; http://mark4sun.jpl.nasa.gov). Figure 4.1-5 below shows an example of such a validation for the “demo” band illustrated in the lower left panel of Figure 4.1-4 above. Evidently the agreement (without any effort to fit actual concentrations, just using a suitable FASCODE atmosphere) is excellent. Similar results were found for all other targeted absorption lines and reference frequencies so that the confidence in the selection is high and the LIO channels as part of the system requirements (section 4.2) are thus specified based on these validated selections.

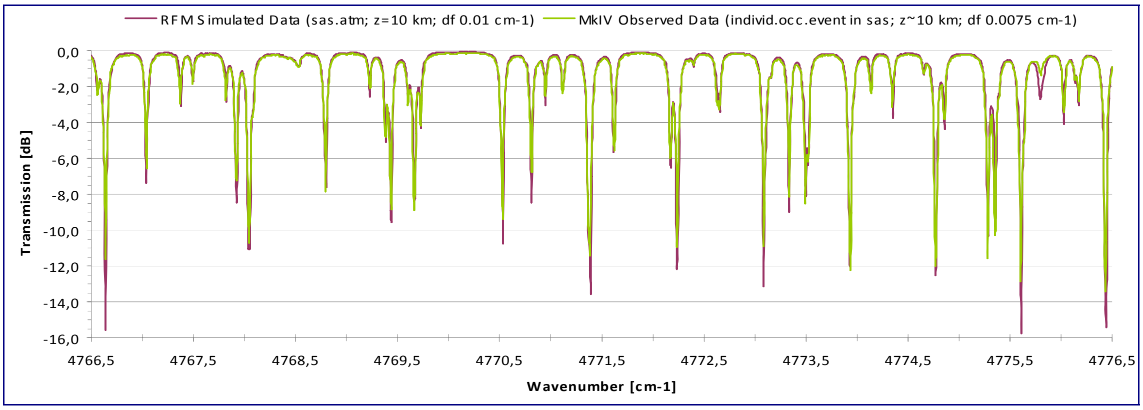


Figure 4.1-5: Comparison of RFM/HITRAN/FASCODE-modeled transmission spectrum of the ACCURATE “demo” band (cf. Figure 4.1-4) with a real measured MkIV solar occultation spectrum.

Figure 4.1-6 illustrates transmission profiles computed using RFM/HITRAN with FASCODE (standard atmosphere) at the selected frequencies and confirms the high contrast of transmissions between absorption and reference frequencies. The transmission range from about 0.25 dB (~95% transmission) relevant at high altitudes to about 13 dB (~5% transmission) relevant at tropospheric altitudes is the best-exploitable range for accurate measurements.

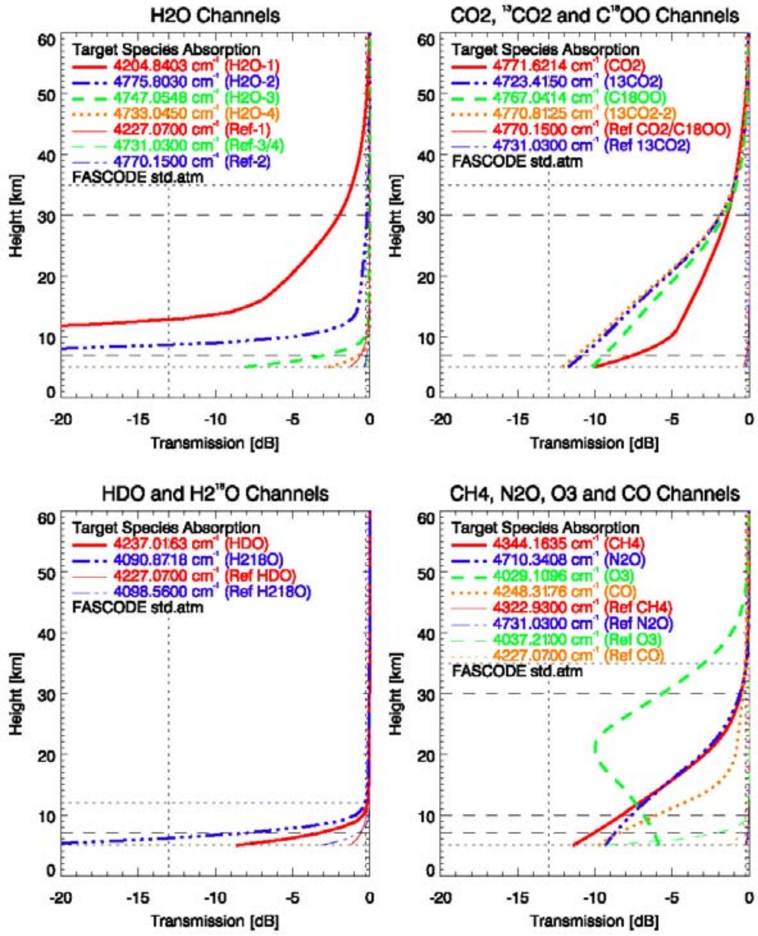


Figure 4.1-6: LIO transmission profiles for the target species at absorption frequencies (heavy lines) and for all species plus continuum at reference frequencies (light lines).

The UTLS domain is well covered by the needed transmission sensitivities and it is likewise visible in Figure 4.1-6 that some species cannot reasonably be expected to be always measured over the full UTLS range (e.g., H_2O isotopes, O_3 below 10 km), which is reflected in the observational requirements in Table 3.2-1 as well as the retrieval results in Figure 3.3-2.

Regarding the λ_{abs}–λ_{ref} wavelength separation of max. ~0.5%, studies (within the ESA project ACTLIMB) showed that signal scintillations due to atmospheric turbulence are the most spectrally variable broadband process that therefore drives this ~0.5% requirement. It was indicated from simulations, and from analyses of GOMOS stellar occultation data which comprehensively measured optical scintillations, that even at separations up to about three times closer (~0.15%) residual scintillation noise in differential transmissions might dominate the instrumental noise in the upper troposphere. This comes from the slight chromatic shift of signal paths at λ_{abs} vs. λ_{ref}, since the IR refractivity is still slightly dispersive at > 2 μm.
Therefore pre-compensation of this chromatic shift of signal travel paths near the tangent point of the occultation by counter-shifting the transmit time of absorption vs. reference laser pulse signals accordingly should be implemented (up to ~0.1 ms needed, depending on refraction). Doing so within 20% refractivity uncertainty robustly mitigates residual scintillation noise for any wavelength separations up to ~0.5%. This 20% refraction accuracy is readily achieved resp. outperformed by co-using the refraction modeling used for instrument pointing (see section 5). Computing the needed transmit time shift profile for any occultation event at each λ_{abs} relative to its corresponding λ_{ref} is thus straightforward and should be done together with the pointing profile computation.

Important to the LIO design is furthermore that before and/or after each laser pulse signal measurement also a background measurement is performed (within 5 ms, i.e., with < 10 m vertical shift, given typical vertical scan velocities of occultation events so that the Rx telescope with a field-of-view of ~3 km vertical extend sees essentially the same scattering both for the pulse and background measurement). The background measurement enables full control of the SNR of each single received pulse, for optimal quality independent of whether scattered radiation is available above detection system noise level or not.
Preferably the background measurement should be averaged from detecting the background power levels at multiple detection pixels before and after the pulse measurement over some small wavelength interval about the pulse wavelength (say < 1 nm or so), since in this case the subtraction of the averaged background power estimate from the pulse signal will only insignificantly increase the noise in the background-corrected pulse signal.
Background correction will be of utility for scenes involving Mie scattering of solar radiation from clouds fractionally covering the telescope field-of-view (e.g., measurements near cloud top), which is the only (natural) background source expected to sometimes exceed the detector noise level during bright day. Regarding Rayleigh scattering, error budget analysis shows that for LIO Rx designs fulfilling the system requirements (section 4.2) the scattered power is below detector noise level over the UTLS also during bright day and thus negligible.

As with any IR system, the LIO signals will be blocked in case of all other than very thin clouds along the propagation path. The LIO design thus is such that no time-continuous link is required between LIO Tx and Rx but rather each single pulse measurement is acquired individually so that individual pulses could be cloud-blocked without affecting the quality of any other pulse and retrievals through intermittent cloudiness are possible. Retrieving cloud layering profiles and subsequently trace species in cloudy air is currently on-going work.

4.2 System Requirements

4.2.1 LMO and LIO Measurement Channels

Table 4.2-1 provides the set of required MW and IR laser measurement channels, consistent with the frequency selection described in section 4.1 and given in Table 4.1-1 as well as consistent with the observational requirements (Table 3.2-1). Payloads shall take this as basis.

Table 4.2-1: Required set of ACCURATE LMO and LIO channels

Channel ID	Channel Frequency	Channel Wavelength	Channel Utility	Target Variables
K1	17.25 GHz	1.7379 cm	Abs/Ref[H_2O] ~UT 5-12 km	p, T, H_2O
K2	20.20 GHz	1.4841 cm	Abs/Ref[H_2O] ~UT 5-12 km	p, T, H_2O
K3	22.60 GHz	1.3265 cm	Abs[H_2O] ~UT 5-12 km	p, T, H_2O
(M1) b.e.	179.00 GHz	1.6748 mm	Abs/Ref[H_2O] ~UT/LS 10-18 km	H_2O
(M2) b.e.	181.95 GHz	1.6477 mm	Abs[H_2O] ~UT/LS 10-18 km	H_2O
I01	4029.110 cm^{-1}	2.4819 µm	Abs[O_3]	O_3
I02	4037.21 cm^{-1}	2.4770 µm	Ref[O_3]	(Ref 1)
I03	4090.872 cm^{-1}	2.4445 µm	Abs[$H_2{}^{18}O$]	$H_2{}^{18}O$
I04	4098.56 cm^{-1}	2.4399 µm	Ref[$H_2{}^{18}O$]	(Ref 2)
I05	4204.840 cm^{-1}	2.3782 µm	Abs[H_2O-1] ~13-48 km	H_2O
I06	4227.07 cm^{-1}	2.3657 µm	Ref[H_2O, HDO, CO]	(Ref 3)
I07	4237.016 cm^{-1}	2.3602 µm	Abs[HDO]	HDO
I08	4248.318 cm^{-1}	2.3539 µm	Abs[CO]	CO
I09	4322.93 cm^{-1}	2.3133 µm	Ref[CH_4]	(Ref 4)
I10	4344.164 cm^{-1}	2.3019 µm	Abs[CH_4]	CH_4
I11	4710.341 cm^{-1}	2.1230 µm	Abs[N_2O]	N_2O
I12	4723.415 cm^{-1}	2.1171 µm	Abs[$^{13}CO_2$]	$^{13}CO_2$, CO_2
I13	4731.03 cm^{-1}	2.1137 µm	Ref[N_2O, $^{13}CO_2$, H_2O]	(Ref 5)
I14	4733.045 cm^{-1}	2.1128 µm	Abs[H_2O-4] ~4-8 km	H_2O
I15	4747.055 cm^{-1}	2.1066 µm	Abs[H_2O-3] ~5-10 km	H_2O
I16	4767.037 cm^{-1}	2.0977 µm	Abs[$C^{18}OO$-w1], wind retrieval	l.o.s. wind
I17	4767.041 cm^{-1}	2.0977 µm	Abs[$C^{18}OO$]	$C^{18}OO$
I18	4767.045 cm^{-1}	2.0977 µm	Abs[$C^{18}OO$-w2], wind retrieval	l.o.s. wind
I19	4770.15 cm^{-1}	2.0964 µm	Ref[$^{12}CO_2$, $C^{18}OO$, H_2O, wind]	(Ref 6)
I20	4771.621 cm^{-1}	2.0957 µm	Abs[$^{12}CO_2$]	CO_2
I21	4775.803 cm^{-1}	2.0939 µm	Abs[H_2O-2] ~8-25 km	H_2O

Color shaded areas: LMO core channels K1-K3 (blue); LIO SWIR A band ~2.1 µm channels I11-I21 (green), wherein the specific demo band I16-I21 is separately highlighted more deep green; LIO SWIR B1 band 2.3-2.4 µm I05-I10 (yellow); LIO SWIR B2 band 2.4-2.5 µm I01-I04 (pink). Consistent with the observational requirements and target variables, if some part is to be discarded for feasibility/affordability reasons, it is first the SWIR B2 band and next I07-I08 from SWIR B1.

Channel ID in parentheses and marked with b.e. (best effort): the M1–M2 channels (focus H_2O > 10-12 km) are valuable optional channels and may be implemented on an as-resources-permit basis.

Ref 1 to Ref 6: reference channels for enabling differential transmission retrieval of trace species and l.o.s. wind as well as for retrieval of by-products (cloud layering, aerosol extinction, turbulence strength; see Table 3.2-2 in section 3.2.3).

4.2.2 Specification of System Requirements

The **main system requirements** are summarized in Table 4.2-2 below. They are consistent with the observational requirements (Table 3.2-1) and have been derived by mission analysis and retrieval performance analyses taking the match to those obs. requirements as basis.

Table 4.2-2: ACCURATE System Requirements

Requirement		**LMO**	**LIO**
Horizontal Domain		Global	
Horizontal Distribution		Homogeneously distributed profiles, regular distribution per day and month; in demo mission fixed 10-30d repeat pattern preferred	
Number of Profiles / Day		first demonstration mission > 50	
Vertical Domain		3–80 km for Bending angle 3–40 km for Transmission (1)	3–60 km for Transmission (1)
Vertical Sampling Rate		1 kHz ($z < 20$ km) 50 Hz ($z > 20$ km)	50 Hz
Time Domain		3 years	
Time Sampling (UT)		< 24 hrs (2)	
Local Time Sampling		All local times within as small as possible UTC time period or Sampling near fixed local time (sun-synchronous) (3)	
Bending Angle RMS Accuracy(4)		Max{0.5 μrad , 0.2%}	—
Transmission RMS Accuracy(5)		Consistent with $C/N_0 = 67$ dBHz at z_m=40km	Consistent with $S/N_0 = 34$ dBHz at z_m=60km
Transmission Stability (drift) (6)		< 0.4% over 20 sec (z_m=40km)	< 0.2% over 20 sec (z_m=60km)
Time-tagging accuracy	**absolute**	< 10 μs (3σ)	
	drift	< 30 ns/s (3σ)	
Real-time orbit accuracy	**position**	< 100 m (3σ)	
	velocity	< 1 m/s (3σ)	
Timeliness	**Climate**	14 days	
	NWP(7)	3 hrs	

(1) transmission profiles required at the frequencies specified in the "Set of LMO and LIO channels"; for LIO both for laser pulse signals and adjacent background signals, always as pairs of absorption and reference channels at the required sampling rate.
(2) UTC time within which the basic horizontal distribution (globally all latitudes) shall be covered.
(3) if drifting through local time at least all local times should be sampled within every single season; if fixed local time, the equatorial nodes of orbits shall be co-located with EPS/MetOp orbit nodes.
(4) understood to be the accuracy at a vertical resolution of Max{ 1 km, Fresnel zone diameter }.
(5) understood to be the accuracy at 1 Hz observation bandwidth; red noise RMSE in the altitude range 5 km < $z < z_m$ (e.g., $1/f$ noise for LMO or noise from Tx frequency and intensity instabilities for LIO) shall be smaller than the Rx thermal noise RMSE in the uppermost 10 km below altitude z_m.
(6) required during the time period while scanning the altitude range 5 km < $z < z_m$.
(7) to be fulfilled on a best-effort basis (for a significant fraction of the data).

For LMO these system requirements are mainly inherited from ACE+ (ESA, 2004b). For the new LIO part they are complemented below by specific LIO Tx and Rx requirements and a baseline link budget to facilitate the LIO payload design. Due to the strong ACE+ heritage such separate tables for LMO are not (i.e., no longer) needed.

LIO Tx system requirements. Table 4.2-3 below complements the main system requirements by specific LIO Tx system requirements, i.e., requirements for the LIO transmitter payload, in order to provide more detailed LIO Tx specifications by the use of which the main requirements may be met.

Table 4.2-3: LIO Tx System Requirements

Tx System Element		Requirement	Comment
Wavelength (wavenumber) range		2–2.5 μm (4000–5000 cm^{-1})	sufficient number of laser lines (signals) for observing all target species according to obs. requirements (use required set of 21 LIO channels)
Set of laser signal channels		see Table 4.2-1	
Emitted laser line	FWHM $\Delta f_L/f_0$	$< 3 \times 10^{-8}$	FWHM, full-width at half maximum
	spectral purity	> 36 dB	SNR of emitted line vs. out-of-line “floor” emission
	mode-hop free tuning range	> $f_{L0} \pm 1.5$ nm	tuning flexibility against nominal (manufactured) laser frequency f_{L0}
Laser pulses	power	1 W	maximum (or lower, depending on link budget realization details)
	duration	1.5 ms	up to 1.5 mJ pulse energy
	repetition rate	50 Hz	one pulse every 20 ms; adequate time-sequencing of all Tx laser signals to meet chromatic shift correction and Rx reception requirements
	trigger time accuracy	< 10 μs	(3σ) to implement chromatic shift correction delta-time of absorption channels with this accuracy
Laser frequency	knowledge $\delta f_L/f_0$	$< 3 \times 10^{-8}$, $< 1 \times 10^{-8}$	(3σ) event-to-event f_L uncertainty; the stronger requirement applies to the two wind channels only
	stability rms df_L/f_0	$< 2 \times 10^{-8}$	pulse-to-pulse f_L instability
	drift $D(df_L/f_0)/Dt$	$< 2 \times 10^{-8}$ / 20 s	f_L drift within occ. event duration
Laser intensity	stability rms dI_L/I_0	< 0.1%	pulse-to-pulse I_L instability
	drift $D(dI_L/I_0)/Dt$	< 0.1% / 20 s	I_L drift within occ. event duration
Laser beam divergence (at e^{-2} radius, full angle)		~3 mrad	selectable within 1–5 mrad (~3–15 km diameter at atmos. tangent point)
Intensity distribution (of beam intensity near the optical axis)	rms variation	< 0.1%	stable Gaussian intensity distribution
	drift	< 0.1% / 20 s	drift within an ~0.6 mrad cone about optical axis of beam
Laser beam pointing	knowledge	< 0.3 mrad	(3σ)
	drift	< 0.05 mrad / 20 s	(3σ)
Optical axis	co-alignment of laser beams for all laser lines	< 0.03 mrad	(3σ) < 100 m inter-offsets at atmospheric tangent point
	residual mis-alignments knowledge	< 0.03 mrad	(3σ)

LIO Rx system requirements. Table 4.2-4 below complements the main system requirements by specific LIO Rx system requirements, i.e., requirements for the LIO receiver payload, in order to provide more detailed LIO Rx specifications by the use of which the main requirements may be met.

Table 4.2-4: LIO Rx System Requirements

Rx System Element	Requirement	Comment
Reception telescope (e.g., Cassegrain-type)		
Front-optics (mirror) diameter	36 cm	circular shape (baseline)
FOV	~1.0 mrad	~3 km diameter at atmospheric tangent point
pointing knowledge	< 0.3 mrad	(3σ)
pointing drift	< 0.1 mrad / 20 s	(3σ)
Optical chain and frequency de-multiplexing		
basic signal integration time	2 ms	contains 1.5 ms pulse duration
observational bandwidth per received laser signal within 2–2.5 μm	~0.1–0.2 nm	accommodating kinematic Doppler shift of set and rise occ. events and solar rejection
bandpass filter sideband (out-of-band) attenuation	> 36 dB	or equivalent suppression of cross-talk in case of spectrometric reception
for each received laser signal, basic signal integration time for pulse reception accompanied within 5 ms by a basic signal integration time for background reception, at 50 Hz rate synchronized with the Tx pulse repetition rate and trigger time sequence of the signal		
simultaneous reception of up to eight laser pulse and up to twelve background signals within any given basic signal integration time slot (triggering and temporal sequence of the pulses of the up to eight signals to be sensibly designed to fit both Tx and Rx)		
sufficient number of filter/de-multiplex/spectrometric modules for unambiguously receiving all Tx laser pulse signals and corresponding background signals, according to the pre-defined Tx pulse rate and trigger time sequences of the signals		
Total optical loss from front-optics to detector	< 50%	threshold requirement, target is < 25%
Detector system (photodetector and pre-amplifier)		
NEP (detector system noise)	$< 8 \times 10^{-13}$ W / 2 ms	i.e., per single-pulse reception
Rise time/response time	< 1 μs	
Dynamic range	NEP–$2\cdot10^{-9}$ W / 2 ms	linear response over ~33 dB range

LIO link budget. Table 4.2-5 below complements the main requirements by a baseline LIO link budget, in order to provide more detailed specification by which type of link budget the main requirements may be met. This link budget is indicative and actual implementation in EE-8 implementation may have further refined/tuned it.

In Figure 4.2-5, the key figure is the S/N_0 at Top-of-Atmosphere (TOA; e.g., 60 km in practice) that shall be 34 dBHz according to Table 1.

Table 4.2-5: LIO Link budget — TOA S/N_0 estimation for ACCURATE LIO Tx-Rx link

Element / Link Process	Budget (dB)	Budget (W)
Emitted laser pulse power (over 1.5 ms), also denoted Tx power	0 dBW	1 W
Propagation loss[1]: laser beam divergence full angle 3 mrad (e^{-2}), 6000 km Tx-Rx distance, 36 cm diameter (circular) Rx optics	-91.1 dB	$7.8 \times 10^{-10}\ ^{W}/_{W}$
Received pulse power	-91.1 dBW	7.8×10^{-10} W
Reception loss: Tx pulse duration / Rx integration time (1.5 ms / 2 ms)	-1.25 dB	$0.75\ ^{W}/_{W}$
Total optical loss – front optics to detector (assumed to be 35%)	-1.85 dB	$0.65\ ^{W}/_{W}$
Pulse power at detector	-94.2 dBW	3.8×10^{-10} W
NEP of IR detector system within 2 ms (detectivity D* ~ 1.4 x 10^{12})	-121.4 dBW	7.2×10^{-13} W
SNR at detector for pulse sequence at 50 Hz sampling rate	27.2 dB	$525\ ^{W}/_{W}$
Downsampling gain (from 25 to 1 Hz bandwidth, SqRt(25))	7.0 dB	$5\ ^{W}/_{W}$
Achieved S/N_0 at TOA at 1 Hz bandwidth	**34.2 dBHz**	**$2625\ ^{W}/_{W}$**
Required S/N_0 at TOA at 1 Hz bandwidth (from Table 1)	34 dBHz	$2500\ ^{W}/_{W}$

[1] Propagation loss $L_{tr} = P_r/P_t$, occurring due to the divergence of the Gaussian beam with full (e^{-2}) angle α_t over the Tx-Rx distance D_{tr}, where P_t is transmitted power (W) and P_r is received power (W), is computed via $L_{tr} = 2\ A_r\ /\ (w_r^2\ \pi)$, where $w_r = D_{tr}\ (\alpha_t\ /2)$ is the Gaussian beam (e^{-2}) radius at the receiver, $A_r = (d_r^2/4)\ \pi$ is the Rx reception area with diameter d_r of the circular optics, and the factor of 2 derives from the ratio of the intensity of the Gaussian beam near the optical axis (Wm^{-2}), received by A_r, to the total transmitted power (W) in the beam.

