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IRDAS – Differential Absorption Spectroscopy in the SWIR for Greenhouse Gas Monitoring using Coherent Signal Sources in a Limb Sounding Geometry
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WP3-4 Report

Scientific Impact of an ACCURATE Mission and Synergies and Complementarities with other Missions and GHG Observations

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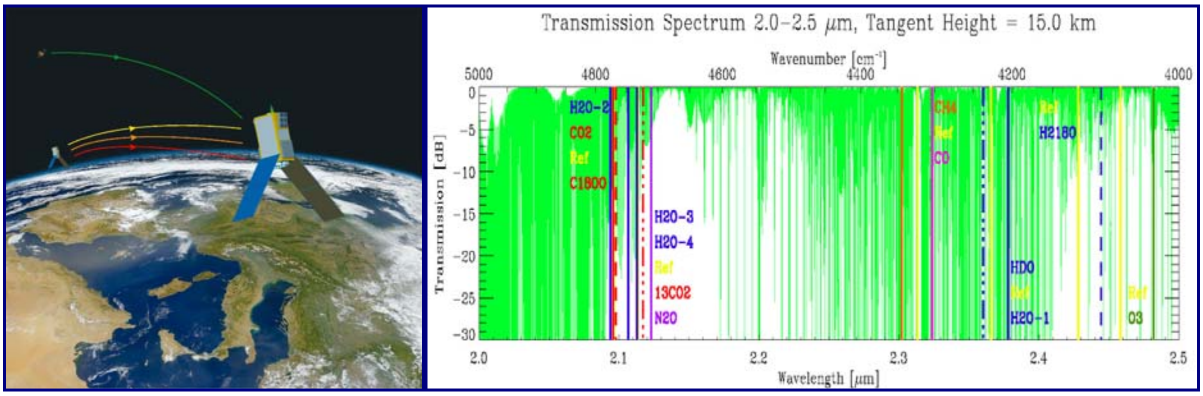

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Document Change Record

Issue	**Date of Change**	**Where**	**Description of Change**
v1	6 May 2009	WEGC	1st draft
v2	10 June 2009	DMI	2nd draft, input on synergy with PREMIER mission, input to table on ACCURATE science objectives
v3	16 June 2009	WEGC	3rd draft, input on ACCURATE performance and scientific impacts, including further consolidation on Impact Level matrices
v4	26 June 2009	WEGC	4th draft, further input from WEGC and DMI included
v5	16 Oct 2009	WEGC	5th draft, advanced version WEGC side, provided to DMI for further contribs re IASI-MetOp and PREMIER
v6	8 Jan 2010	WEGC	6th draft, further advanced version WEGC side, provided to DMI for completing contribs re IASI-MetOp and PREMIER
v7	11 Jan 2010	WEGC	First completed version, including DMI contribs (Sect. 4) and finalizations WEGC of complete report
	Jan 2010	WEGC	Final version, having received final editing, also accounts for final ESA comments, and kept consistent with the IRDAS WP2 report

List of Acronyms

ACCURATE	Atmospheric Climate and Chemistry in the UTLS Region and climate Trends Explorer
ACE	Atmospheric Chemistry Experiment (Canadian solar occultation mission)
ACE+	Atmosphere and Climate Explorer (occultation mission studied by ESA 2002–2004)
ACTLIMB	Active Limb Sounding of Planetary Atmospheres
ALPS	ACCURATE LIO Performance Simulator
ARSCliSys	Atmospheric Remote Sensing and Climate System (Research Group of WEGC)
DFB	Distributed Feed-Back (laser diode)
DMI	Danish Meteorological Institute
ECMWF	European Centre for Medium-Range Weather Forecasts (Reading, U.K.)
EGOPS	End-to-end Generic Occultation Performance Simulator
Envisat	Environmental Satellite (of the European Space Agency)
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
ESA	European Space Agency
ESRL	Earth System Research Laboratories (of NOAA)
FFG-ALR	Austrian Aeronautics and Space Agency of the Austrian Research Promotion Agency FFG
FOV	Field of View (remote sounding area sensed by receiver antennae or optics)
Galileo	European future global navigation satellite system
GCM	Global Circulation Models
GCOS	Global Climate Observing System
GHG(s)	Greenhouse gas(es)
GMD	Global Monitoring Division (of ESRL of NOAA)
GNSS	Global Navigation Satellite Systems (Global Navigation System, GPS, and Galileo)
GOSAT	Greenhouse Gases Observing Satellite
GPS	Global Positioning System
GRAS	GNSS Receiver for Atmospheric Sounding
GRO	GNSS-LEO radio occultation (here Galileo & GPS L band signals, ~1.2 / 1.6 GHz)
HITRAN	High-resolution Transmission molecular absorption database
HT	Higher Troposphere (Equals UT)
IDL	Interactive Data Language (an int Higher Troposphere eractive visual analysis software package)
IR	Infrared
IRDAS	Differential Absorption Spectroscopy in the SWIR for Greenhouse Gas Monitoring using Coherent Signal Sources in a Limb Sounding Geometry
JAXA	Japan Aerospace Exploration Agency
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)
LIO	LEO-LEO infrared laser occultation (here laser crosslink signals within 2–2.5 μm)
LMO	LEO-LEO microwave occultation (here microwave crosslink signals within 17–23 GHz and 178–183 GHz)
LRO	LEO-LEO radio occultation (here microwave crosslink signals within 17–23 GHz and 178–183 GHz)
LS	Lower Stratosphere (WMO: 100–10 hPa / ~15–35 km)
LT	Lower Troposphere (WMO: 1000–500 hPa / ~0–5 km)
MetOp	Meteorological Operational satellite (of EUMETSAT)
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MW	Microwave spectral region (3–300 GHz; here the 17–23&178–183 GHz regions)
NOAA	National Oceanic and Atmospheric Administration

NWP	Numerical weather prediction
OCO	Orbiting Carbon Observatory
PBL	Planetary Boundary Layer
PREMIER	Process exploration through measurement of infrared and millimeter emitted radiation – (Mission selected for ESA phase A studies)
RF	Radio Frequency
RH	Relative humidity
RMS, rms	Root Mean Square (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 (in ACCURATE LIO generally referring to 60 km height)
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)
WEGC/ UniGraz	Wegener Center for Climate and Global Change, University of Graz (Austria)
UoY	The University of York (U.K.)
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)

1 Introduction

This report takes the Scientific Objectives and Observational Requirements report on ACCURATE from WP 2 [ACCUObsReq09] as a starting point and evaluates the scientific impact of an ACCURATE mission via a mission analysis study that provides geophysical profiles performance for a set of constellation scenarios. Based on these results an “Impact Level matrix”, for the dimensions Scientific Objectives vs. Observation Information, is estimated for ACCURATE and compared with analogous “Impact Level matrices” estimated for other missions and GHG observations.

Focus and representative examples for the “other missions” are IASI advanced IR passive downlooking radiometry on MetOp [IASI98, IASI01, IASI10] and IMIPAS/STEAM-R advanced passive limblooking radiometry on PREMIER [PREMIER08]. Focus for the “other GHG observations” are CO_2 and CH_4 measurements from GOSAT [GOSAT09] space-based solar backscattering and thermal IR radiometry as well as from the global ground-based NOAA/GMD-led cooperative air sampling network [CAS-GMD10]. On GHGs from space we did for the present purpose consider GOSAT, the only CO_2/CH_4 mission already flying, as the “strawman” also for other more advanced systems with very similar goals like NASA’s Orbiting Carbon Observatory OCO (launch failed, future not clear) and ESA’s A-SCOPE high-power Lidar sounding concept (still more development needed).

The report structure is as follows. Section 2 introduces the new concept of “Impact Level matrix” (conceived for this report). Section 3 discusses the observational performance for climate measurements achieved by ACCURATE under different constellation sizes, given the observational requirements of [ACCUObsReq09], and at the end estimates the Impact Level matrix for ACCURATE. Section 4 then briefly introduces the “other missions” IASI-MetOp and PREMIER and estimates their Impact Level matrix (this section mainly done by DMI, with expertise as a national meteorological service for radiometric “NWP-type” sounder data). Section 5 follows to introduce the “other GHG observations” by GOSAT and NOAA/GMD network and as well estimates the respective Impact Level matrices. Section 6 then provides a synthesis discussion on unique impacts of ACCURATE, as well as on synergies and complementarities with the other missions and GHG observations. Finally, Section 7 briefly summarizes and collects the main conclusions.

We note that estimating the Impact Level matrices to provide their current form was expert assessment and judgment of the authors (from WEGC, DMI) and reviewers (from Univ. York, ESA) of this report. That is to caution that their current contents is not a “community accord” of a larger group of diverse experts. A refinement in this direction may be worthwhile in the future if the Impact Level concept is found of utility beyond this study. The overall picture of strengths and limitations of impact emerging in the matrices appears to be robustly sound, though. The report thus draws conclusions on uniqueness, synergy, and complementarities from these overall robust features, so that independent of refinement it has a lasting value to aid adequate understanding of the role and significance of an ACCURATE mission in the context of other key atmospheric observing techniques and systems.

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2 Defining Scientific Impact – The Impact Level Matrix

In this report we aim to have a structured comparative look at the scientific impact of different observing systems by the concept of "Impact Level matrices", which indicate the impact of observation information that an observing system can provide in relevant categories for different relevant scientific objectives. Thereby, the definitions for an "Impact Level matrix" are as follows (see Table 2.2 below for a template and the Impact Level matrix for ACCURATE in Section 3.4 as a first example; all others following are of the same format):

The *rows of the matrix denote the Scientific Objectives*, grouped into the following four themes:

Climate, Chemistry&Processes, NWP, Others

The formulation of the objectives for each theme is reflecting the typical objectives of atmospheric missions independent of a specific observing system. In this way the same objectives can be baselined for all "Impact Level matrices" in this report ensuring comparability. Table 2.1 summarizes the objectives and provides a convenient "shortcut form" for them that is then space-effectively used in the row descriptions of any Impact Level matrix (cf. Table 2.1 and the Impact Level matrix template, Table 2.2).

The *columns of the matrix denote the Atmospheric Observation Information* that is distributed into the following seven categories:

ThDyn	Thermodynamics (i.e., T, p, q information)
DynWind	Dynamics/Wind (i.e., U, V wind field and convection/turbulence information)
GHGs	Greenhouse Gases (i.e., CO_2, CH_4, N_2O, H_2O, O_3, CO, halocarbons info)
RAGs	Reactive Atm. Gases (i.e., O_3, CO but also many others, esp. troposph. ones)
Aerosols	Atmospheric Aerosols (sea salt, mineral dust, sulphur, black carbon, etc.)
Cls+Prec	Clouds and Precipitation (all kinds of clouds and precipitation, liquid+ice)
Radiation	Atmospheric Radiation (SW, LW in/out/net and also incl. solar irradiance)

This again is a generic formulation for all atmospheric observing systems so that full comparability is enabled since all observing-system specific matrices share the same rows and columns.

The *impact level* itself is, for each matrix element, indicated according to the following six symbol classes, ranked in decreasing order of impact, from unique impact to no impact:

`***`	unique impact (top; superior to all other known obs.systems for the objective)
`***`	major impact (co-leading impact amongst all other known obs.systems)
`**`	significant impact (adding significant information to that of all other obs.systems)
`*`	contributing impact (contributing useful information to that of all other obs.systems)
`(*)`	indirect impact (providing useful indirect information, e.g., via GHGs to Radiation or via cloud layering info to Cls+Prec)
−	no impact (not covered by the given obs.system; no contribution to the objective)

All impacts are meant to be *positive impacts*, i.e., supporting to reach any scientific objective.

Table 2.1. Scientific objectives used in the Impact Level matrices

Scientific Objective – shortcut form	**Scientific Objective description**
Climate	
Monitor climate trends and variability	Monitoring of climate trends and variability in thermodynamic, dynamics/wind, greenhouse gases, reactive gases, aerosol, cloud/precipitation, and radiation variables, for contributing to accurate long-term observations of climate in the atmosphere
Diagnose and predict climate change	Diagnostics, including detection and attribution, of anthropogenic climate and composition changes in the atmosphere, as well as of changes in the global carbon and water cycles, and support to climate change predictions via accurate data
Validate, test and improve climate GCMs	Validation of global circulation models (GCMs), in simulated mean climate and variability seen in atmospheric physics/composition/radiation variables, and testing and improvement of their process formulations
Understand climate forcings and feedbacks	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
Chemistry&Processes	
Study atmos. processes near-surface & in the LT	Study of atmospheric processes near surface and in the lower troposphere (LT), in the context of atmospheric chemistry and physics research, including also aerosol, cloud, and dynamical variability studies
Study atmos. processes in the UTLS	Study of atmospheric processes in the UTLS region at high resolution, in the context of atmospheric chemistry and physics research, including also aerosol, cloud, and dynamical variability studies
Improve atmos. composition forecasting	Improvement of forecasting and analysis of atmospheric composition including greenhouse gases, reactive gases, and aerosols by atmospheric constituent model and data assimilation systems
Test and improve atmos. constituent models	Testing of constituent models and improvement of their process formulations, in order to enhance their composition forecasting skill
NWP	
Improve NWP forecasting	Improvement of forecasting and analysis of weather conditions, including in thermodynamic, dynamic/wind, cloud/precipitation, and radiation variables, by weather prediction (NWP) and data assimilation systems
Test and improve NWP models	Testing of NWP models and improvement of their process formulations, in order to enhance their weather forecasting skill
Others	
Calibrate data from other atmos. observing systems	Provide reference data for the calibration, validation, and analysis of data from other space missions or airborne/ground-based observing systems
Demonstrate a novel observing technique	Demonstrate the science value of a novel satellite-based atmospheric remote sensing technique not yet used before

Table 2.2. Sci.Objectives-vs-Obs.Information Impact Level Matrix – Template

	Atmospheric Observation Information						
Scientific Objectives	ThDyn	DynWind	GHGs	RAGs	Aerosols	Cls+Prec	Radiation
Climate							
Monitor climate trends and variability							
Diagnose and predict climate change							
Validate, test and improve climate GCMs							
Understand climate forcings and feedbacks							
Chemistry&Processes							
Study atmos. processes near-surface & in the LT							
Study atmos. processes in the UTLS							
Improve atmos. composition forecasting							
Test and improve atmos. constituent models							
NWP							
Improve NWP forecasting							
Test and improve NWP models							
Others							
Calibrate data from other atmos. observing systems							
Demonstrate a novel observing technique							

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3 ACCURATE Observational Performance and Impact Level Matrix

3.1 Starting Point: Observational Requirements

The ACCURATE observational requirements [ACCUObsReq09] provide the basis for assessing the observational performance and, subsequently, the scientific impact (Sect. 3.4). Table 3.1 summarizes these requirements and Figure 3.1 illustrates the accuracy requirements.

Table 3.1. Baseline set of ACCURATE LMO and LIO observational requirements

		LMO				LIO				
		Temperature		Sp. Humidity		Trace Species1)		l.o.s. Wind2)		
Requirement		Target	Thres	Target	Thres	Target	Thres	Target	Thres	Units
Horizontal domain		global								
Horizontal sampling3) (mean distance of adjacent profiles) to be achieved within:		900	1800	900	1800	900	1800	900	1800	[km]
time sampling4)		12	24	12	24	12	24	12	24	[hrs]
No. of profiles per grid box per month5)		40	30	40	30	40	30	40	30	
Vertical domain6)		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 accuracy9)	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]		[%RH10)/dec]		[%/dec]		[(m/s)/dec]		
Timeliness	Climate	7	14	7	14	7	14	7	14	[days]
	NWP11)	1.5	3	1.5	3	1.5	3	1.5	3	[hrs]
Time domain12)		> 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.

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 accu-

racy 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.

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 time frame (3 years or more).

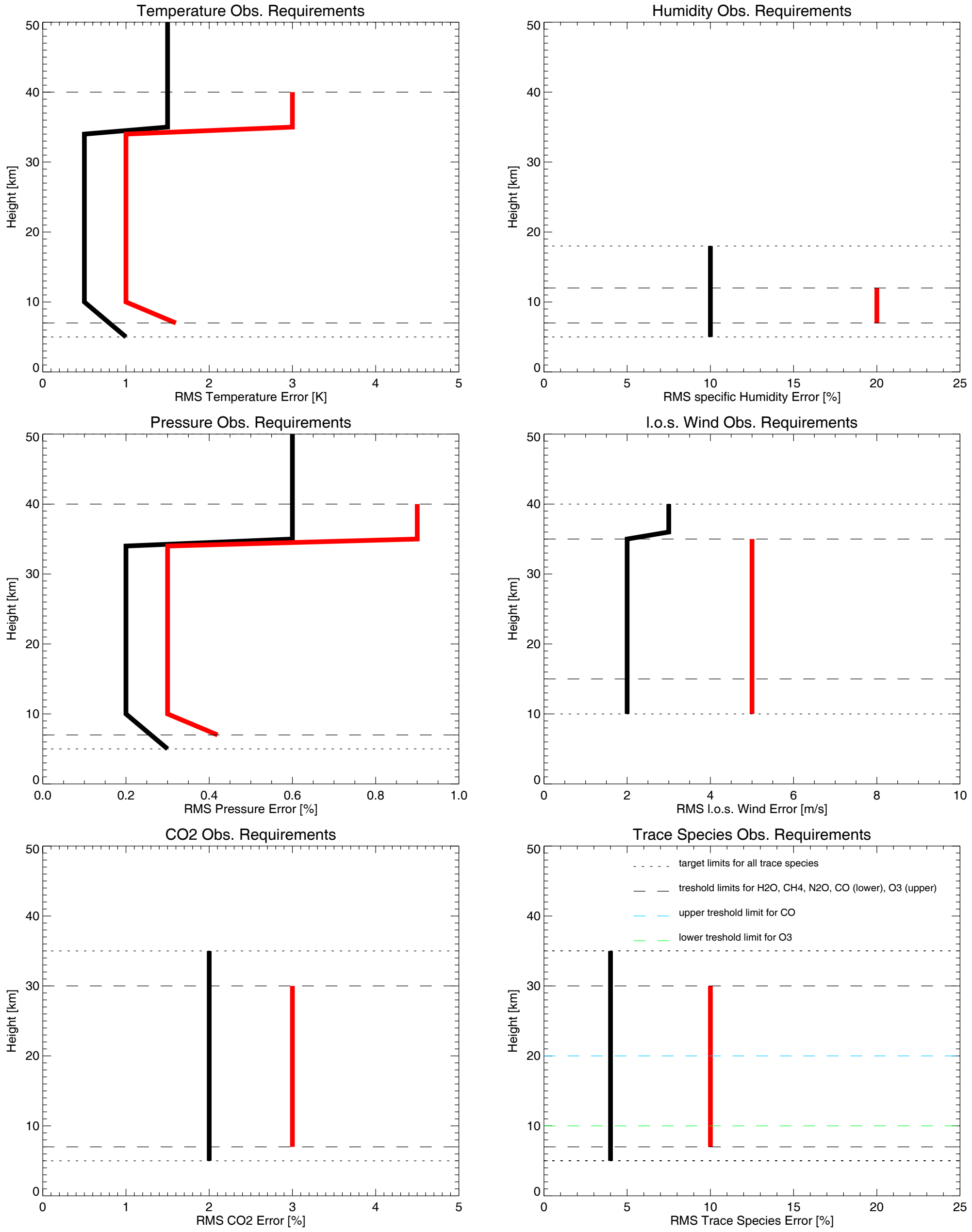


Figure 3.1. Illustration of the ACCURATE LMO and LIO accuracy requirements. The pressure accuracy is set to be consistent with the temperature accuracy requirement.

