

GRAS – Metop’s GPS-Based Atmospheric Sounder

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Introduction

Occultation methods based on effects connected with the refraction of electromagnetic waves in both the optical and radio-frequency domains have been used by astronomers for numerous investigations of planetary atmospheres over the last decades. The first experiment started with the Mars flyby by Mariner-IV in 1964. Since this first attempt, radio-occultation experiments have been carried by the majority of planetary missions.

GRAS is an atmospheric-sounding instrument that forms part of the payload of the Metop series of meteorological satellites. The three Metop satellites form part of the Eumetsat Polar System (EPS), whose primary mission objectives are operational meteorology and climate monitoring. GRAS measurements will provide atmospheric temperature and humidity profiles, which are intended to be assimilated into Numerical Weather Prediction (NWP) models. Possible future developments involving a fleet of GPS receivers could allow temperature and water-vapour profiles of the atmosphere to be recorded with unprecedented vertical resolution and measurement accuracy for tomorrow’s climate models.

The Global Navigation Satellite Systems Radio Occultation Receiver for Atmospheric Sounding, known as GRAS, will use the radio-frequency signals generated by the constellation of satellites of the Global Positioning System (GPS). The validity of this concept was first proven with the launch and successful operation of the GPS/MET experiment by Jet Propulsion Laboratory in 1995. Since then, several missions with onboard radio-occultation GPS receivers have been put into development, including Ørsted, Champ, SAC-C, and Grace. Ørsted was launched in 1999, and Champ is planned to be launched this year. Both missions are precursors, and will pave the way of GRAS to deliver an operational product continuously over 14 years.

Measurement principle

The GPS constellation consists of 24 satellites distributed in six orbital planes around the globe. Each satellite orbit is circular with an inclination of 55 deg, a period of 12 h and an altitude of 20 200 km. A schematic of atmospheric profiling by GPS radio occultation is shown in Figure 1. For the receiver, an occultation occurs whenever a GPS satellite rises or sets and the ray path from its transmitter traverses the Earth’s atmospheric limb. With 24 GPS satellites, a single GPS receiver in a near polar orbit at 824 km will observe over 500 occultations per day, distributed fairly uniformly about the globe (Fig. 2).

The fundamental measurement in the GPS limb-sounding technique is the phase delay resulting from transmission of the GPS signal through the atmosphere. Total atmospheric delay is a function of two factors: ray bending due to refraction, and reduced propagation velocity in the atmosphere. The radio signal propagating from the GPS transmitter to the low-Earth-orbiting receiver follows a path through the atmosphere that curves in response to atmospheric refractive-index gradients.

The cumulative effect of the atmosphere on the ray path can be expressed in terms of the total refractive bending angle α , which has a known relationship to the atmospheric Doppler shift. For the Earth’s atmosphere, the maximum bending angle is in the order of 36 mrad (2 deg) at the Earth’s surface, while at 30 km altitude its magnitude reduces to 0.3 mrad.

The atmospheric Doppler shift, in turn, is determined by taking the time derivative of the observed phase. The variation of α with

