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GADEM Project
WP1200: Scientific Applications

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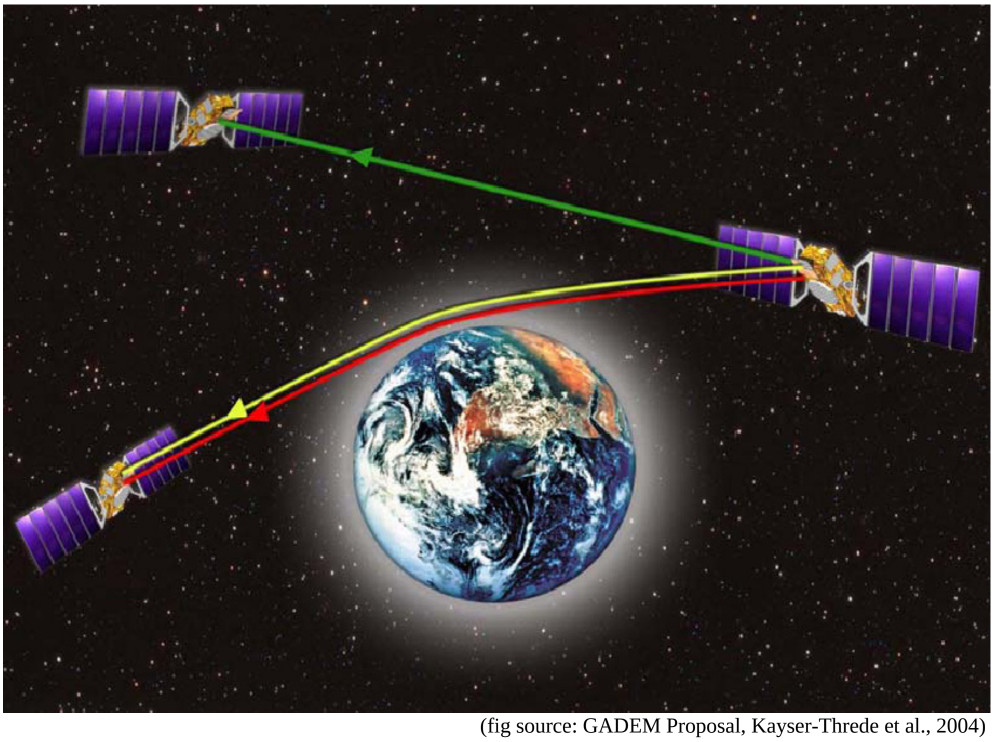
GJU GADEM Project – Tech. Note WP1200
Scientific Applications of Galileo K-band Radio Links



(fig source: GADEM Proposal, Kayser-Threde et al., 2004)

Technical Note by

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List of Acronyms

ACE+	Atmosphere and Climate Explorer (occultation mission concept studied by ESA 2002–2004)
CEOS	Committee on Earth Observation Satellites (www.ceos.org)
ESA	European Space Agency (www.esa.int)
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites (www.eumetsat.int)
GADEM	Galileo Atmospheric Data Enhancement Mission (Kayser-Threde et al. GJU project)
Galileo	Currently developed European GNSS component (operational ~2009/10)
GCM	General Circulation Model or Global Circulation Model (of Earth's atmosphere or climate)
GNSS	Global Navigation Satellite System(s) (generic term)
GNSS RO	GNSS-LEO radio occultation (here Galileo & GPS L band signals, ~1.2 / 1.6 GHz)
GPS	Global Positioning System (GNSS component of the U.S.)
GS	Ground Station (typically Galileo ground station in the context of Galileo-to-GS links)
IWV	Integrated Water Vapour [kg/m^2] (from Galileo-to-GS links; slant IWV or vertical IWV)
K-band RO	K-band radio occultation (K band intersatellite link signals within 17–23 GHz)
L-band RO	L-band radio occultation (L band intersatellite link signals within 1–2 GHz)
LEO	Low Earth Orbit (or satellite in Low Earth Orbit)
LT, HT, LS, HS	Lower Troposphere, Higher Troposphere, Lower Stratosphere, Higher Stratosphere
NOAA	National Oceanic and Atmospheric Administration (of the U.S.; www.noaa.gov)
NWP	Numerical Weather Prediction
PW	Precipitable Water [mm] (from Galileo-to-GS links; derived from vertical IWV data)
SNR	Signal-to-Noise Ratio (typically of the received signals, in the context of this Tech. Note)
TBL	Top of atmospheric boundary layer (located typically ~1–2.5 km above Earth's surface)
TOA	Top of the Atmosphere (in GADEM generally referring to 80 km height)
Tx, Rx	Transmitter (Tx) resp. Receiver (Rx); also Transmitter resp. Receiver satellite
UTLS	Upper Troposphere & Lower Stratosphere region (WMO: 5–35 km / 500–10 hPa)
WMO	World Meteorological Organization (www.wmo.ch)
WRC	World Radiocommunication Conference(s) (www.itu.int/ITU-R/conferences/wrc)

1. Introduction

This GADEM WP1200 Technical Note discusses the scientific applications of GADEM, focusing on the proposed novel K-band radio links, which are envisaged to complement the existing L-band links in a future Galileo system. The scientific applications of L-band GNSS signals are well known [e.g., Melbourne et al., 1994; Hoeg et al., 1995; Kursinski et al., 1997; Steiner et al., 2001; Lee et al., 2001] so that the area of key interest in this Tech. Note are necessarily the additional benefits of K-band links.