4.3 Synergy with and Complementarity to Other Missions

A detailed look for ACCURATE on synergies with and complementaries to other missions was provided by ACCU (2010), based on which we summarize here some essential aspects.

Synergies with Other Missions

ACCURATE can help advanced passive IR and MW down-looking and chemistry limb-looking sounders in providing them with a global mesh of “anchor points” on the thermodynamic, dynamical, and composition state of the free atmosphere at large-scale horizontal resolution, which assists them as an authoritative reference dataset to correct their biases and bringing to full fruition their precision and high horizontal resolution.

This is highly valuable both for process studies with direct synergistic combination of sensor data and for joint fusion of the data sources into data assimilation and modeling systems, for example for improved NWP or composition analyses and forecasts.

Specifically on greenhouse gases, the joint need of both ground-based greenhouse gas monitoring systems and of ACCURATE for highest-precision spectroscopic methods — like Cavity-Ring-down Spectroscopy for obtaining line parameters of targeted absorption lines to the ~0.1% accuracy level by dedicated single-line spectroscopy — strongly and synergistically benefits both systems.

Complementaries to Other Missions

ACCURATE is highly complementary in information content to advanced passive IR and MW down-looking and chemistry limb-looking sounders, which can provide excellent horizontal resolution and observing cycle but have their limitations in vertical resolution, accuracy, and stability.

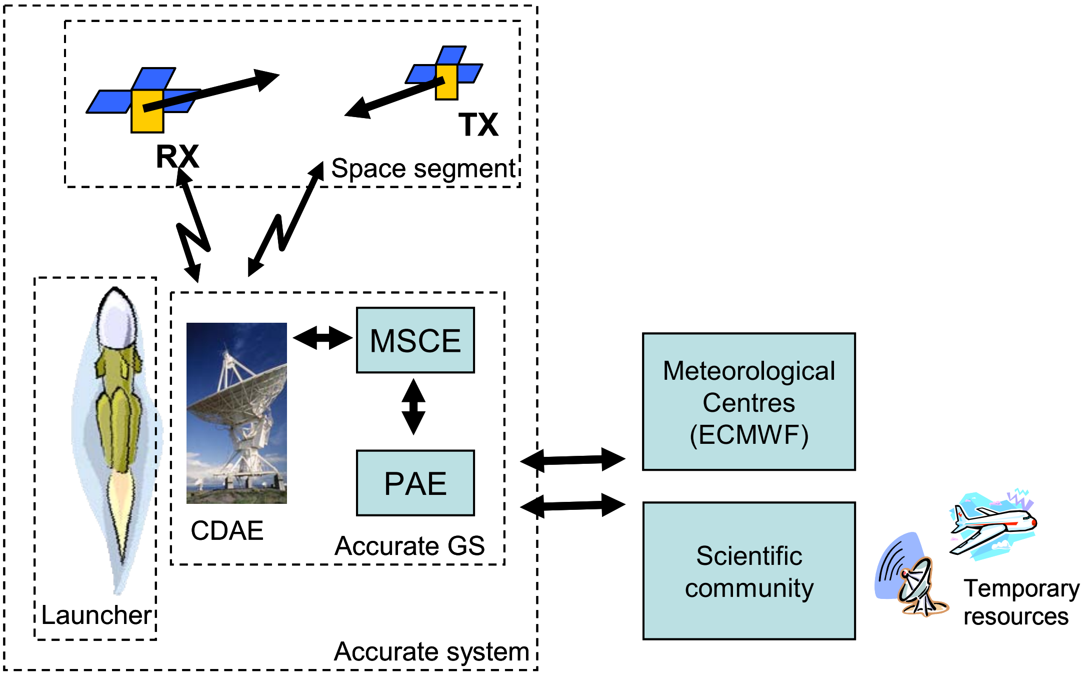
The combination of the active IR/MW limb sounding of ACCURATE and the passive IR/MW radiometric sounders thus provides substantial added value to any system (e.g., data assimilation and modeling system) using both data sources.

Regarding greenhouse gases, given that the surface- and boundary layer-oriented observation systems like GOSAT and ground network sites and the UTLS-oriented ACCURATE system focus on complementary spatial domains, the complementarity of their information content is near-ideal: The former are responsible for the source/sink relationships, flux, and concentration within the boundary layer while the latter provides an authoritative free atmosphere "boundary domain", e.g., in joint assimilation of both data sources into global 3D composition models.

Overall we find ACCURATE to offer in all respects, its own unique strengths as well as its synergies and complementarities with other missions and greenhouse gas data, exciting prospects and a ground-breaking potential especially for climate monitoring and research.

5. Proposed Mission Architecture

5.1 Mission Architecture Overview



CDAE	Command and Data Acquisition Element
MSCE	Mission Operations and Satellite Control Element
PAE	Processing and Archiving Element

Figure 5.1-1: The ACCURATE mission architecture and system context.

Space segment. The space segment consists of the two spacecraft. The TX satellite carries the LIO and the LMO transmitters while the RX satellite carries the receivers of both instruments. Both satellites have an AGSA which allows timing and POD based on GPS.

Ground Segment. The Ground Segment will reuse ESA resources to the maximum extent, there will however be embedded some ACCURATE ground segment infrastructure, even if shared with other missions. In addition the ground segment will incorporate dedicated infrastructure and tools such as planning tools and special flight dynamic functions.

Launcher Segment. The launch is a service from the launcher provider. However, there are elements and activities associated to the launcher within the ACCURATE development.

External interfaces. There are two main external entities providing and receiving data from the ACCURATE system:

- An operational stream of atmospheric short-range forecast data fields (from ECMWF) at coarse resolution (baseline T42) will be used to maintain a refraction modeling capability on which regularly uploaded (baseline daily) refractivity and pointing profile information is based.
- During the early "drifting period" phase of the mission ground/airplane receivers will be served (baseline on a best effort basis) by the TX satellite (see section 5.5).

5.2 Orbits and Profiling Characteristics

The need of producing near-vertical sounding profiles of the atmosphere for adequate climate benchmarking profiles (requirements Tables 4.2-2 and 3.2-1) drives the orbit selection and quickly leads to a so-called "counter-rotating" configuration (ALODM, 2010). The spacecraft involved in the LMIO cross-links fly on orbits having roughly superimposed orbital planes and opposite rotation directions. This way, when they cross each other, the tangent point of the occultation rays quickly crosses the atmosphere with a minimal horizontal displacement (less than 50 km, fulfilling target requirements; cf. footnote 6 of Table 3.2-1).

Figure 5.2-1 illustrates the movement of the tangent point as evaluated for the baseline orbits (see below) from 3D ray tracing through three representative FASCODE atmospheres for MW and IR signals: it samples the altitude range of interest from 3 to 80 km (cf. Table 4.2-2) within 40 s under all atmospheric conditions, with a vertical scan velocity within about 0.5 to 2.8 km/s; the core altitude range from 5 to 60 km is sampled within 30 s at scan velocities of about 1 to 2.8 km/s. These are favorable geometrical conditions for accurate profiling.

The difference of MW and IR occultation rays emerging below 8-12 km (difference between Smith-Weintraub-type MW and Edlen-type IR refractivity in moist air) is rigorously accounted for in the data processing (section 3.3); it is also small enough that the pointing of payload antennas/telescopes driven by IR refractivity accommodates also MW needs down to the 5 km target requirement bottom altitude (difference up to ~0.6 km at 5 km in moist air).

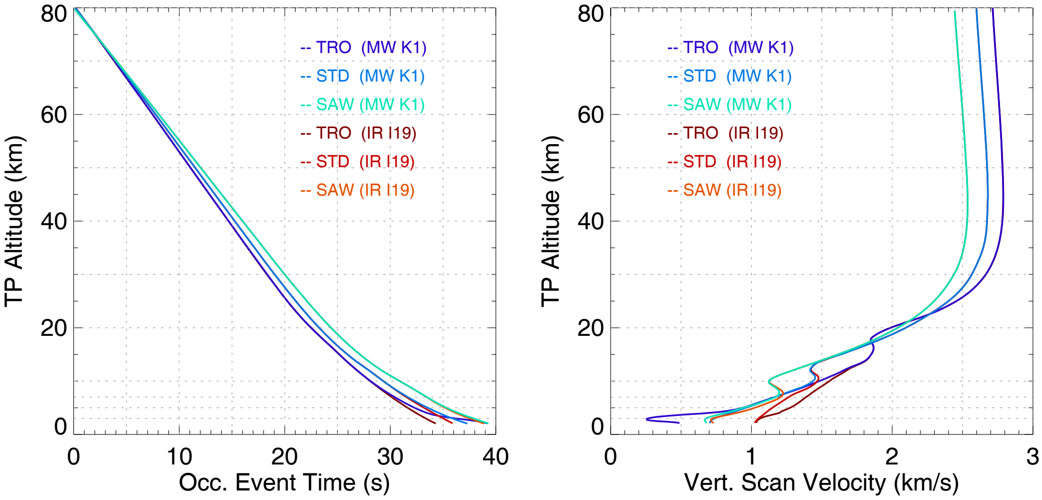


Figure 5.2-1: Occultation event time (left) and vertical scan velocity (right) profiles vs. tangent point altitude for the baseline orbits.

In order to ensure global coverage of the Earth, the proposed two ACCURATE satellites fly on 2 near-polar orbits with slightly different altitudes (512 km and 595 km), optimizing the spatial/temporal sampling characteristics of the geographical distribution of the occultation events, including accounting for the preferences for coverage repeat pattern of this demonstration mission as well as for local time sampling more than once per season (see section 5.5). The counter-rotating configuration is obtained through a RAAN separation of 180°. Combined with the altitude, two slightly different inclinations (80° and 80.4°) provide the same RAAN drift rate and therefore the stability of the constellation.

The 80° inclination has been preferred over true-polar or sun-synchronous inclinations because it provides favorable sampling of the local time (~9.5 min/day). Both orbits cover the entire 24-h local time clock in ~150 days, therefore, taking into account ascending and descending passes, all local time values are sampled near 5 times per year. Table 5.2-1 gathers the mean Keplerian elements of the two baseline orbits.

Table 5.2-1: Mean Keplerian Elements of Baseline Orbits

Mean Keplerian Elements	SatH (Tx) @ 595 km	SatL (Rx) @ 512 km
Semi-major axis	6973 km	6890 km
Eccentricity	1.12e-6 (frozen)	1.09e-6 (frozen)
Inclination	80.0°	80.41°
RAAN	Rx RAAN – 180°	Tx RAAN + 180°
Argument of Perigee	90°	90°
Mean Anomaly	270°	270°

Two Tx–Rx crossings happen per orbit (i.e., every ~48 min), each one producing two occultation events separated by about 12 min: a "rising" one (up arrows on Figure 5.2-2 below) and a "setting" one (down arrows). The satellites point at each other thanks to agile platform pointing (section 5.3.5), which also allows rotating them from the velocity-pointing attitude necessary for a rising event to the anti-velocity-pointing attitude of the next setting event.

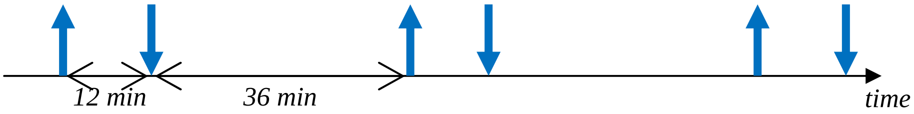


Figure 5.2-2: Time schedule of occultation events occurring per orbit.

Figure 5.2-3 illustrates the distribution of range profiles estimated from the 120 occultation events of 2 days and sampling all latitudes. The high linearity of the delta-signal travel time (constant travel time drift) implies that it can be modeled for the trigger time sequencing of the LIO payload as a simple frequency offset value, and mean time as function of occultation event latitude, all remaining static over the full mission lifetime in the baseline orbits.

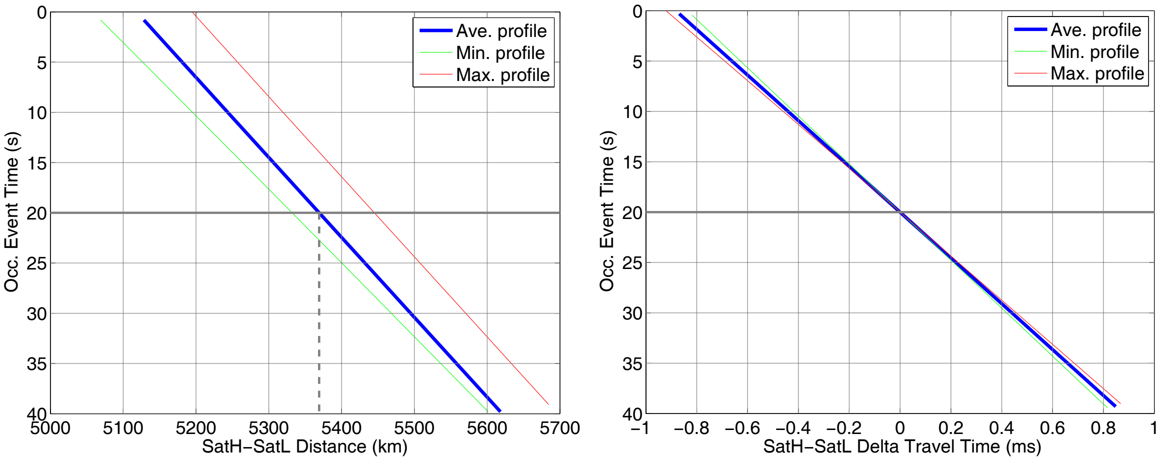


Figure 5.2-3: Variation of the straight-line inter-satellite range (left) and of the delta-signal travel time with respect to the reference travel time at T_{20sec} (right) between SatH and SatL for the baseline orbits (average, min, and max cases; the distance / T_{20sec} value of the average is 5369.3 km / 18.002 ms).

Figure 5.2-4 illustrates the distribution of the kinematic Doppler shift, computed along straight-line rays, between SatH and SatL. The along-ray Doppler shift ranges from about 13.9 km/s for equatorial measurements to about 12.5 km/s for polar ones. It is highly predictable from the precise orbits for the Doppler knowledge needs of the payload. Figure 5.2-5 finally provides a 3D view of the orbits illustrating the typical near-meridional character of occultation event acquisition (in line, e.g., with the l.o.s. wind preferences; Table 3.2-1).

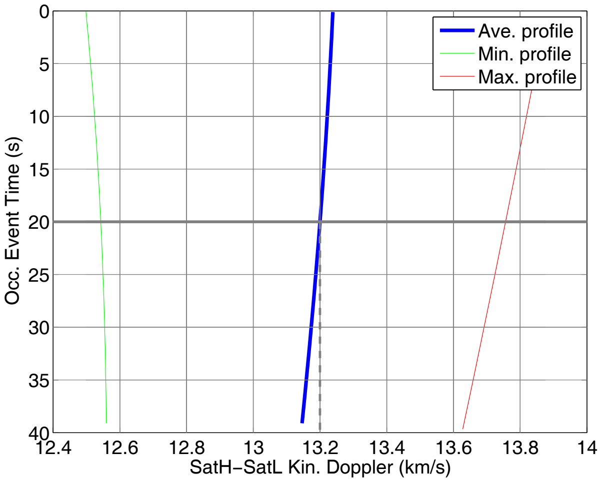


Figure 5.2-4: Kinematic Doppler shift between SatH and SatL (average, min, and max cases).

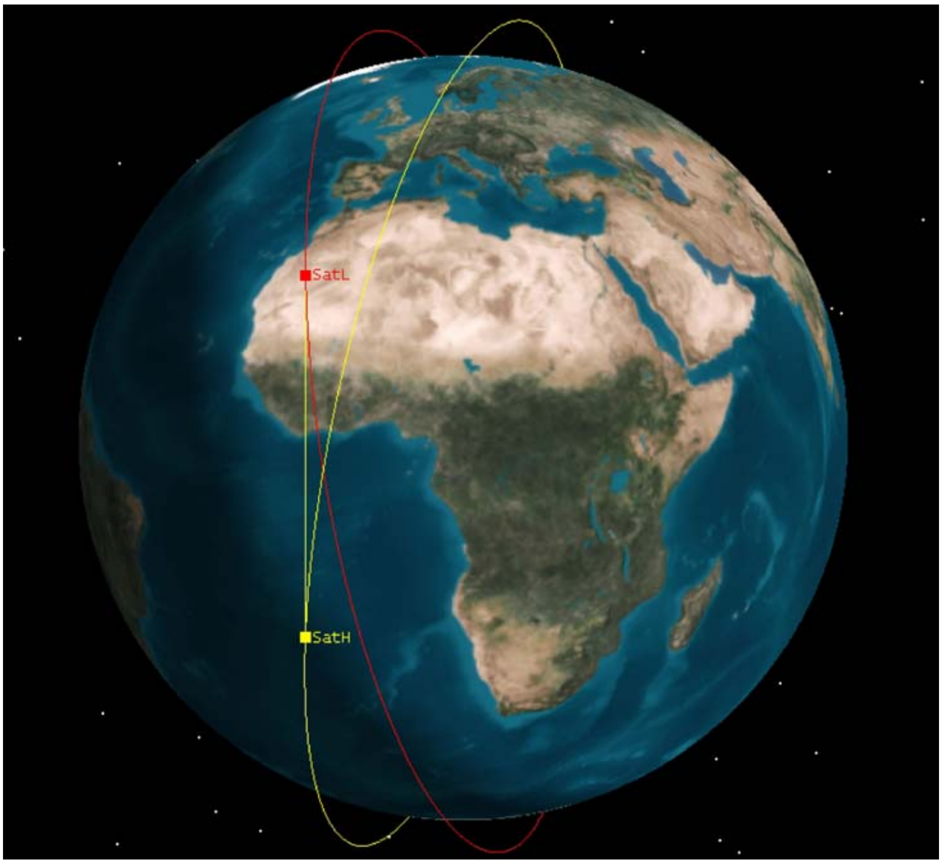


Figure 5.2-5: 3D illustration of ACCURATE counter-rotating satellite configuration.

5.3 Space Segment

5.3.1 Space Segment Architecture and Elements

The suggested space segment concept can be described as a **“snap-shot formation flying concept”**. Both spacecraft will have a basic mode, the Power Mode, which optimises the power generation and ensures an optimal geometry for the **AGSA POD receiver** antenna.
Both spacecraft will perform an attitude manoeuvre to acquire the Observation Mode and perform the occultations four times per orbit (see section 5.2) by the **AMOS and AIOS payloads** (overview in section 5.3.2., then dedicated descriptions in sections 5.3.3 and 5.3.4). After the occultation event the satellites will again return to the Power Mode. This leads collectively to occultation event coverage in line with the requirements (part of section 5.5). The **two-spacecraft system** and the **Tx and Rx platforms** are described in section 5.3.5.
The pointing is performed based on orbital models on both spacecraft that are updated from ground. Each satellite carries a GPS receiver providing data for the orbital predictions which will be performed on ground.
As described in the **operational concept** (part of section 5.5) the baseline is that attitude profiles will be uploaded to the spacecraft, i.e., the on-board autonomy, in terms of attitude control, is limited to the spacecraft and safe modes (initial detumble and Safe Sun).

5.3.2 Payload Instrumentation Overview

The payload of the ACCURATE mission consists of:

- The **ACCURATE Microwave Occultation Sensor AMOS** and **ACCURATE GRAS Support Assembly AGSA**, where AMOS is the LMO K band instrument system composed of the AMOS transmitter (**AMOS-T**) and AMOS receiver (**AMOS-R**) instruments, respectively, and AGSA is the support payload for timing, navigation and AMOS signal processing, the timing and navigation also for the benefit of the AIOS payload,
- The **ACCURATE Infrared-laser Occultation Sensor AIOS**, which is the LIO SWIR band instrument system composed of the AIOS transmitter (**AIOS-T**) and AIOS receiver (**AIOS-R**) instruments, respectively.

AMOS implements the LMO observation technique described in section 4.1.2 while AIOS implements the LIO observation technique described in section 4.1.3. Together they provide the LMIO measurement system of ACCURATE. AGSA is a support payload for timing, navigation, and AMOS data processing with no direct science contribution.

The basis for the payload designs, described for AMOS and AGSA in the following subsection 5.3.3 and for AIOS in subsection 5.3.4, were the system requirements as summarized in section 4.2. It is found that the payloads can serve to meet the system requirements, and in turn the observational requirements, so that the proposing team would look forward to further advance this intriguing mission in a Phase A study.

5.3.3 LMO Payload AMOS (AMOS-T & AMOS-R) and Support Payload AGSA

Functional Overview

The AMOS instrument main objectives are:

- To provide three frequency LEO-to-LEO microwave occultation (LMO) measurements, which are performed by tracking signals emitted by transmitting ACCURATE satellites, as the signal traverse the atmosphere. From these measurements vertical profiles of refractivity and absorption can be derived (see Figure 4.1-1 and the LMO description in section 4.1.2).

The AGSA instrument (support payload) is a standard dual frequency POD receiver that has two main objectives:

- To acquire data for Precise Orbit Determination (POD) of the host satellite, this is performed by tracking GNSS signals received through the zenith chain
- To provide real time navigation solution and timing, this is also performed by tracking GNSS signals received through the zenith chain.