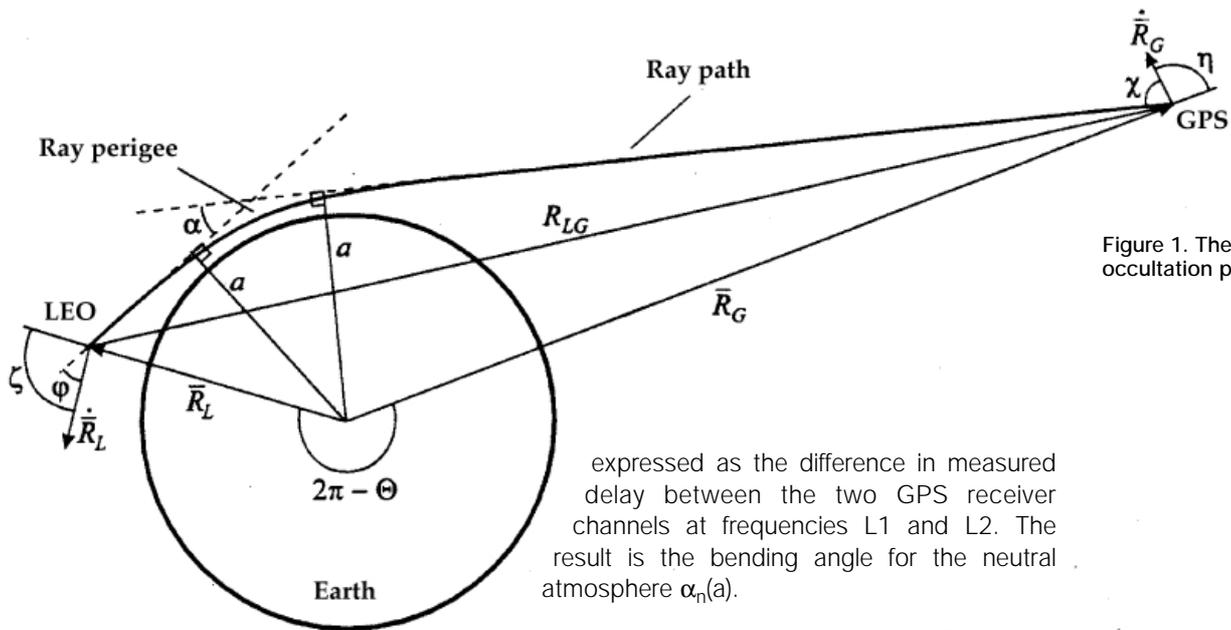


Figure 1. The radio-occultation principle

expressed as the difference in measured delay between the two GPS receiver channels at frequencies L1 and L2. The result is the bending angle for the neutral atmosphere $\alpha_n(a)$.

experiment geometry can be characterised through the use of an impact parameter (a) defined as the perpendicular distance between the centre of the Earth and the straight line followed by the ray approaching the atmosphere. When combined with precise knowledge of the geometry (obtained concurrently from the navigation channels of the GPS receiver), each phase-data sample can be converted to the corresponding values for α and (a).

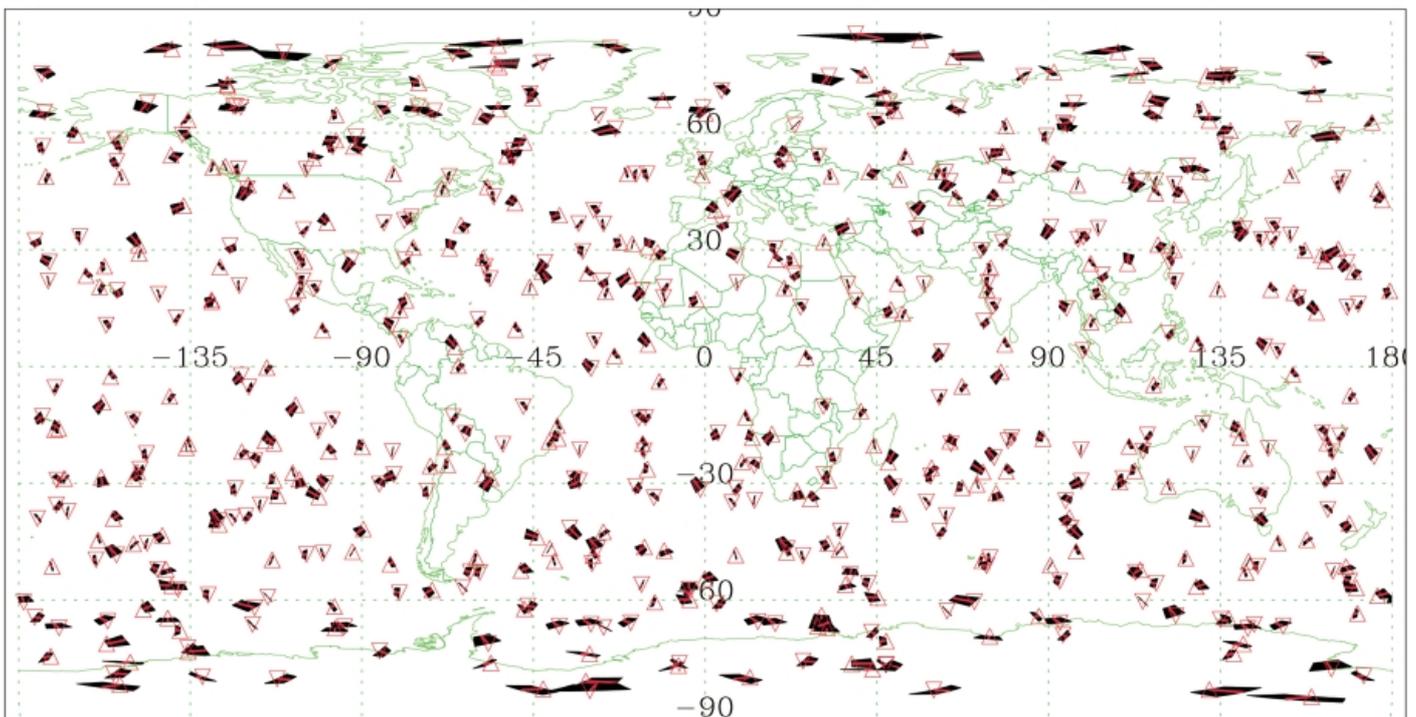
For an atmosphere with local spherical symmetry (i.e. no significant asymmetric horizontal variations in temperature or moisture) and having determined the bending angle $\alpha_n(a)$ as described above, there is a unique relationship between $\alpha_n(a)$ and $\mu(r)$, the atmospheric refractive index as a function of radius r . The refractive index profile $\mu(r)$ is then derived through an Abel transform of the measurements of $\alpha_n(a)$ obtained over a complete occultation.