The Technical Note is organized as follows. First the GADEM objectives for scientific applications are summarized (section 2), where also additional direct benefits for the Galileo system and non-scientific users are noted. Based on this, main scientific applications and the value of GADEM data in these applications are briefly described (section 3). Based on this scientific background, the proposed GADEM K-band link measurement concepts are introduced in section 4, together with the atmospheric data products they deliver to serve the targeted scientific applications. Section 4 includes, furthermore, as the crucial bridge to technically implementing the K-band links with the required performance, the preliminary system requirements derived from scientific observational requirements, where the latter have been defined to ensure adequate data quality for the scientific applications.

The preliminary system requirements and their associated scientific requirements may be further refined in iteration with the Galileo and Commercial Applications assessment (WP1100) and, in particular, also in course of the subsequent detailed requirements definition (WP2000), which includes a quantitative signal characteristics and performance analysis of the measurement concepts via end-to-end simulations (WP2100).

2. GADEM Objectives for Scientific Applications of K-band Links

Scientific application areas of GADEM K-band radio link data can be grouped into

1) Climate monitoring and climate research
2) Operational meteorology and numerical weather prediction (NWP)
3) Atmospheric process modelling and studies

These application areas are complemented by direct benefits from the data products prepared for these scientific applications to the Galileo system and its non-scientific users. Below the main objectives for the scientific application areas are listed, followed by a small list of example "spin-off" benefits for Galileo itself and non-scientific users.

The main objectives of GADEM for *climate monitoring and climate research* are:

- Measure climate variability and trends as an initial key component of long-term occultation observations. The measurements can be made with high accuracy and more homogenously than existing observations, which is essential from a climate monitoring point of view. As a consequence, it is possible to compare data sets separated by many years and taken by GADEM radio links from different satellites.
- Contribution to detection of climate changes and support of climate change predictions via provision of high-quality global reference data,
- Validation of global circulation models (GCMs), both in simulated mean climate and variability,
- Improvement, via data assimilation methods, of physics parameterizations in GCMs, and of the detection of external forcing variations,
- Improvement of the understanding of climate feedbacks determining magnitude and characteristics of climate changes,

Main objectives for using GADEM data in *operational meteorology and NWP* are:

- Contribution to improved operational meteorology services and numerical weather prediction (NWP),
- Support of analysis, validation and calibration of data from other space missions in an operational sense (serving as reference data in continuous quality control of such data).

GADEM objectives for *atmospheric process modelling and studies* include:

- Study of structures in the troposphere and tropopause regions at high vertical resolution, in the context of atmospheric process research,
- Turbulence products and characterization of turbulence in the troposphere,
- Assessment and improvement of present water vapour attenuation models.

As noted introductorily above, the scientific data products prepared to achieve these scientific objectives will at the same time also bring significant direct benefit to the Galileo system itself and to its non-scientific users. For example, such benefits will include:

- Improved tropospheric models derived from the scientific data products will reduce the User Differential Range Error (UDRE) for Galileo Local Element Users, as well as in EGNOS broadcast tropospheric corrections,
- Short and local tropospheric events can be monitored by the products in near real-time, allowing for the improved integrity for Safety of Life users,
- Based on the high quality of the data products, corrections broadcast as part of the Galileo Long Baseline Real-Time Kinematic (RTK) Local Element can be improved, allowing greater accuracy for users,
- Ingestion of products brings the possibility of a reduced elevation mask on observations, thereby increasing the number of satellites in view, improving the Dilution of Precision (DoP) and increasing ranging source redundancy.

3. Description of Scientific Applications of GADEM K-band Data

3.1 Context and Heritage for the Scientific Applications

Satellite-based GPS L-band occultation techniques have a successful international heritage from past and present missions, including GPS/MET [Ware et al., 1996], SAC-C [Hajj et al., 2004] and CHAMP [Wickert et al., 2001 and 2004]. Very recently, on 14th April 2006, also the six satellites of the U.S./Taiwan COSMIC small satellite constellation have been launched, the first multi-satellite GPS occultation mission [Lee et al., 2001; Wu et al., 2005; www.cosmic.ucar.edu]. Furthermore, ESA is providing the L-band radio occultation instrument GRAS for the EUMETSAT/ESA MetOp mission [Loiselet et al., 2000; Silvestrin et al., 2000], of which the first satellite, to be named Metop-A, is scheduled for launch in October 2006 (www.eumetsat.int > What We Do > Satellites >EUMETSAT Polar System). Also L-band space-to-ground links for atmospheric sounding have long and considerable heritage from exploitation of GPS signals [e.g., Bevis et al., 1994; Ware et al., 1997; Foelsche and Kirchengast, 2001; Reigber et al., 2002].

The K-band occultation technique as proposed for GADEM is a new complementary concept without predecessor, but building on the same principle as the L-band missions and having study heritage from investigating the ACE+ K-band occultation concept for LEO-to-LEO links in ESA context within 2002–2004 [Kirchengast and Hoeg, 2004; ESA, 2004a and 2004b] (see section 4 for more information on measurement concepts). GADEM K-band in radio occultation mode will provide measurements of the atmospheric real refractivity and imaginary refractivity (absorption coefficient), while L-band occultation provides only the real refractivity. Similarly, GADEM K-band space-to-ground links will provide direct estimation of wet delays, and associated along-ray slant integrated water vapour (slant IWV, from which also precipitable water, PW, can be derived), while L-band space-to-ground links provide total delay only and need separate modelling assumptions to derive IWV and PW from the total delay.