The payload is configured in one Transmitting (Tx) Satellite Configuration and one Receiving (Rx) Satellite Configuration. The AGSA instrument is accommodated on both Tx and Rx-satellites. The two instruments share one Ultra Stable Oscillator (USO), physically integrated to AGSA. Figure 5.3.3-1 below shows the payload block diagram for the Tx Satellite configuration.

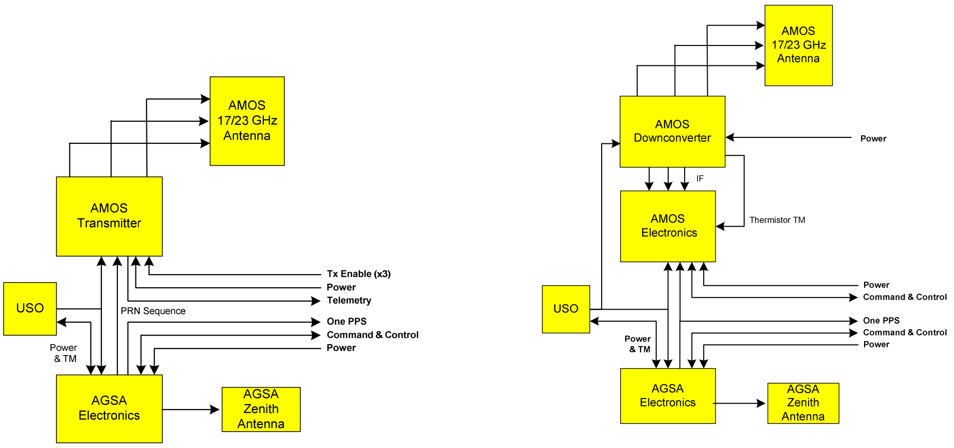


Figure 5.3.3-1: AMOS/AGSA block diagrams for Tx satellite (left) and Rx satellite (right) configuration.

AMOS Instrument

The AMOS has a heritage from the ESA WATS and ACE+. The instrument is divided into AMOS-T for the transit part and the AMOS-R for the receive part, see Figure 5.3.3-2. AMOS-T generates signals at three different frequencies in Ku- and Ka-band, referred to as A3, A2 and A1. These signals are derived from, and will be phased locked to, the USO reference, which is part of the AGSA. The AMOS-T consists of the following units:

AMOS-T is composed of:

- AMOS K-band Antenna (AKA)
- AMOS Transmitter Units (ATU-A1, -A2, -A3), which generates and high power amplifies the A1, A2 and A3 signals.

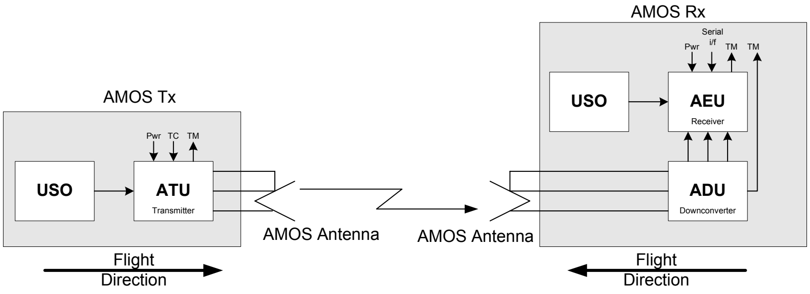


Figure 5.3.3-2: AMOS instrument overview.

The received A1, A2 and A3 signals are routed to the downconverters (ADUs). The ADU amplifies the low-level signals by approximately 35 dB and converts them to L-band. These L-band intermediate frequency (IF) signals are passed to the AMOS electronic unit (AEU), which downconverts them to a lower IF frequency suitable for A/D conversion. These signals are further processed on the digital side, after which they are sent via a serial interface to the spacecraft for down loading to ground. To summarise, AMOS-R consists of the following sub-systems (S/S):

AMOS-R is composed of:

- AMOS K-band Antenna (AKA)
- AKA Downconverter Units (ADU-A1, -A2, -A3), which filters and down-converts the A1, A2 and A3 signals.
- AMOS Electronic Unit (AEU), which performs the signal processing.

Smooth conical horns are baseline for the AMOS antennas, one for each satellite. All three frequencies can be operated by the antenna. In order to accommodate three independent ports, the upper and lower frequencies will be combined with a diplexer to one of the linear polarisation ports, and the middle frequency to the orthogonal polarisation port.

Preliminary designs are made, optimised for maximum gain with a limitation on the length. An increased gain could be desired from a link budget point of view, but the rather narrow beam-widths of the achieved design generate non negligible gain errors due to pointing variation. The selected antenna size, gain and beamwidth is an optimum compromise between accommodated dimensions, required gain and beamwidth to control amplitude variations due to pointing stability.

The AMOS Transmitter Units (ATU-A1, -A2, -A3) will be 3 W SSPAs with automatic level control, (ALC). The ALC function implies that the SSPA have to be backed-off to allow for gain regulation. This will have impact on the power efficiency.

The AMOS Downconverter Units (ADU-A1, -A2, -A3) will convert the K-band signal to L-band and will be equipped with low loss WG RFI filter.

The AMOS electronic unit (AEU) is basically a GPS occultation receiver with L-band input and adapted software for the LMO mission.

AGSA Instrument (Support Payload)

The AGSA instrument is foreseen to be the existing RUAG POD receiver as developed for SWARM and the Sentinel missions. The basic function of the AGSA instrument is to measure the carrier and code phase of the signal emitted by the GPS satellites to provide real time navigation solutions and for POD processing on ground. The instrument supports the L1, L2 and L5 signals from GPS.

The AGSA is very mature at the TRL 8 level (cf. technology readiness levels at the end of this section 5.3.3).

AMOS Link Budget

The nominal AMOS link budget is shown in Table 5.3.3-1, for high altitudes above the atmosphere. Subtracting the total defocusing and absorption we obtain the signal C/N_0 for a specific altitude and atmosphere. The components in the budget are to be regarded as nominal. A total system margin of 1 – 2 dB is obtained when compared to the system requirement of 67 dBHz (Table 4.2-2). The link budget is made for the chosen baseline orbits 595 km and 512 km (see section 5.2).

Table 5.3.3-1: AMOS C/N_0 budget above atmosphere

Band	A3	A2	A1	Unit	Comment
Frequency	17.25	20.2	22.6	GHz	
Wavelength	17.4	14.8	13.3	mm	
Free space att	-191.9	-193.3	-194.2	dB	
TX Power (filter 0.1dB)	32.9	32.9	32.9	dBm	2 W Tx
Antenna loss	-0.45	-0.2	-0.45	dB	
TX Directivity	29.6	30.5	31.3	dBi	
RX Directivity	29.6	30.5	31.3	dBi	
Antenna loss	-0.45	-0.20	-0.45	dB	
Received power @ Ant.	**-100.7**	**-99.8**	**-99.6**	**dBm**	
System noise temp	371	399	395	K	
System noise temp	25.7	26.0	26.0	dBK	
Boltzmann’s const	-198.6	-198.6	-198.6	dBm/Hz/K	
Noise power density	-172.9	-172.6	-172.6	dBHz	
Implementation loss	1.0	1.0	1.0	dB	
System margin	3.0	3.0	3.0	dB	
C/No @ high altitude	**68.2**	**68.8**	**69.0**	**dBHz**	

Payload Budgets

Mass Budgets

The estimated mass for the AMOS and AGSA instruments is show in the Table 5.3.3-2 below. A contingency 20% has been applied to the AMOS instruments since this is a new design. The mass of the harness is based on assumed length between the units.

Table 5.3.3-2: Mass budget for AMOS Tx and Rx configurations

Unit / sub-unit	Mass [kg]	Remark
AKA	0.9	
Harness	0.4	Cables between CKA/ CTU
ATU	6.6	3 physical units
Total	**7.9**	
Contingency 20%	1.6	
AMOS-T Total	**9.5**	Including 20 % contingency
AKA	1.8	
ADU	3.0	3 physical units
Harness	0,2	Cables between CDU and CEU
AEU	4,3	
Total	**9.3**	
Contingency 20%	1.9	
AMOS-R Total	**11.2**	Including 20 % contingency

Table 5.3.3-3 below summarises the estimated mass for AGSA. The mass of the harness is based on an average length between the antennas and the AEU of 1.5 meters.

Table 5.3.3-3: Mass budget for AGSA

Unit / sub-unit	Mass [kg]	Remark
AZA	0.35	
Harness	0.2	1.0
AEU	3.1	Including USO
Total	**4.7**	**Including USO**

Physical Dimensions

Table 5.3.3-4 below summarises the estimated dimensions for the AMOS units.

Table 5.3.3-4: Dimensions of the AMOS units

Unit	Size (H x W x D) [mm^3]	Remark
AMOS-R: ADU (3x) AEU AKA	240 x 80 x 140 88 x 261 x 236 ϕ175 x 600	one unit per frequency band A1, A2 and A3
AMOS-T: ATU (3x) AKA	350 x 220 x 190 ϕ175 x 600	one unit per frequency band A1, A2 and A3

Table 5.3.3-5 below summarises the dimensions for the AGSA units.

Table 5.3.3-5: Dimensions of the AGSA units

Unit	Size [mm^3]	Remark
AZA	∅160 x 60	
AEU (H x W x D)	104 x 322 x 240	Including mounting feet, RF filters
USO (H x W x D)	31 x 51 x 51	

Power Consumption

Table 5.3.3-6 below summarises the estimated power consumption for AMOS-T and AMOS-R, which shows the average over an orbit. A contingency of 30% has been applied to account for uncertainties. The primary power bus voltage is assumed to be nominally 28 V.

Table 5.3.3-6: Power budget for AMOS Tx and Rx – average figures over an orbit

Unit / sub-unit	**Power [W]**	**Remark**
ATU	34.3	60 s warm-up, 15% utility, Peak: 103 W, Standby: 21 W
Contingency 30%	10,3	
Total AMOS-T	**45.0**	
ADU	16.7	
AEU	13.9	
Contingency 30%	9.2	
Total AMOS-R	**39.8**	

Table 5.3.3-7 below summarises the estimated power consumption for AGSA, which shows the average over an orbit. A contingency of 10% has been applied to account for uncertainties. The primary power bus voltage is assumed to be nominally 28 V. After power on, the USO has a warm-up period of 20 minutes when the power consumption is 6 W higher than the figures given below. The peak power during normal operation (occultation measurements) will not exceed the given figures by more than +10% after USO warm-up period.

Table 5.3.3-7: Power budget for AGSA – average figures over an orbit

Unit / sub-unit	**Power [W]**	**Remark**
AGSA Electronic Unit	16	average (20 W peak)
Reference Oscillator	1.8	(7.8 W during warm-up)
Contingency 10%	1.8	
Total AGSA	**20**	

Technology Readiness Levels

Table 5.3.3-8 shows the technology readiness of the AMOS and AGSA elements. AGSA is fully ready (TRL 8) and also for AMOS all subsystems are at least at TRL 5. These payloads are thus very mature and ready to go towards implementation without genuine new pre-developments. For AMOS this mainly holds true due to the heritage from ACE+ Phase A and related studies. The AMOS and AGSA payloads can meet their applicable LMO system requirements given in Table 4.2-2 (see to this end also ESA, 2004b).

Table 5.3.3-8: TRLs for the AMOS and AGSA payloads

Mission Element	**TRL**	**Comment**
AMOS Subsystem	5	New system Based on existing technology
AMOS: Receiver	6	Known technology but demanding performance requirements
AMOS: Antennas	8	
AMOS: Transmitters	7	Efficiency crucial for small S/C
AGSA Receiver	8	

5.3.4 LIO Payload AIOS (AIOS-T & AIOS-R)

Baseline AIOS Payload Design

The AIOS payload consists of transmitter, receiver, and calibration units. The transmitter emits multiple laser wavelengths which cross the Earth's limb and reach the receiver (see, e.g., Figure 4.1-1 in section 4). The receiver measures the intensity of the incoming laser wavelengths using three interferometric spectrometers. The calibration unit provides stabilisation and monitoring of the intensity and wavelengths of the emitters.

Both the transmitter and the receiver are built on modular principles. Multiple transmitter and receiver modules are used to cover the measurement wavelengths. All transmitter modules share a common electro-opto-mechanical transmitter design. Similarly, all receiver modules share a common electro-opto-mechanical receiver design. This solution provides significant advantages in terms of cost efficiency, flexibility to mission scenarios and science goals:

- The basic transmitter module requires one time development. It can be tuned to other wavelengths by replacing the diode lasers. The basic receiver module also requires one time development. It can be shifted to a different wavelength range by replacing optical components or detectors of the same type. This approach greatly reduces the space qualification costs.
- The design of the modules is common for all mission scenarios also beyond proposed pioneering ACCURATE mission, such as separate transmitter and receiver satellites, combined transmitter/receiver satellites or multiple pair of satellites.
- It is possible to extend the science measurements by adding more laser wavelengths at low engineering cost simply by increasing the number of laser modules. Additionally it is possible to tune the lasers to other wavelengths during flight for real-time response to scientific needs.

Each transmitter module provides 5 laser wavelengths via a common optical output. It should be noted however that a solution is possible in which one transmitter module provides 6 laser wavelengths. The trade-offs concerning mass, power, cost and reliability require analysis at the stage of the detailed design.

Each receiver module covers a certain spectral range around a selected central wavelength. Separate receiver modules cover 2100 nm, 2350 nm and 2450 nm regions. Increasing the number of measurement wavelength in these measurement ranges does not require increasing the number of the receiver modules.

The proposed mission scenario uses one transmitter and one receiver satellite, Figure 5.3.4-1. The transmitter satellite provides up to 24 discrete laser wavelengths. Baseline is that it would use six laser modules with 5 lasers each to cover these wavelengths (including some spares). Five modules could also be used but lead to wavelength combinations that are technologically less convenient. Four modules of 6 wavelengths could also be used at the cost of low redundancy and more complex module design. A calibration module is envisaged on the transmitter satellite to meet the stringent measurement accuracy requirements. The receiver consists of three spectrometer modules – one for SWIR A and two for SWIR B and a calibration module (not shown). The calibration module on the receiver satellite is fairly simple. It has auxiliary health monitoring function and is not critical for the science measurement.

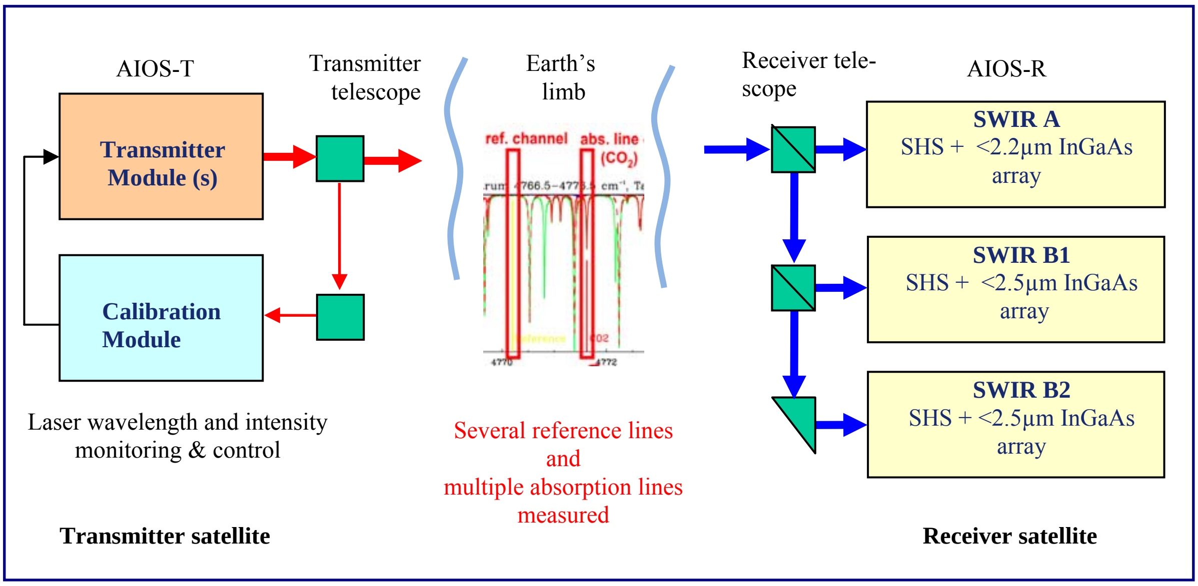


Figure 5.3.4-1: Baseline structure of the optical section of the IR laser payload AIOS.

The outputs of the laser modules are combined externally into a single transmitter telescope. The receiver modules share a single receiver telescope. The wavelength separation is challenging for purely optical multiplexing and de-multiplexing. For this reason additional time multiplexing and de-multiplexing is implemented.

AIOS-R Payload

The spectrometer design requires a combination of narrow FWHM and high cross-channel attenuation, Table 5.3.4-1. Further to that the low signal level and the short detection time call for maximum signal collection efficiency from the optical system.

Table 5.3.4-1: Overall main specifications of the receiver spectrometer of AIOS-R

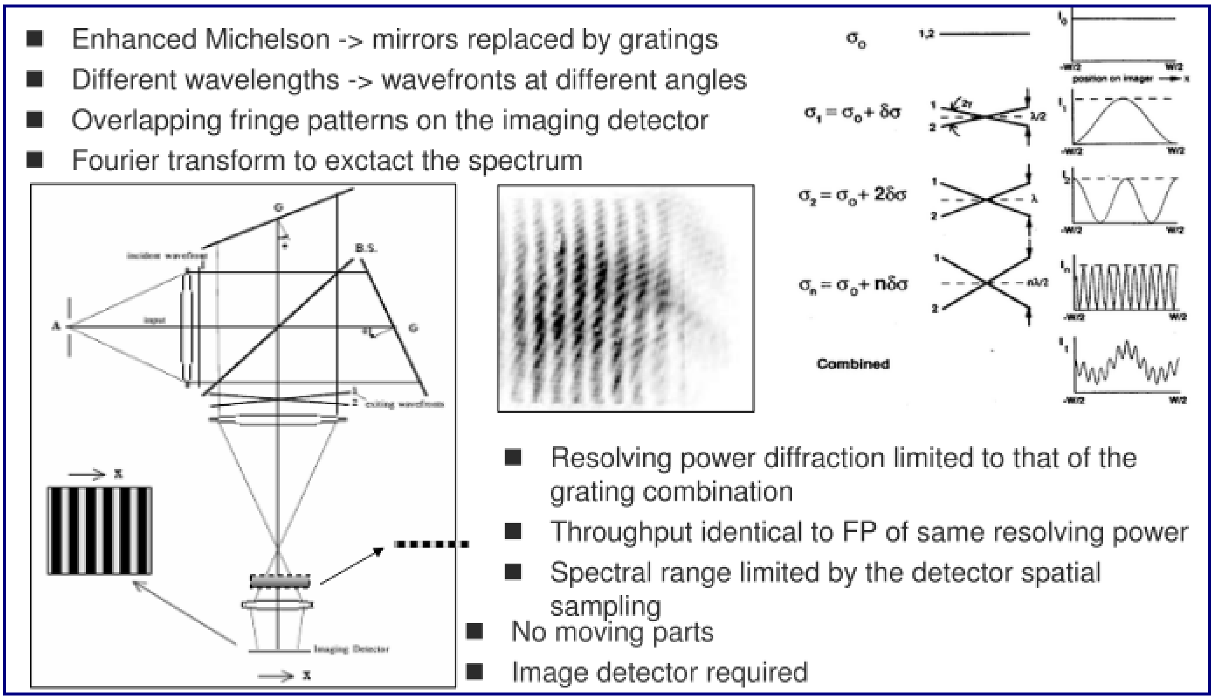
Parameter	**SWIR A**	**SWIR B1**	**SWIR B2**
Channel (spectral) resolution $\delta\lambda_{ch}$, nm	**< 0.64**	**< 1**	**< 1**
Instrument function FWHM max $\delta\lambda_{FWHM\ max}$, nm	**< 0.12**	**< 0.16**	**< 0.16**
Spectral range $\lambda1 \ldots \lambda2$, nm	2090...2130	2300...2380	2435...2485
Span $\Delta\lambda = \lambda1 - \lambda2$, nm	40	80	50
Ratio $\Delta\lambda / \delta\lambda_{ch}$	**63** (1)	**80** (1)	**50** (1)
Ratio $\Delta\lambda / \delta\lambda_{FWHM\ max}$	**333** (2)	**500** (2)	**313** (2)
Resolving power $R = \lambda / \delta\lambda_{FWHM\ max}$	**17500** (3)	**14600** (3)	**15400** (3)
Cross-channel attenuation, dB	**>36**		
Equivalent cross-channel transmission	$< 2.5 \cdot 10^{-4}$		
NEP for 2ms integration time, W	$< 8 \times 10^{-13}$		
Dynamic range	> 2000		
Required SNR	> 500		
Detector readout time $\tau_{R/O}$, ms	< 0.5		
Notes: (1) Spectral channels in each range. One spectral channel must cover several FWHM in order to satisfy the crosstalk suppression requirement; (2) Indicative for the number of detectors required in a (1D) detector array used; (3) Defined for FWHM of the instrument function			

The evaluation of the optical throughput during the preliminary studies showed that a diffractive grating solution cannot be used within reasonable mass and size constrains. Interferometric measurement provides significant advantages terms or spectral resolution and throughput.

The standard DIAL approach using fixed interference filters for the reference and measurement wavelengths looks like a natural solution for the detection system. However, the detailed analysis shows that it is difficult to scale up to such number of wavelengths. Additionally, there is a technological challenge of producing filters with the required bandpass combined with high suppression ratio close to the peak transmission. An alternative is using multiple Fabry-Perot etalons. However, the etalons cause further complications related to matching the peak of their narrow pass band with the incoming laser wavelengths, which are subjected to variable Doppler shift during the descending and ascending occultations.

In contrast, an interferometric spectrometer design solves these issues by providing a measurement that is inherently insensitive to Doppler shifts and absolute position of the laser wavelength. It also allows background measurement in the regions outside laser channels. This feature can be used to increase the accuracy of a single pulse measurement.