To extract information on the neutral atmosphere, propagation delays caused by the ionosphere must be isolated and removed from the signal. The correction required can be

For dry air at the top and above the troposphere, the refraction index can be expressed as a function of temperature and pressure as:

$$N(r) = [\mu(r) - 1] 10^6 = 77.6 P/T$$

Figure 2. Example of occultations seen by GRAS over a one-day period



Using the equation of state and integrating the equation of hydrostatic equilibrium, the temperature and pressure of the atmosphere for a given altitude can be determined.

Below the tropopause, the procedure described above needs to be modified to account for the presence of water vapour. The index of refraction can be expressed with two terms, the dry and wet terms. The second term, due to water vapour, exhibits considerable variations with location and time and increases considerably close to the Earth's surface.

Figure 3. The GRAS instrument elements on the Metop satellite

The individual contributions to $\mu(r)$ of the dry and wet terms cannot be distinguished uniquely through occultation measurements. Deeper in the troposphere, water-vapour concentrations increase, contributing to 30% of the total refractivity. A planned technique for recovery of the water vapour from measurements of $\mu(r)$ is to use existing temperature analyses from meteorological offices. The accuracy to which lower tropospheric water-vapour profiles can be retrieved has been estimated by Kursinsky et al. at about 20%.

Instrument design

GRAS is a bi-frequency GPS receiver with codeless-mode operating capabilities. A dual-frequency operating instrument is needed for ionospheric correction. The codeless capability is mandatory in order to mitigate the anti-spoofing (encryption of the precise code), which prevents civilian users from benefitting from the P-code on the L2 frequency. The signals of the occulting satellites are received through two

antennas, one dedicated to the rising and one to the setting occultations. Shaped antenna patterns (10 to 12 dB gain) and dedicated radio-frequency front-ends ensure a high sensitivity and the ability to measure at low altitudes in the atmosphere – just a few kilometres – where the atmospheric attenuation due to absorption and diffraction is high.