The K-band occultation component of the GADEM mission will provide high-quality data sets of tropospheric and stratospheric temperature and pressure profiles, simultaneously measured with upper tropospheric and lower stratospheric humidity profiles with high vertical resolution. The consistent and simultaneous measurement of high-quality and high-resolution humidity and temperature profiles in this altitude range is new and unique. No other previous or presently planned satellite mission provides this type of atmospheric measurement despite of the urgency of the product. The K-band space-to-ground link component of GADEM will provide directly estimated IWV and PW time series, of superior quality to L-band estimates, at all Galileo ground terminals/receivers equipped with the K-band capability.

The scientific applications briefly described in the subsections 3.2 to 3.4 below build on these high-quality atmospheric data products.

3.2 Climate Monitoring and Climate Research

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

The humidity measurements will be insensitive to ice clouds, in clear contrast to other remote sensing techniques. Furthermore, the quality of the simultaneously measured humidity and temperature profiles will be high enough to accurately determine relative humidity as well as associated moist temperature lapse rates. In contrast, traditional humidity measurement techniques perform poorly in the upper troposphere domain. Thus the lack of such humidity data is one of the main reasons why the magnitude of the water vapour feedback in the upper troposphere remains a controversial issue. The self-calibration nature of the GADEM radio occultation observations will allow accurate tracking of changes in atmospheric water vapour content on short and long time scales.

The field of climate monitoring is a key application, as GADEM data are ideally suited to monitor variations and changes in the Earth’s climate. Such variations and changes can be due to processes internal to the climate system as well as due to external forcing effects. No anomalous forcing is needed to initiate internal climate variability, which basically occurs because of the differential radiative heating between high and low geographic latitudes. Externally forced variations and changes are on the other hand due to anomalous influence such as from a change in the solar constant, volcanic eruptions, or the human-made increase of the greenhouse effect. GADEM provides the capability to isolate and detect those climate variations during the mission period, and in particular to provide a strong and reliable observational constraint for anthropogenic climate change detection and attribution studies. In summary one prime goal of GADEM is to establish, with global coverage, accurate tropospheric and lower stratospheric climatologies of humidity and temperature as two of the most important atmospheric parameters for climate research.

In the field of climate model validation and improvement, advanced data assimilation concepts, including parameter and sensitivity estimation methods far beyond state estimation, will play a key role. Due to their high absolute accuracy, GADEM measurements can improve data assimilation bias correction schemes and provide evidence for model deficiencies, allowing subsequent model improvement. From a more general perspective, the potential of GADEM to aid climate model validation and improvement is so important since it extends the mission value decades beyond the actual data acquisition period in that better models will lead to decreased uncertainty in and increased credibility of long-term climate predictions. These improved predictive capabilities are, in turn, vital for sensible climate policy, where a key issue is what actions to take consistent with uncertainties in climate predictions.

GADEM will also scientifically perform, in addition to rigorously assessing the performance for simultaneous independent determination of humidity, temperature, and pressure (geopotential height), an assessment of sensing at the same time cloud liquid water in cloudy situations.

Turning finally to the versatile utility of GADEM data for climate research in general, the mission can help advance the understanding of many important atmospheric physics and climate change processes by addressing issues such as:

- Global warming and related changes in atmospheric water vapour levels,
- Tropical heat and mass exchange with extra-tropical regions,
- Transport across subtropical mixing barriers, relevant for information on the lifetime of greenhouse gases,
- Stratospheric temperatures and atmospheric wave phenomena,
- Polar front dynamics and mass exchange together with tropospheric water vapour feedback on climate stability,
- High latitude tropospheric-stratospheric exchange processes related to polar vortex conditions,
- Climatology of Rossby waves and atmospheric internal waves.

Overall, the GADEM data are thus expected to become invaluable for climate research and they will help to significantly improve our understanding of the climate system.

3.3 Operational Meteorology and Numerical Weather Prediction (NWP)

In addition to climate applications, GADEM data products will be highly valuable for operational meteorology and weather forecasting, with the data delivered in near real-time (within 3 hours of observation) to NWP Centres. At present our observational information on the temperature and humidity over the oceans and the tropics is limited to few radiosonde stations and the relatively inaccurate and coarse vertical soundings of temperature and humidity from the orbiting NOAA satellites. This, for example, severely limits the predictability over continental Europe in relation to synoptic disturbances developing over the North Atlantic ocean.

There are numerous examples of forecasts missing severe extra-tropical lows, which can be ascribed to missing or incomplete upper air information over the ocean west of Europe. Thus deficiencies in the current observing system degrade present day weather forecasting. Not only improved temperature and humidity observations are needed to improve the weather prediction skills. Mutual information on mass and wind field has to be known in modelling the atmospheric state.

The atmospheric mass field, characterized by temperature, pressure, and water vapour, dominates the main features of the large-scale atmospheric wind systems via the geostrophic balance. This, together with the fact that massive amounts of latent heat are transported via the atmospheric dynamics and released in areas of condensation, underlines the importance of water vapour and temperature in controlling the atmospheric circulation.

In the tropics, information about the wind field is, in general, relatively more important than mass field information. However, for synoptic and larger scale disturbances in the extra-tropical regions there is little doubt that high quality mass field observations over the oceans are the main factor limiting the skill of operational numerical weather prediction systems. Taking into account that data delivery to NWP Centres from GADEM can certainly be achieved within a 3-hour near real-time frame, the mission is very attractive for operational meteorological services and NWP.