The proposed baseline receiver design uses a Fourier transform spectroscopy technique known as Spatial Heterodyne Spectrometry (SHS), Figure 5.3.4-2. It allows building high resolution interferometric spectrometers with no moving parts at the cost of operating in relatively narrow (tens of nm) fixed spectral range. In this application, because of the a-priory known spectrum of the incoming signal, a modified SHS design can be used. It incorporates 1D detector array instead of the standard for the SHS method 2D array. Given the limited choice of space qualified 2D detectors for the spectral range of 2100 nm to 2500 nm, such modification significantly simplifies the development of the detection system.



- Enhanced Michelson -> mirrors replaced by gratings
- Different wavelengths -> wavefronts at different angles
- Overlapping fringe patterns on the imaging detector
- Fourier transform to exctact the spectrum

- Resolving power diffraction limited to that of the grating combination
- Throughput identical to FP of same resolving power
- Spectral range limited by the detector spatial sampling
- No moving parts
- Image detector required

Figure 5.3.4-2: Principle of operation of the SHS interferometer of the AIOS-R payload.

AIOS-T Payload

The Calibration module is a critical element of the Transmitter payload. It provides information about the laser intensity and wavelength so that the respective measurement errors are minimized. As a baseline the module includes a gas absorption reference, its own laser source, means for multiplexing of several laser inputs, wavelength shift measurement device and electronics generating laser wavelength correction signal. The own laser source is stabilized with respect to the absorption reference. The transmitter module includes a detector part for monitoring the intensity of the outgoing laser signals.

The structure of the transmitter is illustrated on Figure 5.3.4-3. Two modules only are shown to demonstrate the principle. Note these serve, same as in the subsequent Table 5.3.4-2 and Figure 5.3.4-4, as generic examples only, holding still Channel ID names from the ESA LODM study (ALODM, 2010); actual design will directly use the channel set of Table 4.2-1.

The wavelengths are combined inside the laser modules using fibre optics. The optical outputs of the modules are combined by external beam combiners and fed into a common transmitting telescope. The transmitter uses seeders that are separated from the amplifiers and coupled as needed. Both the seeders and the amplifiers are pumped continuously for better stability. To avoid pulsing of the amplifiers they run at the same average power all the time, always amplifying two wavelengths. One of them is constant while the other one changes. In a fully used 5 wavelengths module four wavelengths would be consecutively coupled into SOA in parallel with the fifth one. The stability of the output pulse intensity and power is improved by using the seed lasers in CW mode, externally modulating them before the SOA and keeping the SOA at constant load. The modulation solution uses fibre coupled standard electro-optics modulators. It will be optimized at the detailed design as it must provide high suppression along with controllable phase delay of the pulse with respect to the clock.

The field of view of the telescope covers the angular zone in which the receiver satellite moves during the occultation event. This eliminates the need of tracking mechanism in the transmitter telescope. However, it also leads to loss of energy for illuminating such a large zone. Additionally, potential non-uniformity of the laser intensity in the illuminated zone would be a source of additional measurement error. To compensate for this the design makes use of the facts that both satellites rotate in the same plane and the SOA provide good beam quality. The transmitting telescope incorporates beam shaping optics, which converts the output Gaussian beam into highly elliptical beam with uniform intensity, illuminating only the plane of rotation of the receiving satellite.

The timing is organised around a 20 ms measurement period (50 Hz sampling rate; cf. Table 4.2-2), and Figure 5.3.4-4 is divided in 4 time slots. Each module emits two wavelengths in every time slot to keep the average load on the SOA constant. One of them is usually the common reference. In the generic example shown in Table 5.3.4-2 and Figure 5.3.4-4 the reference is emitted by module 1. Module 2 uses the same reference but to keep the load on the SOA constant it repeats the wavelength I21 instead. One spare laser is available in module 2. Each time slot is further split into four parts – 2 ms for laser pulse measurement, 0.5 ms for data readout, 2 ms for background measurement and another 0.5 ms for data transfer.

A key part on the overall AIOS is the use of time multiplexing. In a non-multiplexing scheme the design of the spectrometer would be driven by the closest pair of wavelength that need to be resolved. These are the wind measurement channels which require extremely high spectral resolution. Using time multiplexing, the system trades off the spatial (vertical) resolution in the wind channels for simple receiver design. The time multiplexing enables measurement of wavelength pairs that are beyond the spectral resolution of the spectrometer.

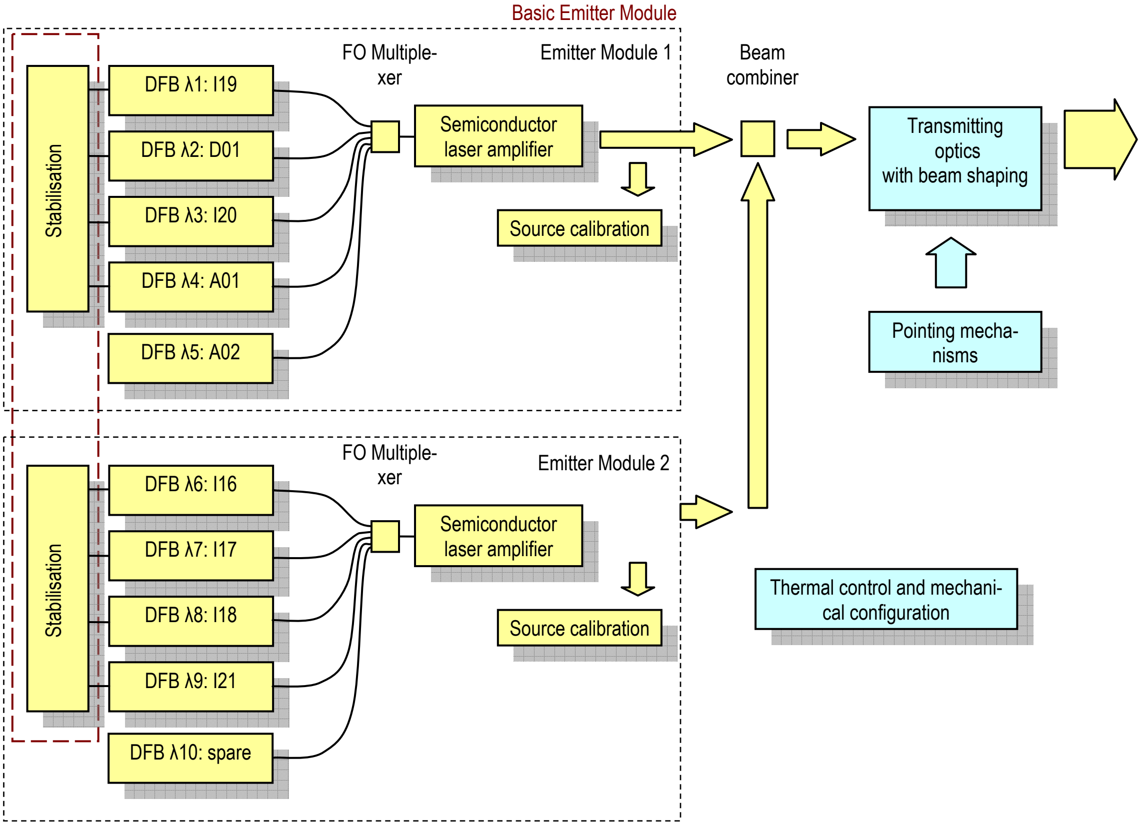


Figure 5.3.4-3: AIOS-T configuration showing the chain from emitter modules to transmission.

Table 5.3.4-2: Time multiplexing example

	Module 1					Module 2				
	I19	D01	I20	A01	A02	I16	I17	I18	I21	spa-re
T1	🟩	🟧				🟧			🟧	
T2	🟩		🟧				🟧		🟧	
T3	🟩			🟧				🟧	🟧	
T4	🟩				🟧				🟧	

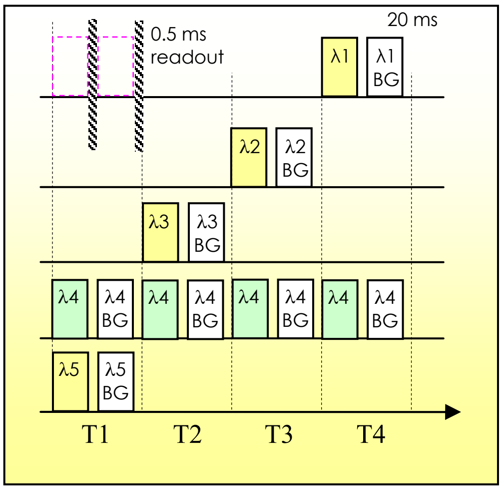


Figure 5.3.4-4: Time-spectral organization for Module 1 (λ4 = I19, λ5=D01, λ3=I20, λ2=A01, λ1=A02). The timing of Module 2 is similar except λ5 is not used.

Table 5.3.4-3 shows the estimated link budget from this design in the same form as the example link budget was provided in section 4.2.2. The budget reflects the performance of the relevant AIOS elements considered, mostly based on the ESA LODM study work (ALODM, 2010) but work for proposal preparation further consolidated it (also the example link budget was based on that work so in Table 5.3.4-3 the difference is from shorter Tx-Rx distance). The AIOS design meets the system requirements on the link budget with some margin, ensuring the science performance of the LIO measurements.

Table 5.3.4-3: AIOS baseline link budget for the LIO measurements

Element / Link Process	**Budget (dB)**	**Budget (W)**
Emitted laser pulse power (over 1.5 ms), also denoted Tx power	0 dBW	1 W
Propagation loss1): laser beam divergence full angle 3 mrad (e^{-2}), 5600 km Tx-Rx distance, 36 cm diameter (circular) Rx optics	-90.5 dB	8.9 x 10^{-10} $^{W}/_{W}$
Received pulse power	-90.5 dBW	8.9 x 10^{-10} W
Reception loss: Tx pulse duration / Rx integrat. time (1.5 ms / 2 ms)	-1.25 dB	0.75 $^{W}/_{W}$
Total optical loss – front optics to detector (assumed to be 35%)	-1.85 dB	0.65 $^{W}/_{W}$
Pulse power at detector	-93.6 dBW	4.4 x 10^{-10} W
NEP of IR detector system within 2 ms (detectivity D* ~ 1.4 x 10^{12})	-121.4 dBW	7.2 x 10^{-13} W
SNR at detector for pulse sequence at 50 Hz sampling rate	27.8 dB	600 $^{W}/_{W}$
Downsampling gain (from 25 to 1 Hz bandwidth, SqRt(25))	7.0 dB	5 $^{W}/_{W}$
Achieved S/N_0 at TOA at 1 Hz bandwidth	**34.8 dBHz**	**3000 $^{W}/_{W}$**
Required S/N_0 at TOA at 1 Hz bandwidth (from Table 1)	34 dBHz	2500 $^{W}/_{W}$

Mass and Power Estimates

The mass/power estimates are given in Table 5.3.4-4, where here “basic mission” stands for an implementation without channels I01-I04 and I07-I08 (cf. Tables 3.2-1 and 4.2-1 and their footnotes) and “full mission” stands for the complete implementation of all 21 channels which is the baseline.

The transmitter section includes partial redundancy, the calibration and the receiver sections do not include redundancy. The mass estimate of the receiver module is driven by the overall instrument size. It depends on the required spectrometer resolution. Cold stops are envisaged for reducing the internal background emission. The calibration module is assumed to be similar in size, mass and power consumption to a laser module. On estimated volumes, these have been provided to the proposal system partner SSC and found compliant with their platform.

Table 5.3.4-4: Mass and power estimates per satellite unit / module

		One generic module	Basic mission	Full mission
Wavelengths		5	15	21
Transmitter Unit AIOS-T				
Mass	kg	10	40	**60**
Power peak (during occultation)	W	25	100	**150**
Power average off occultation	W	1	4	**6**
Calibration Unit AIOS-T				
Mass	kg	10	10	**10**
Power peak (during occultation)	W	25	25	**25**
Power average off occultation	W	5	5	**5**
Receiver Unit AIOS-R				
Mass	kg	9	**18**	**27**
Power peak (during occultation)	W	45	**90**	**135**
Power average	W		**20**	**30**

Technology Readiness Levels

The preliminary TRL review shows high maturity of most AIOS technologies needed for the mission. The majority of the technologies required for the implementation of the mission are at high TRL. The following ones were evaluated at TRL higher that 4: DFB seed lasers SWIR A (2.1 µm); Detector Array <2.2µm; Gas absorption cell; Optical fibres; Wavelength multiplexing; Detector cooling; Optical path cooling; Pulse shape measurement; Pulse energy measurement; Laser and detector electronics.

The technologies that were evaluated at TRL 4 or lower are given in Table 5.3.4-5.

The critical system components that require development are the semiconductor optical amplifiers and the DFB lasers for the SWIR B region of 2.3-2.5µm. However, the starting point of these technologies is relatively high. Alternatives can also be considered, however the chosen transmitter solution has the advantage of SOA sharing. The detector readiness is considered relatively high.

Pre-developments at least on the transmitter module components and consolidation of wavelength control solution should be done in parallel to Phase A, all pre-developments to ensure TRL 5 throughout during Phases A and B.

Table 5.3.4-5: Summary of AIOS-required technologies with TRL 4 or lower

	Transmitter module	TRL	Risk	Effort	Possible options
T1	SOA SWIR A	4	L	M	Technology development is needed.
T2	DFB seed lasers SWIR B (2.3-2.5µm)	3 - 4	M	M	Technology development is needed.
T3	SOA SWIR B	3	M	M	Technology development is needed.
	Calibration module				
C1	Wavelength shift control	4	L	M	Specialized wavelength control devices can provide the necessary shift for Doppler compensation. The system take advantage of the long time available for laser preparation.
C2	Wavelength meter	3	M	M	Will be needed if wavelength shifters cannot be multiplexed satisfactory.
C3	Beam shaping	4	L	L	Must be implemented to ensure the link budget and relax the requirements to the intensity stability of the laser. Does not require technology development. Custom designed optical components may need to be produced using established technologies.
	Receiver module				
R1	Interferometer	4	L	M	NASA demonstrated in-flight. Requires dedicated ESA design effort but can be produced with standard grade optical components.
R2	Detector Array <2.5µm	4	L	M	Prototypes exist, but technology development will be required
R3	Detector Read-Out electronics	4	L	M	Existing camera electronics expected to be usable. Customization may be required to address the dynamic range and the timing of the signals.

5.3.5 Spacecraft System: Tx and Rx Platforms

The platform concept is based on the Prisma satellites. The Prisma platform has similar requirements on orbit manoeuvring capabilities and pointing performance. In addition, the payload mass is close to the one required by the ACCURATE mission. Prisma is a fully redundant platform with a high degree of autonomy. The software and the failure management are fully reusable for the ACCURATE satellites. In addition, the Prisma satellites, just as is foreseen for the ACCURATE mission, are launched in a combined configuration and are separated after orbit injection.

Even though the Prisma platform is highly suitable for the mission it is obvious that some areas must be adapted and customised e.g.:

- Structure, in particular the consequences of the stacked launch configuration, overall mass and delta-V capacity
- Pointing stability
- ΔV capacity
- Power subsystem performance
- Solar array configuration
- Payload interface

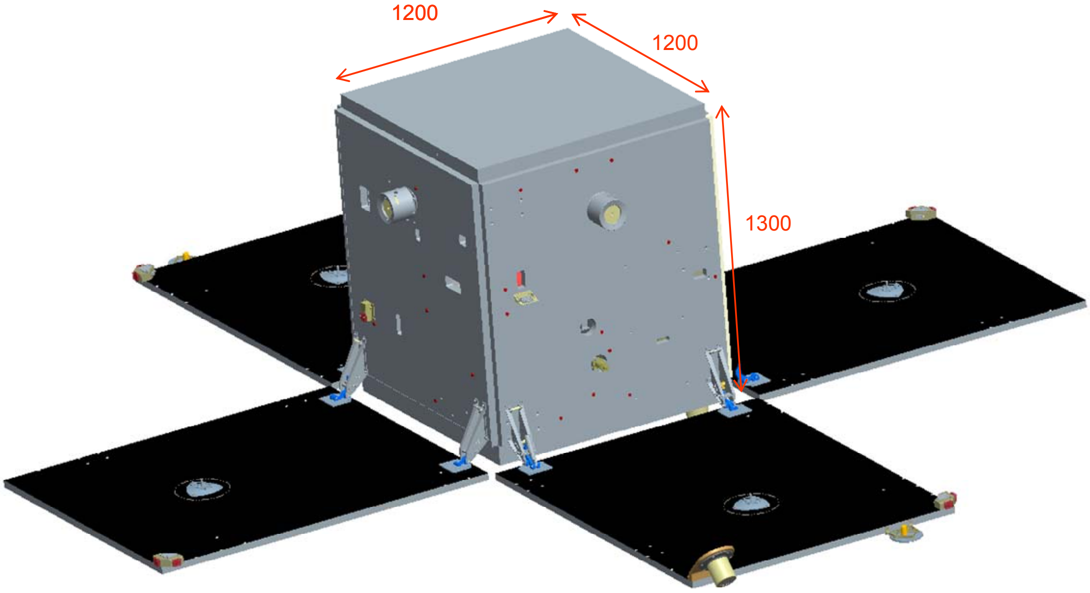


Figure 5.3.5-1: The modified Prisma platform.

The ACCURATE platform is dimensioned to accommodate a propellant tank of the right capacity as well as the electronic units for both platform and payload. The mounting of the payload transmitting and receiving equipment will be on the “top” panel in the figure. The panel does not contain any platform sensor apertures and provides ample space for the LIO telescope elements and the MW antennas. The design of the payload sensor interface is a critical area to be studied in the next phase, in particular for the lower satellite in a stacked configuration where a solution including the inter-satellite adapter must be found.

5.3.5.1 Data Handling

The Data Handling, including the on-board software, subsystem is based on the Prisma avionics which is built around a LEON 3 processor. The system includes; mass memory, TMTC handling, CAN and Spacewire busses and is considered well suited for the ACCURATE requirements on data rates and processor performance. The architecture provides redundancy and fundamental services in the area of system start-up and survival.

5.3.5.2 Structure and Mechanical Layout

Based on the Prisma design a preliminary assessment has been made of the impact on the design parameters. The proposed concept is to make the TX satellite the lower satellite in the launch stack since it carries considerably more propellant. The structural requirements, in particular for the "lower" spacecraft will be driven by the stiffness required by the Vega launcher. The consequences of this on the Prisma structure must be carefully assessed and might lead to that the "lower" spacecraft needs to have a structural design especially adapted for the launch configuration. In addition, an inter-satellite adapter and a separation system must be added. An alternative could be to exploit the concept of a dispenser. The Vega Launcher manual indicates that this could be a possibility.

Element	**Mass [kg]**
Platform	**222,9**
Power	62,6
Radio	7,4
Data handling	10,4
AOCS	43,1
Structure & Mechanisms	62,0
Propulsion	19,5
Thermal Control	3,0
Harness	15,0
Payload	
Transmitter S/C P/L	98,04
Receiver S/C P/L	63,1
GRAS POD	5,1
Separation system, Adaptor etc	48,0
TX S/C dry	**374,0**
TX Propellant	181,2
TX S/C wet	**555,2**
System Margin	**55,5**
Tx S/C final	**610,7**
RX S/C dry	**291,1**
RX Propellant	46,8
Rx S/C wet	**337,9**
System Margin	**33,8**
Rx S/C final	**371,7**
Total Launch mass	**982,4**

Table 5.3.5-1: Mass budget.

5.3.5.3 Thermal Control

The thermal system is based on passive control. For the payload instruments with high dissipation dedicated radiators might be required to ensure the thermal interface to the spacecraft platform. The system employs radiators, thermal blankets, MLI and heaters. Thermistor readings and heater control is performed by the On-Board software. For units which cannot survive a heater line failed "ON", hardware thermostats are connected in series with the heaters.

5.3.5.4 Attitude and Orbit Control System

The task of the Attitude and Orbit Control System (AOCS) is to control the spacecraft's orbit and attitude during all mission phases.

The AOCS will provide the following top-level functionalities:

- Measurement of spacecraft attitude via sensors
- Measurement of the spacecraft position via sensors
- Control of attitude through the use of actuators. In the sensing mode, reference attitude profiles will be used that have been determined on ground and uploaded to the spacecraft beforehand. The reference attitude profiles are based on GNSS data from the AGSA payload and bending angle models.
- FDIR to guarantee mission and spacecraft safety. Status control of attitude control hardware
- Communication with the system computer, including Telecommand handling and telemetry generation
- Autonomous angular momentum management

The attitude control and determination system uses full 3-axis control with reaction wheels, dual star cameras and rate gyros. Momentum dumping is performed via magnetorquers. One sun sensor and five sun presence detectors are used for safe mode handling.

The Pointing budget below is based in the Prisma platform performance. The contribution from the Payload uncertainties is limited to the uncertainty of the physical mounting of the payload (mirror cube alignment knowledge) and is assumed to be compensated for after in-flight calibration.

ACCURATE Error Summary		
Error Type	**Angle**	
With In-Orbit Calibration		
Absolute Pointing Error	0,05	mrad
Relative Pointing Error Over 20 s*	0,03	mrad

* with respect to a scanning profile

Table 5.3.5-2: Optimised pointing performance based on the Premier study.

The conclusion of a preliminary assessment is that the pointing performance of the Prisma AOCS concept is close to the ACCURATE requirements and that an optimisation of the performance will be successful, which is also backed up by study results for PREMIER.

The AOCS mode design is re-used from PRISMA and consists of the following modes:

The Safe mode has two sub-modes:

- Safe Detumble. This is the entry mode after separation and any other restart of the satellite. When body rates have been reduced a transition to Safe Sun will occur.

- Safe Sun. In this mode the satellite will ensure power and attitude safety.
- Observation mode is based on the pointing profiles uploaded from ground.
- Orbit Control Mode. The operations in this mode are planned fully on ground. A pre-defined attitude and thruster burn schedule will be performed onboard.

5.3.5.5 Propulsion

The architecture of the propulsion system shall be determined during the study. The TX SC will have the higher requirements on both “tangential” and out-of-plane manoeuvres. The baseline proposal is a 2 thruster configuration using either hydrazine or green propellant (HPGP). A preliminary assessment gives a propellant mass of 150 kg for the TX SC and 39 kg for the RX SC (without margin).