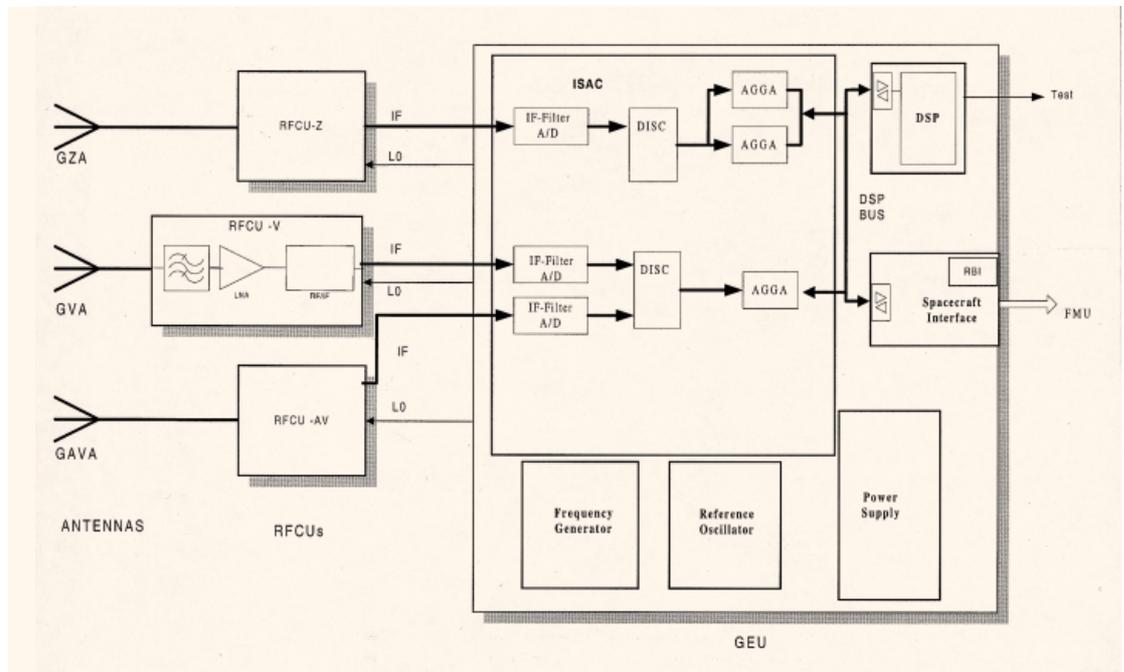
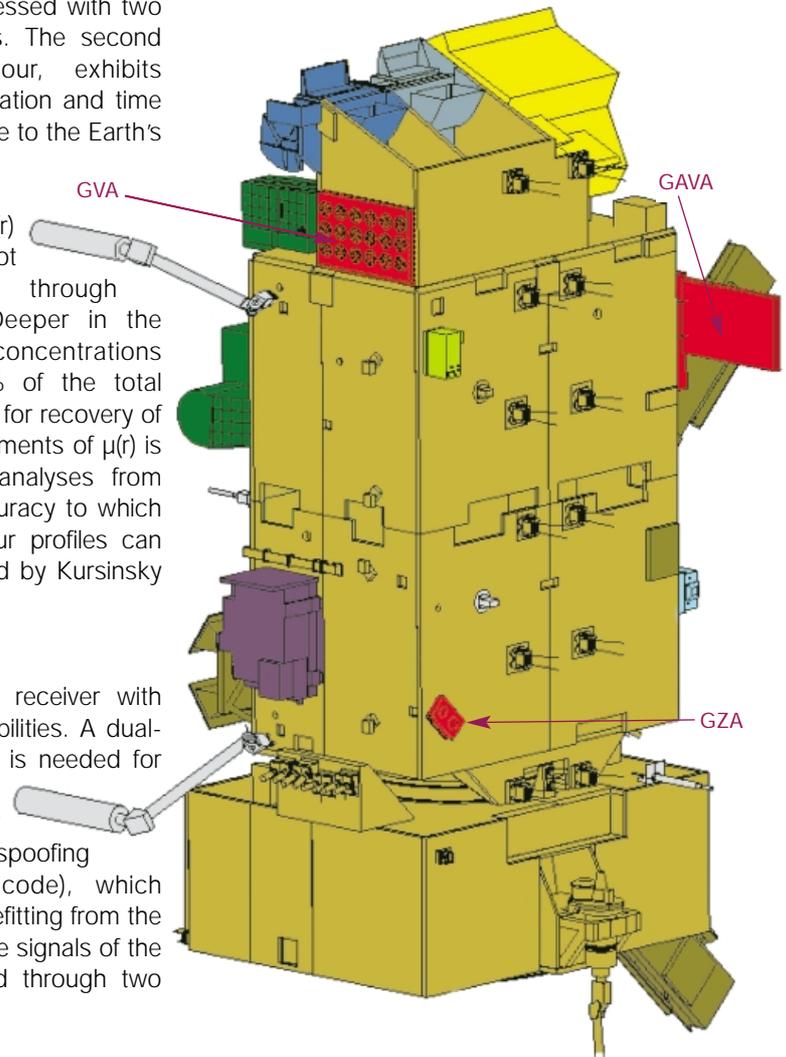