The derivation of and rationale for these requirements, in terms of the underlying ACCURATE scientific objectives and the context requirements from bodies of the WMO, has been discussed in [ACCUObsReq09]. Here they provide the starting point for the analysis of space/time sampling characteristics and corresponding climatological accuracies obtainable.

Given that the primary scientific objectives focus on climate [ACCUObsReq09], we gauge the observational performance by the climate (monthly-mean) accuracies achieved at reasonable levels of horizontal resolution in line with space/time sampling requirements of Table 3.1. The individual-profile errors used as error baseline are as well those of Table 3.1 and illustrated in Figure 3.1. In order to set the pressure accuracies adequately consistent with the temperature accuracy requirements, we used heritage knowledge on the inter-connection of the thermodynamic parameters in occultation data from GRO and MWO retrieval studies ([SteinKirc05], [Schweitzetal09]).

3.2 Performance Analysis Setup and Error Modeling

We took the approach to assess the observational performance by way of investigating event distributions and climatological accuracies obtained for three representative example constellations in Low Earth Orbit (LEO-LEO crosslink constellations):

- **1 Tx + 1 Rx "minimum" constellation (MC):** One transmitter (height ~800 km) and one receiver (height ~650 km) in counter-rotating near-circular orbits
- **2 Tx + 2 Rx "baseline" constellation (BC):** Two transmitters (height ~800 km, in-orbit spaced by 180 deg) and two receivers (height ~650 km, in-orbit spaced by 90 deg) in counter-rotating near-circular orbits
- **6 Tx + 6 Rx "large" constellation (LC):** Two times three transmitters (height ~800 km, in-orbit spaced by 120 deg) and three receivers (height ~650 km, in-orbit spaced by 90 deg) in counter-rotating near-circular orbits, in two orbital planes (equatorial node separation 90 deg) with 3 Tx + 3 Rx each

We assessed these three cases with both using true-polar orbits (inclination 90 deg) and sun-synchronous orbits (inclination ~98 deg). In the sun-synchronous cases orbital nodes were aligned with the MetOp orbit (9:30/21:30 LT descending/ascending equatorial nodes). We illustrate and discuss below the results from the true-polar orbits only, since those from the sun-synchronous orbits are very closely the same.

Regarding the specific requirement to focus on observing the meridional wind ("Brewer-Dobson circulation"), as noted in footnote 2 of Table 3.1, the true-polar orbit is optimal to fulfil this particular need, while sun-synchronous orbits will also see some zonal wind component in their Tx-to-Rx crosslink line-of-sights during occultation events. Regarding the specific requirement on local time sampling, noted in footnote 4 of Table 3.1, the true-polar orbits will sample over all local times (twice per year) while the sun-synchronous ones will sample near fixed local times (the local times also covered by the MetOp data in case of co-alignment of orbits with MetOp).

The End-to-end Generic Occultation Performance Simulation and Processing System (EGOPS) [EGOPS07] was used to perform the mission analysis for these constellations and to provide the geographical distributions of occultation events as well as the numbers of profiles furnished into defined climatological bins (called "grid boxes" in Table 3.1) per month.

The computation of numbers of profiles per bin per month was done for large-scale climatological bins and, based on these, within each large-scale bin for equal-area bins of a size consistent with the horizontal sampling threshold requirements in Table 3.1, i.e., choosing a basic area of 1800 km x 1800 km = 3.24 Mio. km^2 (25 % of this area for the LC 12-sat case). The large-scale bins were adopted to be zonal bands of 10 deg latitudinal width, yielding 18 bins from south pole to north pole, corresponding to a classical large-scale subdivision frequently used with GPS radio occultation data for climatological performance assessments (e.g., [Foelschetal09] and references therein). The size of the basic area of ~3 Mio. km^2 corresponds to a geographic cell size of about 10 deg lat. x 25 deg lon. near the equator.

Computing the numbers per equal-area bin for each of these large-scale bins allows to properly see as a function of latitude how the “No. of profiles per grid box per month” requirement in Table 3.1 is reached by a certain constellation case. The actual profile number per equal-area bin, N_{eab}, is obtained by just multiplying the given number per large-scale bin, N_{lsb}, by the ratio of the basic area, A_{eab}, to the area of the large-scale bin, A_{lsb},

$$N_{\mathrm{eab}} = \mathrm{Rnd}[\, N_{\mathrm{lsb}} \cdot (A_{\mathrm{eab}} / A_{\mathrm{lsb}}) \,], \tag{1}$$

where the result is rounded, Rnd[.], to the nearest integer number.

The climatological errors of each parameter P per latitude bin l as a function of height z, $E_{\mathrm{clim,P,l}}(z)$, either large-scale or equal-area, are subsequently obtained by multiplying the rms accuracy requirements of Table 3.1/Figure 3.1, properly interpreted as prescribed individual-profile rms errors $E_{\mathrm{rms,P}}(z)$, by the inverse-square-root of the number of profiles, N_{l}, representing statistical error averaging, and also counting in a current-best-guess systematic error bound per parameter, $E_{\mathrm{sys,P}}(z)$,

$$E_{\mathrm{clim,P,l}}(z) = \mathrm{Sqrt}[\, (E_{\mathrm{rms,P}}(z)/\mathrm{Sqrt}(N_{\mathrm{l}}))^2 + (E_{\mathrm{sys,P}}(z))^2 \,]. \tag{2}$$

Here the rms error has been used to represent the statistical error, $E_{\mathrm{sdev,P}}(z) = E_{\mathrm{rms,P}}(z)$, since the systematic error bound is much smaller than the individual-profile statistical error for occultation measurements such as from ACCURATE.

The current-best-guess of the residual systematic error bound, based on experience from previous GRO, MWO, and ILO work (e.g., [Steinetal09], [Schweitzetal09], [ACCUPERF07]), was formulated as

$$E_{\mathrm{sys,P}}(z) = f_{\mathrm{sys,P}} \cdot E_{\mathrm{rms,P}}(z), \tag{3}$$

where the fraction $f_{\mathrm{sys,P}}$ of systematic error relative to rms error was set to 0.1 (10 %) of the threshold (“Thres”) rms errors of Table 3.1 for the thermo-dynamic parameters temperature, pressure, and l.o.s. wind, and to 0.05 (5 %) of the target (“Target”) rms errors of Table 3.1 for the species parameters humidity and all LIO trace species, respectively. This leads to residual systematic error estimates as follows: temperature 0.1 K, pressure 0.03 %, l.o.s. wind 0.5 m/s, specific humidity 0.5 %, CO2 (incl. its isotopes) 0.1 %, other LIO trace species 0.2 %.

We note, especially for the LIO-derived parameters and LMO humidity, that these systematic error bounds are understood to cover the residual time-varying component of systematic error, i.e., the one that would alias climate trend and variability estimates. In addition, an absolute constant offset from “truth” will occur that is higher – at least initially before calibrations and

traceability are perfected – due to the current limits of absolute knowledge of the spectroscopic parameters of the LIO and LMO target absorption lines.
Dedicated standard spectroscopy of all target lines can bring this absolute knowledge to ~1 % uncertainty (currently from HITRAN database and Liebe MW absorption model more ~5 % uncertainty or so [HITRAN08], [Nielsetal03]), which is well sufficient so that any temporal trends and variability of species concentrations (and l.o.s. wind) can be tracked at ~0.1 % accuracy.
Still beyond this it is desirable, similarly to the knowledge of refractivity coefficients in GRO that is available to within ~0.1 % uncertainty (e.g., [Foelsch99]), to also constrain the ACCURATE target line knowledge with advanced spectroscopy to this ~0.1 % uncertainty. Modern methods of cavity-ringdown spectroscopy (CRDS), that could use the DFB diode lasers made for the ACCURATE target lines as seed lasers, are able to provide this spectroscopic accuracy (e.g., wavelength-scanned CRDS [RellaVP09]). In this way we really will establish an absolute trace species concentration reference standard in the global free atmosphere without needing additional ground- or other cross-calibration to estimate residual absolute constant concentration offsets of ~1 % size.

In line with the six different $E_{\mathrm{rms,P}}(z)$ cases shown in Figure 3.1, we estimated the climatological errors via Eq. (2) separately for the thermodynamic parameters temperature T, specific humidity q, and pressure p derived from MWO data, the dynamical parameter l.o.s. wind V_{los} derived from ILO data, and the trace species parameters CO_2 (incl. its isotopes) and other non-CO_2 trace species derived as well from ILO.
For the H_2O isotopes (HDO and $H_2{}^{18}O$), for which “required accuracy over the best possible height range up to 12 km” is specified in Table 3.1, i.e., a best-effort retrieval in this sense, we adopt a more conservative individual-profile rms error as starting point, assuming it to be a factor of 2 higher than for the other non-CO2 trace species.

We did not separately estimate sampling error in this analysis but assume in this respect that the sampling error for our climatological parameters of interest in the UTLS is either about as small as the assumed residual systematic error bound $E_{\mathrm{sys,P}}(z)$ or can be properly estimated and subtracted to bring the residual sampling error to this small error level.
Sampling error estimation and subtraction methodology has been extensively studied and demonstrated in the GRO context for similar size occultation observing systems as considered here (e.g., CHAMP and Formosat-3/COSMIC GRO) and it has been shown for the thermodynamic parameters that very low residual error levels are achieved (e.g., < 0.1 K in temperature; [Foelschetal09b], [Steinetal09], [Hoetal09], and references therein).
In the context of this report, when subsequently assessing the levels of potential scientific impact, we thus keep in mind sampling error as a component of similar size as the residual systematic error bound, so that the total error including both residual components will still be of about the same size as the residual systematic error bound accounted for here.

We computed the climatological accuracy results both for adopting the target and the threshold accuracy requirements as individual-profile rms errors but we save space below in restricting to show the results from using the target requirements only. On the one hand this is well justified because ACCURATE retrieval performance analyses (e.g., [Schweitzetal09], [ACCUPERF07]) show that the actual retrieval errors are expected to generally lie within target requirements, i.e., would generally even outperform the results shown below. On the other hand it is fairly simple to scale the climatological error results via use of Eq. (2) with any rms error different from the target requirements plus use of the number-of-profile information also illustrated below.

We show the climatological accuracy results in Sect. 3.3 for a representative reference height of 12 km (H_2O isotopes 8 km, due to their restricted height range) that well illustrates the general performance over the UTLS since the height dependence of error specifications is simple as shown in Figure 3.1. For those limited height ranges of some parameters, where the rms accuracy requirements are specified differently from 12 km it is again easy to scale the results to such different initial rms errors (see prev. paragraph). While we collectively computed single error estimates each for the CO_2 species and the non-CO_2 species (with the H_2O isotope errors separately adjusted) we show the results individually for all trace species. This evidently implies that some of them just receive identical estimates currently but the approach is taken for flexibility to individually adjust settings and visualize species by species.

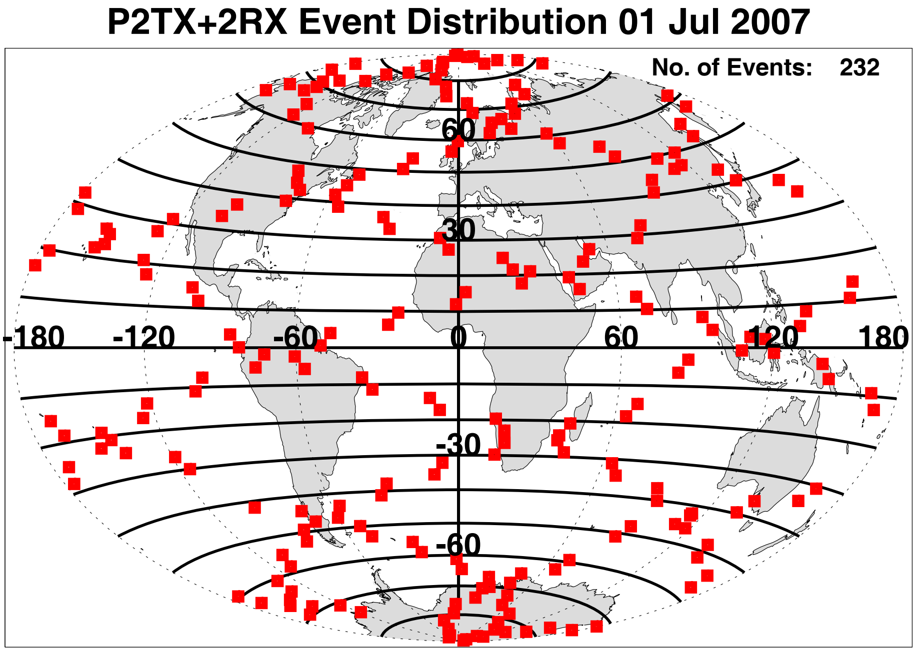
3.3 Performance Analysis Results

We present first the results for the baseline (BC) four-satellite case (Sect. 3.3.1), which was the baseline also of the ACCURATE proposal [ACCU05] as well as of its predecessor LMO-only mission concept ACE+ [ESAACE+04]. Following this, the minimum (MC) two-satellite case (Sect. 3.3.2) and the large (LC) twelve-satellite case (Sect. 3.3.3) are shown to provide context on how the space/time sampling characteristics and expected climatological accuracies vary from the baseline if either such a “minimum” first-demonstration-type MC mission is implemented or a large-operational-type LC mission. A brief comparative commentary in the final paragraph of Section 3.3.3 closes Section 3.3.
The choice of largely common y-axis ranges for all panels of figures with bin-vs-latitude results, also across figures of the different constellation cases as far as found suitable, is intentional in order to ease visual intercomparison of all results.

3.3.1 Baseline Case – Four-Satellite Constellation

Figures 3.2 to 3.7 show the results for the BC case, where Figure 3.2 shows the geographical distribution, Figure 3.3 the numbers of profiles per climatological bins, Figures 3.4 and 3.5 the estimated climatological errors for the thermodynamical parameters and wind for the large-scale bins resp. the equal-area bins, and Figures 3.6 and 3.7 the corresponding estimated climatological errors for the trace species.

Figure 3.2 illustrates how the profiles gather over time in a quasi-regular manner and lead to very even global coverage for every month. Figure 3.3 shows that the BC case has a very comfortable number of profiles in the large-scale bins, more than the very successful CHAMP GRO mission could supply every month (e.g., [Steinetal09] and references therein).
The BC case fulfils also the space/time sampling threshold requirements specified in Table 3.1. (at least 30 profiles per grid box per month in average and at least 80% of this for each individual grid box).



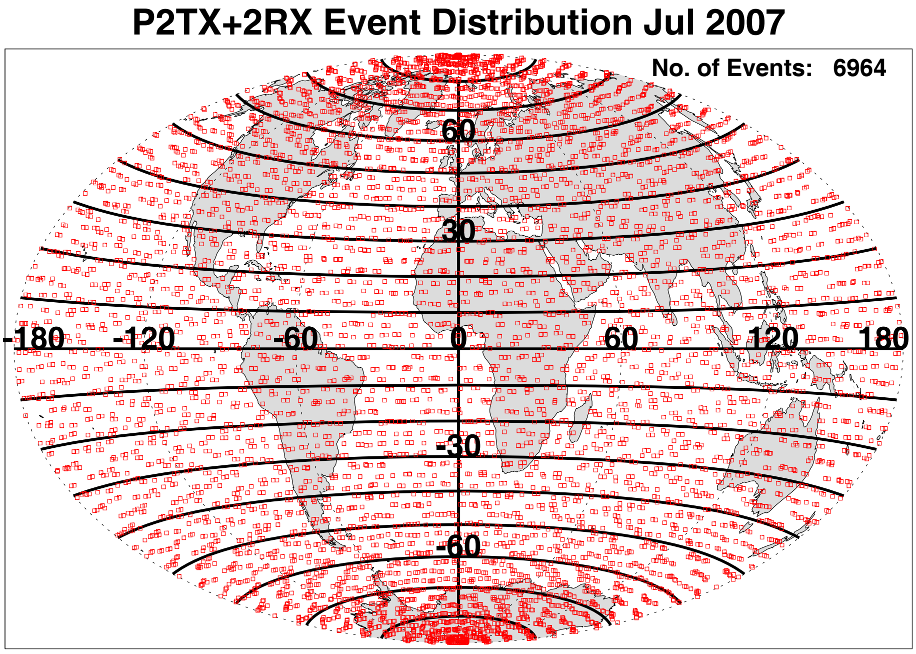


Figure 3.2. Occultation event distribution for a day and a month of data for the baseline constellation (BC case). Each event location is the spot of a retrieved set of individual LMO and LIO profiles.