In summary, GADEM will provide a highly accurate temperature and humidity data set, with particular strength in the upper troposphere from the occultation mode and in the lower troposphere from the space-to-ground links, which can be used in NWP data assimilation systems. Also the atmospheric model improvement work in the climate applications context, mentioned in the previous subsection on climate, will at the same time benefit NWP models. The other way round, advances in NWP will benefit climate studies, because the atmospheric analyses, a routine by-product of NWP systems, are highly valuable also for climate purposes, in particular the re-analyses (consistent analysis sequences over decades).

Support in analysis, calibration and validation of concurrent space missions was noted as a further important objective in section 2. During the time of future GADEM operations, certainly a series of space missions, European and non-European, will be able to sensibly exploit GADEM data as accurate reference data for their quality control, calibaration and validation. As one example, the close collaboration with future operational weather and climate satellite systems of EUMETSAT and NOAA will be of particular interest.

Looking at future advanced instruments on these upcoming operational weather and climate satellites, GADEM offers a key complement to the advanced nadir-sounding high spectral resolution infrared instruments (AIRS, IASI, CrIS), which are blocked by cloudiness, in that the GADEM techniques can observe through clouds thanks to the long wavelengths > 1 cm. Also the GADEM strengths are in vertical resolution and absolute accuracy, while the nadir sounders have their focus on resolution and coverage in the horizontal. GADEM thus offers a highly attractive alternative and complement to the traditional sounding techniques, also capable of serving as an invaluable reference for inter-validation of atmospheric data products.

3.4 Atmospheric Process Modelling and Studies

GADEM data are very well suited for the study and the modelling of atmospheric processes associated with troposphere, tropopause, and stratosphere small-scale vertical structures, as these will specifically exploit the high vertical resolution and accuracy of the occultation data. Furthermore, the K-band space-to-ground IWV and PW data are very well suited for the study of atmospheric processes at small-horizontal scales, including the possibility to use tomographic setups for studying and modelling two- and three-dimensional tropospheric water vapour distributions based on ground station networks. These applications will benefit in terms of accuracy and reliability of data from the advantages that K-band tropospheric delay data are 1) highly robust against ionospheric disturbances (at least two orders of magnitude less ionospheric influences, both bulk ionosphere and ionospheric scintillations, compared to L-band data) and 2) enable direct water vapour estimation due to sensitivity to water vapour absorption in addition to refraction (L-band sensitive to refraction only).

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

A further valuable contribution of GADEM to improved process modelling and understanding is its possible aid to advance K-band water vapour attenuation models. Improved water vapour attenuation coefficients are important pieces of fundamental spectroscopic information that the GADEM mission can contribute to via its limb (occultation) attenuation measurements of unprecedented accuracy near the centre and along the wing of the 22 GHz water vapour line in the K band. These GADEM data, complemented by accurate water vapour validation data (e.g., from water vapour lidar campaigns), are expected to allow the derivation of improved spectroscopic coefficients for the K band water vapour line, including improved knowledge of the coefficient’s temperature dependence.

4. GADEM Measurement Concepts and Mission Requirements

4.1 Measurement Concepts for the K-band Radio Links and Data Products

For realizing the promising scientific applications described in section 3, and for achieving the associated objectives summarized in section 2, the GADEM mission is set to exploit three measurement concepts, complementary to analogous L-band measurements,

1) Galileo-to-LEO K-band radio occultation
2) Galileo-to-Galileo K-band radio occultation
3) Galileo-to-GS K-band radio links

The first and the third measurement concept are in principle well known, and extensively demonstrated for use of L-band signals, based on the existing U.S. GPS constellation:

- GPS-to-LEO L-band radio occultation is the meanwhile almost classical “GPS occultation”, as used in missions such as GPS/MET and CHAMP mentioned in section 3. The key value-adding assets of GADEM are the use of Galileo instead of GPS and of K-band in addition to L-band, respectively.
- Likewise, GPS-to-GS L-band radio links for atmospheric delay and IWV/PW data are also meanwhile classic, as e.g. produced by the IGS for their global network. The key value-adding assets of GADEM are again the use of Galileo instead of GPS and of K-band in addition to L-band.

For the second concept, Galileo-to-Galileo inter-satellite occultation, no such direct GPS-to-GPS role model exists, since GPS satellites are not equipped with suitable L-band receivers in addition to their L-band transmitters, i.e., inter-satellite link capability is not implemented. Thus the attractive asset proposed by GADEM in this respect is a pioneering demonstration of inter-satellite radio links within a GNSS navigation satellite constellation, and in the context of the topic of this Technical Note, of the utility of derived atmospheric data products for scientific applications. The main technical challenge for this concept, for scientific applications, is to ensure sufficient signal-to-noise ratio (SNR) of received signals despite of the long Galileo-to-Galileo inter-satellite distance.

The K band frequency domain of particular interest for GADEM is the 17-23 GHz domain, covering the wing and the centre of the 22.31 GHz water vapour absorption line. The two major advantages of K band signals, in terms of the additional utility they provide relative to standard L band signals, are:

- Measurements of amplitude and phase of signals at different frequencies, at least two, within 17-23 GHz allow to separate the contribution of water vapour to the total attenuation of the signal. Based on this, they allow to independently derive temperature and humidity profile information in occultation mode, and dry and wet path delays in space-to-ground links. Figure 1 illustrates the frequency-dependent water vapour absorption along the wing of the 22 GHz line. The differential absorption between the different frequencies is exploited for extracting humidity information. GADEM baseline K-band frequencies at 17.25 GHz and 22.6 GHz are indicated in Figure 1.