Figure 4. Functional block diagram of GRAS



Figure 5. GRAS's GZA (top) and GVA/GAVA (bottom) antennas



To track the Metop satellite's position, the instrument also operates as a navigation receiver. In this context, it receives GPS signals via a third antenna with hemispherical coverage, pointing at zenith. It acquires and tracks a set of GPS signals through eight bi-frequency channels having codeless capabilities, and uses a limited-precision navigation solution to support the autonomous instrument operation. It also provides the positional data as part of its measurement data to the Payload Module to be transmitted to the ground segment. Within the ground segment, the data are then used to compute the precise orbit of the spacecraft.

The GRAS antennas accommodated on the Metop spacecraft are shown in Figure 3.

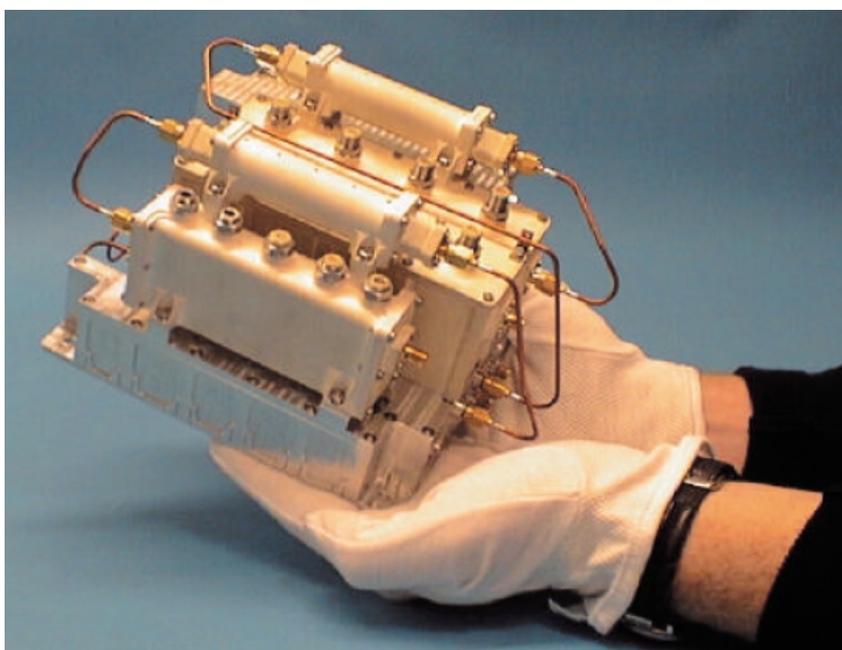
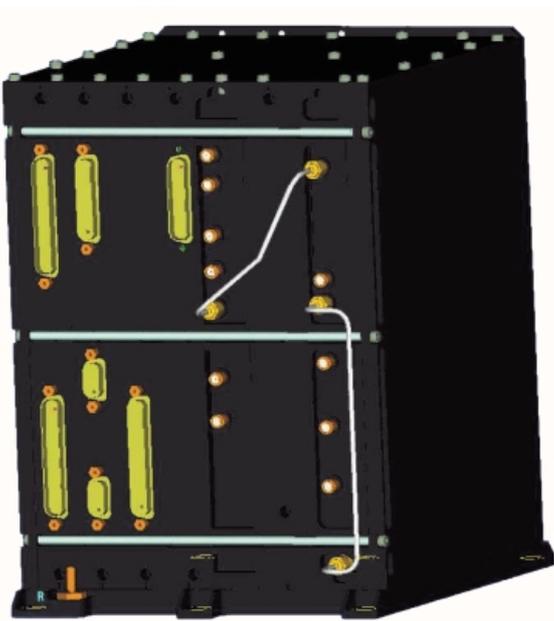