In average the BC provides well more than 30-40 profiles per equal-area bin, with the high-latitude bins receiving significantly more than this (> 60 profiles) and the tropical bins receiving a more marginal number (~28-30 profiles). Since we require polar orbits for global coverage (or near-polar in case of sun-synchronous), this latitude dependence of sampling per equal-area is natural as the constellation supplies an equal amount of profiles to all latitude bands while the area per unit latitude diminishes as the cosine of latitude, increasing the number per unit area accordingly.

Figure 3.3. Latitude dependence of the number of events (measurement profiles) in climatological zonal bands of 10-deg latitude width (“large-scale bins”) for the baseline constellation (BC case). Shown is the number of profiles per large-scale bin per day (top) and per month (middle) as well as for each band the number of profiles per equal-area bin of 3.24 Mio. km^2 size (bottom), where also the requirements from Table 3.1 on number of profiles per bin are marked (horizontal lines).

However, because the tropical UTLS is comparatively less variable at smaller scales, these characteristics are quite acceptable. In other words, the sampling error left for a given number of profiles in large-scale averages is significantly smaller in the tropics than at middle and high latitudes (e.g., [Foelschetal09], [Hoetal09], and references therein) so the prevailing latitude dependence per equal-area is welcome in this respect.

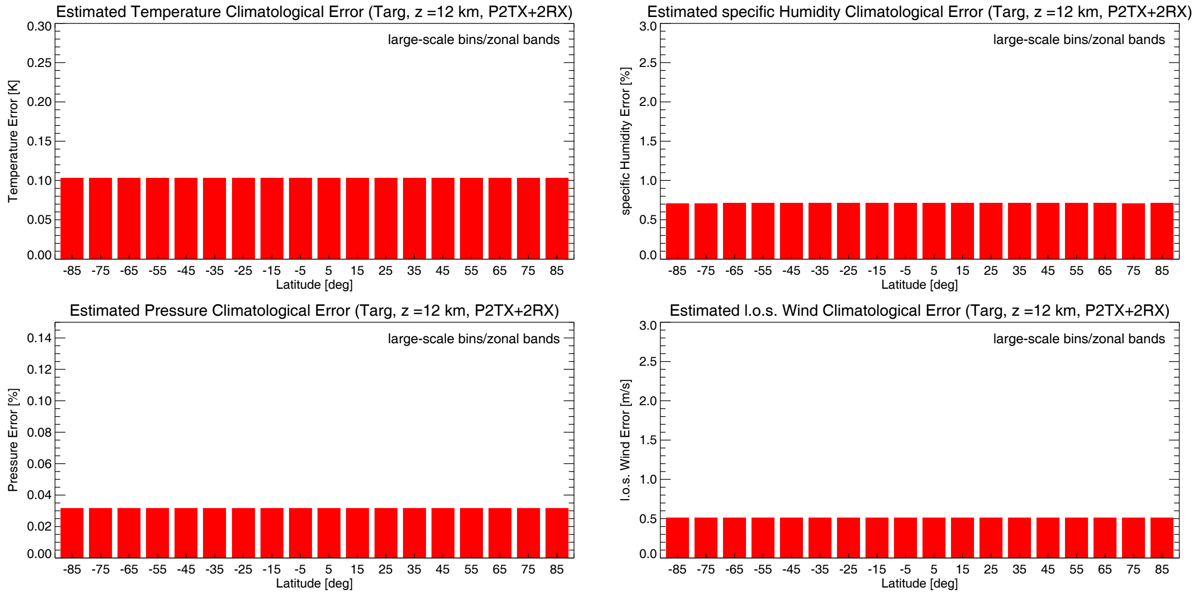


Figure 3.4. Estimated climatological errors of T, p, q, V_{los} at a representative height of 12 km for large-scale bins (zonal 10-deg bands) for the baseline constellation (BC case). Target accuracy requirements were adopted as individual-profile rms errors.

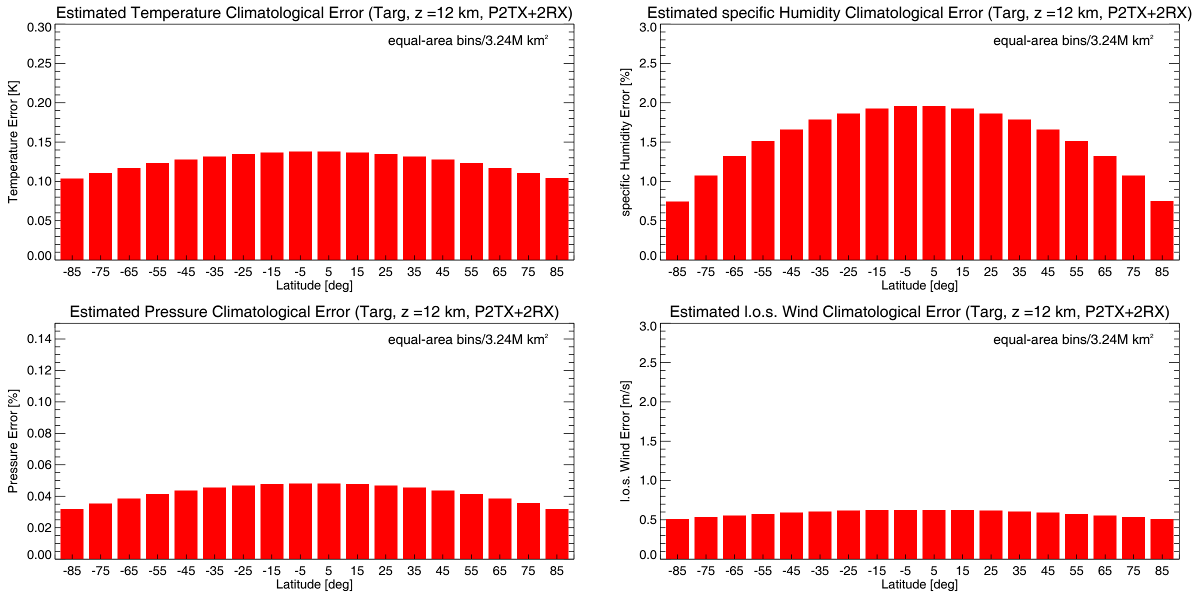


Figure 3.5. Estimated climatological errors of T, p, q, V_{los} at a representative height of 12 km for equal-area bins of 3.24 Mio. km^2 size in each 10-deg zonal band for the baseline constellation (BC case). Target accuracy requirements were adopted as individual-profile rms errors.

Figure 3.4 shows that for averaging over the several hundreds of profiles per large-scale bin the residual systematic error will dominate the error of the parameters, similarly as shown in a climate trend analysis of real GRO data by [Steinetal09]. That is the resulting monthly-mean profiles are very accurate (dT~0.1 K, dq<1 %, dp<0.05 %, dV_{los}~0.5 m/s) and ensuring very small residual systematic errors is evidently key to the ACCURATE observing system design as a climate benchmarking concept.

Figure 3.5 shows the same type of result as Figure 4 but for the much smaller equal-area bins corresponding within the 10-deg zonal bands to ~1100 km x 2900 km metric size, or equivalently to 10 deg latitude x ~26 deg longitude geographic size near equator (with the longitude extend increasing with latitude with the inverse cosine of latitude).
Therefore the much smaller number of events in these bins (cf. Figure 3.3, bottom) leads to a still dominant contribution of statistical error in the estimated climatological error. However, even with these basic bin sizes the individual-profile errors are mitigated by the averaging by factors of >5 to >10 – from tropics to high latitudes – so that the resulting monthly-mean thermodynamic and wind profiles are still very accurate (dT<0.15 K, dq<1-2 %, dp<0.05 %, dV_{los}~0.6 m/s), beyond the capabilities of any existing free-atmosphere observing systems.

The trace species results of Figure 3.6 for the large-scale bins show, similarly to Figure 3.4, that the large number of averaged profiles allows to reach dominance of the residual systematic errors in the estimated climatological errors (except for the H_2O isotopes which received different assumptions as noted in Sect. 3.2 above). There is still a more appreciable statistical component than for T, p, and V_{los}, though, since for the species parameters the fraction $f_{sys,P}$ (Eq. 3 in Sect. 3.2) of systematic error was assumed smaller and also related to target rather than threshold requirements. The accuracy is very favorable (CO_2 species <0.15 %, corresponding to <0.6 ppm for the main CO_2 species; non-CO_2 species <0.3 %; H_2O isotopes <0.6 %) and is unprecedented for measurements of these trace species in the free atmosphere.
Figure 3.7 complements with the results for the equal-area bins where the statistical error contribution is, similar to Figure 3.5, accordingly larger but also at this basic cell size the accuracy is excellent and unprecedented (CO_2 species <0.2-0.4 %, corresponding to <0.8-1.6 ppm for the main CO_2 species; non-CO_2 species <0.4-0.8 %; H_2O isotopes <0.6-1.6 %).

We note that this type of four-satellite case also provided the basis for the ACCURATE retrieval performance studies of [Schweitzetal09] (LMO) and [ACCUPERF07] (LIO), where the individual-profile errors were a study output and monthly-mean profiles were assumed to receive an error mitigation by about a factor of 6, similar to the one achieved here for the equal-area bins. Since these studies estimated individual-profile errors generally more accurate than the rms errors taken here from the target accuracy requirements, the estimated climatological errors were generally even smaller. It is in this sense certainly sufficiently conservative if we take the present performance results as basis for gauging scientific impact levels.

Overall the BC case can deliver an observational performance that fully meets the observational requirements (Table 3.1) and that in turn is able to fully support the underlying scientific objectives as laid out in [ACCUObsReq09].

The following subsections Sect. 3.3.2 and 3.3.3 will inspect to what extend a “minimum” constellation (MC case) and a “large” constellation (LC case) do degrade against resp. improve upon these BC case results.

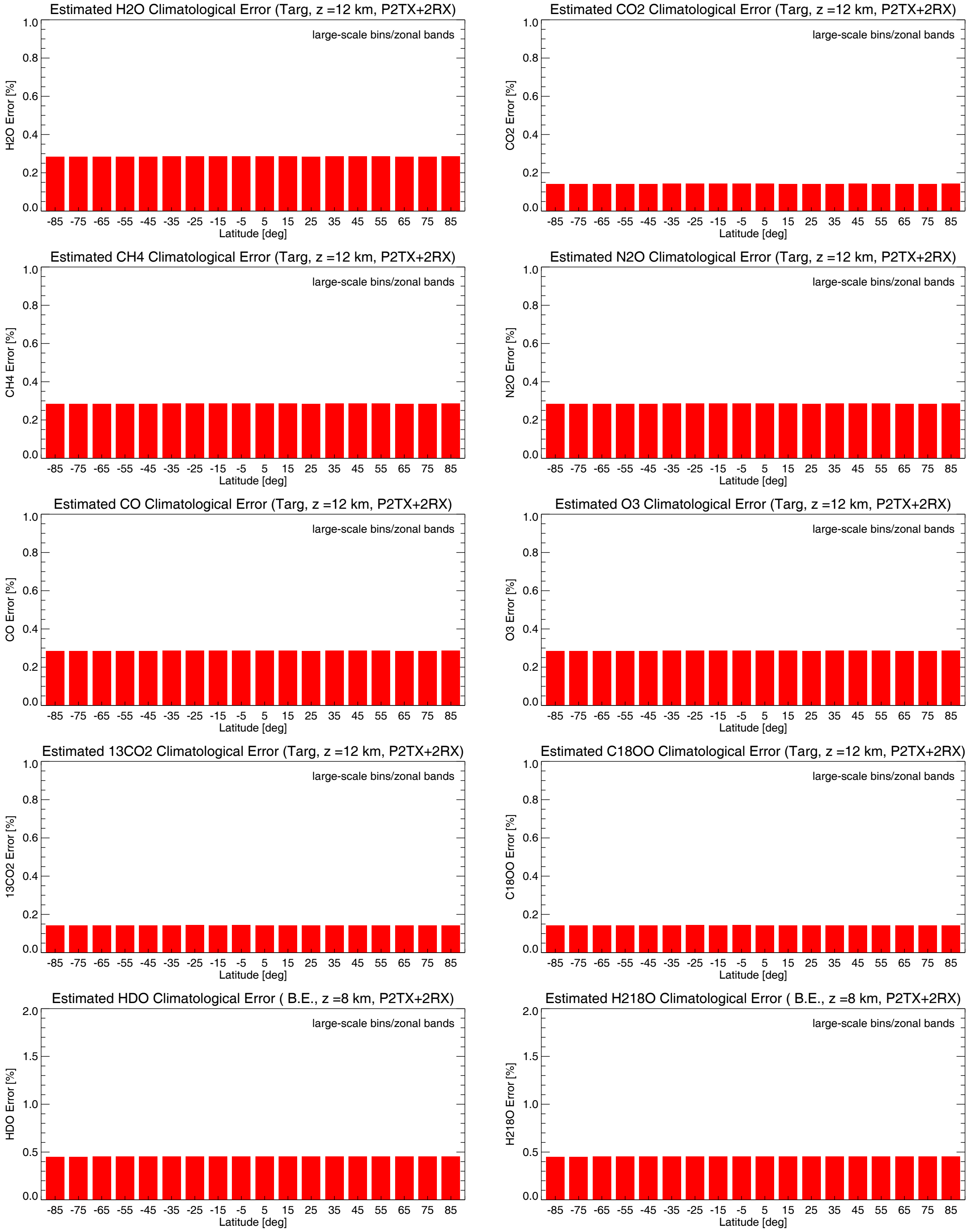


Figure 3.6. Estimated climatological errors of the LIO-derived trace species at a representative height of 12 km (H_2O isotopes 8 km) for large-scale bins (zonal 10-deg bands) for the baseline constellation (BC case) with individual-profile rms errors from target requirements.

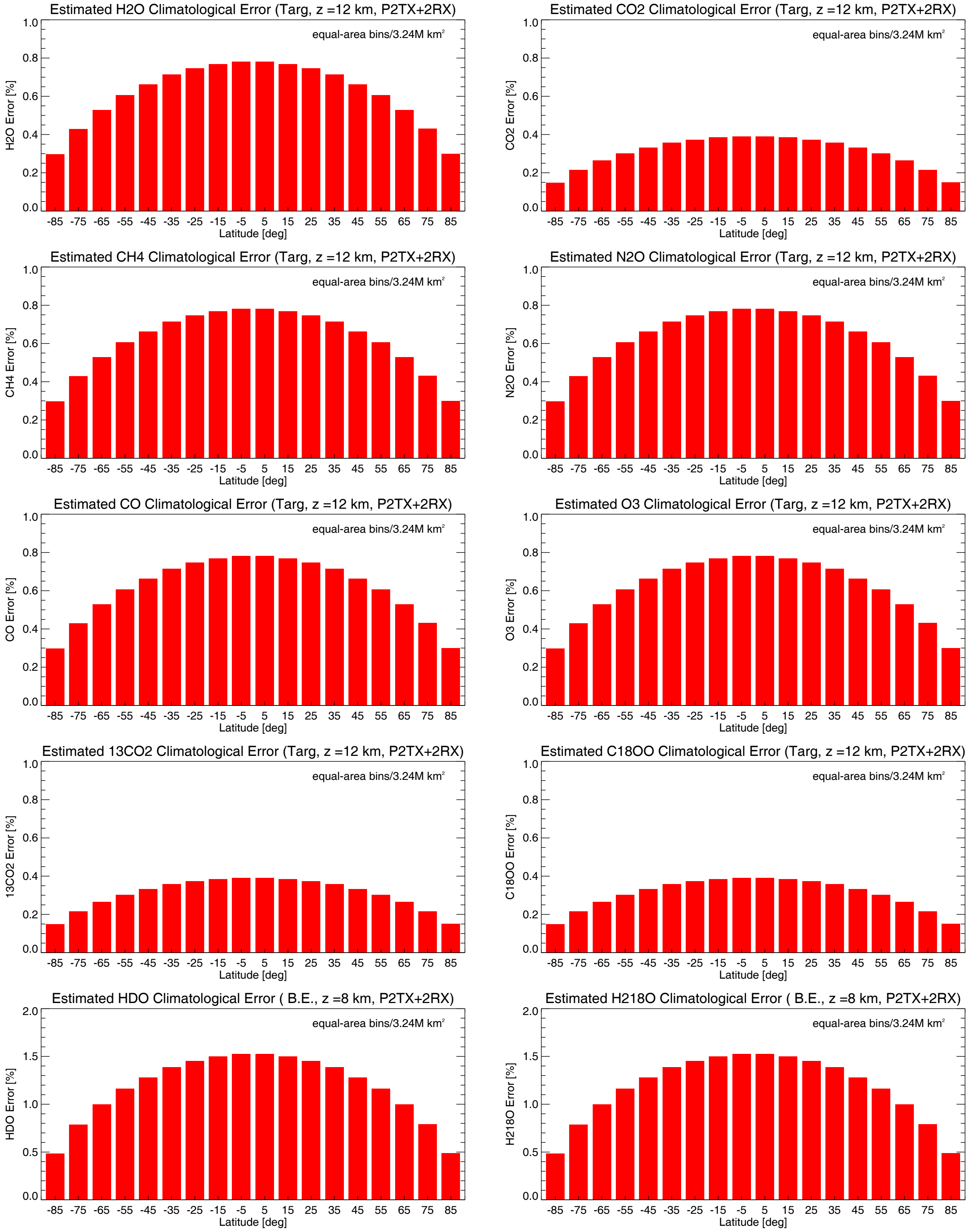


Figure 3.7. Estimated climatological errors of the LIO-derived trace species at a representative height of 12 km (H_2O isotopes 8 km) for equal-area bins of 3.24 Mio. km^2 size in each 10-deg zonal band for the baseline constellation (BC case) with individual-profile rms errors from target requirements.