- 17-23 GHz K-band signals, focusing on atmospheric applications in the troposphere and stratosphere, have two to three orders of magnitude less perturbation by ionospheric residual errors compared to 1-1.6 GHz L-band signals, since the ionospheric influences diminish (at least) with the inverse-squared frequency. This includes bulk ionosphere path delay effects, Faraday rotation effects, and scintillation effects due to small-scale ionospheric turbulence. Thus standard dual-frequency ionospheric correction for ionospheric path delay/advance will eliminate the bulk ionospheric influence down to negligible residual error and also the other effects are generally negligible at frequencies > 15 GHz, including under high-solar activity conditions.

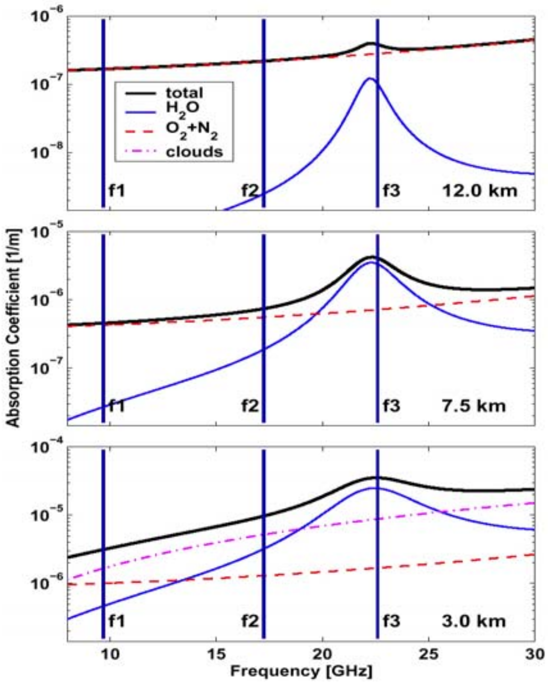

Figure 1. Absorption due to the atmosphere as function of the frequency at three different height levels (3 km, 7.5 km, 12 km) for a mid-latitude summer atmosphere. The two GADEM baseline frequencies (f2=17.25 GHz and f3=22.6 GHz) are indicated (f1 is a separate X band frequency considered previously in the framework of the ESA ACE+ mission concept studied 2002–2004). In addition to total absorption, water vapor (H_2O), bulk air (O_2), and liquid water (clouds; lowest panel) absorption are shown.
[from Kirchengast and Hoeg, 2004]

The GADEM baseline concept assumes that the (prospective future) Galileo satellites transmit, in addition to their L band signals, at least two K band signals within 17-23 GHz, for which previous experience [e.g., ACEPASS, 2005] shows 17.25 GHz and 22.6 GHz being very good selections, also compatible with WRC frequency regulations. These allow to well cover the crucial upper troposphere humidity measurement need in occultation mode (cf. section 3), besides other requirements. An optional third frequency, further enhancing the system for providing improved separation also of liquid water from water vapour, might be transmitted at about 20.2 GHz (leading to two differential transmissions in occultation mode, instead of the single 17.25-22.6 GHz differential transmission in a dual-frequency system).

The corresponding K-band receivers on complementary LEO satellites (Galileo-LEO concept), other Galileo satellites (Galileo-Galileo concept), and at ground stations (Galileo-GS concept) are assumed capable of precisely tracking the defined K band signals and of precisely measuring their amplitudes and phases, similarly to high-quality GPS L-band receivers but with more emphasis on accurate amplitude measurements.

The raw data products and derived atmospheric data products expected from the GADEM measurements are summarized in Table 1 for the occultation concepts and in Table 2 for the

Galileo-to-GS links, respectively. In both cases, the L-band data products are also shown for reference to highlight the added-value of the K-band data. The data products are categorized, following the CEOS (Committee on Earth Observation Satellites; www.ceos.org) definitions, into Levels 0 to 2. (Level 3 products, i.e., value-added products such as derived two- or three-dimensional temperature or water vapour fields, are not included here).