The determination of the optimal thrust force, especially considering the efficiency of the inclination manoeuvres will be carefully evaluated. In this context the requirements on the needed resilience to the parasitic forces created by the manoeuvres will be determined and could lead to a conclusion that a four thruster configuration with off-modulation would be more efficient.

5.3.5.6 Power

The combination of high instrument peak loads and the selected (local time drifting) orbits are the design drivers for the power subsystem performance. The conclusions of a preliminary analysis, using conservative assumptions, are presented below.

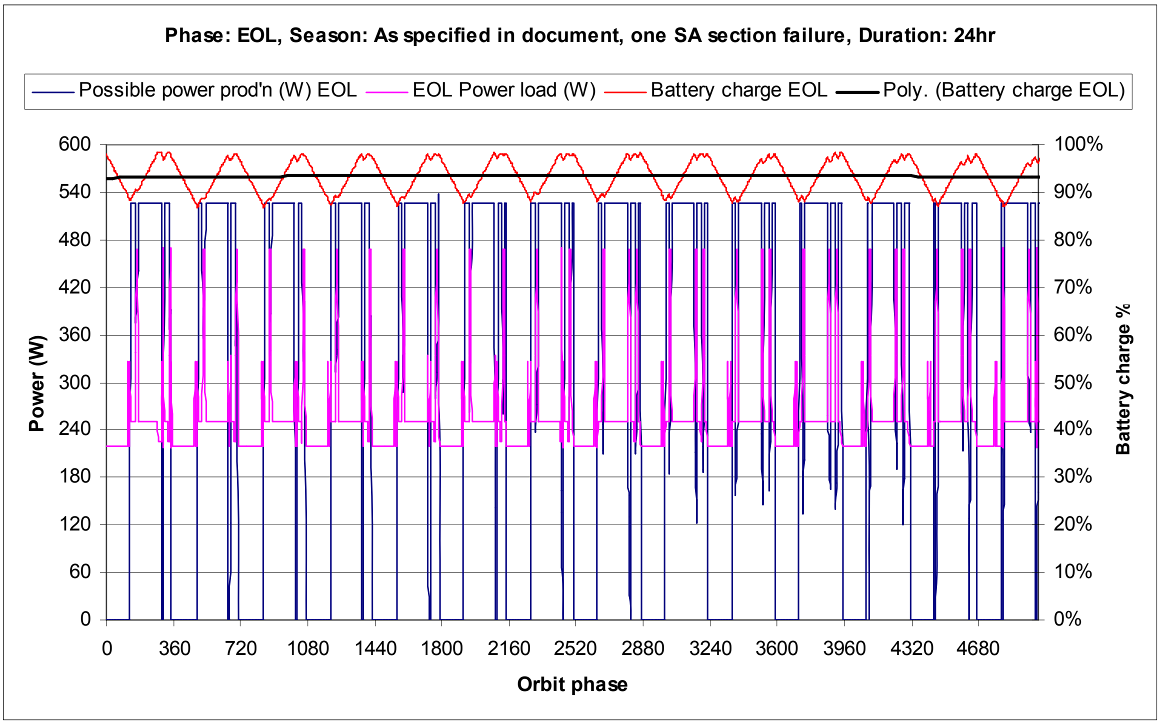


Figure 5.3.5-2: Power subsystem sizing.

The power subsystem contains the solar array, the battery and the Power Control and Distribution Unit (PCDU). The power bus is a regulated 28V bus. Power users are provided with power through resettable latching current limiters.

The PCDU "collects" the power produced by the solar arrays and the battery and distributes it to the various power users. Power is collected from the solar panels through solar array shunts also used to limit the power on the system bus by shunting parts of the solar array. Redundancy is achieved by using several shunts in parallel. Power users are connected to Latching Current Limiters. The solar array is divided into 4 deployable panels. The panels have heritage from the PRISMA mission.

5.3.5.7 Communication and On-board Memory Sizing

The average data generation rate is estimated to be:

Data Rate (kbps)	TX	RX
AIOS-T (~4% high rate)	8	
AIOS-R (~4% high rate)		8
AMOS-T	5	
AMOS-R (~4% high rate)		15
Platform TM	10	10
Total (kbps)	**23**	**33**

Table 5.3.5-3: Data rates.

Preliminary data management analysis assuming a high latitude station (Kiruna) and a typical 600 km orbit shows that an on-board memory of approximately 200 MB can sustain the nominal mission. In the graph below the nominal dynamic state of the mass memory is shown. Kiruna has 4 blind orbits during which the memory is being filled and subsequently it is emptied during the following 10 orbits. In the graphs below a downlink rate of 1.4 Mbps has been assumed. An S-band downlink below 2 Mbps has no restrictions in terms of special modulation techniques and is the baseline for the ACCURATE mission.

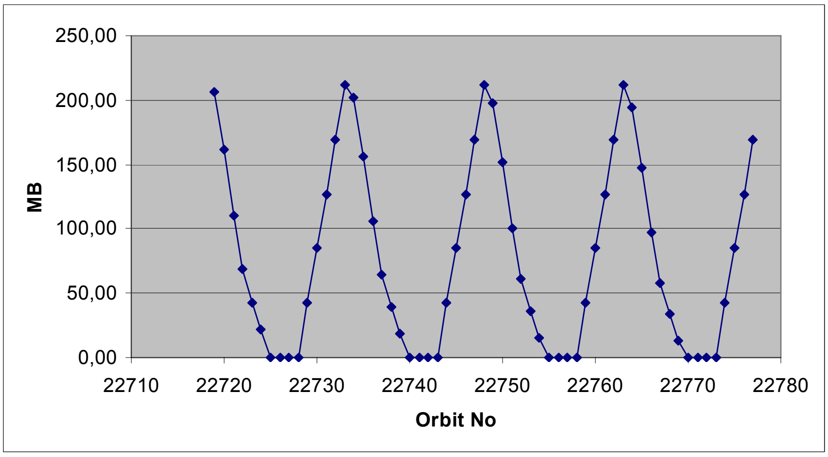


Figure 5.3.5-3: On-board memory sizing.

In order to allow some fault tolerance it can be decided how much margin shall be implemented. The phase A study will include an optimisation of the communication system and investigate which is the appropriate down link characteristics. Also the orbit determination aspects in case of AGSA outage will be addressed.

5.3.6 Launcher and Launch Configurations

The reference Vega mission is a polar orbit bringing a spacecraft of 1,500 kilograms to an altitude of 700 kilometres.
The ACCURATE mass is well below the capacity of Vega and an overall optimisation will be performed during the study. The fairing constraints are considered not to be critical for a dual launch of the ACCURATE satellites. Figure 5.3.5-4 illustrates the launch configuration.

The structural requirements, in particular for the "lower" spacecraft will be driven by the stiffness required by the Vega launcher. The Vega launcher manual states:

> "The cantilevered fundamental mode frequencies of a spacecraft hard-mounted at the interface with an off-the shelf adapter must be:
> In lateral axis:
> ≥ 15 Hz for spacecraft mass ≤ 2500 kg
> In longitudinal axis:
> 20 Hz ≤ F ≤ 45 Hz for spacecraft mass ≤ 2500 kg
> The cumulated effective mass associated to the longitudinal modes within the above frequency range must exceed 60% of the total mass."

The consequences of this on the Prisma structure must be carefully assessed and might lead to that the "lower" S/C needs a structural design especially adapted for the launch configuration. In addition a cylindrical inter-satellite adapter and a separation system must be added.

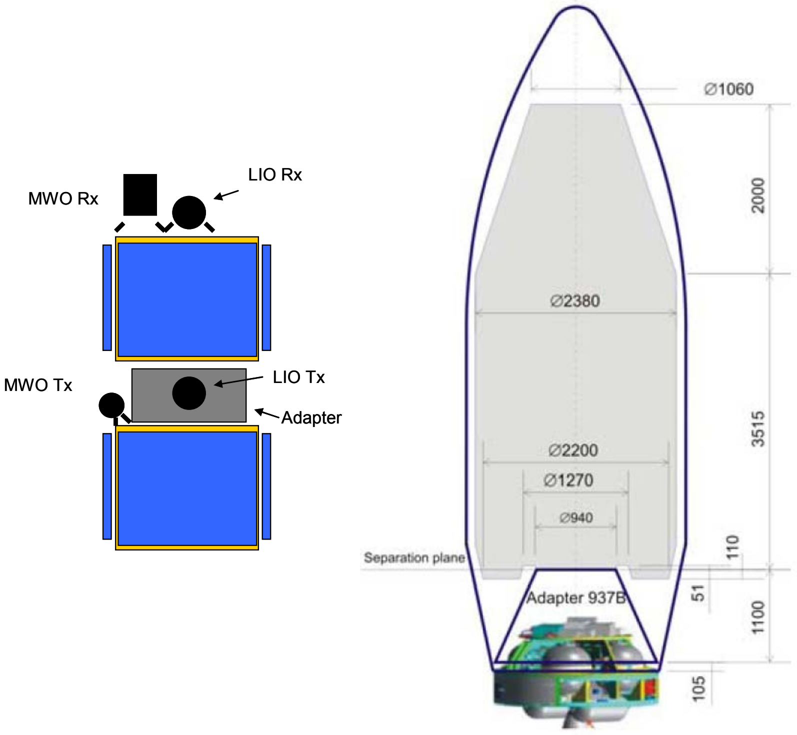


Figure 5.3.5-4: Launch configuration in the Vega launcher.

An alternative could be to exploit the concept of a dispenser. The Vega Launcher manual indicates that this could be a possibility: "For the multiple payload configurations, Arianespace proposes the use of the dedicated dual carrying structure or dispenser based on the experience and technologies developed through the Ariane 4 and 5 programmes (Sylda, Spelda, and Speltra)." This option shall be evaluated during the phase A study.

5.4 Ground Segment

5.4.1 Ground Segment Architecture and Elements

The Ground Segment consists of one or several ground stations, a spacecraft control system and a data processing element. Due to the fact that the ACCURATE mission is considered as a science and demonstration mission rather than an operational system the timeliness requirements are not severe. This allows for ground stations also on lower latitudes resulting in longer visibility outages. It is desirable that already existing ESA ground segment infrastructure is used. The up- and down link conforms to the PUS standard and the down link is using S-band. This means that the adaptations needed of any existing ESA ground station or mission control system should be limited. Apart from the timeliness of sensing data a low latitude station affects the on-board memory sizing, the required down link rate and the required platform autonomy. It is suggested to perform a system trade-off to arrive at an optimal solution adapted to the ACCURATE mission requirements.

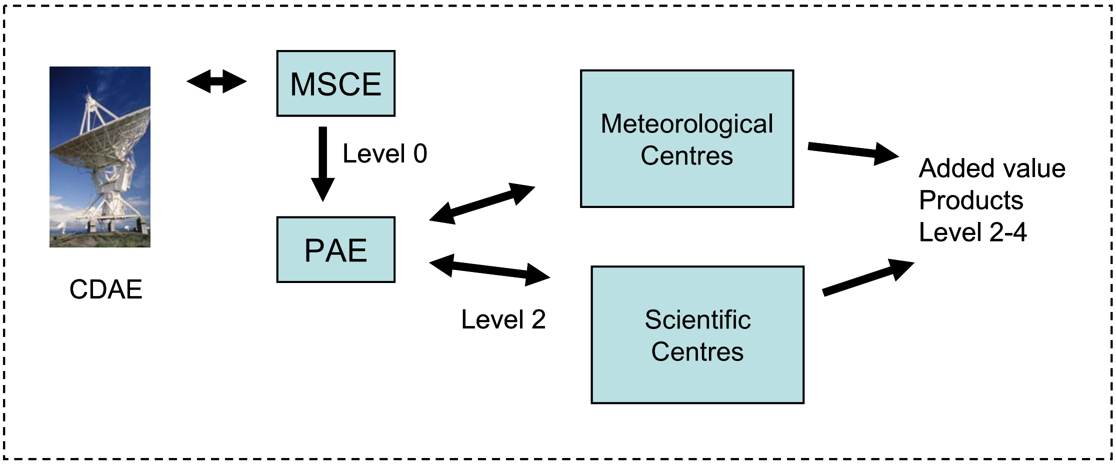


Fig 5.4.1-1: Ground Segment interfaces.

The ESAs facilities at ESOC will be baseline selection for the ACCURATE mission.
The CDAE consists of the primary station nominally located at Kiruna, supporting the following functions:

- Local monitoring and control of the ground station
- S-band satellite commanding and housekeeping telemetry acquisition (TT&C)
- Payload data acquisition
- Formatting of data at Level 0 and short-term archiving
- Distribution of housekeeping data and AGSA POD data to the MSCE
- Distribution of Level 0 data to the PAE.

The Mission Operation and Satellite Control Element (MSCE), located at ESOC, provides the following classical functions:

- Overall mission planning and coordination (including operating the planning cycle described in section 5.5.4)
- Satellite monitoring and control
- Flight dynamics for maneuver planning
- On-board software maintenance

- Ground segment technical supervision.

The Processing and Archiving Element (PAE), located at ESRIN, is in charge of:

- Acquisition of level 0 data (including ancillary data) from the CDAE
- Acquisition of required auxiliary data from NWP centres
- Generation of products at level 1b and associated quality control (also generation of level 2 data as a baseline)
- Archiving of mission products
- Distribution of mission products to the end user community
- Long term monitoring of payload performance
- Provision of user services

The three constituting elements of the ground segment are connected via appropriate communication infrastructure ensuring the timely exchange of the relevant data.

The Scientific Centres in Figure 5.4.1-1 represent a notional interface to the user community, which further processes the data to (value-added) Level 2 and higher and supports the payload operations.

5.4.2 Data Processing

Data processing in terms of its approach and flow will strongly use the heritage prepared for ACE+ as described in ESA (2004b) and other documents. Table 5.4.2-1 below summarizes the related ACCURATE LMIO data products. Down to Level 1b processing is foreseen as core function in ESRIN, as of Level 2 also science centers will be involved.

For a description of the related processing and retrieval algorithms approach see section 3.3.1 and for the data evaluation and data exploitation approach section 3.3.2, respectively.

Table 5.4.2-1: ACCURATE LMIO data products

Level	**Key data and products**	
	LMO	**LIO**
Level 0	MW K-band science data: carrier phases and amplitudes at 3 frequencies (17.25, 20.2, 22.6 GHz) All needed LMO housekeeping data	SWIR IR laser science data: Raw signal intensity and frequency / background intensity data for the defined LIO frequency channels from LIO Tx / Rx All relevant LIO housekeeping data
	• Raw orbit data from Tx and Rx navigation receivers and all needed related health data • Earth orientation data • All needed Tx and Rx LEO platform housekeeping, attitude, pointing data	
Level 1a	(all profiles as function of time) • LEO Tx and LEO Rx precise orbit data (based on navigation receivers at Tx and Rx)	
	• Excess phase data (at all MW freq.) • Amplitude data (at all MW freq.)	• Tx pulse signal frequency and intensity data (at all IR freq.) • Rx pulse and background signal intensity data (at all IR freq.)
Level 1b	• Doppler shift and Raw **Transmission** (1) profiles (at all MW freq.) vs. time • Transmission profiles (at all MW freq.) vs. impact parameter • **Bending angle** (1) profiles vs. impact parameter	• Raw **Transmission** (1) profiles (at all IR freq.) vs. time • Transmission profiles (at all IR freq.) vs. impact parameter • Target species transmission profiles (at all absorption channel freq.) and Wind delta-transmission profiles (of wind channel freq. pair) vs. impact parameter

Level 2	(all profiles as function of altitude)	
	- Refractivity profiles - Differential absorption coefficient profiles (at all MW freq. pairs) - **Sp. Humidity** (2) profiles - **Temperature** (2) profiles - Pressure and Geopot. Height profiles	- Target species absorption coefficient profiles (at all absorption channel freq.) - **Trace Species** (2) profiles (of all required species according to Obs. Requirements) - **l.o.s. Wind** (2) profiles
	Error estimates and meta-data for all retrieved Level 1b and Level 2 profiles	
(by-products)	- Cloud liquid water profiles - Turbulence strength profiles (MW)	- Cloud layering profiles - Aerosol extinction profiles - Turbulence strength profiles (IR)

(1) driving parameter for main system requirements (see section 4.2.2). The “Raw Transmission” is the normalized received power ($Tr = I/I_0$) including defocusing and absorption, whilst the “Transmission” is understood to include absorption only (*Transmission* = 1 – *Absorption*).

(2) driving parameter for observational requirements (see Table 3.2-1 in section 3.2). Specific humidity and temperature can also be determined within clouds (temperature in severe scintillation/cloudiness conditions by extrapolating from above cloud top into clouds), trace species and l.o.s. wind outside clouds and on a best effort basis through intermittent cloud layering (see also footnote 9 of Table 3.2-1).

5.5 Mission Analysis and Operations Concept

5.5.1 LEOP Strategy for Single Launch

The counter-rotating orbital configuration would *a priori* require two launches. However, the LODM study (ALODM, 2010) has demonstrated the feasibility of a constellation deployment allowing reaching it via a single dual launch after a drifting period of about 1 year.

Figure 5.5-1 shows a breakdown of the operations of such a LEOP strategy: both satellites are inserted into a low orbit (350 km, ~80°). One of them then raises its altitude up to about 1200 km. The great altitude difference provides 2 different RAAN drift rates that slowly lead to a counter-rotating configuration. When the RAAN difference reaches 180°, the higher satellite lowers its altitude and the lower satellite raises its one, so that they reach their operational orbits (at 512 km and 595 km, baseline orbits, see section 5.2).

Depending on the properties of the platform, the drifting period lasts about 1 year, during which it may be interesting and is possible to perform occultations between the spacecraft at 350 km, which should therefore be the Tx satellite, and dedicated ground sites (or airplanes campaign-wise) equipped with (prototype) LMO and LIO receivers. A suitable set of baseline high-altitude ground stations for such purpose has been identified, contacted and visited (Teide Observatory/Tenerife, 2410 m; Sonnblick Observatory/Austria, 3105 m; Mauna Kea Observatory/Hawaii, 4205 m), which would welcome to support such meaningful utilization of the ACCURATE drifting phase year based on space-to-ground/space-to-airplane concepts that have also been investigated in ESA studies (e.g., ESA project ACTLIMB). There is no impact on transmitter design and this is probably best followed on a best-effort basis.

After drifting it is better to have the Tx satellite flying on the higher orbit (595 km) during operational life (e.g., somewhat easier in terms of POD and pointing than 512 km). Therefore, Figure 5.5-1 presents the baseline LEOP scenario, in which the satellites “cross” each other in altitude after the drifting period: the Tx (orange) goes from 350 km to 595 km and the Rx (green) goes from ~1200 km to 512 km. In order to lighten the delta-V budget of the Rx satellite, the out-of-plane thrust necessary to change the inclination is left to the Tx satellite. The system analysis (section 5.3.5) shows that this LEOP scenario is well feasible despite an alternative scenario without “swapping” the orbits would save about 100 m/s delta-V.

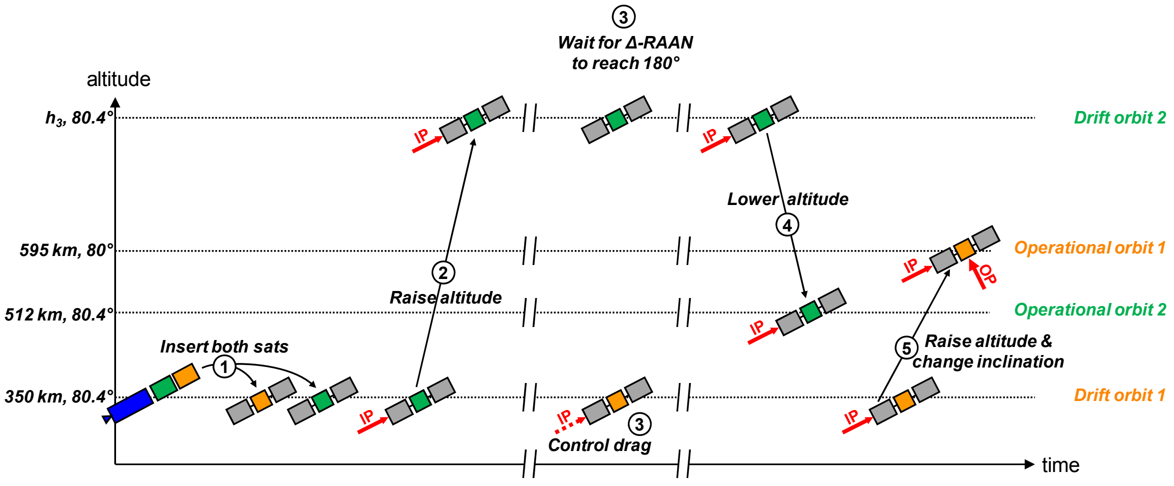


Figure 5.5-1: ACCURATE baseline LEOP scenario. SatH (Tx) in orange, SatL (Rx) in green. Arrows marked IP: In-Plane Manoeuvres, Arrows marked OP: Out-of-Plane Manoeuvres.

Figure 5.5-2 left panel shows the delta-V necessary for each satellite to achieve the counter-rotating orbital configuration after a single launch, as a function of the duration of the drifting period. Both the baseline scenario (red lines) of Figure 5.5-1 and an alternative “non-swapping” scenario (blue lines) are considered. In order to reach the operational configuration in one year, the Rx satellite must be able to reach a 1200 km altitude, using ~850 m/s of delta-V. This approach assumes a fairly conservative delta-V budget of 100 m/s/year for the altitude control of the Tx satellite when waiting at 350 km. System analysis shows the Figure 5.5-1 approach is a good and feasible baseline and the space-to-ground/airplane options offered during the drifting period are scientifically attractive.