3.3.2 Minimum Case – Two-Satellite Constellation

Figures 3.8 to 3.13 show the results for the minimum constellation (MC) case, where Figure 3.8 shows the geographical distribution, Figure 3.9 the numbers of profiles per climatological bins, Figures 3.10 and 3.11 the estimated climatological errors for the thermodynamical parameters and wind for the large-scale bins resp. the equal-area bins, and Figures 3.12 and 3.13 the corresponding estimated climatological errors for the trace species.

Figure 3.8 (to be compared to Figure 3.2) shows that the MC case delivers a quarter of the number of events of the BC case only, which is clear since 2 Tx + 2 Rx will quadruple the number of events against single Tx and Rx given that each receiver can cross-link with two transmitters and on top two receivers operate instead of one. While the daily event number of the MC is sparse, still every month a decent global distribution of about 1750 profiles accumulates (here 30 days were simulated for the example month).

Figure 3.9 (to be compared to Figure 3.3) shows that the MC case therefore still comfortably enables climatologies with ~ 100 profiles per bin per month in the large-scale zonal bands but will meet the number-of-profiles sampling requirements for equal-area bins only at polar latitudes > 70°. In the MC case the binning strategy for climatological products would thus emphasize larger-scale averaging in tropical and mid-latitude regions to ensure ~30 profiles per bin. This still allows designs like 5-deg zonal bands, or selected continental-scale or oceanic regions, for which experience with the CHAMP satellite has shown for radio occultation data that also at these scales benchmark climatologies are of very high value for climate monitoring and diagnostics as well as for providing fundamental reference to other less accurate but higher-resolved data (e.g., [Steinetal09], [Hoetal09], [Foelschetal09a], and refs therein).

Figure 3.10 (to be compared to Figure 3.4) shows that for averaging over the ~100 profiles per large-scale bin the residual systematic error will dominate the error of the parameters similar to the BC case, except for humidity from LMO where the statistical error mitigation by a factor of 10 leaves a statistical error about twice as large as the assumed systematic error (see Sect. 3.2). The resulting monthly-mean profiles are very accurate (dT~0.1 K, dq~1 %, $dp<0.05$ %, dV_{los}~0.5 m/s), closely the same as in the BC case, except for humidity with an error increase by a factor of about 1.4.

Figure 3.11 (to be compared to Figure 3.5) shows that in the much smaller equal-area bins the climatological accuracy of the MC case is clearly decreased against the BC case, as expected in line with Figure 3.9. The achievable accuracies (dT~0.1-0.2 K, dq~2-4 %, dp~0.04-0.08 %, dV_{los}~0.5-1 m/s) are still excellent. To fully reach the accuracies of the BC case, more coarse horizontal averaging is required (effectively by a factor of 2 more coarse horizontal resolution in order to reach the same number of profiles per area).

The trace species results of Figure 3.12 (to be compared to Figure 3.6) for the large-scale bins show as expected that the accuracy is somewhat degraded against the BC case, by about a factor of 1.6, but it is still very good (CO_2 species <0.25 %, corresponding to <1 ppm for the main CO_2 species; non-CO_2 species <0.5 %; H_2O isotopes <0.9 %).

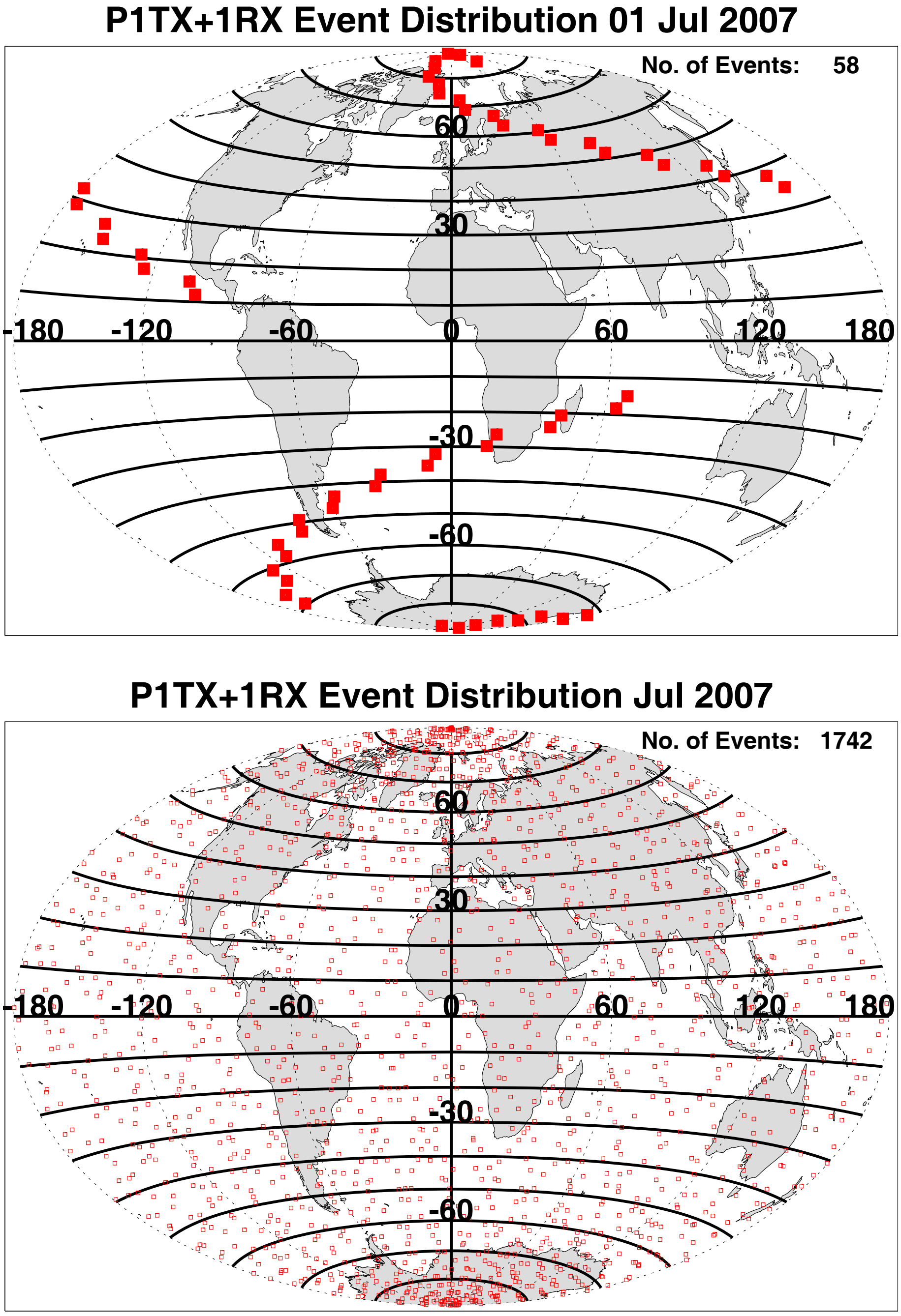


Figure 3.8. Occultation event distribution for a day and a month of data for the minimum constellation (MC case). Each event location is the spot of a retrieved set of individual LMO and LIO profiles.

Figure 3.13 (to be compared to Figure 3.7) complements for the equal-area bins with an error increase by a factor of ~1.2 to 2 against the BC case, but also here the accuracy is still very good compared to existing observing systems (CO_2 species <0.25-0.8 %, corresponding to <1-3 ppm for the main CO_2 species; non-CO_2 species <0.5-1.6 %; H_2O isotopes <0.9-3 %). Furthermore, if the achieved individual-profile accuracy of the actual instrument outperforms the target accuracy specified in Table 3.1 (e.g., by a factor of 2-3 or so as suggested by [ACCUPERF07]), the MC case can basically reach the climatological accuracy as shown for the BC case in the previous section.

Figure 3.9. Latitude dependence of the number of events (measurement profiles) in climatological zonal bands of 10-deg latitude width (“large-scale bins”) for the minimum constellation (MC case). Shown is the number of profiles per large-scale bin per day (top) and per month (middle) as well as for each band the number of profiles per equal-area bin of 3.24 Mio. km^2 size (bottom), where also the requirements from Table 3.1 on number of profiles per bin are marked (horizontal lines).

In practice, sampling error (e.g., [Foelschetal07]) will still definitely be higher for the MC case, however, so that somewhat larger-scale horizontal averaging will be advisable.

Overall the MC case can deliver an observational performance that can meet the observational requirements (Table 3.1) except for the specified horizontal sampling requirements. Thus implementation of the BC case, meeting all requirements, is clearly preferable. Still the MC case may be seen as an excellent model for a first least-cost demonstration of the ACCURATE concept, since within its factor-of-2 coarser horizontal resolution also this minimum case is already capable to fully address the underlying scientific objectives as laid out in [ACCUObsReq09].

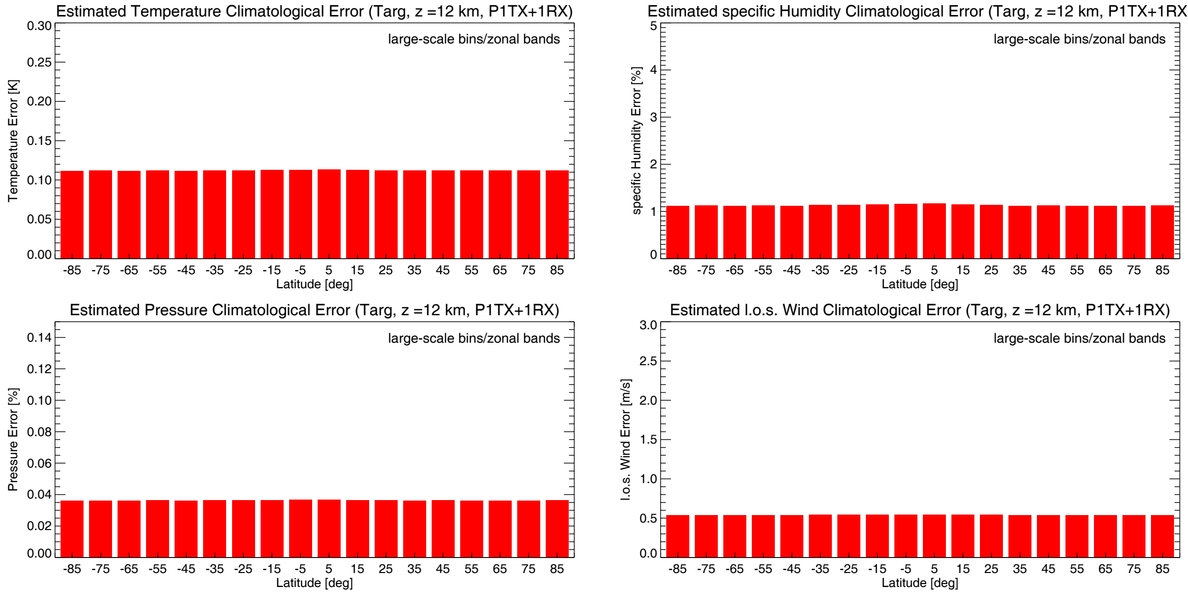


Figure 3.10. Estimated climatological errors of T, p, q, V_{los} at a representative height of 12 km for large-scale bins (zonal 10-deg bands) for the minimum constellation (MC case). Target accuracy requirements were adopted as individual-profile rms errors.

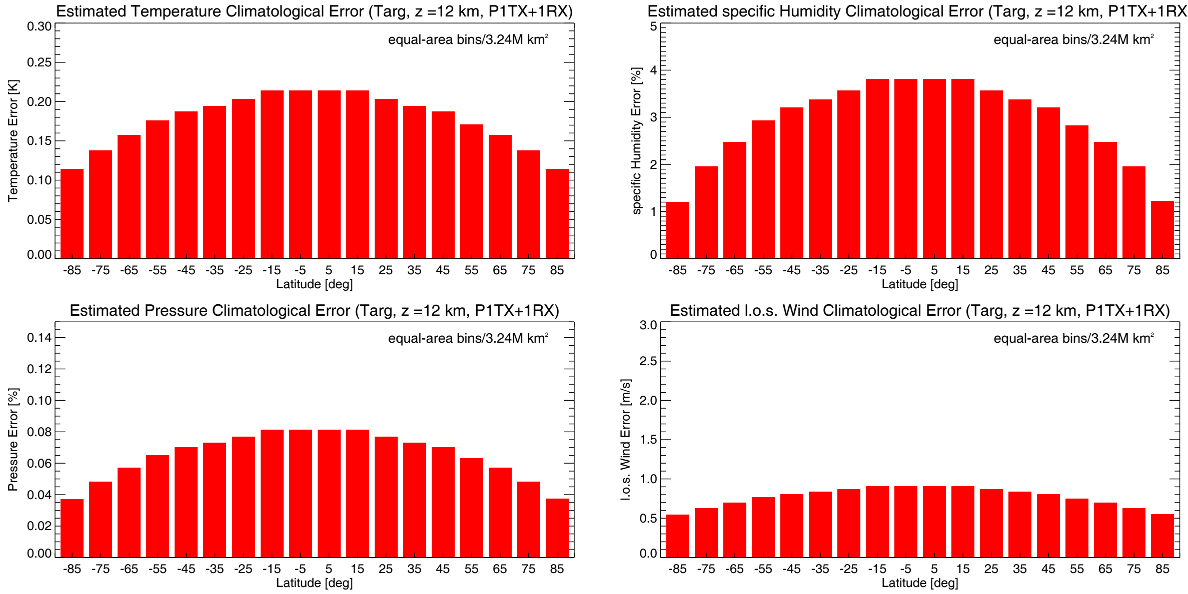


Figure 3.11. Estimated climatological errors of T, p, q, V_{los} at a representative height of 12 km for equal-area bins of 3.24 Mio. km^2 size in each 10-deg zonal band for the minimum constellation (MC case). Target accuracy requirements were adopted as individual-profile rms errors.

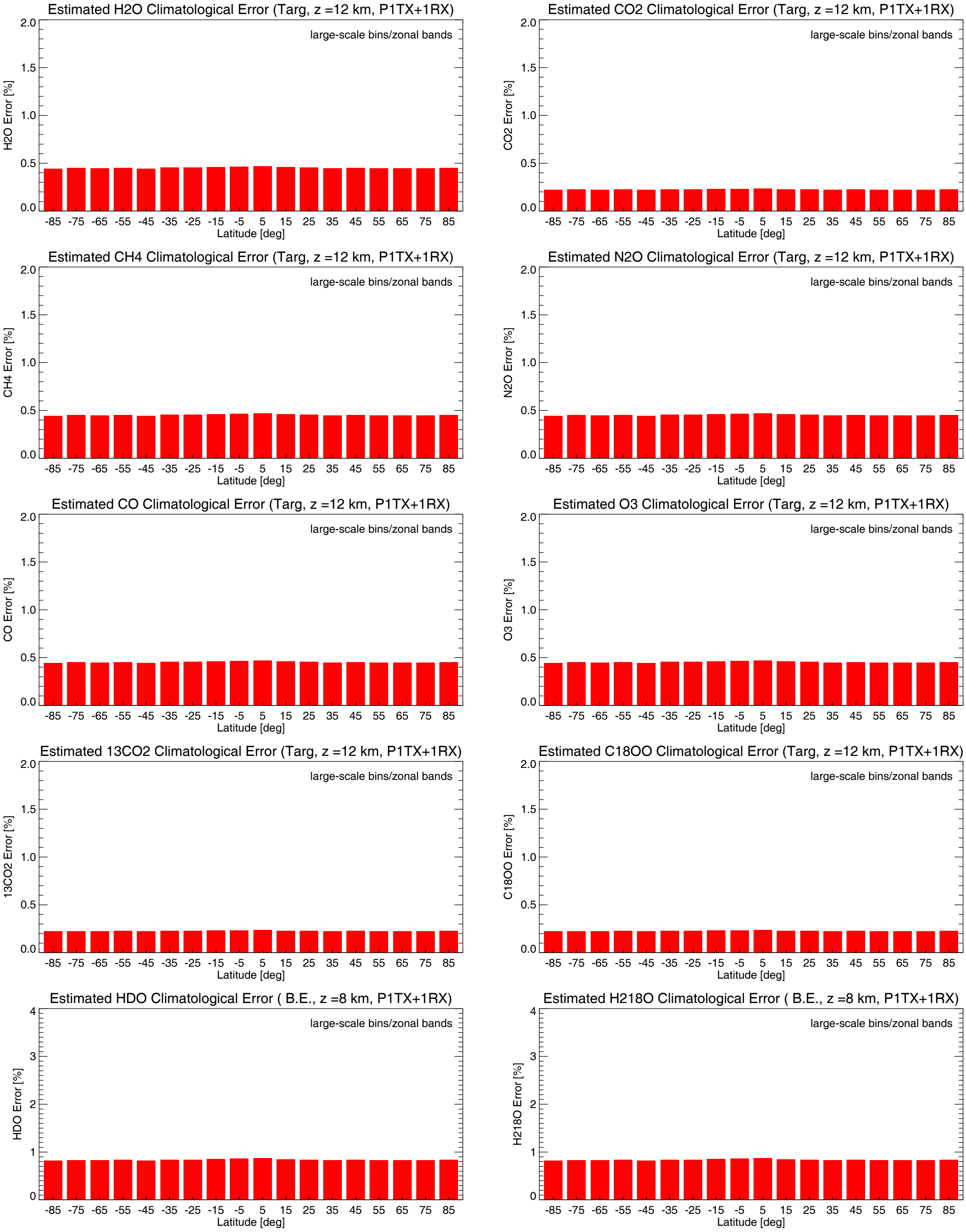


Figure 3.12. Estimated climatological errors of the LIO-derived trace species at a representative height of 12 km (H_2O isotopes 8 km) for large-scale bins (zonal 10-deg bands) for the minimum constellation (MC case) with individual-profile rms errors from target requirements.