Table 1. GADEM Data Products – Occultation Measurements

Level	Key data and products	
	Galileo-LEO/Galileo-Galileo K-band data	Galileo-LEO L-band data (for reference)
Level 0	K-band data: carrier phases and amplitudes at 2-3 frequencies (baseline: 17.25 GHz and 22.6 GHz, optional 3^{rd} frequency 20.2 GHz) K-band transmitter data: corresponding amplitudes at the freq. (TBC; for gain correction, if needed)	L-band data: L1 and L2 carrier and code phase; L1 and L2 signal amplitudes; L1 raw samples and auxiliary information to estimate signal carrier phase and amplitude
	• Galileo and LEO ephemeris data • Galileo and LEO health data (incl. from ground control) • Ground fiducial station Galileo (and LEO) tracking data • Earth orientation data • LEO instrument housekeeping data • LEO attitude/pointing data	
Level 1a	• Determined LEO ephemeris data (precise orbits) • Extracted LEO clocks (precise clocks) • Determined Galileo ephemeris data (precise orbits) • Extracted Galileo clocks (precise clocks) • Residual phase observations (at all frequencies) • Amplitude observations (at all frequencies) (all profiles as function of time)	
Level 1b	• Doppler shift and Raw **Transmission** [(1)] profiles (at 2-3 frequencies) vs. time • Transmission profiles (at 2-3 frequencies) vs. impact parameter • **Bending angle** [(1)] profiles vs. impact parameter	• Doppler shift and Raw **Transmission** [(1)] profiles (at L1 and L2) vs. time • **Bending angle** [(1)] profiles vs. impact parameter
Level 2	• Real Refractivity profiles vs. height • Imaginary Refractivity profiles (at 2-3 frequencies) vs. height	• Real Refractivity profiles vs. height
	• **Humidity** [(2)] profiles vs. altitude • **Temperature** [(2)] profiles vs. altitude • Pressure and Geopotential Height profiles vs. altitude Error estimates and meta-data for all retrieved level 1b & level 2 profiles	
	• Tropospheric turbulence parameters • Cloud Liquid Water profiles[(3)]	• Ionospheric profiles of diverse parameters (electron density etc.)

[(1)] driving parameter for main system requirements. The "Raw Transmission" is the normalized received power ($Tr = I/I_0$) including defocusing and absorption, whilst the "Transmission" is understood to include absorption only (*Transmission* = 1 – *Absorption*).
[(2)] driving parameter for observational requirements. Humidity and temperature can also be determined in presence of clouds (temperature in severe scintillation/cloudiness conditions by extrapolating from above cloud top into clouds).
[(3)] cloud liquid water profiles are a non-committal by-product.

The data product structure in Table 1 reflects the present – at the time of start of the GADEM study – definition of occultation data products. The structure will be updated as needed based on the results of the GADEM study work.

Table 2. GADEM Data Products – Galileo-to-GS Measurements

<table>
<tr><th rowspan="2">Level</th><th colspan="2">Key data and products</th></tr>
<tr><th>Galileo-to-GS K-band data</th><th>Galileo-to-GS L-band data (for ref.)</th></tr>
<tr><td rowspan="2">Level 0</td><td>K-band data: carrier phases and amplitudes at 2-3 frequencies (baseline: 17.25 GHz and 22.6 GHz, optional 3rd frequency 20.2 GHz); for all Galileo satellites visible from given GS sites</td><td>L-band data: L1 and L2 carrier phase and signal amplitudes; for all Galileo satellites visible from given GS sites</td></tr>
<tr><td colspan="2">• Galileo ephemeris data and GS positioning data
• Galileo and GS health data
• Earth orientation data (reference frame)
• GS auxiliary data for all GS sites (e.g., local pressure, temperature)</td></tr>
<tr><td>Level 1a</td><td colspan="2">• Determined Galileo ephemeris data (precise orbits)
• Determined GS positioning data (precise positions)
• Residual phase observations (at all frequencies) for each tracked Galileo-GS link
• Amplitude observations (at all frequencies) for each tracked Galileo-GS link
(all variables as function of time)</td></tr>
<tr><td>Level 1b</td><td>• Derived total atmospheric delay[1] vs. time
• Derived atmospheric attenuation[1] vs. time
• Derived dry atmospheric delay vs. time
• Derived wet atmospheric delay vs. time
(all time series for each tracked Galileo-GS link)</td><td>• Derived total atmospheric delay[1] vs. time for each tracked Galileo-GS link</td></tr>
<tr><td rowspan="3">Level 2</td><td>• Slant Integrated Water Vapour (sIWV[1,2]) vs. time
(time series for all Galileo-GS links per GS site)</td><td>• sIWV[1] vs. time; requires a priori information for dry delay to determine wet delay from total delay</td></tr>
<tr><td colspan="2">• Vertical Integrated Water Vapour (IWV) vs. time (over each GS site)
• Precipitable Water (PW[2]) vs. time (over each GS site)
Error estimates and meta-data for all determined level 1b & level 2 time series</td></tr>
<tr><td>• Liquid water content (LWC) vs. time[3]
• Real-time tropospheric (water vapour) error estimation/correction for navigation users</td><td>• Total Electron Content (TEC) vs. time (ionosphere)</td></tr>
</table>

[1] driving parameter for main system requirements.
[2] driving parameter for observational requirements. sIWV and PW are also determined in presence of clouds.
[3] liquid water content time series are a non-committal by-product.

The Galileo-to-GS K band data products shown in Table 2 evidently complement analogous data products retrieved from the standard L-band frequencies, but the latter are obtained with less accuracy and invoking a range of (empirical) model assumptions. Also in Table 2 the data product structure reflects the present – at the time of start of the GADEM study – definition of Galileo-to-GS data products, which will be updated as needed based on the GADEM results.

4.2 Scientific Observational Requirements for the GADEM Data Products

In terms of deriving concrete mission requirements — scientific *observational requirements* for the atmospheric data products and, derived from the observational requirements, *system requirements* for the technical implementation of the mission (following subsection) — the heritage from the demonstrated L-band systems is of great value. This heritage and experience constitutes a solid basis for formulating the appropriate requirements needed for realizing the GADEM scientific applications and for achieving its scientific objectives.