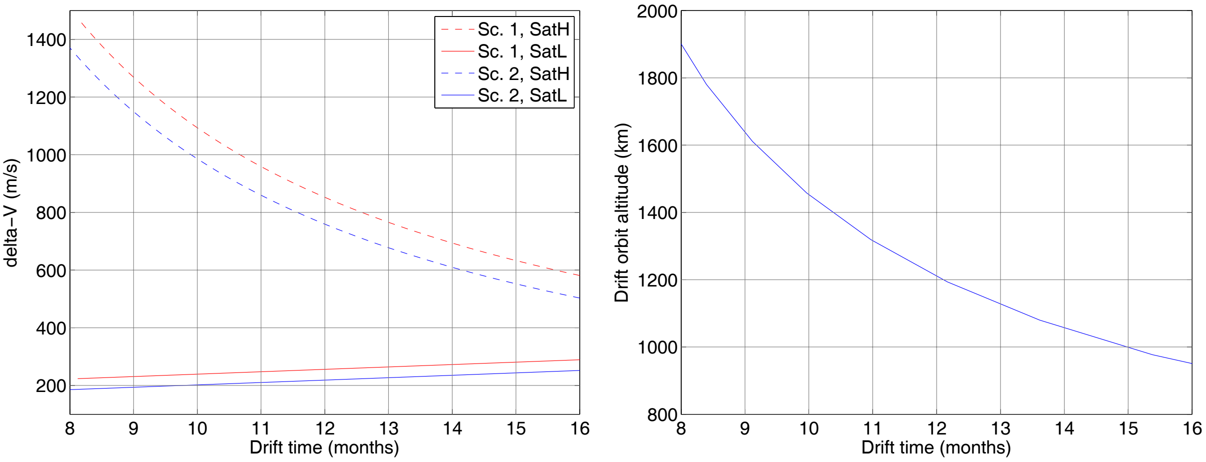


Figure 5.5-2: Necessary Delta-V for constellation deployment vs. drift period time (left) and corresponding altitude of the high-drift orbit vs. drift period time (right).

5.5.2 Repeat Cycle and Coverage Design

When two satellites demonstrate LMIO observations on counter-rotating orbits, it is attractive (see section 3.3.2) to study the geographical distribution of the occultation events with concepts similar to the ones used for classical coverage analysis, especially if the satellites fly on repeating orbits. For 2 satellites flying on orbits having Repeat Cycles of D_1 and D_2 days, the occultations geographical distribution repeats exactly, event by event, after N days, being N the least common multiple of D_1 and D_2. N is called Combined Repeat Cycle (CRC). Figure 5.5-3 shows as example the pattern of a 4-day repeating orbit and a 5-day repeating orbit after 20 days (CRC) and 25 days. As expected, both figures are perfectly equal.

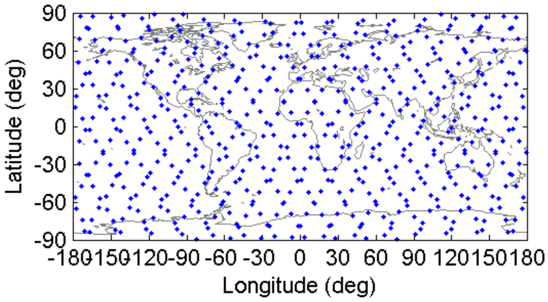
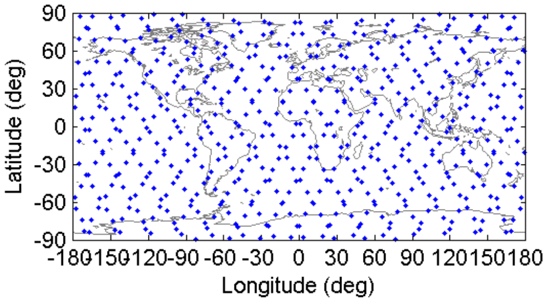
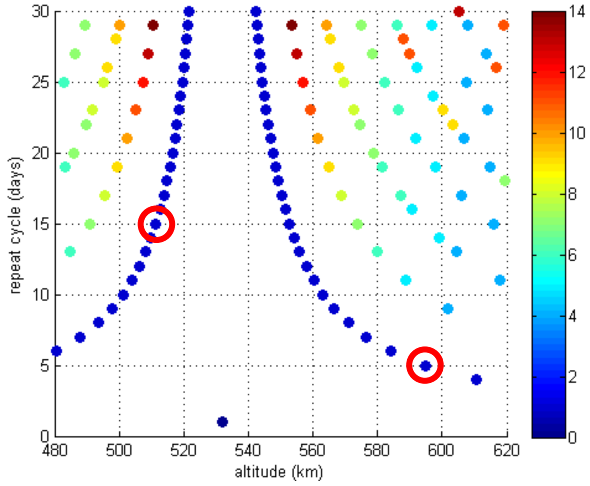
After 20 days (CRC)	After 25 days (>RC)
	

Figure 5.5-3: Occultation event distribution of example orbits 14+4/5 (595km) and 14+3/4 (610km).

The previous considerations have been applied in mission analysis for ACCURATE orbit selection, taking into account the following constraints (to fulfill requirements; Table 3.2-1):

- Inclinations: about 80°, but not lower
- Operational altitudes: between 500 km and 600 km
- Observational Repeat Cycle: 15 days

The operational orbits have been chosen among the repeating orbits complying with the constraints: see the red circles on the left panel of Figure 5.5-4 (the color is the orbit sub-cycle) so that their combination provides a CRC of 15 days. The higher orbit has the lower inclination: 80°. Then, the inclination and the altitude of the lower orbit are refined so that its repeat cycle remains the same and its RAAN drift rate is the same as the one of the higher orbit. The right panel table of Figure 5.5-4 shows the main characteristics of the selected orbits (consistent with Table 5.2-1 in section 5.2).



	SatL (Rx)	SatH (Tx)
Altitude	512 km	595 km
Inclination	80.41°	80.00°
Phasing Grid	15+1/15	14+4/5
Repeat Cycle	15 d	5 d
Combined RC	15 d	

Figure 5.5-4: Repeating orbits with inclination 80 deg, RC < 30 days and height between 480 km and 620 km (left). The proposed ACCURATE baseline orbits are highlighted (red circles and table info).

5.5.3 Coverage Performance

Figure 5.5-5 shows the number of occultation events per 12 million km² (Mkm^2) after one month from the baseline orbit defined above, based on an equal-area meshing of the globe. It provides a good qualitative understanding of the geographical events distribution. Figure 5.5-6 features a plot extracted from the same dataset where the blue bars show the longitude-averaged geographical density of events for each 26-deg latitude band and the red vertical bars show the standard deviation of these distributions:

- The smoother the envelope of the bars, the smoother the events latitudinal distribution
- The shorter the red bars, the smoother the events longitudinal distribution

The operational pair of orbits provides about 60 events in per day, i.e., about 900 events per RC (15 days). In one month, the 12 Mkm² bins receive from about 28 (near the equator) to about 120 events (near the poles), the average being ~42 events/12Mkm²/month. This well fulfills the observational requirements (Table 3.2-1) for a first demonstration mission and also fulfills the scientific preferences for coverage repeat as discussed in section 3.3.2.

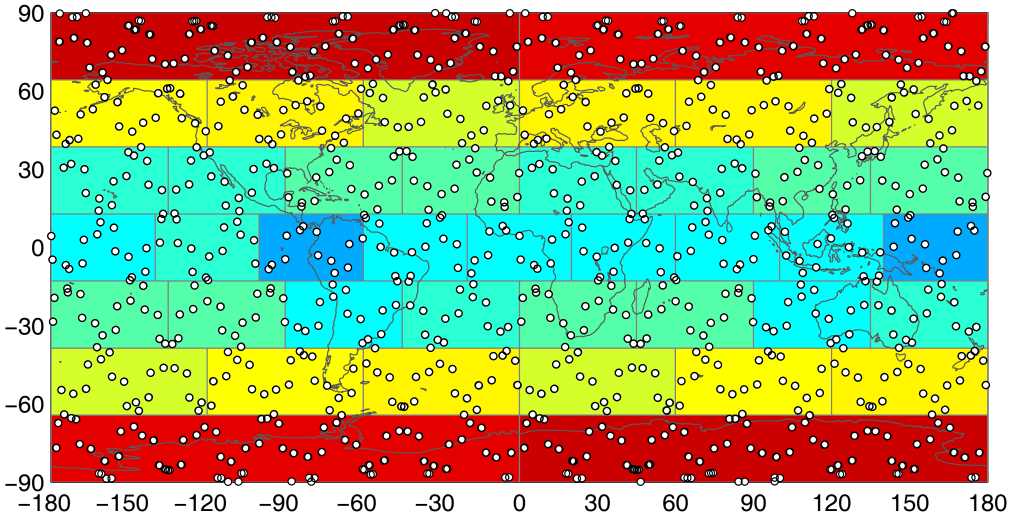


Figure 5.5-5: Occultation events geographical density (events/12Mkm²) within one month from the baseline orbits defined above. Each of the about 900 locations is visited twice per months based on the chosen 15-days repeat pattern. The patterns location can be customized as discussed in section 3.3.2.

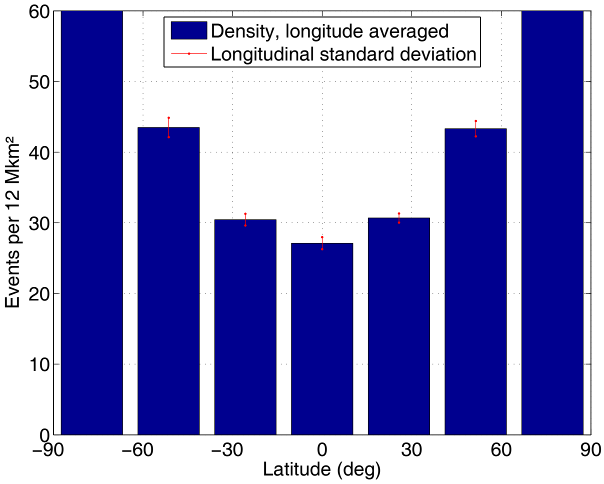


Figure 5.5-6: Occultation events longitude-averaged geographical density within one month (extreme latitude values near the poles clipped, they reach ~120 events/12Mkm² with an ~ ±4 events red bar).

5.5.4 Mission Operations Concept

For the mission performance, the updating of the respective satellites of the orbit predictions is critical. Each satellite carries a Precise Orbit Determination payload (AGSA). It is foreseen that the orbit propagation and the refraction model resides in the ground segment and the true, i.e. not from straight-line occultation assumptions only, predictions are uploaded to the spacecrafts in a polynomial form. With this concept, the spacecraft software can be simplified and the refraction model can easily be optimised throughout the mission. Figure 5.5-7 illustrates the main functions being part of the related planning cycle.

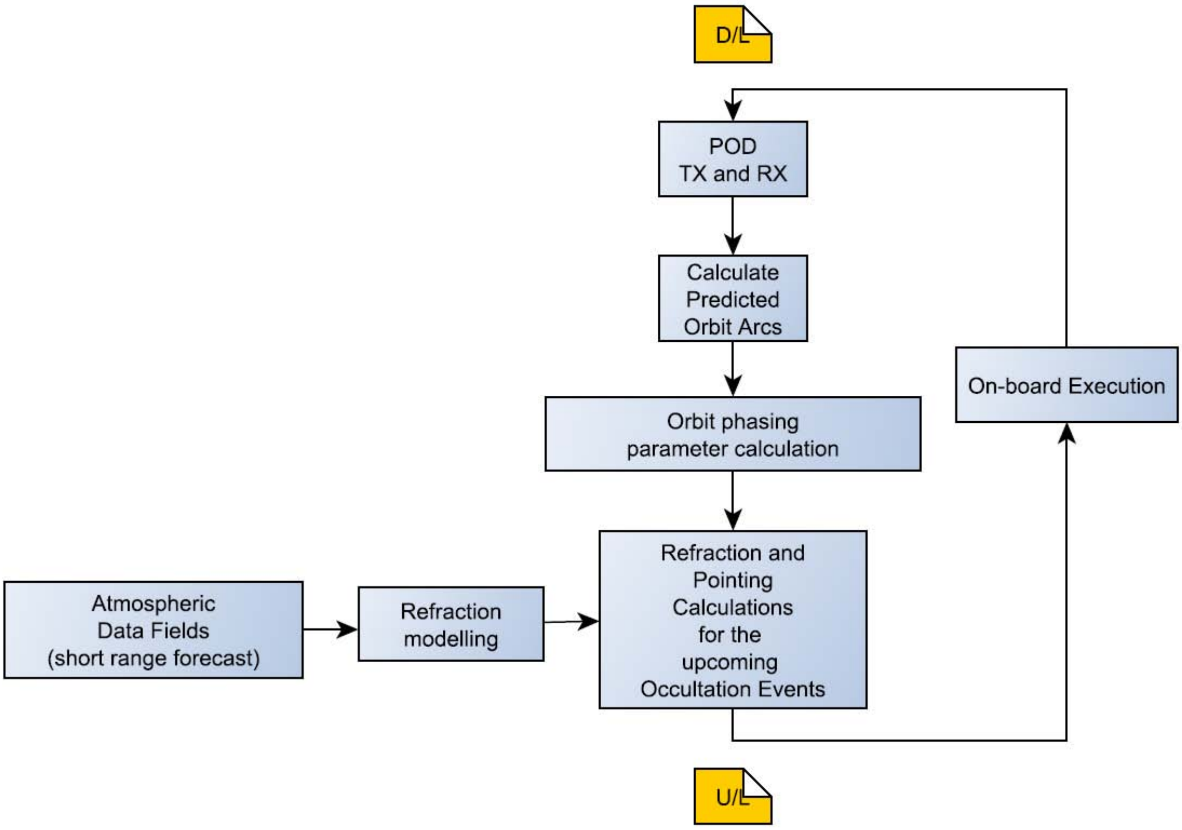


Figure 5.5-7: The ACCURATE planning cycle providing (baseline daily updates) orbit knowledge and occultation information support as part of mission planning and control.

According to preliminary analysis the predicted orbit accuracy is sufficient for 24 hours during nominal conditions, i.e., the above cycle is required to be iterated daily. Payload data is stored on-board and dumped during station contact. The same applies for the housekeeping data. The PUS implementation ensures the flexibility of both up- and down-link, e.g., in terms of telecommand management, TM packet definition and Event services.

6. Programmatic Elements

6.1 Design, Development and Verification Plan

6.1.1 Overall DDV Approach

Satellites design rules
Clear interfaces are designed, between both instruments, and between the instruments and the platform. This allows parallel and uncoupled design and qualification of each instrument, reducing thus the risk of schedule slippage and offering planning flexibility. The TX and RX versions of the satellites are implemented with a maximum of commonalities, so that

- most of the qualification process may be performed on an “envelope” satellite model
- The platforms of both spacecraft are in principal identical. Any deviation shall be motivated in a trade-off during phase A
- the technical and operational documentation may be largely common to both models

The satellite avionics is designed with the objective of promoting functions implementation by software rather than by hardware, to reduce the recurring costs.

Satellite model philosophy
The model philosophy is defined with the objective of limiting the amount of hardware to be manufactured and tested, while keeping the development risks at an acceptable level.

For ACCURATE, the following low risk approach is proposed as a first iteration:

- Only one satellite structural model is built (SM-TX). The TX satellite will have a larger mass du to the higher propellant load. The RX satellite will be qualified by similarity. This concept needs careful attention when defining the test definition of the Structural Model
- One satellite avionics validation model (AVM) will be used
- Two satellites proto-flight models (PFM-TX, and PFM-RX) will be developed

The purpose of the satellite structural models is to qualify the satellites mechanical design against mainly the launcher environment and interface requirements. Sine, acoustic noise and shocks tests are applied to the satellite SM. The composition of this model is the following:

- One satellite structure, manufactured at flight standard, and tested at supplier premises against static loads;
- Mass dummies representing the platform equipment;
- Mass dummies and/or structural models of the payload equipment, and corresponding to the envelope of the RX & TX configurations.

The SM programme is run early enough in phase C, so that the mechanical loads at payload equipment level may be confirmed in due time before the payload units mechanical qualification campaign.

Quasi in parallel with the SM programme, the satellite avionics validation model (AVM) programme is run. The objective is to qualify the electrical and functional performances of the satellites, successively in the RX and the TX configurations. This validation campaign includes electrical interfaces verification (intra-platform, and between platform and payloads), as well as functional and performances validation (data management, software, FDIR, AOCS). The AVM operates in closed-loop mode with hardware in the loop; it is built with:

- Dummy platform panels, with test harness (so-called flat sat configuration)
- Depending on their development status: bread-boards, (BB), or electrical models (EM) or flight models (FM) of the platform avionics units (mainly DHS and AOCS)
- BB or EM of the payload units interfacing directly with the platform avionics
- Flight software evolving versions
- EGSE

The PFM's satellites are built with flight standard equipment. The qualification and acceptance programmes are planned as follows:

- The most demanding PFM satellite (PFM-TX), will undergo a complete mechanical, thermal, electrical, functional and RF qualification campaign.
- The second PFM satellite (PFM-RX) will be submitted to a subset of the PFM-TX tests and any needed delta-qualification tests to qualify differences in design.

During the phase A study, details will be worked out concerning the tests sequence, in particular for the science performance tests such as RFC cleanliness, gain stability, and antenna patterns characterisations. Also, the System integrated tests and Ground segment compatibility tests will be defined.

6.1.2 Development Status and Maturity Assessment

Platform

The Swedish Space Corporation has had a strong involvement in the study of the Earth's atmosphere. The ACCURATE satellites will benefit from the heritage from concepts already developed at SSC; the ODIN telescope is a limb scanning satellite with pointing performance matching the ACCURATE requirements. It was launched in 2001 and still being operated by SSC. It features many of the operational capabilities required by the ACCURATE mission. The ACE+ concept was developed in a previous ESA activity and many of its elements and considerations can be used as references for the ACCURATE study. The main difference from the ACE+ mission architecture is the non-sun-synchronous orbit which results in a different solar array configuration.

As can be seen in the suggested ACCURATE platform the agility provided by the Prisma formation flying platform together with the heritage from ODIN and ACE+ will constitute an appropriate foundation for the ACCURATE design. Additionally, in the payload area the SteamR development performed by SSC in the Premier phase A study makes SSC a knowledgeable counterpart in the refinement of the ACCURATE concept.

Element	Current level	Comment
Platform	TRL 6	The platform will be based on the Prisma satellite bus, presently being prepared for launch. Even though the platform will need modifications, the similarity of the mission requirements on the platform makes it possible to state that the platform has a high TRL level.

AMOS Payload (section 5.3.3)

The AMOS has heritage from the ESA WATS and ACE+.

Element	Current level	Comment
AMOS Subsystem	TRL 5	New system Based on existing technology
AMOS: Receiver	TRL 6	Known technology but demanding performance requirements
AMOS: Antennas	TRL 8	
AMOS: Transmitters	TRL 7	Efficiency crucial for small S/C

AGSA Payload (section 5.3.3)

The AGSA instrument is foreseen to be the existing RUAG POD receiver as developed for SWARM and the Sentinel missions.

Element	Current level	Comment
AGSA receiver	TRL 8	No pre-development needed

AIOS Payload (section 5.3.4)

The preliminary TRL review shows high maturity of most technologies needed for the mission. The majority of the technologies required for the implementation of the mission are at high TRL. The following ones were evaluated at TRL higher that 4: DFB seed lasers SWIR A (2.1 µm); Detector Array <2.2µm; Gas absorption cell; Optical fibres; Wavelength multiplexing; Detector cooling; Optical path cooling; Pulse shape measurement; Pulse energy measurement; Laser and detector electronics.

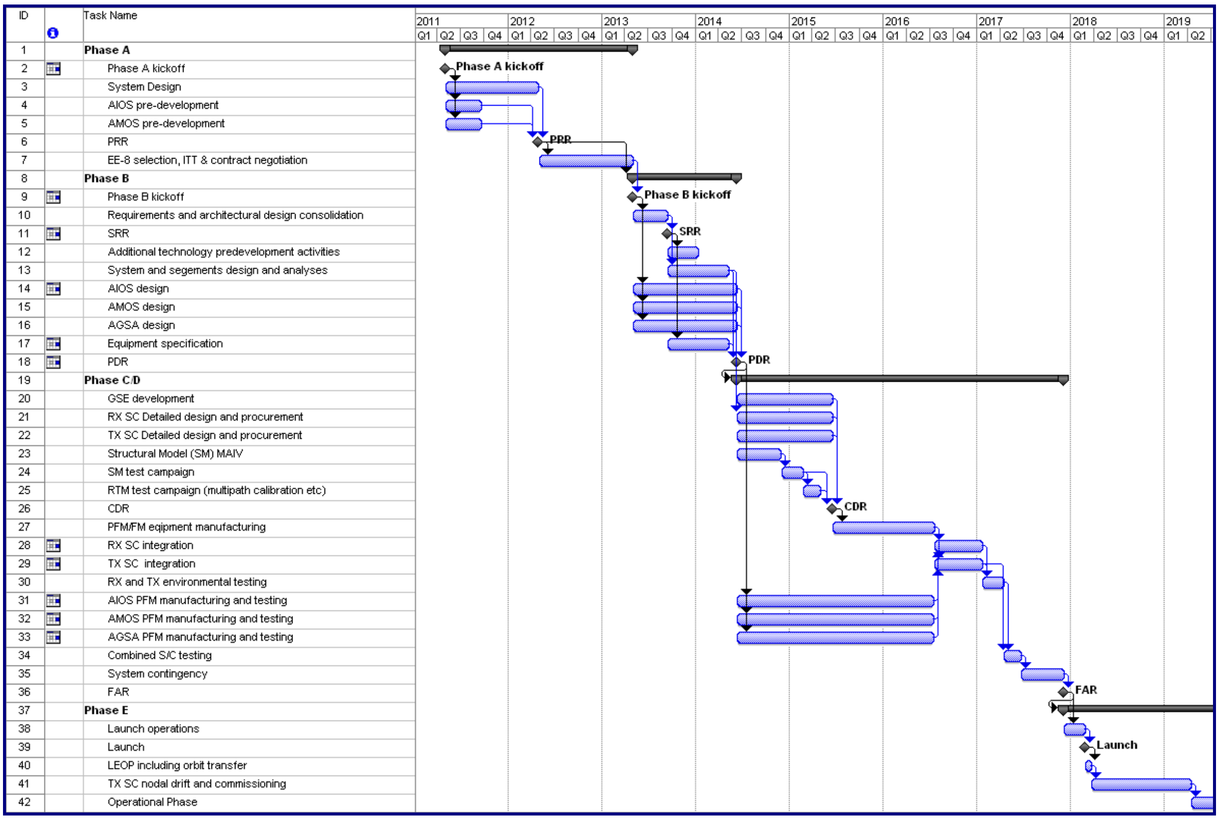
The technologies that were evaluated at TRL4 or lower are given below.