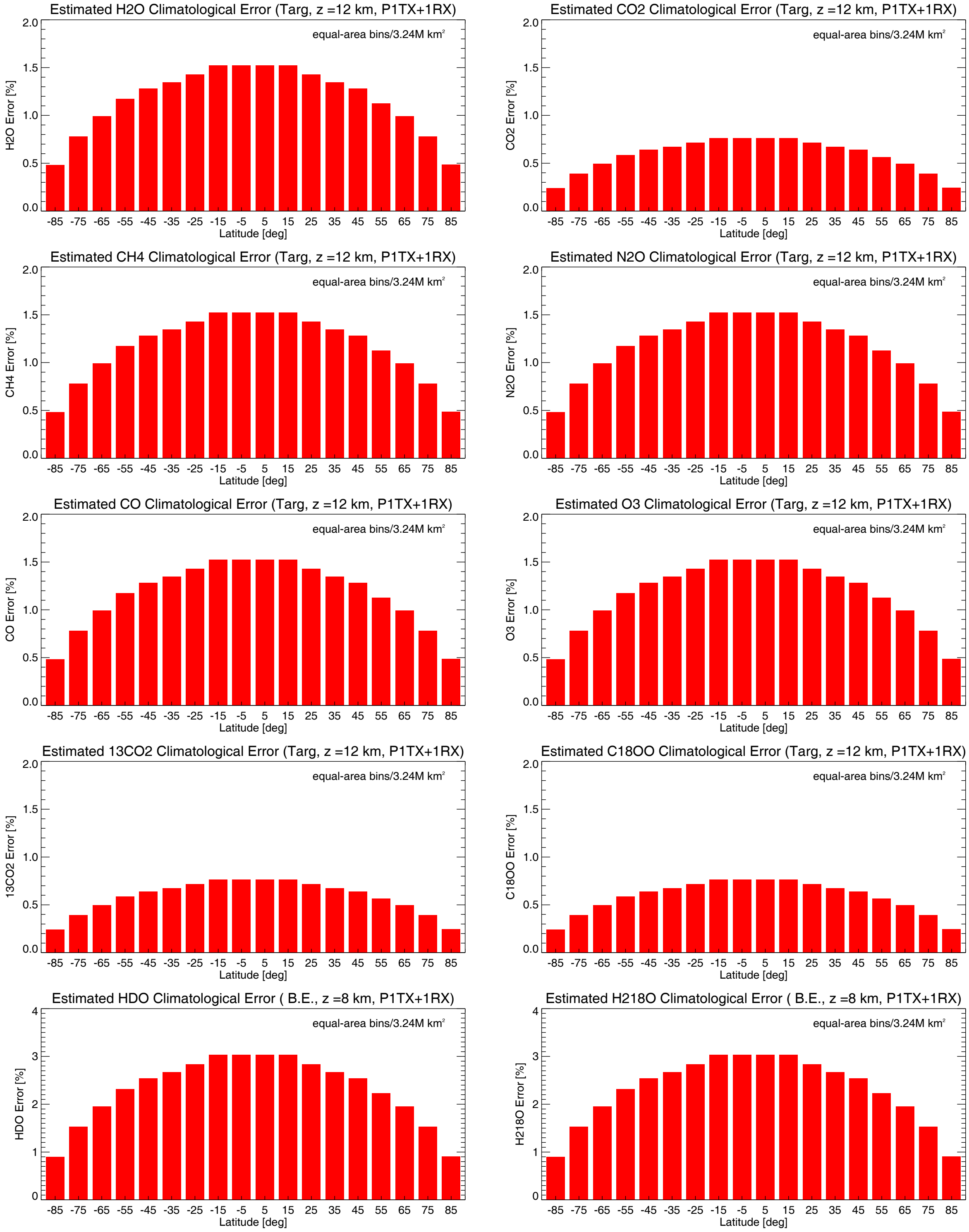


Figure 3.13. Estimated climatological errors of the LIO-derived trace species at a representative height of 12 km (H_2O isotopes 8 km) for equal-area bins of 3.24 Mio. km^2 size in each 10-deg zonal band for the minimum constellation (MC case) with individual-profile rms errors from target requirements.

3.3.3 Large Case – Twelve-Satellite Constellation

Figures 3.14 to 3.19 show the results for the LC case, where Figure 3.14 shows the geographical distribution, Figure 3.15 the numbers of profiles per climatological bins, Figures 3.16 and 3.17 the estimated climatological errors for the thermodynamical parameters and wind for the large-scale bins resp. the equal-area bins, and Figures 3.18 and 3.19 the corresponding estimated climatological errors for the trace species.

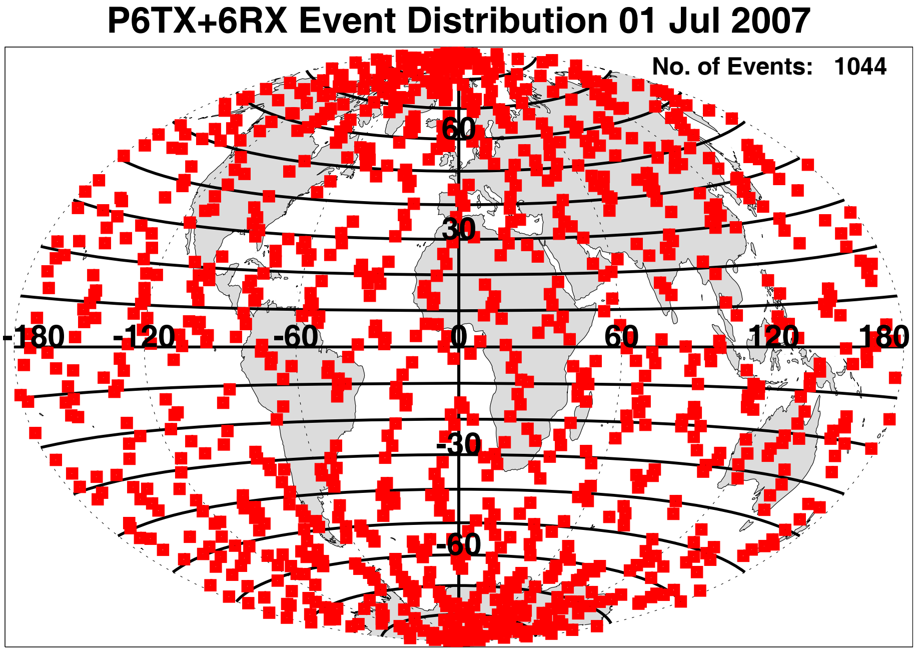
Figure 3.14 (to be compared to Figure 3.2) shows that the LC case delivers 4.5 times the number of events of the BC case (1044 vs. 232 events). This derives from the fact that each of two orthogonal orbit planes with 3 Tx + 3 Rx delivers 522 events per day (174 events per Rx acquiring 12 events per orbit given 3 Tx, over 14.5 orbits per day), which yields a total of 1044 events per day. Note the numbers per month (30 days) do not exactly match multiplication by 30 since the chosen constellation leads to closely but not exactly 14.5 orbits per day.

Figure 3.15 (to be compared to Figure 3.3) shows that the LC case therefore provides 4.5 times the number of profiles per bin per month in the large-scale zonal bands and meets the number-of-profiles requirement for equal-area bins even for the target horizontal sampling requirement (900 km), i.e., bin areas of 0.81 Mio. km^2 instead of the 3.24 Mio. km^2 in the BC case. The LC case, closely similar to a constellation that was studied in ESA's first-proposed LMO concept WATS [WATS01], is thus clearly most appealing in terms of horizontal data density. The gain of horizontal resolution from 1800 km to 900 km comes from a tripling of the number satellites against the BC case, however. Thus in terms of trade-off of scientific return to needed investment still the BC case, or the least-cost MC case, may be considered preferable for a demonstration of the concept, with later in an operational scenario potentially implementing an LC-type case.

Figure 3.16 (to be compared to Figure 3.4) shows that for averaging over the more than 1600 profiles per large-scale bin, reducing statistical errors by more than a factor of 40, the residual systematic error fully dominates the error of the parameters. The resulting monthly-mean profiles are therefore very accurate (dT~0.1 K, dq~0.5 %, dp~0.03 %, dV_{los}~0.5 m/s), at the level of the assumed residual systematic error.

Figure 3.17 (to be compared to Figure 3.5) shows that for the 0.81 Mio. km^2 equal-area bins the climatological accuracy is similar to the BC case for the 3.24 Mio. km^2 bins, as expected in line with Figures 3.15 and 3.3 and given that the area decrease by a factor of 4 here adopted for the LC case roughly compensates for the number-of-event increase by the factor of 4.5. The achievable accuracies (dT<0.15 K, dq<1-2 %, dp<0.05 %, dV_{los}~0.6 m/s) thus reflect those (excellent ones) of the BC case.

The trace species results of Figure 3.18 (to be compared to Figure 3.6) for the large-scale bins show, like Figure 3.16, that also here the residual systematic error is closely reached (CO_2 species ~0.1 %, corresponding to ~0.4 ppm for the main CO_2 species; non-CO_2 species ~0.2 %; H_2O isotopes ~0.3 %), obviously a tremendous performance.



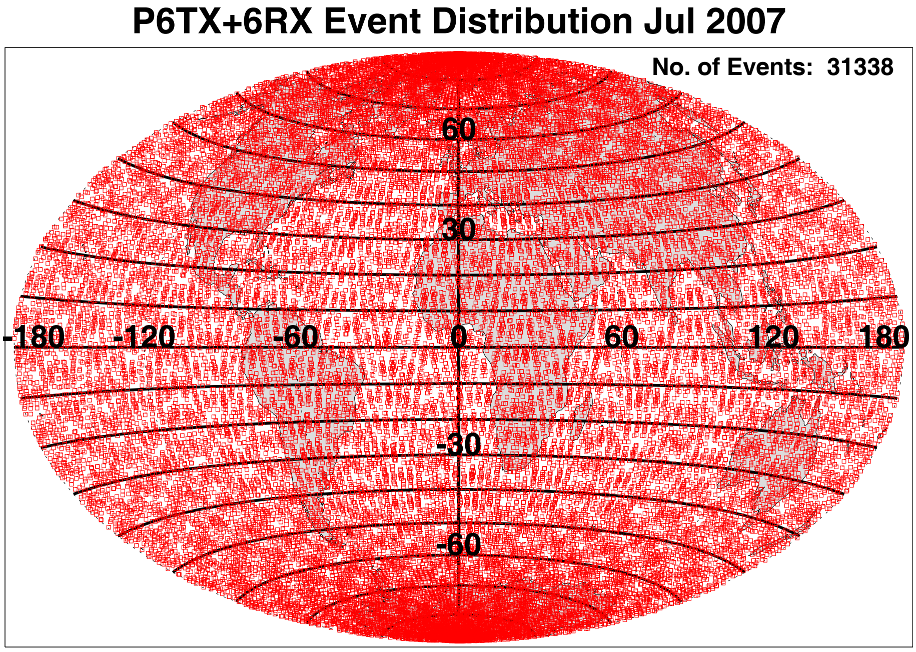


Figure 3.14. Occultation event distribution for a day and a month of data for the large constellation (LC case). Each event location is the spot of a retrieved set of individual LMO and LIO profiles.

Figure 3.19 (to be compared to Figure 3.7) again shows, as Figure 3.17, similar accuracies as the BC case (CO_2 species <0.2-0.4 %, corresponding to <0.8-1.6 ppm for the main CO_2 species; non-CO_2 species <0.4-0.8 %; H_2O isotopes <0.5-1.5 %), given areas of 0.81 Mio. km^2 here. Thus the LC case plays its edge of delivering the same accuracy at twice the horizontal resolution. Overall the LC case can deliver an observational performance that fully meets the observational requirements (Table 3.1), including the horizontal sampling target requirement, and can fully support the scientific objectives laid out in [ACCUObsReq09].

Figure 3.15. Latitude dependence of the number of events (measurement profiles) in climatological zonal bands of 10-deg latitude width ("large-scale bins") for the large constellation (LC case). Shown is the number of profiles per large-scale bin per day (top) and per month (middle) as well as for each band the number of profiles per equal-area bin of 0.81 Mio. km^2 size (bottom), where also the requirements from Table 3.1 on number of profiles per bin are marked (horizontal lines).

We note that an LC case with a single orbit plane (6 Tx and 6 Rx in the same plane), leading to a further doubling of the number of events per day compared to the LC case discussed here (2088 events per day; 348 events per Rx acquiring 24 events per orbit given 6 Tx, over 14.5 orbits per day), would even fulfil the target requirements of both horizontal sampling and (UTC) time sampling (12 hrs). On the other hand, such a single orbit plane would enable twice-less frequent local-time sampling than the present LC case can achieve, so this one may be considered the better trade-off on UTC-vs.-local time for a climate-oriented mission.

In summary on all three cases, the MC case appears to be an ideal least-cost initial demonstration case, already addressing all aspects of scientific return at coarser horizontal resolution, the BC case appears to be the best trade-off in scientific return to investment, already fully meeting all observational requirements of Table 3.1, and the LC case appears to be a potentially attractive option for a later operational solution after MC/BC cases have established the technique, meeting all requirements with highest data density.

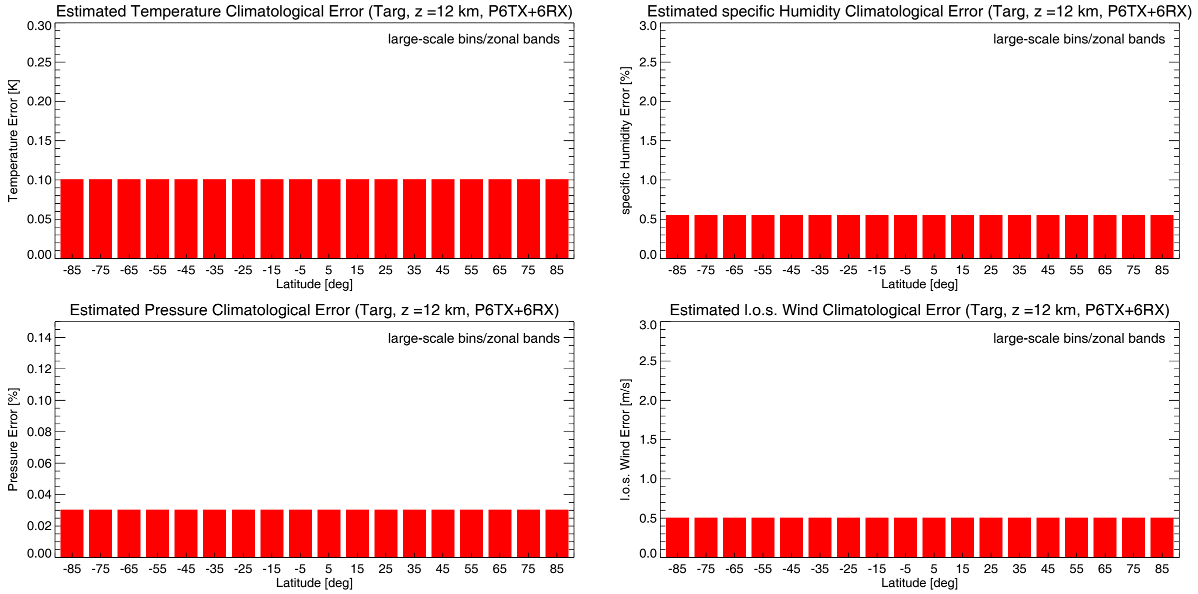


Figure 3.16. Estimated climatological errors of T, p, q, V_{los} at a representative height of 12 km for large-scale bins (zonal 10-deg bands) for the large constellation (LC case). Target accuracy requirements were adopted as individual-profile rms errors.

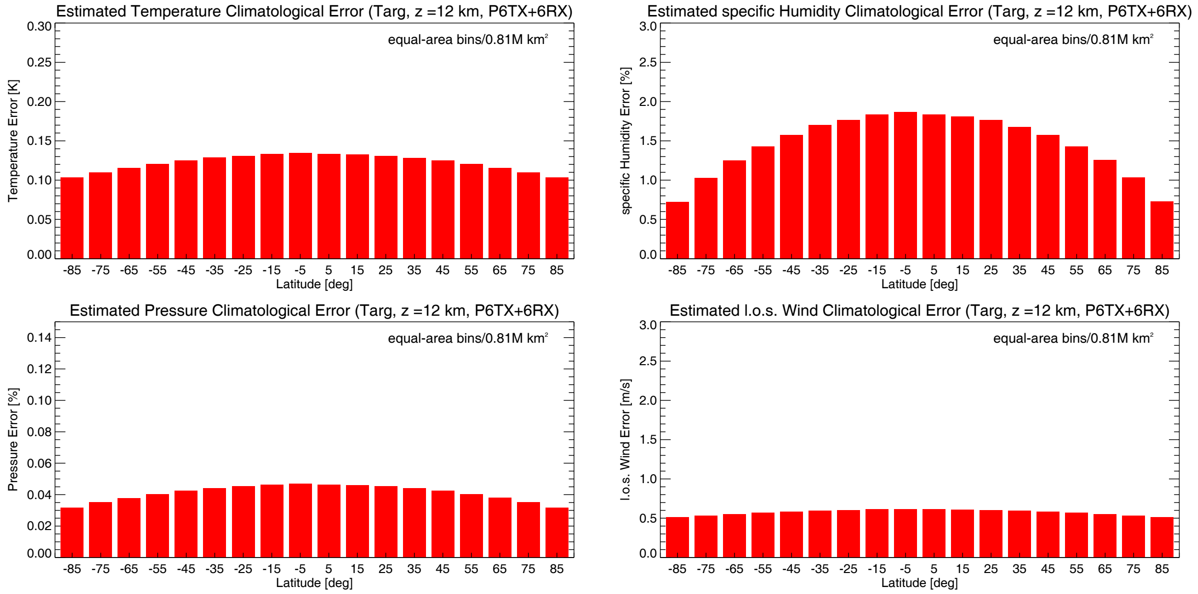


Figure 3.17. Estimated climatological errors of T, p, q, V_{los} at a representative height of 12 km for equal-area bins of 0.81 Mio. km^2 size in each 10-deg zonal band for the large constellation (LC case). Target accuracy requirements were adopted as individual-profile rms errors.