This subsection and the following subsection 4.3 provide, based on the GPS L-band related heritage and on further heritage from preparatory activities for a LEO-to-LEO K-band occultation mission in the ESA context in the years 2002–2004 [ACE+ mission concept; Kirchengast and Hoeg, 2004; ESA, 2004a and 2004b], preliminary requirements for the GADEM mission. These requirements are for designing the GADEM K-band radio links. It is understood that, as the basic system, at least two L-band signals (L1 and L2 frequencies near 1.2 and 1.6 GHz) would be available in any case.

The observational requirements for occultation measurements, formulated in terms of the scientific key variables humidity and temperature, are summarized in Table 3 below. Likewise, the observational requirements for Galileo-to-GS measurements, specified in terms of the scientific key variables slant IWV and PW, are summarized in Table 4.

The formulated requirements are consistent with the needs of the scientific applications discussed in section 3. If these requirements for humidity, temperature, slant IWV, and PW are fulfilled, all other data products of interest will be of adequate quality as well, due to their association with humidity, temperature, slant IWV and PW data quality. The requirements reflect the present – at the time of start of the GADEM study – understanding of observational requirements. Thus Tables 3 and 4 may be updated as found needed in course of the GADEM study work.

Table 3. GADEM Observational Requirements – Occultation Measurements

		specific humidity		temperature	
		target	threshold	target	threshold
horizontal domain		global			
horizontal sampling, *to be achieved within:*		1000 km	2000 km	1000 km	2000 km
time sampling		24 hrs			
No. of profiles per grid box[1] per month		40	30	40	30
vertical domain[2]		TBL[3] +3 km to 15 km	6 to 12 km	TBL[3] +3 km to 50 km	6 to 40 km
vertical sampling	LT HT LS HS	0.5 km 0.5 km – –	1 km 1 km – –	0.5 km 0.5 km 0.5 km 1 km	1 km 1 km 1 km 5 km
RMS accuracy[4]	LT -*TBL* LT -*top* HT -*top* LS HS	0.6 g/kg 0.2 g/kg 0.003 g/kg – –	1 g/kg 0.4 g/kg 0.025 g/kg – –	1 K 1 K 0.5 K 0.5 K 1.5 K	2 K 2 K 1 K 1 K 3 K
long-term stability		2% RH[5] per decade	3% RH[5] per decade	0.1 K per decade	0.15 K per decade
timeliness	climate NWP[6]	30 days 1.5 hrs	60 days 3 hrs	30 days 1.5 hrs	60 days 3 hrs
time domain[7]		> 2 years			

[1] Grid box defined as square of horizontal sampling (=mean distance of adjacent profiles) requirement (box of size 'horiz. sampling' [km] x 'horiz. sampling' [km]).
[2] Below about 3 km (typical atmospheric conditions) to 6 km (severe scintillation/cloudiness conditions), retrievals may involve weak prior temperature information (e.g., extrapolation from above the top height of such conditions into the lower troposphere) to separately derive humidity and temperature from refractivity/absorption; above, humidity, temperature, and pressure shall be derived as function of height without such prior information.

(3) Top of atmospheric boundary layer, located typically 1-2.5 km above the surface. For the purpose of this specification, TBL = 2 km shall be understood. Below TBL + 3 km (=5 km), retrievals shall be performed on a best-effort basis.
(4) Understood to be the accuracy at a vertical resolution consistent with the required sampling (i.e., a resolution of 2 x Vertical Sampling [km]). The humidity accuracy requirement shall be understood to decrease linearly between the specified values at LT-*TBL*=2km and LT-*top*=5km and to decrease logarithmically, as ln(humidity), from *LT-top*=5km until it reaches the specified HT-*top* value at 10 km; above, the height dependence shall be constant. The temperature accuracy requirement shall be understood constant between the specified values at LT-*TBL*=2km and LT-*top*=5km and to decrease linearly from *LT-top*=5km until it reaches the HT-*top* value at 10 km; above, the height dependence shall be constant. As noted above, occultation data shall aim to fulfil the requirements below TBL + 3 km (i.e., below LT-*top*=5km) on a best-effort basis.
(5) Stability is specified for Relative Humidity (RH) here, a quantity with well-defined and linear range over the vertical domain. There are standard formulae to convert between RH and specific humidity as functions of temperature and pressure.
(6) NWP is a main mission objective, so the timeliness requirement is important. Also, often NWP analyses are used for the forcing of climate GCM runs. Therefore, the climate mission objectives will benefit as well from the fulfilment of the NWP timeliness requirement.
(7) Climate monitoring and research prefers long-term observations many years and decades. GADEM observations should thus be followed by similar missions. The GADEM demonstration mission objectives, however, can be fulfilled within the given minimum time frame (2 years or more).

Table 4. GADEM Observational Requirements – Galileo-to-GS Measurements

		slant IWV		PW	
		target	threshold	target	threshold
horizontal domain		global			
horiz. sampling/GS sites[1]		globally distributed GS sites; demonstration with at least six sites			
time sampling[2]		5 min	15 min	5 min	15 min
RMS accuracy[3]		5%	10%	5%	10%
long-term stability (of *vertical* IWV / PW)		2% per decade	3% per decade	2% per decade	3% per decade
timeliness	climate	30 days	60 days	30 days	60 days
	NWP[4]	1.5 hrs	3 hrs	1.5 hrs	3 hrs
time domain[5]		> 2 years			

(1) all requirements following this horizontal sampling requirement in the list shall be understood site-specific, i.e., they shall be fulfilled at each individual GS site included as official GADEM GS site.
(2) Sampling period (interval between consecutive independent observations) of all data product time series.
(3) The percentage root-mean-square accuracy of derived sIVW and PW data, for 5-min time sampling.
(4) NWP is a main mission objective, so the timeliness requirement is important. Also, often NWP analyses are used for the forcing of climate GCM runs. Therefore, the climate mission objectives will benefit as well from the fulfilment of the NWP timeliness requirement. Also non-scientific users, such as navigation users, will benefit, e.g., for rapid-update tropospheric error modelling/corrections in their positioning/time applications.
(5) Climate monitoring and research prefers long-term observations many years and decades. GADEM observations should thus be followed by similar missions. The GADEM demonstration mission objectives, however, can be fulfilled within the given minimum time frame (2 years or more).