The critical system components that require development are the semiconductor optical amplifiers and the DFB lasers for the region of 2.3-2.5µm. However, the starting point of these technologies is relatively high. Alternatives can also be considered, however the chosen transmitter solution has the advantage of SOA sharing. The detector readiness is considered relatively high.

	Transmitter module	TRL	Risk	Effort	Possible options
T1	SOA SWIR A	4	L	M	Technology development is needed.
T2	DFB seed lasers SWIR B (2.3-2.5µm)	3 - 4	M	M	Technology development is needed.
T3	SOA SWIR B	3	M	M	Technology development is needed.
	Calibration module				
C1	Wavelength shift control	4	L	M	Specialized wavelength control devices can provide the necessary shift for Doppler compensation. The system take advantage of the long time available for laser preparation.
C2	Wavelength meter	3	M	M	Will be needed if wavelength shifters cannot be multiplexed satisfactory.
C3	Beam shaping	4	L	L	Must be implemented to ensure the link budget and relax the requirements to the intensity stability of the laser. Does not require technology development. Custom designed optical components may need to be produced using established technologies.
	Receiver module				
R1	Interferometer	4	L	M	NASA demonstrated in-flight. Requires dedicated ESA design effort but can be produced with standard grade optical components.
R2	Detector Array <2.5µm	4	L	M	Prototypes exist, but technology development will be required
R3	Detector Read-Out electronics	4	L	M	Existing camera electronics expected to be usable. Customization may be required to address the dynamic range and the timing of the signals.

6.1.3 Schedule

The development and implementation schedule below summarizes the foreseen activities from Phase A to operational phase.
Launch is planned early 2018 which is found clearly feasible.



ID	ℹ	Task Name
1		**Phase A**
2	▦	Phase A kickoff
3		System Design
4		AIOS pre-development
5		AMOS pre-development
6		PRR
7		EE-8 selection, ITT & contract negotiation
8		**Phase B**
9	▦	Phase B kickoff
10		Requirements and architectural design consolidation
11	▦	SRR
12		Additional technology predevelopment activities
13		System and segements design and analyses
14	▦	AIOS design
15		AMOS design
16		AGSA design
17	▦	Equipment specification
18	▦	PDR
19		**Phase C/D**
20		GSE development
21		RX SC Detailed design and procurement
22		TX SC Detailed design and procurement
23		Structural Model (SM) MAIV
24		SM test campaign
25		RTM test campaign (multipath calibration etc)
26		CDR
27		PFM/FM eqipment manufacturing
28	▦	RX SC integration
29	▦	TX SC integration
30		RX and TX environmental testing
31	▦	AIOS PFM manufacturing and testing
32	▦	AMOS PFM manufacturing and testing
33	▦	AGSA PFM manufacturing and testing
34		Combined S/C testing
35		System contingency
36		FAR
37		**Phase E**
38		Launch operations
39		Launch
40		LEOP including orbit transfer
41		TX SC nodal drift and commissioning
42		Operational Phase

6.2 Rough Order of Magnitude Cost Estimation

The costing is based on the following methodology:

- All figures is including cost, overheads and profit, in order to represent a Rough Order of Magnitude not-committing price
- The system is broken down to subsystem level and each subsystem is assessed in comparison to previous developments
- The ROM prices given are based on industrial experience from other national and ESA projects including actual prices and ROM proposals from these projects
- The Cost Estimate is using he economic conditions of 2009.

Assumptions and prerequisites for the costing

The costing of the platforms exploits the fact that the ACCURATE mission requirements are similar to the Prisma satellite bus. The similarities in driving requirements include payload mass, pointing performance and orbital agility. Obviously there are areas in which substantial re-design efforts are necessary such as for the increased propellant tank size and the stacked launch configuration.

- The costing is making the assumption that the TX and RX platforms can utilise maximum similarity. This is made possible by the fact that the combined mass of the two satellites are well below the Vega capacity and therefore a mass optimisation of the RX satellite is not strictly necessary.
- The costing is based on that the two platforms are developed by the same industrial supplier. This is not mandatory but is considered to be cost efficient.
- The platform cost is given for the two spacecraft platforms, including development units such as Structural Models and the avionics validation model (AVM).
- All test activities including facility cost are included.
- A maximum use of COTS equipment is used.

No pre-development activities, i.e., prior to the start of the phase B activities, are foreseen for the platform development. The areas in which re-design are necessary are handled within the normal A/B/C phased development logic. A preliminary risk analysis has not singled out any particular area. The developments needed in the areas where redesign of the Prisma platform, e.g., the structure modification, is necessary have been taken into account in the costing.

The Ground Segment costing is based on the following assumptions:

- There is nothing mission specific processing in the CDAE. The down link is using standard S-band and the data format will follow CCSDS/PUS. Given that the AGSA data (from the zenith antenna for timing and POD) are routed to ESOC, in addition to the classical HK data, this should still be routine.
- The MSCE will need to implement the ACCURATE mission planning and operations support (AMPOS) tool and an external interface to exchange data with the Scientific and Meteorological Centres
- The implementation of the ACCURATE Level 1 data processor, for processing Level 0 to Level 1b needs to be done in the PAE (ESRIN). The cost includes the prototype algorithms definition and preparation.

Cost in kEuro 2009	PRE DEV	PHASE B	C/D/E1	TOTAL
ACCURATE Mission Prime				**15050,0**
Project office	0,0			4100,0
Management	0,0	500,0	2400,0	2900,0
PA	0,0	100,0	1100,0	1200,0
Engineering	0,0	1400,0	3500,0	4900,0
System AIV	0,0	150,0	3800,0	3950,0
GSE	0,0	500,0	1600,0	2100,0
AIOS				**19100,0**
Project Office	50,0	50,0	900,0	1000,0
Engineering	1000,0	1000,0	5000,0	7000,0
AIOS elements				11100,0
Transmitter	0,0	800,0	4100,0	4900,0
Receiver	0,0	1200,0	5000,0	6200,0
AMOS				**10040,0**
Project Office	10,0	50,0	800,0	860,0
Engineering	240,0	640,0	4000,0	4880,0
AMOS elements				4300,0
Transmitter	0,0	450,0	1200,0	1650,0
Receiver	0,0	550,0	2100,0	2650,0
AGSA				**2500,0**
Project Office	0,0	10,0	10,0	20,0
Engineering	0,0	40,0	60,0	100,0
AGSA elements	0,0	0,0	2380,0	2380,0
Platform hardware and software				**40500,0**
Structure	0,0	800,0	4000,0	4800,0
AOCS	0,0	1400,0	6700,0	8100,0
DHS	0,0	1400,0	4800,0	6200,0
OBSW	0,0	700,0	2200,0	2900,0
Propulsion	0,0	400,0	5400,0	5800,0
Power	0,0	1200,0	8000,0	9200,0
Thermal	0,0	100,0	900,0	1000,0
TT&C	0,0	500,0	2000,0	2500,0
Mission Specific Ground Segment				**2950,0**
MCSE	0,0	200,0	550,0	750,0
PAE	0,0	350,0	1850,0	2200,0
Risk&Management Margin %				
TOTAL	**1300,0**	**14490,0**	**74350,0**	**90140,0**

As can be seen in the **total industrial cost** summary above the total ROM cost arrives at a figure of about **90 Million Euros**, below the target budget. However, it should be noticed that the risk margin needs to be further discussed and agreed before a final project cost envelope can be settled.

– end of proposal document, Annexes A and B follow –

Annex A. Evaluation of the ACCURATE-2005 Proposal

ESAC and Joint Assessment Panels evaluation of the ACCU (2005) proposal.

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12/06/06

Evaluation of the ACCURATE Proposal by the ESAC (ESA Earth Science Advisory Committee), following the Joint Assessment Panel Reports [extract of overview and ACCURATE-related pages: p. 3-4, 6-7, 13; appended is the Joint Assessment Panels Report on ACCURATE]

The Second Call for Earth Explorer Core Mission Ideas:
The Evaluation of the Twenty-Four Proposals

1. Overview of the Proposals

All of the twenty-four proposals, received in response to the Second Call for Earth Explorer Core Mission Ideas, have been reviewed by the Earth Science Advisory Committee (ESAC). The ESAC was very impressed with the high scientific standard attained by the proposals, also noting that several proposals represent substantial improvements on proposals submitted during previous calls for Earth Explorer missions. The Committee also noted the breadth of the proposals which addressed all areas of Earth Observation, and in particular responded well to the scientific priorities that were formulated for the Call.

All the proposals have been evaluated scientifically and technically by the Committee in line with the procedures laid down in the Call using the seven criteria defined for the evaluation and taking due note of the scientific priorities issued with the Call, as well as the financial limits.

Based on the findings emerging from this exercise and in line with the instructions of the PB-EO, the ESAC has selected six proposals and listed them in order of priority. This paper outlines the procedures followed and details the results of this assessment exercise.

It should be noted that at all stages in the evaluation proposals have been assessed as submitted, neither the ESAC nor the five Joint Assessment Panels have introduced modifications to any of the proposals.

The first step in the evaluation exercise was to assess each of the twenty-four proposals individually and for this five Joint Assessment Panels were set up, namely:

- The Atmospheric Chemistry Joint Assessment Panel
- The Atmospheric Physics Joint Assessment Panel
- The Land Joint Assessment Panel
- The Ocean and Ice Joint Assessment Panel
- The Solid Earth Joint Assessment Panel

Each JAP was chaired by a member of the ESAC and consisted of external scientists assisted by internal technical experts. Each JAP was asked to assess a sub-set of the proposals scientifically as well as technically and programmatically. Proposals that spanned the sphere of competence of more than one JAP were assessed by all relevant JAPs leading to an overall assessment report. The individual assessment reports are attached as an annex to this paper.

Each JAP report contains a specific set of recommendations including an indication of whether, in the view of the JAP, the particular proposal should be further considered for selection or not. The ESAC has reviewed all these reports and endorsed their findings. It has also endorsed the recommendations for proposals to be retained for further consideration for implementation with the exception of three proposals recommended by the JAP (SPACE WAVES, HABITAT and WATER) but whose costs would have most probably exceeded the limits of the Call, or that would have presented strong technological risks.

Seven proposals fall into this final category, namely PREMIER, FLEX, ACCURATE, BIOMASS, TRAQ, A-SCOPE and CoreH2O. For the purposes of the ESAC assessment, these seven proposals were considered as a short-list from which to select the final list of proposals to be recommended for assessment studies at pre-feasibility level. All seven are considered to be of very high scientific merit and potentially compliant with the boundary conditions.

Section 2 contains the ESAC assessment of the seven short-listed missions, section 3 the recommendations for selection of mission concepts to be studied at pre-feasibility level and section 4 recommendations related to missions not recommended for pre-feasibility studies.

2. Assessment of the Short List

As regards the seven proposals, which the ESAC considered were candidates for recommendation for further studies, the Committee's position can be summarised as follows (not in order of priority):

PREMIER (CCM2-2)
Prediction of climate change fundamentally relies on understanding the underlying processes. Many of the most important processes occur in the upper troposphere and lower stratosphere. For example the largest effects of water vapour, ozone and clouds on the thermal radiation budget come from near the tropopause. Global observations of this region are very limited and often at the edge of an instrument's capability, hence our knowledge of these processes is poor, especially compared to our understanding of upper stratospheric and lower tropospheric processes.

PREMIER aims to elucidate many of the processes that link trace gases, radiation, chemistry and climate in the atmosphere, concentrating on the processes in the upper troposphere/lower stratosphere (UTLS) region. This requires high vertical and horizontal resolution data and a key mission objective is to observe this region at unprecedented resolution with a high signal to noise ratio. By linking with MetOP/NPOESS data the mission also aims to provide useful insights into processes occurring in the lower troposphere.

The mission will measure the concentrations of a wide range of chemical species in the UTLS, together with temperature, thin cirrus, polar stratospheric clouds and aerosols. From these, information can be inferred on trace gas climate-chemistry interactions, The final link between multi-spectral fluorescence measurements and an improvement of the LUE as the final level 3 product has to be strengthened in order to convince the carbon cycle modellers to use the FLEX derived products in future models.

Early efforts shall therefore be dedicated to the demonstration of fluorescence measurements feasibility (SNR, variability, etc.) over heterogeneous natural vegetation and of the relation between fluorescence and canopy LUE. In addition an end-to-end evaluation of all potential errors is needed as the higher level products rely on very accurate measurements and corrections of influencing factors.

ACCURATE (CCM2-13)

The ACCURATE (Atmospheric Climate and Chemistry in the Upper troposphere lower stratosphere And climate Trends Explorer) mission is designed to measure climate variability and trends in atmosphere thermodynamic variables (temperature, humidity and pressure as a function of geopotential altitude), greenhouse gases (H2O, CH4, N2O, O3, CO2, CO and several isotopes of water vapour and carbon dioxide), and UTLS (Upper Troposphere Lower Stratosphere) chemicals. The mission employs the occultation measurement principle to perform LIO (LEO[1]-LEO Infrared Occultation) and LRO (LEO-LEO Radio Occultation) measurements. It includes an optional GRO (GNSS[2] Radio Occultation) instrument that would provide normal radio occultation sounding data products.

The ACCURATE mission is tailored to provide soundings of the upper troposphere and lower stratosphere with absolute calibration. The tropopause region is a key region for chemistry-climate interactions where global scale measurements of the spatial distribution of trace gases are needed. Especially accurate upper tropospheric and lower stratospheric humidity measurements are required for climate monitoring. The ACCURATE mission addresses these needs by providing measurements of several trace gases, humidity, temperature, and pressure/geopotential height. The ACCURATE mission allows simultaneous measurements of different species and several atmospheric state parameters with an effective vertical resolution of 1-2 km. The LRO and the GRO measurements will work in all-weather conditions. Global observations of this kind are very useful to support atmospheric UTLS modelling with the goal to detect climate and global change finger prints and to quantify the man made impact. Though the infrequent horizontal sampling of ACCURATE may limit its impact on some applications in the field of atmospheric chemistry, the high vertical accuracy, global coverage, good absolute calibration (self-calibration) and a very good long-term stability of the data products make the ACCURATE mission very useful also as a potential benchmark and a reference for all climate monitoring measurements. This would be beneficial for calibrating the data from measurements with a relative calibration and would support building of long-term climate monitoring databases.

The scope of the ACCURATE mission is wide and it addresses almost all priorities for the 2005 Call for Ideas. The ACCURATE mission contains a combination of two innovative active occultation techniques in the microwave and infrared portions of the spectrum in order to infer humidity and trace gas concentrations in the upper troposphere

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[1] Low Earth Orbit

[2] GNSS (Global Navigation Satellite System) in the context of the ACCURATE proposal means the GPS and the Galileo navigation satellite systems.

and lower stratosphere. The humidity and trace gas measurements have unique absolute calibration enabling long-term climate monitoring and are accompanied by accurate temperature and pressure information from radio occultation. The proposed mission benefits from the previous theoretical work on the feasibility of the ACE+ mission.

ESAC considers the mission of high scientific value.

BIOMASS (CCM2-17)

Biomass is a major component of the global carbon cycle and its contribution remains one of the most uncertain as no estimation of the CO_2 flux associated to land use change is proposed so far. The BIOMASS mission is designed to remedy this lack of information. Its main objectives are to quantify the forest biomass, the extent of forest and deforested areas and the delimitation of flooded forests.

The mission is based on a P-band SAR, offering high spatial resolution and working in two modes (full polarization or dual polarization HH and HV). Biomass strongly influences the P-band backscattering coefficients and a quantitative relationship can be obtained on different forest types using a crude empirical relationship between radar backscatter and forest biomass up to a level of 150t/ha. Using the polarimetric and (repeat pass) interferometric capabilities coupled with forest functioning models it is expected to obtain reliable estimates beyond this level with particular relevance for tropical forests.

Important secondary objectives are subsurface imaging in arid areas, the characterization of the ice cover in the Antarctic, the soil moisture in the root zone (existing tools are limited to the top layer) and some characteristics of the sea surface (salinity, low frequency surface roughness).

ESAC considers that the BIOMASS mission would provide a key contribution to the understanding of the terrestrial part of the carbon cycle through the observation of the forest biomass. The schedule and cost of the mission are considered feasible within the boundary conditions of the third cycle of the Earth Explorer Core Missions, taking into account the development required for the large deployable antenna. It has been shown from experimental results including airborne campaign that the measurements of the P-Band SAR can lead to reliable quantitative products. The success of this mission would offer a potential important tool for complying with the Kyoto commitment.

Clarifications are needed regarding space-borne P-Band polarimetric interferometry, its sensitivity to ionospheric influence (Faraday rotation), its use for retrieving high biomass levels (above 150 t/ha e.g. in tropical forests), as well as the use of the BIOMASS products in data assimilation in carbon cycling modelling. Given the fact that P-Band is protected for remote sensing only as a secondary user, interferences e.g. by tracking radars and potential implications for the satellite system safety, as well as its temporal and spatial coverage will have to be investigated. In light of these potential constraints, undertaking comparative studies for biomass retrieval using L-band could be desirable.

TRAQ (CCM2-18)

The determination of tropospheric chemical composition from space remains a great challenge even though its feasibility has been demonstrated by recent instruments. Many questions regarding the chemistry and transport processes in the troposphere are yet

ESAC. The ESAC has in addition made some further recommendations of its own. Many of the scientific and technical recommendations will form the basis for future preparatory activities undertaken by the Agency.

4. Recommendations on missions not recommended for pre-feasibility studies

For the one mission on the short-list that was not recommended for pre-feasibility studies, ACCURATE, the ESAC made the following recommendations:

> **ACCURATE** is designed to measure climate variability and trends in atmosphere thermodynamic variables, greenhouse gases and upper troposphere lower stratosphere chemicals. In view of the high scientific value of the mission the ESAC recommends various studies. Technological predevelopments should address the qualification of the laser diodes, which have not been used in space at these wavelengths, and, on the detector side, the demanding sensitivity in the short-wave infrared domain. Scientific studies should address the following issues, namely LIO data product retrieval consolidation, end-to-end analysis of the LIO measurement to analyse the product accuracy, impact of the cloud contamination on trace gas, aerosol, and cloud characteristics retrievals, and the impact of the limited occultation sampling in tropical regions for transport studies.
>
> It is recommended that the feasibility of including the optional GRO sounding into the ACCURATE mission should be explored because this element would complement operational radio occultation missions in providing data to the NWP user community.

Three mission proposals, HABITAT, SPACE WAVES and WATER, had been recommended by the Joint Assessment Panels for further consideration due to their high scientific value, but were discarded because their cost would most probably exceed the Earth Explorer Call limit, or because of the technological risk they would imply. ESAC emphasizes the difficulty to support, within a limited budget frame, missions that propose technological breakthroughs.

> **HABITAT** presents a unique and innovative mission consisting of an active satellite flying in formation with three receiving satellites (cartwheel concept) to observe the biomass, wetlands and earthquakes and volcanoes and to improve process understanding. The novel measurement technique is very well explained regarding exploitation of the various pieces of information contained in interferometric images generated at different polarizations, baselines and time lags.
>
> Given the novelty of the approach, on one side, several issues about the actual implementation of both the satellite system and of the performance of the measurement technique are open. On the other side, the degree of innovation and the potential contribution to the advancement of European Earth Observation capabilities are high.
>
> The proposed mission is very attractive in terms of science and technology return when implemented in full, in which case it would significantly exceed

12.06.06

ACCURATE
Atmospheric Climate and Chemistry in the UTLS Region And climate Trends Explorer
CCM2-13

Submitted by: Gottfried Kirchengast,
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1. Scientific Rationale

The ACCURATE (Atmospheric Climate and Chemistry in the Upper troposphere lower stratosphere And climate Trends Explorer) mission employs the occultation measurement principle to perform LIO (LEO[1]-LEO Infrared Occultation) and LRO (LEO-LEO Radio Occultation) measurements. The ACCURATE mission is designed to measure climate variability and trends in atmosphere thermodynamic variables (temperature, humidity and pressure as a function of geopotential altitude), greenhouse gases (H_2O, CH_4, N_2O, O_3, CO_2, CO and several isotopes of water vapour and carbon dioxide), and UTLS (Upper Troposphere Lower Stratosphere) chemicals. The mission includes an optional GRO (GNSS[2] Radio Occultation) instrument that would provide normal radio occultation sounding data products. The scientific objectives of the ACCURATE mission are defined to support the research areas identified as priorities in the 2005 Call for Ideas for Earth Explorer Core Missions.

The primary mission objectives are

- Monitoring of climate variability and trends in thermodynamic variables (temperature, pressure, humidity), in greenhouse gases including H_2O and CO_2 isotopes, and of UTLS chemical, cloud structure and radiative changes, as an initial key component of long-term benchmark observations of climate in the atmosphere,
- Contribution to the detection of anthropogenic climate and chemical changes in the atmosphere, as well as of changes in the global carbon and water cycles, and support of climate change predictions via global reference data of climate benchmark quality,
- Validation of global circulation models (GCMs), in simulated mean climate and variability as well as in atmospheric physics/chemistry/radiation variables in the UTLS,
- Improvement, in particular via data assimilation methods, of physics and chemistry parameterizations in GCMs, such as related to radiation and energy balance, and of the characterization of external forcing variations,
- Improvement of the understanding of climate feedbacks determining magnitude and characteristics of climate changes, especially related to chemistry-climate interactions and the carbon and water cycles,
- Study of processes in the UTLS region at high vertical resolution, in the context of atmospheric physics and chemistry research, including aerosol, cloud, and dynamical variability studies,
- Demonstration of the novel LEO-LEO radio & infrared occultation technique (LRO+LIO),
- Optionally demonstration of the new use of Galileo-LEO radio occultation.

Secondary objectives of ACCURATE are:

- Contribution to improved numerical weather prediction (NWP),
- Contribution to improved "chemical weather" prediction by currently developed data assimilation/forecast systems for atmospheric composition and dynamics,
- Support of analysis, validation and calibration of data from other space missions.

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[1] Low Earth Orbit

[2] GNSS (Global Navigation Satellite System) in the context of the ACCURATE proposal means the GPS and the Galileo navigation satellite systems.