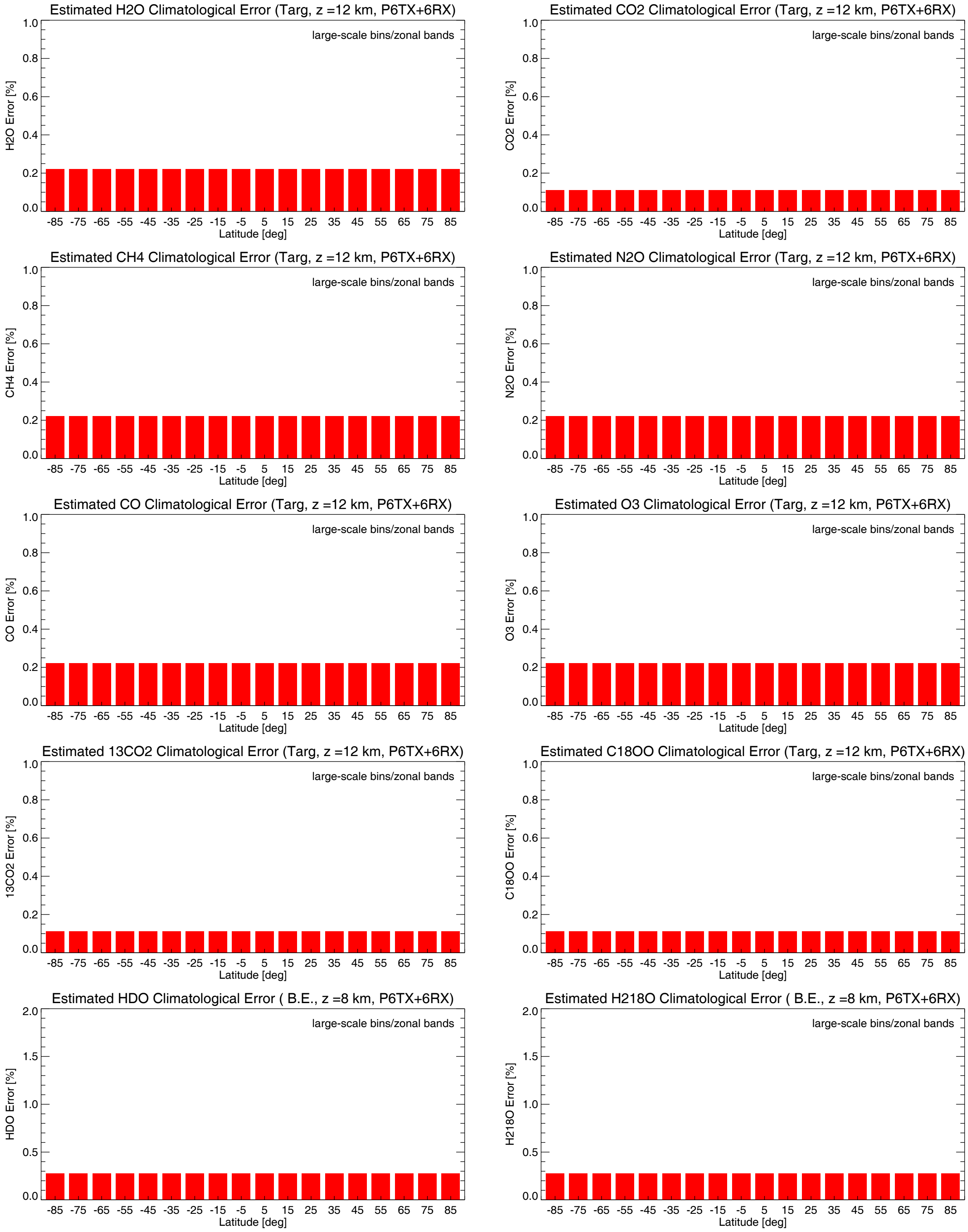


Figure 3.18. Estimated climatological errors of the LIO-derived trace species at a representative height of 12 km (H_2O isotopes 8 km) for large-scale bins (zonal 10-deg bands) for the large constellation (LC case) with individual-profile rms errors from target requirements.

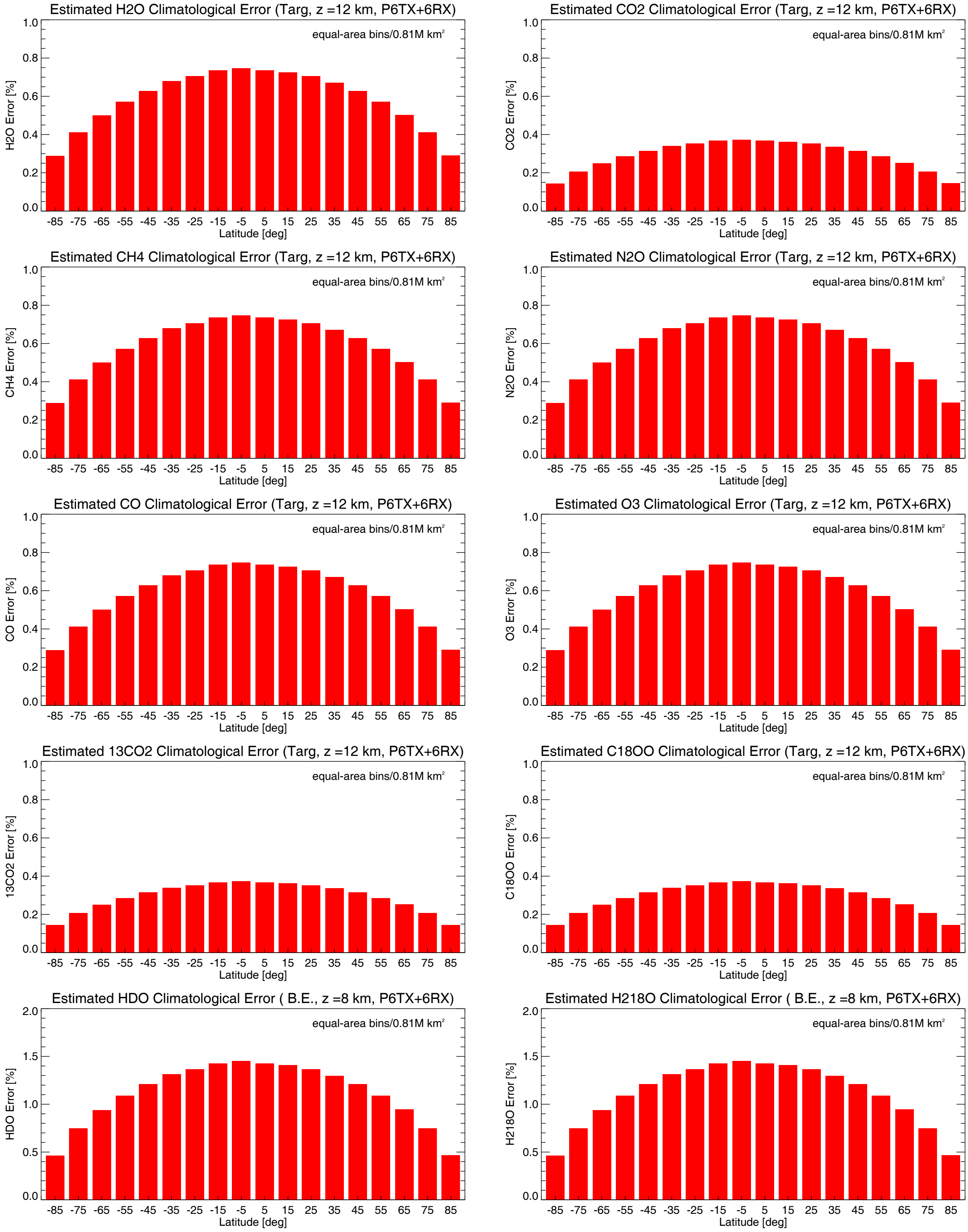


Figure 3.19. Estimated climatological errors of the LIO-derived trace species at a representative height of 12 km (H_2O isotopes 8 km) for equal-area bins of 0.81 Mio. km^2 size in each 10-deg zonal band for the large constellation (LC case) with individual-profile rms errors from target requirements.

3.4 ACCURATE Impact Level Matrix

Table 3.2 shows the Impact Level matrix for ACCURATE (cf. Sect. 2). As is well visible, its unique and major strengths fall mainly into the field of climate science, where its primary mission objectives reside [ACCUObsReq09], via observing thermodynamic variables, greenhouse gases, and wind from space with climate benchmark quality and with focus on the UTLS. Due to their accuracy and high vertical resolution, the ACCURATE data also will have unique and major impact to atmospheric chemistry and process studies in the UTLS, GHG composition modeling, and calibration of data from other observing systems. Furthermore, it is a very novel technique wherefore also its demonstration is strongly unique.
Beyond these core strengths, ACCURATE in addition provides significant impact and further useful information on many other atmospheric variables to all other objectives as well.

Table 3.2. Sci.Objectives-vs-Obs.Information Impact Level Matrix for ACCURATE

	Atmospheric Observation Information						
Scientific Objectives	ThDyn	DynWind	GHGs	RAGs	Aerosols	Cls+Prec	Radiation
Climate							
Monitor climate trends and variability	***	* * *	***	* *	* *	*	(*)
Diagnose and predict climate change	* * *	* *	* * *	*	*	*	(*)
Validate, test and improve climate GCMs	* * *	* *	* * *	*	*	(*)	(*)
Understand climate forcings and feedbacks	* * *	* *	***	*	*	(*)	(*)
Chemistry&Processes							
Study atmos. processes near-surface & in the LT	*	–	*	*	*	–	(*)
Study atmos. processes in the UTLS	* * *	* *	***	* *	* *	*	(*)
Improve atmos. composition forecasting	* *	*	* * *	* *	*	–	(*)
Test and improve atmos. constituent models	* *	*	* * *	*	*	–	(*)
NWP							
Improve NWP forecasting	* *	* *	*	*	(*)	(*)	(*)
Test and improve NWP models	* *	*	*	*	(*)	(*)	(*)
Others							
Calibrate data from other atmos. observing systems	***	* * *	***	* *	*	(*)	(*)
Demonstrate a novel observing technique	***	***	***	* * *	* *	*	(*)

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4 Other Representative Missions: IASI-MetOp and PREMIER Observational Performance and Impact Level Matrices

4.1 IASI-MetOp Observational Performance

IASI-MetOp science objectives: (Cited directly from ESA homepage on IASI, [IASI10]).

The IASI (Infrared Atmospheric Sounding Interferometer) system aims at observing and measuring the infrared spectrum emitted by the earth. These measurements are compatible in terms of sampling, resolution, accuracy and overall performances with the mission objectives of providing information on (see also Table 4.1 summarizing observational requirements):

- The profile of temperature in the troposphere and lower stratosphere with an accuracy of 1 K, a vertical resolution of 1 km in the low troposphere and an horizontal sampling of 25 km.
- The profiles of water vapour in the troposphere with an accuracy of 10% on relative humidity, a vertical resolution of 1 km in the lower troposphere and an horizontal sampling of 25 km.
- The total amount of ozone with an accuracy of 5 % and an horizontal sampling of typically 25 km, possibly also ozone vertical distribution with an accuracy of 10% and a vertical resolution providing two or three pieces of independent information.
- Fractional cloud cover and cloud top temperature/pressure.
- Sea and land surface temperatures

In addition, IASI has the ability to measure the total column content of the main greenhouse gas. It will supply valuable data for scientific studies to achieve a closer understanding of climate processes and to represent them better in global models.

Table 4.1. IASI-MetOp observational requirements

Geophysical variables	Vertical resolution	Horizontal resolution	Accuracy
Temperature profile	1 km (low Troposphere)	25 km (cloud free)	1 K (cloud free)
Humidity profile	1-2 km (low Troposphere)	25 km (cloud free)	10 % (cloud free)
Ozone total amount	Integrated content	25 km (cloud free)	5 % (cloud free)
CO, CH_4, N_2O	Integrated content	100 km	10 % (cloud free)

Synergies:

The IASI instrument onboard MetOp is as stated above capable of measuring chemical constituents. As for synergies with the ACTLIMB mission scenario and also the PREMIER mission the main difference is on the measurement geometry. The IASI is a nadir view instrument, with many spectral bands to provide vertical resolution. However when is comes to determine the chemical species IASI can only provide the Integrated content, and not a vertical profile, for Ozone, CO, Methane, and N_2O.

4.2 IASI-MetOp Impact Level Matrix

In Table 4.2 the IASI Impact Level matrix is presented highlighting the strengths of the IASI instrument and of similar advanced IR nadir viewing, across-track scanning instruments also found on the NOAA satellites. The IASI is the latest development with the most frequency channels, hence proving the best possibilities for vertical resolution and to distinguish different atmospheric constituents. The main measurement is the emitted thermal infrared radiation from the atmosphere measured with a spectral resolution of about 0.5 cm^{-1}.

Table 4.2. Sci.Objectives-vs-Obs.Information Impact Level Matrix for IASI-MetOp

	Atmospheric Observation Information						
Scientific Objectives	ThDyn	DynWind	GHGs	RAGs	Aerosols	Cls+Prec	Radiation
Climate							
Monitor climate trends and variability	*	(*)	*	*	*	*	* * *
Diagnose and predict climate change	*	(*)	*	*	*	*	* * *
Validate, test and improve climate GCMs	* *	(*)	* *	*	*	*	* * *
Understand climate forcings and feedbacks	* *	(*)	* *	*	*	* *	* * *
Chemistry&Processes							
Study atmos. processes near-surface & in the LT	* *	(*)	* *	*	*	*	* * *
Study atmos. processes in the UTLS	* *	(*)	* *	*	*	*	* * *
Improve atmos. composition forecasting	* * *	(*)	* *	*	*	* *	* * *
Test and improve atmos. constituent models	* * *	(*)	* *	*	*	* *	* * *
NWP							
Improve NWP forecasting	* * *	*	*	*	*	* *	* * *
Test and improve NWP models	* * *	*	*	*	*	* *	* * *
Others							
Calibrate data from other atmos. observing systems	* *	(*)	* *	*	*	*	* *
Demonstrate a novel observing technique	*	(*)	*	*	*	*	*

4.3 PREMIER Observational Performance

PREMIER science objectives: (denoted as Research Objectives in the PREMIER report for assessment of November 2008, [PREMIER08]).

PREMIER will achieve its aims by resolving 3D structures of chemical species, thin clouds and temperature in the UTLS atmospheric region on finer scales than has previously been possible from space, allowing the following specific objectives to be addressed:

a. *To quantify relationships between atmospheric composition and climate.* Processes controlling the detailed distribution of climate gases, water vapor, ozone, methane, and cirrus (notably including ultra-thin tropical tropopause cirrus) will be quantified in the height range of particular importance to climate.

b. *To quantify atmospheric transport processes important to climate and air quality.* Processes linking the tropical troposphere and lower stratosphere will be characterized, including convective transport of the trace gases in the tropical tropopause layer. Plumes of biogenic, pyrogenic and anthropogenic origin will be observed in 3D and characterized globally.

c. *To quantify relationships between atmosphere dynamics and climate.* Mesoscale dynamics in this height-range will be examined be resolving (3D) temperature structure down to fine scales, including propagating gravity waves and their influence on stratospheric circulation. In combination with weather forecast and climate models, the downward influence of the stratosphere on the lower atmospheric circulation and weather will be better quantified.

PREMIER measures similar atmospheric gases as does ACCURATE. An important difference is that ACCURATE measures the CO_2 concentration while PREMIER does not measure CO_2.

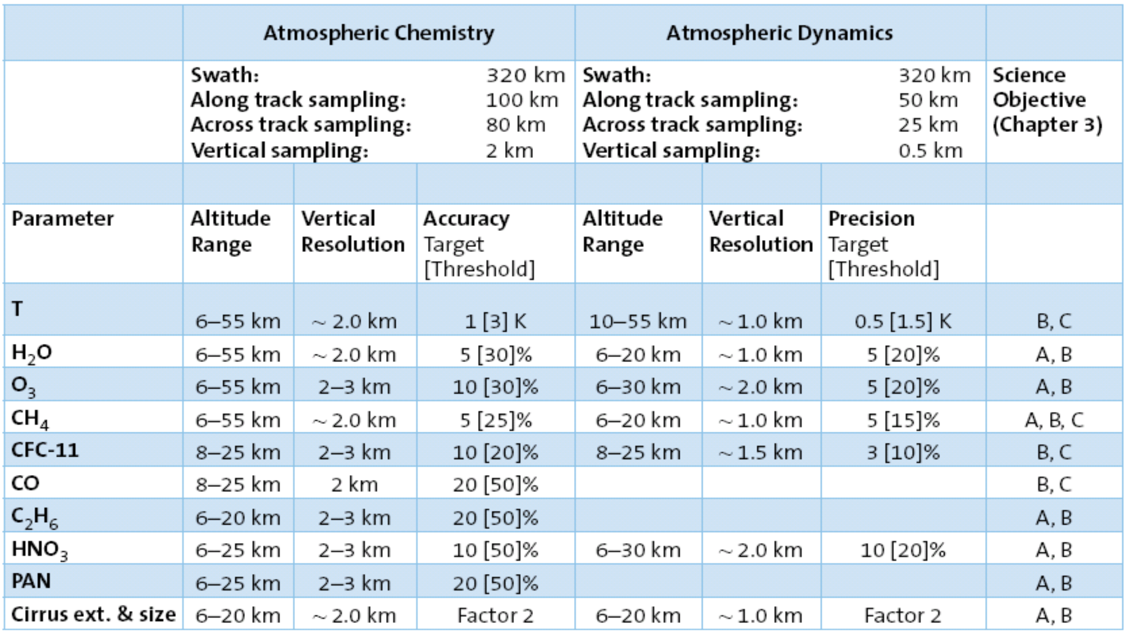
For NWP the ACCURATE mission is better suited. PREMIER will be best use to improve understanding of atmosphere dynamics and hence used to refine the parameterization of the atmospheric processes in the forecast models. PREMIER will operate in two modes, and the foreseen switching between modes will possibly make direct data assimilation difficult.