4.3 GADEM System Requirements derived from the Observational Requirements

Table 5 below summarizes the main GADEM system requirements for the K-band measurement concepts, showing for convenience as a reference the corresponding requirements for implementing a well-performing L-band occultation system.

The requirements given reflect the present – at the time of start of the GADEM study – understanding of the main system requirements as they are derived from and consistent with the observational requirements in subsection 4.2 above. These current specifications are preliminary (their main heritage is ESA ACE+ mission concept work in 2002–2004) and expected to be updated based on the results of the dedicated Signal Characteristics and Performance Analysis study carried out under WP2100 as well as based on the results of the requirements definition of WP2000 in general.

Table 5. Main GADEM System Requirements

		Galileo–LEO/Galileo-Galileo and Galileo-GS K-band data	**Galileo–LEO and Galileo-GS L-band data (for reference)**
Horizontal Domain		Global	
Horizontal Distribution		*Occultations:* Homogeneously distributed events globally, per day & month *Galileo-to-GS:* Homogeneously in the GS site regions; use globally distributed GS sites; use > 6 GS sites for a demonstration mission	
Number of Profiles (*Occultations*) / GS time samples (*Galileo-GS*) per Day		> 200 (1)	*Occultations:* > 500 (1) *Galileo-GS:* > 100
***Occultations:* Vertical Domain**		2–80 km for Bending angle, 2–50 km for Transmission (2)	1–80 km (3) for Bending angle and Transmission
***Occultations:* Vertical Sampling Rate**		1 kHz	100 Hz (z < 8 km) 50 Hz (z > 8 km)
Time Domain		> 2 years	
Time Sampling (UT)		*Occultations:* < 24 hrs *Galileo-GS:* < 5 min	*Occultations:* < 12 hrs *Galileo-GS:* < 15 min
Local Time Sampling		All local times within as small as possible time (UT) period or, for *Occultations*, sampling near fixed local time (sun-synchronous) (4)	
***Occ:* Bending angle RMS Accuracy(5)**		Max{1 μrad , 0.4%}	
***Occ:* Transmission *Tr* RMS Accuracy(6)**		Consistent with C/N_0 = 66 dBHz at z=25km	7.5% (Tr_{min}=0.02) (7)
***Occ:* Transmission Vertical Stability**	**Linear drift** **Higher order**	< 0.5% over 20 sec (z_m=25km) (8) < (0.02%/sec)·T (for T=1–20sec) (9)	< 10% over 30 sec (z_m=10km) (8) –
***Galileo-GS:* Total atm. Delay (TD), atm. Attenuation (A), diff. atm. Transmission (d*Tr*), sIWV RMS Accuracy(10)**		< 5 mm (TD), C/N_0 = 50 dBHz (A) (11), < 0.02 dB/min (d*Tr*)(12), < 5% (sIWV)	< 5 mm (TD), < 20% (sIWV)
Timeliness	**Climate** **NWP**	< 30 days < 1.5–3 hrs	

(1) for demonstration of a novel system such as the K-band system, experience from GPS-LEO demonstrations (e.g., CHAMP) shows that > 200 profiles per day is sufficient, but shall include setting and rising events; regarding the Galileo-LEO concept, a single LEO satellite will lead to > 500 profiles per day (> 250 each set and rise).
(2) transmission profiles required at 2-3 frequencies within 17 to 23 GHz (recommended from ACE+ mission concept studies experience: 17.25 GHz and 22.6 GHz; optional 3rd frequency 20.2 GHz).
(3) up through the ionosphere towards LEO orbit height on a best-effort basis, for ionospheric occultations.
(4) if fixed local time, the equatorial nodes of orbits may benefit from co-location with EPS/Metop orbit nodes.
(5) understood to be the accuracy at a vertical resolution of Max{ 1 km , Fresnel zone diameter }; < 1 μrad RMS for bending angle corresponds to < 2 mm RMS for phase delay; also corresponds to < 2 mm/30 sec phase drift.
(6) understood to be the accuracy at 1 Hz observation bandwidth.
(7) applicable to $Tr_{min} < Tr < 1$, computation of reference intensity (I_0 in $Tr = I/I_0$) at z = 25 km.
(8) assumed relative to the time corresponding to $z = z_m$ tangent height, for times scanning $z < z_m$ km.
(9) max. amplitude of any wave in *Tr* of period T in the specified T-interval, for all times at z < 25 km.
(10) understood to be the accuracy at 5-min time sampling of the TD, A, dA, and sIWV time series.
(11) understood to be the C/N_0 figure for vertical links, required for adequate attenuation measurement accuracy; for 15°-elevation links the C/N_0 figure is ~2.5 dBHz smaller.
(12) max. differential transmission drift of the differential transmission profile from any 2 K-band frequencies.

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