As the objectives show, the ACCURATE mission is primarily driven by climate research, but also UTLS process studies and methodological objectives reaching beyond climate (e.g., model validation and improvement will also benefit NWP and chemistry modelling) are important.

All ACCURATE measurements (LRO, LIO, and the optional GRO) offer high absolute accuracy, good long-term stability, high vertical resolution, and global coverage in the retrieval of the thermodynamic variables. The simultaneous sounding of nearly the same atmosphere volume by LRO and LIO produces independent measurements of temperature, pressure, humidity and several trace gases. The proposal promises measurements of key trace species such as CO_2, CH_4, N_2O, CO and O_3. It also promises measurements of the isotope species HDO, $H_2{}^{18}O$, $^{13}CO2$ and $C^{18}OO$. The first two are important because of their implications for condensation processes, e.g. in determining which meteorological processes are important in determining stratospheric water vapour values. The other two are important in determining exchange of CO_2 between atmosphere, ocean and the terrestrial biosphere.

2. Technical Description

The ACCURATE mission consists of a constellation of 4 satellites in two Sun-synchronous counter-rotating orbits (two transmit satellites at 800 km altitude and two counter-rotating receive satellites at 650 km). Each transmit satellite includes a LEO-LEO infrared occultation laser part, generating 1.5 mJ pulses at 20 frequencies in the SWIR (short-wave infrared, 2-2.5 µm) with 50 Hz rate, and a Ka-band transmitter for LEO-LEO radio occultation (LRO), generating signals at 17.25, 20.2 and 22.6 GHz. Each receive satellite includes receivers for the signals mentioned above. The LIO receivers contain a telescope with an aperture of 16 cm, field of view of 1.5 mrad and 2 ms integration time. The LRO uses Ka-band radio receivers. Both transmit and receive satellites optionally include a GRAS-like instrument to perform L-band radio occultation measurements of GNSS signals.

The ACCURATE satellite platform is based on the design derived for ACE+. Each satellite will weigh approximately 180 kg and consume on average about 290 W of power. The active sounders produce on average a data rate of 14 kb/s in the transmitting satellites and about 25 kb/s in the receive ones. The GRAS-like sounders, if retained, produce a data rate of about 30 kb/s. A mass memory of 1 Gb and a downlink in the S-band at 1 Mb/s are sufficient to store and transmit this payload information to the ground.

The microwave part of the ACCURATE mission builds on an advanced and at the same time compacted version of the ACE+ mission system. ACE+ was scientifically and technically studied in depth within 2002 - 2005. With respect to ACE+, the ACCURATE mission concentrates on the study of the upper troposphere and the stratosphere (heights below 5 km sounded on a best effort basis), which allows optimizing the frequencies of the LEO-LEO Radio Occultation (LRO) experiment and so also avoiding issues on the scintillation effects that may still be left after the (post-ACE+) data processing method developed to cope with turbulence. The microwave part is therefore close to ACE+, in which the three Ka-band frequencies were considered. ACCURATE provides a very good balance of continuity (GRO and LRO) and innovation (joint LRO + LIO).

3. Programmatics Description

No specific inputs.

4. Assessment and Boundary Conditions

4.1 Relevance to the ESA research objectives for Earth Observation

Upper troposphere water vapour is a key component in the radiative budget of the earth's atmosphere. The ACCURATE mission supports the research objectives in the Earth Observation Theme 2 - Physical Climate and to Theme 4 - Atmosphere and Marine Environment: Anthropogenic Impact. By providing soundings of the UTLS temperature, and humidity profiles, and by measuring greenhouse gases and chemicals the ACCURATE mission addresses the First Challenge (Improved Understanding of Processes and their Interactions), the Third Challenge (Model-Data Integration), and the Fourth Challenge (Including the Human Dimension in Earth System Models) in the Call for Ideas for the Next Earth Explorer Core Missions. Finally, the ACCURATE mission addresses directly the Global Water Cycle and the Atmospheric Chemistry and Climate priorities for the 2005 Call, and contributes to the Human Element priority. ACCURATE will provide constraints on the upper tropospheric component of the global carbon cycle.

4.2 Need, usefulness and excellence

The ACCURATE mission is tailored to provide soundings of the upper troposphere and lower stratosphere with absolute calibration. The tropopause region has been identified in the literature as a key region for many composite-climate interactions and where global scale measurements of the spatial distribution of trace gases would be needed. Especially accurate upper tropospheric and lower stratospheric humidity measurements are needed for climate monitoring. The ACCURATE mission addresses these needs by providing measurements of several trace gases, humidity, temperature, and pressure/geopotential height. It should also be noted that the LRO and GRO soundings will in most cases continue into the lower troposphere even though the proposal does not commit on any specific measurement accuracy in this region. The ACCURATE mission allows simultaneous measurements of different species and several atmospheric state parameters with an effective vertical resolution of 1-2 km. The LRO and the GRO measurements will work in all-weather conditions. Global observations of this kind are very useful to support atmospheric UTLS modelling with the goal to detect climate and global change finger prints and to quantify the man made impact.

Though the infrequent horizontal sampling of ACCURATE may limit its impact on some applications in the field of atmospheric chemistry, the high vertical accuracy, global coverage, good absolute calibration (self-calibration) and a very good long-term stability of the data products make the ACCURATE mission very useful also as a potential benchmark and a reference for all climate monitoring measurements. This would be beneficial for calibrating the data from measurements with a relative calibration and would support building of long-term climate monitoring databases.

It is understood that the range of chemical species and other physical quantities to be measured have an important role in atmospheric chemistry and climate, particularly in the UTLS region, and that ACCURATE measurements will be potentially very valuable. These measurements will allow improved validation of chemistry-climate models and hence lead to more confidence in the ability of models to make predictions.

An assessment of the feasibility of experimental near real-time dissemination of the ACCURATE data products to the users would be beneficial to enable the use of the data in NWP applications and to allow for impact studies with the operational NWP systems.

4.3 Uniqueness and complementarity

The new LIO sounding technique and its combination with LRO soundings make ACCURATE a unique mission. No other satellite missions with a similar instrumentation and product characteristics are currently being planned. These measurements complement each other with respect to humidity, where LIO observations have the potential to provide an upward extension of the LRO humidity measurements into the stratosphere. The simultaneous and collocated measurement of methane, being the major source of water vapour in the middle and upper stratosphere, is important for the observation of the complete water vapour chemistry in the stratosphere.

The ACCURATE mission is independent of any input data from other satellite missions. However, ACCURATE provides data that can potentially complement nadir looking instruments e.g. in the MetOp/EPS, EarthCARE, OCO, and GOSAT missions. It should be noted that the support from ACCURATE for nadir looking carbon sensors like OCO and GOSAT would probably be limited. However, if the missions are flown simultaneously, the ACCURATE could provide complementary information on higher altitude levels.

The optional GRO measurement would complement RO soundings from the MetOp/EPS GRAS in NWP applications. ACCURATE would also be the first time that the European Galileo navigation satellite system would be used as a signal source for radio occultation soundings from space.

4.4 Degree of Innovation and contribution to the advancement of European Earth Observation capabilities

The ACCURATE mission proposes a new LIO measurement technique and a new concept of performing simultaneously laser and Ka band active microwave limb sounding measurements from LEO. This is a significant innovation and it would provide a new observation capability in Europe. The optional GRO measurement would additionally complement the overall data produced by the ACCURATE mission and take advantage of the European Galileo navigation satellite system.

The mission would therefore be highly valuable to improve the European Earth Observation capabilities and reinforce the European lead acquired in the field of sounding by occultations.

4.5 Feasibility and level of maturity

In general, the derivation of requirements for each instrument is good and supported by adequate simulations, the proposal making good use of the past experience of ACE+.

The scientific level of maturity for the LRO and for the optional GRO is high. The LRO measurement has been rigorously reviewed in the ACE+ mission evaluation framework in 2004 and the GRO concept has been demonstrated by several small satellite missions (GPS/MET, CHAMP, GRAS, COSMIC).

The innovative LIO concept requires technology and data retrieval studies. The SWIR laser occultation technique has no space heritage. Technological predevelopments should address the qualification of the DFB (Distributed FeedBack) laser diodes, which have not been used in space at these wavelengths, and, on the detector side, the demanding sensitivity in the SWIR domain. The LIO retrieval requires further analysis during the next phase of the mission preparation to analyze the product accuracy, vertical range of the measured profiles due to clouds, and the impact of cloud contamination in aerosol and trace gas measurements.

4.6 Timeliness

The ACCURATE mission can be performed independently from other satellite missions.

From the point of view of the data users, the need for upper tropospheric and lower stratospheric water vapour measurements for climate monitoring has been clearly pointed out in the literature. An increasing interest in the role of the UTLS for climate change and the chemical composition of the Earth's atmosphere has also occurred over the last few years. Thus, an implementation of the ACCURATE mission would be highly timely.

4.7 Programmatics

Thanks to previous work on similar missions, the mission is reasonably mature.

The proposal is based on instruments for which the technology is well mastered in Europe.

4.8 Boundary conditions

The ACCURATE mission has no launch data boundary conditions, as the mission does not depend on other satellite missions. ACCURATE can potentially complement nadir looking instruments in other missions.

5. Conclusions

The proposal for the ACCURATE mission covers all main elements of the mission planning as requested in the guidelines for the proposals. The scope of the ACCURATE mission is wide and it addresses almost all priorities for the 2005 Call for Ideas. The ACCURATE mission contains a combination of two innovative active occultation techniques in the microwave and infrared portions of the spectrum in order to infer humidity and trace gas concentrations in the upper troposphere and lower stratosphere. The humidity and trace gas measurements have unique absolute calibration enabling long-term climate monitoring and are accompanied by accurate temperature and pressure information from radio occultation. The combined set of measurements would provide timely and essential data for the Global Water Cycle and Atmospheric Chemistry and Climate priorities for the 2005 Call and contributes to the Human Element priority while the strength lies in the atmospheric physics part of the mission.

The proposed mission benefits from the previous theoretical work on the feasibility of the ACE+ mission. The general mission concept as well as the feasibility of the microwave based LEO–LEO crosslink measurement can be considered as mature. The innovative LIO'measurement is an extension of the original ACE+ framework. The LIO concept is new and it requires further analysis and technology development during the mission preparation.

It is recommended that the feasibility of including the optional GRO sounding into the ACCURATE mission should be explored because this element would complement operational radio occultation missions in providing data to the NWP user community.

The proposal is recommended.

Annex B. Pages 17-19 of the ACCURATE-2005 Proposal

ACCU (2005) proposal contents on the seven ESA Earth Explorer evaluation criteria.

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4. Relevance to Evaluation Criteria

Relevance to the Objectives of the Earth Explorer Programme and the Scientific Priorities of the Call

ACCURATE is very relevant to Theme 2 (Physical Climate) and Theme 4 (Atmosphere and Marine Environment: Anthropogenic Impact) of ESA's Living Planet/Earth Explorer programme. Regarding the scientific priorities of the Call (section 6 in ESA, 2005), ACCURATE will be a cornerstone contribution to the priority "Atmospheric Chemistry and Climate" and also provide important contributions related to the atmospheric subsystem of the Earth system for the priorities "The Global Water Cycle" and "The Global Carbon Cycle".

Need, Usefulness and Excellence

ACCURATE will improve the monitoring of greenhouse gas concentrations and of the water, carbon, and energy cycles of the Earth climate system and will advance their understanding. A major advantage of ACCURATE is that the absolute calibration of measurements of refractivities and differential transmissions can be maintained over the lifetime of the mission and can easily be reproduced in any follow up mission, even if there is no overlap between missions. This climate benchmark observation feature makes the occultation techniques used in ACCURATE particularly interesting for studying the slow changes in atmospheric parameters that are connected with climate change. For climate change studies it is essential that long time series of absolutely calibrated parameters are available. ACCURATE has the potential to be the beginning of a long time series or to build a reference data set of the conditions during its mission lifetime against which observations from later decades can be compared.

At the same time ACCURATE has enormous potential in the field of analyzing atmospheric climate and chemical variability, and in the context of atmospheric physics, chemistry and radiation process studies, due to its consistent and simultaneous measurement of all major greenhouse gases and the H_2O and CO_2 isotopes, co-located with temperature and pressure measurements as a function of height.

More information on the utility and excellence of ACCURATE is provided in the mission objectives description (section 1).

Uniqueness and Complementarity

The ACCURATE mission will provide accurate LRO+LIO profiling of the state vector $\mathbf{X} = (z, T, p/Z, q/H_2O, CO_2, CH_4, N_2O, O_3, CO, HDO, H_2{}^{18}O, {}^{13}CO_2, C^{18}OO)$ in the UTLS region, together with profiling of aerosol, cloud layering, and turbulence characteristics, optionally complemented by the dense GRO profiling of refractivity and derived parameters. The consistent and simultaneous measurement of high-quality and high-resolution profiles of all these parameters from space, as available from the LRO+LIO joint occultation technique, is new and unique. Section 1 provided more details on the set of unique properties of ACCURATE (subsection 1.5) enabling it to meet its mission objectives (subsections 1.2–1.4).

The self-calibration and tight-synergy capability of the joint LRO+LIO technique is particularly unique in this context and is strongly complementary to the most widely used radiometric temperature, humidity, and greenhouse gas measurements from space, which require height calibration and measurement series overlapping in time in order to maintain calibration from one mission to the next. For greenhouse gases, the height-resolving limb sounding measurements of ACCURATE in the UTLS are also highly complementary to the downlooking sounder greenhouse gas column measurements focusing on lower troposphere concentrations (e.g., from selected bands of IASI on MetOp or the dedicated Japanese GOSAT mission and NASA's OCO mission).

From the technical standpoint, the uniqueness lies in the fact that ACCURATE will be the first mission to demonstrate the LRO and LIO techniques as well as, regarding the optional GRO payload, the first mission to demonstrate the use of Galileo-LEO occultation in addition to GPS-LEO occultation.

Degree of Innovation and Contribution to the Advancement of European Capabilities

The degree of innovation of ACCURATE is very high since the LRO and LIO techniques have not been used before. The LRO part builds on strong heritage from ACE+, the LIO part is a new highly complementary and synergistic component for extending the measurements of thermodynamic variables (pressure, temperature, humidity) as a function of height from LRO by measurements of profiles of the greenhouse gases (H_2O, CO_2, CH_4, N_2O, O_3, CO) and the major H_2O and CO_2 isotopes HDO, $H_2{}^{18}O$, $^{13}CO_2$, and $C^{18}OO$ from LIO. Dependent on LIO payload design also other trace species accessible in the SWIR could be included. The scientific innovation is thus very high, since the joint LRO+LIO technique will for the first time allow simultaneous observation of accurate, consistent and long-term stable sets of UTLS profiles of thermodynamic variables, greenhouse gases and H_2O and CO_2 isotopes from space. In addition, the optional GRO part would be innovative with respect to the use of measurements from the new European Galileo system.

As a consequence, European capabilities would be reinforced and strongly advanced, in particular with respect to atmospheric climate benchmark and chemistry measurements. Presently European industry and scientists are worldwide leaders as to operational radio occultation instruments and advanced retrieval and assimilation techniques. ACCURATE will be instrumental in maintaining this leadership and to expand it by the new joint LRO+LIO science and technology.

Feasibility and Level of Maturity

As the ACCURATE mission builds on ACE+ heritage in terms of general mission architecture, constellation geometry, and LRO (and GRO) payloads, the feasibility of all these parts is already demonstrated via the ACE+ Phase A studies and related scientific studies conducted 2002–2005 (ESA, 2004a,b; ACEPASS, 2005a,b).

The ESAC and ESA, in evaluating the technical feasibility in the course of the last Earth Explorer round for mission selection in 2004, thus concluded that the technical feasibility of the ACE+ mission has been demonstrated and the risks associated to the only critical item, namely the LRO instrument, have been substantially reduced through experimental activities, thanks also to a national initiative on the front-ends and their verification. Considering that only developed technologies are involved, the frequency bands used being rather conventional, and that the required experience is available, the level of technical maturity was considered high.

On scientific feasibility of LRO, aspects related to turbulence in the troposphere were found weakly consolidated at ACE+ mission assessment time in 2004, which is in particular relevant to the lower troposphere (< 5 km). ACCURATE builds in this respect on a substantially more consolidated basis since it firstly focuses on the UTLS (> 5 km), where turbulence is significantly weaker, and secondly uses the new differential transmission approach described in ACEPASS (2005b). This approach actively corrects for diffraction and scintillations due to turbulence and is expected to safely lead to the required scientific performance over the UTLS domain. It is also expected to lead to improved results in the lower troposphere, a domain ACCURATE will treat on a best-effort basis. Based on the heritage described, the overall ACCURATE system and its LRO (and optionally GRO) components can thus be considered to be fully feasible and of a high maturity level.

The novel LIO concept went through an initial scientific and technical feasibility assessment study in the 1st half of 2005, as described in sections 2 and 3. It was found that an LIO system fully meeting the preliminary observational and system requirements is technically feasible using available technologies, both at the LIO transmitter and LIO receiver sides. Also, from technology parts not yet space qualified, no technology elements were detected where the required space qualification might pose a feasibility problem. Breadboarding of representative laser frequency cross-links of the LIO system, and space qualification of various components, could start immediately. Companies with LIO technology expertise called on for advice on potential launch readiness date of an LIO system rated this readiness achievable by 2009, since all necessary technologies are available. In summary, while having no direct space-based heritage, the innovative LIO system is thus expected to be feasible. A pre-Phase A study would be an ideal means to further develop this new laser occultation concept being an integral part of the LRO+LIO core payload of ACCURATE.

Timeliness

As noted under “Uniqueness and Complementarity” above, the ACCURATE mission with its measurement of high-quality and high-resolution profiles of thermodynamic variables, greenhouse gases, and main isotope species from space, as available from the LRO+LIO profiling, is new and unique. No other previous or presently planned satellite mission provides this type of atmospheric measurements despite the urgency of the geophysical products in the context of atmospheric climate and chemistry research and greenhouse gas and climate trends monitoring.

Realization of the ACCURATE mission would thus be highly timely from a scientific and societal point of view. Furthermore, it would be very timely in order to maintain and secure the European leadership in the fields of LRO+LIO and Galileo-LEO science and technology.

Programmatics

The ACCURATE mission builds on an advanced and at the same time compacted version of the ACE+ mission system, which was scientifically and technically studied in depth within 2002–2005. As described above under “Feasibility and Level of Maturity” this provides a very solid starting point from strong heritage, which in ACCURATE is complemented by the highly innovative IR laser occultation concept to form the powerful LRO+LIO core payload. ACCURATE thus provides a very good balance of continuity (GRO and ACE+ LRO) and innovation (joint LRO+LIO). Given the leadership of ESA built up by its substantial occultation science and technology activities over the last decade it would seem very attractive to adopt the ACCURATE concept as a potential future mission, based on its science potential strongly in line with the scientific priorities of the Call, its uniqueness, timeliness, degree of innovation, and expected feasibility.

Regarding time schedule, the current estimate of the Responding Team and technical advisors from industrial side is that the ACCURATE mission could in principle be ready for launch by 2009/10. It is understood that this is not the implementation timeline foreseen for missions selected after pre-Phase A and Phase A activities following this Call, but it is to indicate that Phase A/B/C/D implementation is expected to be feasible for ACCURATE within a 4–5 years timeframe.

Regarding cost, preliminary estimates found that ACCURATE in its proposed baseline configuration (ACE+ type four satellite constellation; section 2) with the LRO+LIO core payload is well compatible with the 300 MEUR ceiling cost mentioned in the Call. Including the optional GRO payload results in marginal compatibility as does inclusion of the option of two further LEO Rx satellites. The cost estimates of the different options, and the programmatics of the options, would thus need to be further analysed in the pre-Phase A context.

The resources for inclusion of options might be available from non-ESA partners (cf. section 2), since there is considerable non-ESA member states interest in ACCURATE, as also reflected by the many non-European scientists in the Responding Team. During the pre-Phase A period more detailed clarifications on potential international cooperation and non-ESA contributions would need to be sought.

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Abstract:
ACCURATE—climate benchmark profiling of greenhouse gases and thermodynamic variables and wind from space is a mission to initiate a novel fundamental atmospheric state dataset for climate and composition monitoring and research in the global free atmosphere using combined microwave and infrared-laser occultation between Low Earth Orbit (LEO) satellites (LEO-LEO Microwave and IR-laser Occultation, LMIO). The LMIO method has potential to provide ground-breaking contributions to science goals such as monitoring climate variability and trends, testing of global climate and composition models, study of atmospheric processes, and provision of authoritative reference data for calibration and validation of data from other spaceborne, airborne, or ground-based observing systems. The ACCURATE EE-8 proposal presented by this report focuses on a first demonstration of this novel and unique method. Starting with an Executive Summary the report then describes the mission in detail, from the science objectives via the observation principles and technical requirements to the proposed mission architecture and programmatic aspects.

Zusammenfassung:
ACCURATE—Klima-Referenzdaten von Treibhausgasen und thermodynamischen Variablen sowie von Wind ist eine Satellitenmission, die einen neuartigen fundamentalen Datensatz für die Überwachung und Erforschung des Klimas und der Zusammensetzung der globalen freien Atmosphäre (über der bodennahen Grenzschicht) starten will. Die dazu vorgeschlagene Methode LMIO (engl. Abkürzung) kombiniert Mikrowellen- und Infrarotlaser-Signalverdunkelungsmessungen zwischen Satelliten in niedrigen Umlaufbahnen (~500–600 km Höhe). Sie hat hohes Potenzial, bahnbrechende Beiträge zu wissenschaftlichen Zielen wie Monitoring des Klimawandels, Evaluation von Klimamodellen, Studium atmosphärischer Prozesse und Referenzmaßstab zur Eichung anderer Beobachtungsdaten zu leisten. Der in diesem Bericht vorgestellte Missionsvorschlag ACCURATE EE-8 fokussiert auf eine erste Demonstration der neuartigen LMIO-Methode. Beginnend mit einem Executive Summary wird die Mission ausführlich beschrieben, angefangen von den wissenschaftlichen Zielen über Beobachtungsprinzipien und technische Erfordernisse bis hin zur gesamten Architektur der Satellitenmission und zu programmatischen Aspekten.

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