Vertical resolution of PREMIER (~2-3 km) is somewhat coarser than that of ACCURATE (~1-2 km).

Measurement accuracy for PREMIER is not as high as for ACCURATE. This is compensated for by the much denser horizontal sampling. For climate monitoring and detection of climate trends ACCURATE is better suited through the high measurement accuracy and long-term stability of the measurements.

Table 4.3 summarizes observational requirements for PREMIER.

Table 4.3. PREMIER observational requirements



	Atmospheric Chemistry			**Atmospheric Dynamics**			
	Swath: 320 km **Along track sampling:** 100 km **Across track sampling:** 80 km **Vertical sampling:** 2 km			**Swath:** 320 km **Along track sampling:** 50 km **Across track sampling:** 25 km **Vertical sampling:** 0.5 km			**Science Objective (Chapter 3)**
Parameter	**Altitude Range**	**Vertical Resolution**	**Accuracy** Target [Threshold]	**Altitude Range**	**Vertical Resolution**	**Precision** Target [Threshold]	
T	6–55 km	~ 2.0 km	1 [3] K	10–55 km	~ 1.0 km	0.5 [1.5] K	B, C
H_2O	6–55 km	~ 2.0 km	5 [30]%	6–20 km	~ 1.0 km	5 [20]%	A, B
O_3	6–55 km	2–3 km	10 [30]%	6–30 km	~ 2.0 km	5 [20]%	A, B
CH_4	6–55 km	~ 2.0 km	5 [25]%	6–20 km	~ 1.0 km	5 [15]%	A, B, C
CFC-11	8–25 km	2–3 km	10 [20]%	8–25 km	~ 1.5 km	3 [10]%	B, C
CO	8–25 km	2 km	20 [50]%				B, C
C_2H_6	6–20 km	2–3 km	20 [50]%				A, B
HNO_3	6–25 km	2–3 km	10 [50]%	6–30 km	~ 2.0 km	10 [20]%	A, B
PAN	6–25 km	2–3 km	20 [50]%				A, B
Cirrus ext. & size	6–20 km	~ 2.0 km	Factor 2	6–20 km	~ 1.0 km	Factor 2	A, B

Table 4.1: Geophysical product requirements for altitude ranges typical of mid-latitude.

4.4 PREMIER Impact Level Matrix

The Impact Level matrix for the PREMIER mission is presented in Table 4.4. PREMIER is undergoing phase A studies for possible selection as an ESA Earth Explorer Mission. It is using the passive limb sounding technique in the infrared spectrum. The techniques in PREMIER (infrared and microwave) allow for novel 3D measurements of the temperature and the atmosphere constituents. As for ACCURATE the geometry is limb sounding, however, the strength of the PREMIER mission is on the high number of measurement allowing for 3D information, whereas the strength for ACCURATE is on the high measurement accuracy and precise calibration for climate monitoring and research.

Table 4.4. Sci.Objectives-vs-Obs.Information Impact Level Matrix for PREMIER

	Atmospheric Observation Information						
Scientific Objectives	ThDyn	DynWind	GHGs	RAGs	Aerosols	Cls+Prec	Radiation
Climate							
Monitor climate trends and variability	* *	*	* *	*	*	* *	*
Diagnose and predict climate change	* *	*	* *	*	*	* *	*
Validate, test and improve climate GCMs	* * *	* *	* *	* *	* *	* *	*
Understand climate forcings and feedbacks	* * *	* *	* *	* *	* *	* *	*
Chemistry&Processes							
Study atmos. processes near-surface & in the LT	*	*	*	*	*	*	*
Study atmos. processes in the UTLS	* * *	*	* * *	* * *	* *	* *	* *
Improve atmos. composition forecasting	* * *	* *	* * *	* *	* *	* * *	* *
Test and improve atmos. constituent models	* * *	* *	* * *	* *	* *	* * *	* *
NWP							
Improve NWP forecasting	* *	*	* *	*	*	*	*
Test and improve NWP models	* *	*	* *	*	*	*	*
Others							
Calibrate data from other atmos. observing systems	* *	*	* *	* *	*	* *	*
Demonstrate a novel observing technique	* * *	*	* *	* * *	* *	* *	* *

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5 Other GHG Observations: GOSAT and NOAA/GMD Network Observational Performance and Impact Level Matrices

5.1 GOSAT Observational Performance

The Japanese Greenhouse Gas Observing Satellite (GOSAT), launched in January 2009, is the world's first satellite focusing on measurements of concentrations of CO_2 and CH_4 from space, whereby GOSAT will in particular aim to constrain the geographical distribution of and seasonal and inter-annual variations in the fluxes (i.e., emissions and sinks) of CO_2 and CH_4. The mission objectives and observational/data product requirement information below is distilled directly from detailed official GOSAT project information [GOSAT09].

There is no more quantitative observational requirements or performance information available on the targeted CO_2 and CH_4 data quality from the mission specifications (somewhat different from, e.g., the European way of observational performance specification). The product development and evolution during the years of operations will show the degree and coverage to which the goals, especially related to the regional source/sink flux estimations, can be quantitatively met by the passive IR/VIS sounding techniques utilized by GOSAT.

GOSAT mission objectives:

1) The foremost purpose of the GOSAT Project is to produce more accurate estimates of the flux of greenhouse gases on a subcontinental basis (several thousand kilometers square). This is expected to help contribute to environmental administration efforts such as ascertaining the amount of CO_2 absorbed or released per region and evaluating the carbon balance in forests.
2) Furthermore, by engaging in research using the GOSAT data, we will accumulate new scientific knowledge on the global distribution of greenhouse gases and its temporal variations, and the mechanism of the global carbon cycle and its effect on climate, which will prove useful in predicting future climate change and assessing its impact.
3) Additionally, the Project will expand upon existing earth-observing satellite technologies, develop new methodologies to measure greenhouse gases, and promote the technological development necessary for future earth-observing satellites.

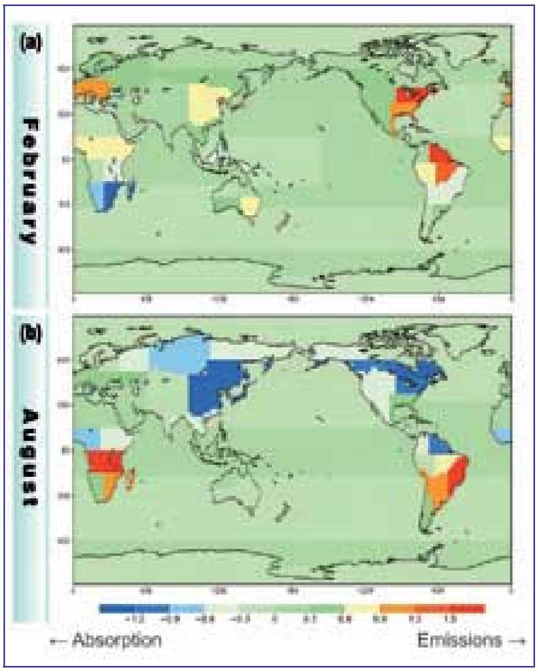


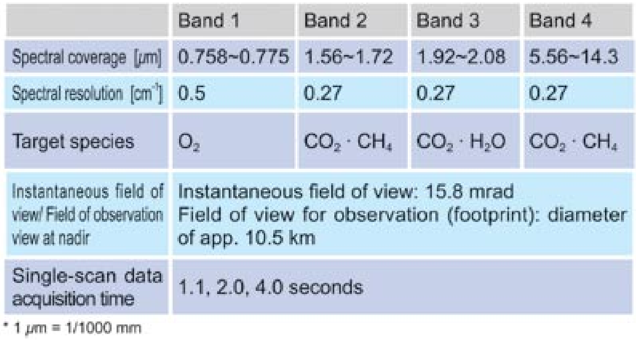
Fig. 5.1: The data obtained through GOSAT are expected to allow for this kind of computation of the global distribution of CO_2 flux (Simulation, (a) February, (b) August, carbon conversion [$gC/m^2/day$])

Observational requirements/data products information:

Underlying observing techniques and related observational requirements.

GOSAT will observe IR and VIS radiation reaching its sensors from the Earth's surface and atmosphere and give IR spectra which can be used to calculate the column abundances of CO_2 and CH_4. The column abundances are expressed as the number of molecules of target gases per unit surface area or as the ratio of target gas molecules to the number of molecules in dry air per unit surface area.
GOSAT will orbit the Earth in ~100 min at an altitude of ~666 km and have a three-day repeat cycle. The instrument onboard the satellite is called the Thermal And Near-infrared Sensor for carbon Observation (TANSO). TANSO is composed of two sensors: a Fourier Transform Spectrometer (FTS) and a Cloud Aerosol Imager (CAI). Tables 1 and 2 summarize the species, bands, and other specifications of the two sensors.

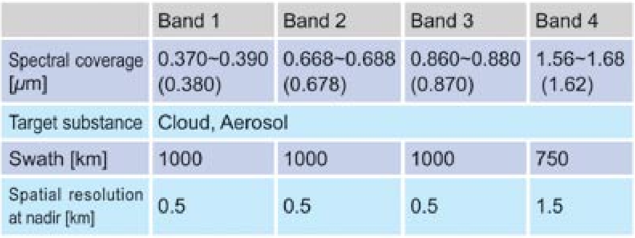
Table 5.1: Specifications of the TANSO FTS Sensor.



	Band 1	Band 2	Band 3	Band 4
Spectral coverage [μm]	0.758~0.775	1.56~1.72	1.92~2.08	5.56~14.3
Spectral resolution [cm^{-1}]	0.5	0.27	0.27	0.27
Target species	O_2	CO_2 · CH_4	CO_2 · H_2O	CO_2 · CH_4
Instantaneous field of view/ Field of observation view at nadir	Instantaneous field of view: 15.8 mrad Field of view for observation (footprint): diameter of app. 10.5 km			
Single-scan data acquisition time	1.1, 2.0, 4.0 seconds			

* 1 μm = 1/1000 mm

Table 5.2: Specifications of the TANSO CAI Sensor.

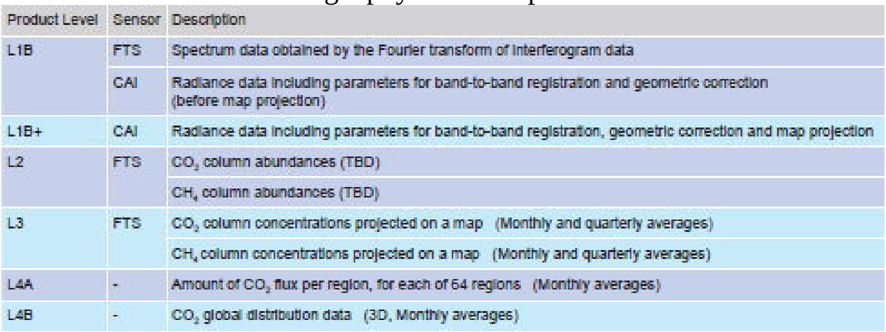


	Band 1	Band 2	Band 3	Band 4
Spectral coverage [μm]	0.370~0.390 (0.380)	0.668~0.688 (0.678)	0.860~0.880 (0.870)	1.56~1.68 (1.62)
Target substance	Cloud, Aerosol			
Swath [km]	1000	1000	1000	750
Spatial resolution at nadir [km]	0.5	0.5	0.5	1.5

Data product information.

A GOSAT Data Handling Facility (DHF) was developed, which will process GOSAT data. At the DHF, the GOSAT data and reference data from other sources will be used to generate the column abundances of CO_2 and CH_4, CO_2 flux, and the 3D distribution of CO_2 with the cooperation of external computing centers.

Table 5.3: List of GOSAT geophysical data products.



Product Level	Sensor	Description
L1B	FTS	Spectrum data obtained by the Fourier transform of interferogram data
	CAI	Radiance data including parameters for band-to-band registration and geometric correction (before map projection)
L1B+	CAI	Radiance data including parameters for band-to-band registration, geometric correction and map projection
L2	FTS	CO_2 column abundances (TBD)
		CH_4 column abundances (TBD)
L3	FTS	CO_2 column concentrations projected on a map (Monthly and quarterly averages)
		CH_4 column concentrations projected on a map (Monthly and quarterly averages)
L4A	-	Amount of CO_2 flux per region, for each of 64 regions (Monthly averages)
L4B	-	CO_2 global distribution data (3D, Monthly averages)

Table 5.3 shows the standard products that the GOSAT DHF will provide (there are more, e.g., also cloud products, see [GOSAT09]). L1 data provided by JAXA (L1B of FTS observation) and higher-level products generated from them (L1B and L1B+ of CAI and L2, L3, L4A and L4B of FTS) will be available for users via the DHF.

Compared to ACCURATE, GOSAT focuses on CO_2 and CH_4 gases only, and on the near-surface and lower troposphere column-integrated concentrations rather than UTLS profiles. In the horizontal GOSAT has the potential to achieve more geographical resolution for its data products than a small number of ACCURATE satellites (baseline or minimum); it will depend on how well effects of clouds as well as surface effects can be controlled and mitigated.

5.2 GOSAT Impact Level Matrix

Table 5.4 shows the Impact Level matrix for GOSAT (cf. Sect. 2). As is visible, its unique and major strengths fall, in line with its goals described above, into the field of climate science, with focus on GHGs. Since GOSAT is the first dedicated GHG satellite, targeting CO_2 and CH_4, it is clearly expected to well complement the existing GHG ground networks such as the currently leading NOAA/GMD network (Sect. 5.3). Due to its use of upwelling IR radiation, including over a thermal IR range similar to IASI (Sect. 4.1) but with higher spectral resolution, the data also provide useful outgoing long-wave radiation information. In addition, the TANSO CAI provides useful cloud and aerosol information at ~1 km horizontal resolution. The complementarity with ACCURATE is high as noted at the end of Sect. 5.1 above.

Table 5.4. Sci.Objectives-vs-Obs.Information Impact Level Matrix for GOSAT

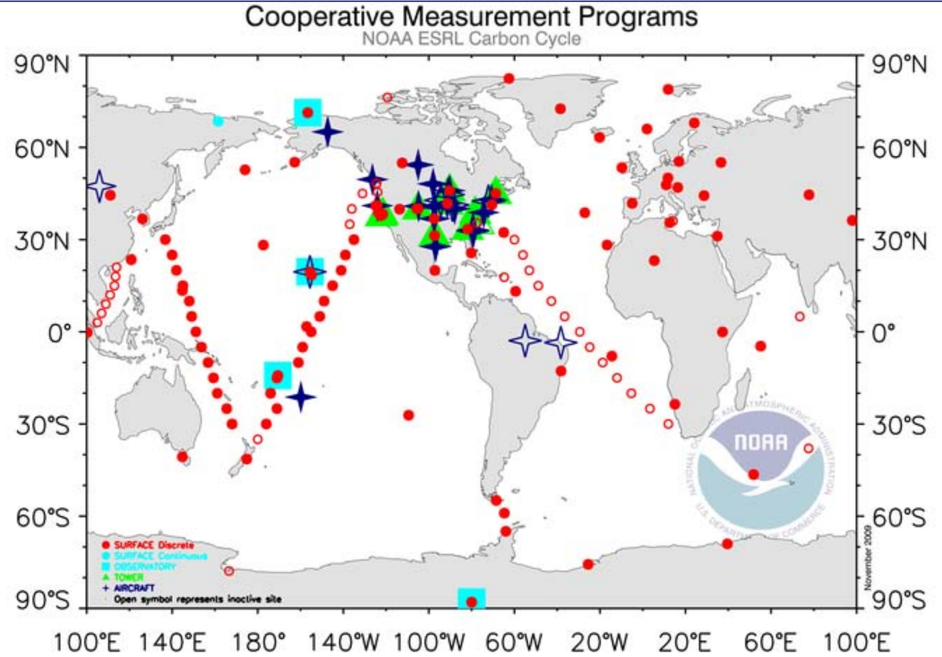
	Atmospheric Observation Information						
Scientific Objectives	ThDyn	DynWind	GHGs	RAGs	Aerosols	Cls+Prec	Radiation
Climate							
Monitor climate trends and variability	*	(*)	***	–	*	**	**
Diagnose and predict climate change	*	(*)	***	–	*	**	**
Validate, test and improve climate GCMs	*	(*)	**	–	*	**	**
Understand climate forcings and feedbacks	*	(*)	**	–	*	**	**
Chemistry&Processes							
Study atmos. processes near-surface & in the LT	*	(*)	***	(*)	**	**	***
Study atmos. processes in the UTLS	*	(*)	*	–	–	(*)	**
Improve atmos. composition forecasting	*	(*)	***	–	*	*	**
Test and improve atmos. constituent models	*	(*)	**	–	*	*	**
NWP							
Improve NWP forecasting	*	(*)	*	(*)	*	**	**
Test and improve NWP models	*	(*)	*	–	*	**	**
Others							
Calibrate data from other atmos. observing systems	*	(*)	**	–	*	*	**
Demonstrate a novel observing technique	–	(*)	***	–	*	*	*

5.3 NOAA/GMD Network Observational Performance

The NOAA/GMD Carbon Cycle Greenhouse Gases Group's (CCGG) cooperative air sampling (CAS) network is an international ground-based GHG observation network effort, which includes data from NOAA/GMD baseline observatories, cooperative fixed sites, and ships. CO_2 and CH_4 measurements (including their stable isotopes) are primary products. The objectives and observational/data product information below is distilled directly from detailed official NOAA/GMD information on the CAS network and its data [CAS-GMD10].
Since the CAS network is ground-based also for this data source there is no quantitative observational requirements of satellite data style available. However, since this is a longstanding exercise already, the main techniques, flask measurements and gas analysis by IR gas analyzers and mass spectrometry, have received extensive error characterization for all relevant species. That is the performance is well known and monitored and in particular the data from the four baseline observatories (see [CAS-GMD10] under Observatory Measurements) are cross-validated amongst different on-site techniques. Newest techniques included, that gradually will start to replace flask measurements, are based on exploitation of Cavity-Ringdown Spectroscopy (e.g., [RellaVP09]; cf. also Sect. 3.2) which can provide highly accurate time series measurements of the GHGs of interest at any site.

Network measurement objectives:

The NOAA/GMD CAS network effort began in 1967 at Niwot Ridge, Colorado. At current state, the network is an international effort which includes 4 NOAA/GMD baseline observatories, cooperative fixed observing sites, and commercial ships. Air samples are collected approximately weekly from the globally distributed sites (see map Fig. 5.2). Samples are analyzed in Boulder by CCGG for CO_2, CH_4, CO, H_2, N_2O, and SF_6; and by Univ. of Colorado Stable Isotope Lab for isotopes of CO_2 and CH_4. Measurement data are used to identify long-term trends, seasonal variability, and spatial distribution of the carbon cycle gases.



NOAA ESRL Carbon Cycle operates 4 measurement programs. Semi-continuous measurements are made at 4 baseline observatories, a few surface sites and from tall towers. Discrete surface and aircraft samples are measured in Boulder, CO. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, the stable isotopes of carbon dioxide and methane, and halocarbon and volatile organic compounds are measured. Contact: Dr. Pieter Tans, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6678, pieter.tans@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

Fig. 5.2: World map showing the NOAA/GMD CCGG Cooperative Air Sampling Network.

At NOAA/GMD the data are, for example, used to feed the CarbonTracker tool (see [CAS-GMD10] under CarbonTracker). This is a system that calculates CO_2 uptake and release at the Earth's surface over time. It estimates the CO_2 exchange from an "atmospheric point of view". Since CO_2 concentrations in the atmosphere reflect the sum of all the CO_2 exchange at the surface, they form an authoritative record of combined human and natural influences.

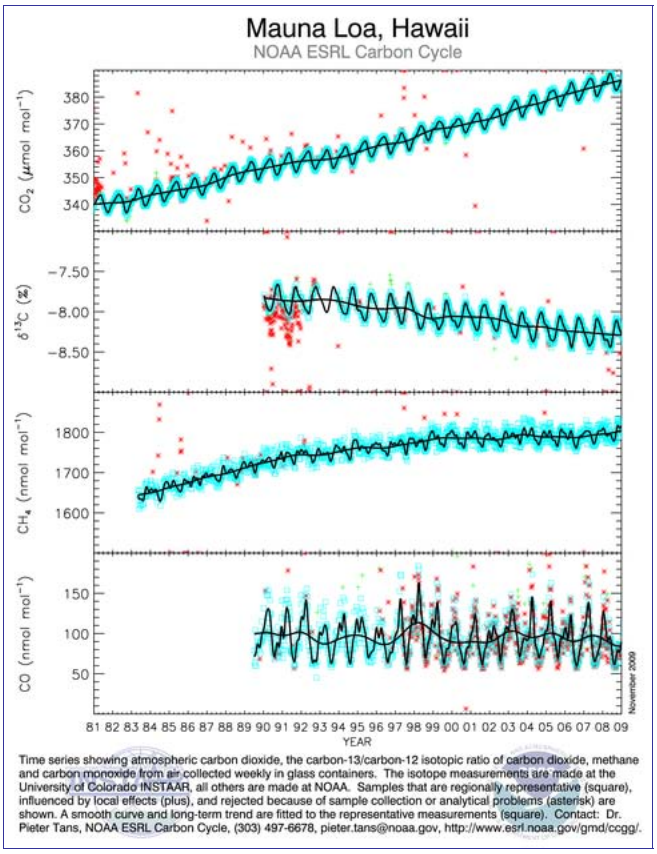
Observational/data product information:

The [CAS-GMD10] information on the CarbonTracker (noted above) as well as on another product tool named GLOBALVIEW serves as a decent source of observational/data product information on the NOAA/GMD network data. The GLOBALVIEW data products are designed to enhance the spatial and temporal distribution of atmospheric observations of CO_2 and CH_4 (and other related greenhouse gases). GLOBALVIEW products are specifically intended as tools for use in carbon cycle modeling studies.

Figure 5.3 shows CO_2 and CH_4 (and CO) long-term records, including the ^{13}C isotope ratio record from $^{13}CO_2$, for indication of the monitoring quality of the GHG data.

On the accuracy and precision of the CO_2 and CH_4 data products of the CAS network, detailed analysis studies available via [CAS-GMD10] and its references lead to estimates of ~0.03% (accuracy) and ~0.01% (precision) which monthly-mean values of these ground-based GHG benchmark data achieve. Thereby the accuracy is established by carefully maintaining traceability to standard gases in well conserved cylinders and employing, e.g., high-precision manometric systems [Zhaoetal07].

In the sense of Level 3 and Level 4 data from satellites, the CAS network provides latitude- and season-dependent as well as global maps of its products, via its CarbonTracker and GLOBALVIEW tools.



Time series showing atmospheric carbon dioxide, the carbon-13/carbon-12 isotopic ratio of carbon dioxide, methane and carbon monoxide from air collected weekly in glass containers. The isotope measurements are made at the University of Colorado INSTAAR, all others are made at NOAA. Samples that are regionally representative (square), influenced by local effects (plus), and rejected because of sample collection or analytical problems (asterisk) are shown. A smooth curve and long-term trend are fitted to the representative measurements (square). Contact: Dr. Pieter Tans, NOAA ESRL Carbon Cycle, (303) 497-6678, pieter.tans@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

Fig. 5.3: GHG time series at a baseline observatory.

Compared to ACCURATE, the NOAA/GMD network focuses on GHG data from individual ground-based sites only (Fig. 5.2), including near-surface as well as tall tower boundary layer measurements up to 500 m altitude, where it provides accurate and precise climate benchmark data. With near-ideal complementarity ACCURATE focuses on complete and regular global coverage in the free atmosphere above the boundary layer, providing accurate and precise GHG vertical profiles at ~1 km resolution over the UTLS and beyond as climate benchmark data. Thereby the accuracy and precision of ACCURATE monthly-mean values in any point in the global free atmosphere aims to reach close to the one of these ground-based sites.

5.4 NOAA/GMD Network Impact Level Matrix

Table 5.4 shows the Impact Level matrix for the NOAA/GMD network (cf. Sect. 2). As is well visible, its unique and major mission, in line with its goals described above, is near-surface GHG data of climate benchmark quality for serving climate monitoring and for serving as calibration and validation reference for other data like satellite data from GOSAT (Sect. 5.1). Due to co-measurements also of non-GHG trace gases at many sites, as well as of complete meteorological sets of parameters, the data also usefully contribute to the study of near-surface and boundary layer/lower troposphere processes. The complementarity with ACCURATE is near-ideal as noted at the end of Sect. 5.3 above.

Table 5.5. Sci.Objectives-vs-Obs.Information Impact Level Matrix for NOAA/GMD Net

	Atmospheric Observation Information						
Scientific Objectives	ThDyn	DynWind	GHGs	RAGs	Aerosols	Cls+Prec	Radiation
Climate							
Monitor climate trends and variability	–	–	***	*	–	–	–
Diagnose and predict climate change	–	–	***	*	–	–	–
Validate, test and improve climate GCMs	–	–	**	*	–	–	–
Understand climate forcings and feedbacks	–	–	**	*	–	–	–
Chemistry&Processes							
Study atmos. processes near-surface & in the LT	(*)	–	***	*	–	–	–
Study atmos. processes in the UTLS	–	–	–	–	–	–	–
Improve atmos. composition forecasting	(*)	–	**	(*)	–	–	–
Test and improve atmos. constituent models	(*)	–	**	(*)	–	–	–
NWP							
Improve NWP forecasting	–	–	*	–	–	–	–
Test and improve NWP models	–	–	*	–	–	–	–
Others							
Calibrate data from other atmos. observing systems	–	–	***	–	–	–	–
Demonstrate a novel observing technique	–	–	**	–	–	–	–

6 Comparative Discussion of Impact: Unique Impacts, Synergies, and Complementarities

6.1 ACCURATE Unique Impacts

The report [ACCUObsReq09] from WP 2 concluded "In summary, an ACCURATE mission is found to be capable of a comprehensive and unique contribution to fulfilling the international observational requirements as a key part of the future global satellite observing system for climate, atmospheric composition, and NWP. It can provide an unprecedented climate benchmark dataset of the atmospheric thermodynamic, chemical, and dynamical state with high vertical resolution, accuracy, consistency, and long-term stability."

In utilizing those ACCURATE observational requirements in order to assess ACCURATE scientific impacts, this report confirmed the uniqueness of the combination of properties termed "unprecedented" above, mainly by means of inter-comparing systematic Impact Level matrices (Sect. 2) of other key atmospheric observing techniques with ACCURATE.

The unique and major strengths of ACCURATE fall mainly into the field of climate science, where its primary mission objectives reside [ACCUObsReq09], via observing thermodynamic variables, greenhouse gases, and wind from space with climate benchmark quality and with focus on the UTLS. Due to their accuracy and high vertical resolution, the ACCURATE data also will have unique and major impact to atmospheric chemistry and process studies in the UTLS, GHG composition modeling, and calibration of data from other observing systems. Furthermore, it is a very novel technique wherefore also its demonstration is strongly unique.

6.2 Synergies with Other Missions and GHG Observations

When comparing ACCURATE with the other representative missions IASI-MetOp and PREMIER, as well as other GHG observations from GOSAT and the NOAA/GMD network, a range of synergies is found as follows.

Other missions. ACCURATE can help advanced passive IR down-looking and chemistry limb-looking sounders in providing them with a global background 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. In the latter application it can lead, for example, to significantly improved NWP or composition forecasts and analyses beyond what the individual sensors could deliver to the result.

Especially for the PREMIER-type concept, a synergistic combination of ACCURATE and PREMIER can be particularly fruitful for unprecedented quality of remote chemical analysis over the UTLS region. This since the similar probing geometry of soundings and good vertical profiling capability also of PREMIER as well as the availability of quite a range of joint parameters neatly combines with the complementary foci to accuracy and stability vs. precision and spatial detail.

GHG observations. Since the surface-, boundary layer-, lower troposphere-oriented GHG observation systems like GOSAT and NOAA/GMD network and the UTLS-oriented ACCURATE intentionally focus on complementary GHG measurement domains (see next Sect. 6.3), the "simultaneous" spatial synergy is limited. It occurs for the region from top of boundary layer to upper troposphere, though, in case of GOSAT-type systems (would also include OCO-type measurements and active down-looking Lidar systems); in this altitude range the two "information contents" assist each other.
An additional important synergy exists between NOAA/GMD-type high-quality ground-based GHG measurement techniques and the ACCURATE technique at spectroscopy level, i.e., in the frequency domain: both techniques strive for highest-precision manometry and IR spectroscopy for serving their needs of high-accuracy knowledge of instrument, spectroscopic, and processing system database parameters at the ~0.1% level or better. Thus developments in these fields, like the mentioned cavity-ringdown spectroscopic methods for single-line spectroscopy (Sect. 3.2 and Sect. 5.3), strongly and synergistically benefit both systems.

6.3 Complementarities with Other Missions and GHG Observations

When comparing ACCURATE with the other representative missions and GHG observation techniques, even more then synergies a series of complementarities – directly visible from inter-comparing the respective Impact Level matrices – are found as follows.

Other missions. ACCURATE is highly complementary in information content to advanced passive IR 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 combined IR/MW limb sounding of ACCURATE and those passive IR/MW radiometric sounders thus provides substantial added value to any system (e.g., data assimilation and modeling system) privileged to have both data sources simultaneously available.
Looking at the respective Impact Level matrices in comparison, it becomes clear in addition that there is such high complementary also with respect to the different scientific objectives; for example while ACCURATE has its most important contributions to the climate objectives, PREMIER has them to the chemistry&processes objectives. IASI, on the other hand, has strong complementary contributions in the Earth thermal (long-wave) radiation part.

GHG observations. Given that the surface-, boundary layer-, lower troposphere-oriented GHG observation systems like GOSAT and NOAA/GMD network and the UTLS-oriented ACCURATE system intentionally focus on complementary GHG measurement domains, the complementary of their information content is near-ideal: The former are responsible for the immediate source/sink relationships, flux, concentration, and isotope ratio information within the boundary layer while the latter provides an authoritative free atmosphere "boundary condition", e.g., in joint assimilation of both data types into global 3D composition models (or as [CAS-GMD10] puts it in its CarbonTracker description, "since CO_2 concentrations in the atmosphere reflect the sum of *all* the CO_2 exchange at the surface, they form the ultimate record of the combined human and natural influence on GHG levels").
In addition ACCURATE's ^{18}O isotope ratio measurements (from $C^{18}OO$ and $^{12}CO_2$) are fully complementary: while the near-surface systems focus on source/sink estimation these can focus on signals of changing stratospheric (ozone) chemistry in ^{18}O ratios (e.g., [Laemmereetal02], which ACCURATE would measure for the first time globally from space.

7 Summary and Conclusions

This report has, after providing a general introduction (Section 1), introduced the new concept of "Impact Level matrix" (Section 2). We then discussed the observational performance for climate measurements by ACCURATE under different constellation sizes, given the observational requirements of [ACCUObsReq09], and estimated the Impact Level matrix for ACCURATE (Section 3). For enabling to investigate potential synergies and complementarities with other representative missions and GHG observations, we then briefly introduced these other missions/observations (IASI-MetOp, PREMIER, GOSAT, NOAA/GMD network) and estimates their respective Impact Level matrices (Sections 4-5). Based on this a synthesis discussion on unique impacts of ACCURATE, as well as on synergies and complementarities with the other missions/observations, could be provided (Section 6). The following main conclusions can be drawn.

The concept of Impact Level matrices as defined in Section 2, which indicate the impact of information that an observing system can provide to different relevant scientific objectives, is found very useful for enabling a structured comparative look at the scientific impact of different observing systems. Though the current impact estimations in these matrices are based on expert assessment and judgment by the small group of authors (from WEGC, DMI) and reviewers (from Univ. York, ESA) of this report, the overall picture of strengths and limitations of impact emerging in the matrices appears to be robustly sound. The matrices aid in adequate understanding of the role and significance of an ACCURATE mission (or of any other mission put as primary mission under study) in the context of other atmospheric observing techniques and systems, including unique features, synergies, and complementarities.

From the analysis of the observational performance of ACCURATE for climate observations for the three representative constellation cases 4 satellites (baseline case, BC), 2 satellites (minimum case, MC), , and 12 satellites (large case, LC), respectively, we found as follows: In comparatively assessing the three cases, the MC case appears to be an ideal least-cost initial demonstration case, already addressing all aspects of scientific return at coarser horizontal resolution, the BC case appears to be the best trade-off in scientific return to investment, already fully meeting all observational requirements (as seen in Section 3, Table 3.1), and the LC case appears to be a potentially attractive option for a later operational solution after MC/BC cases have established the technique. This latter case meets all requirements with highest data density.

From investigating the uniqueness of ACCURATE and its synergies and complementarities we found as follows:

Uniqueness. ACCURATE can provide an unprecedented climate benchmark dataset of the atmospheric thermodynamic, chemical, and dynamical state with high vertical resolution, accuracy, consistency, and long-term stability. Based on this combination of properties, and from inter-comparing the Impact Level matrices of the other atmospheric observing techniques with ACCURATE, its unique and major strengths are found mainly in its contributions to climate science, where its primary mission objectives reside [ACCUObsReq09], via observing thermodynamic variables, greenhouse gases, and wind from space with focus on the UTLS. Due to their accuracy and high vertical resolution, the ACCURATE data also will have unique and major impact to atmospheric chemistry and process studies in the UTLS, in

GHG composition modeling, and in calibration of data from other observing systems. Furthermore, it is a very novel technique wherefore also its demonstration is strongly unique.

Synergies. ACCURATE can help advanced passive IR 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 improved NWP or composition analyses and forecasts. On GHGs the joint need of both ground-based NOAA/GMD-type systems and of ACCURATE for highest-precision spectroscopy, like cavity-ringdown spectroscopic methods for single-line spectroscopy to the ~0.1% accuracy level, strongly and synergistically benefits both systems.

Complementarities. ACCURATE is highly complementary in information content to advanced passive IR 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 GHGs, given that the surface- and boundary layer-oriented observation systems like GOSAT and NOAA/GMD sites and the UTLS-oriented ACCURATE system focus on complementary spatial domains, the complementary 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 types 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 GHG data, exciting prospects and a ground-breaking potential especially for climate monitoring and research.

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