Figure 6. The Radio-Frequency Conditioning Unit (RFCU)



The GRAS instrument (Fig. 4) consists of :

- 3 antennas
- 3 RF Conditioning Units (RFCUs)
- 1 GRAS Electronics Unit (GEU).

The three antennas point in the satellite's velocity, anti-velocity and zenith directions. The velocity and anti-velocity antennas are phased arrays, each containing 18 patches with a shaped antenna pattern optimised for the occultation of the Earth's limb and its atmosphere (Fig. 5).

The RFCU (Fig. 6) consists of two bandpass filters, a low-noise amplifier and a single down-converter stage. The RFC units are accommodated within the Payload Module close to their respective antennas in order to minimise ohmic losses.

Figure 7. The GRAS Electronics Unit (GEU)

The GEU (Fig. 7) is built around three dedicated Advanced GPS GLONASS ASICs (AGGA) and a Digital Signal Processor (DSP). After filtering and a single-stage down-conversion in the RFCU, the signals are digitally down-converted with an 8-bit ADC, and filtered in a DISC ASIC, then sampled at a high rate (141.25 MHz) and delivered to the channel processor. The core of the processor is the AGGA, which simultaneously performs the final down-conversion, de-spreading and correlation of four bi-frequency GNSS channels. It also provides the codeless functionality. It is being developed by ESA and contains functionality for tracking the phase and frequency of code and carrier. The AGGA ASIC provides a number of observables to the DSP, which the latter uses to close the tracking loops and to produce the actual measurement data.

atmospheric measurements with a high accuracy in the stratosphere. The frequency generator provides the necessary frequencies for down-conversion and clock-signal generation using the reference oscillator. The power supply converts primary power to secondary power for the instrument units.

The mass budget for the whole GRAS instrument is around 30 kg, including the harness and deployment mechanism for the anti-velocity antenna. The power consumption in full operation (navigation and occultation signals) is 38 W. The average GRAS data rate is 22 kbit/s, with peaks of up to 60 kbit/s.

Instrument performance

The GRAS instrument's performance requirements are driven by the meteorological community. Near-real-time weather forecasting calls for an accuracy of 1 K in the temperature profile. This is equivalent to an error budget on the bending angle and the atmospheric Doppler of 1.2 μ rad and 3.8 mm/s at 30 km altitude. Two inversion techniques have been used, the geometrical-optics approximation and the back-propagation method. With the former, the signal path is treated as a single ray that curves in accordance with Snell's law. The vertical resolution is then limited by the first Fresnel zone, which is of the order of 1.5 km in the stratosphere and reduces to 300 m in the lower troposphere. The geometrical-optics approximation does not resolve the atmospheric multipath, but the latter is important in the troposphere due to the large gradient in the refractive index (water vapour), which will cause significant error on the sounding profile and will disturb the receiver, even to the point of loss of tracking.

Moreover, as the temperature gradient in the troposphere is of the order of 7.5 K/km, the temperature accuracy requirement cannot be met. By using more advanced techniques that take into account the wave nature of the radio signal, such as the back-propagation inversion method based on Helmholtz equations, the multipath propagation can be resolved and the vertical accuracy improved by a factor 2 to 5 up to 100 m.

The best results in terms of temperature-profile errors are obtained between 5 to 30 km altitude. Below this range, the attenuation due to the water-vapour content of the troposphere penalises the instrument's signal-to noise ratio, while above it residual correction errors due to the ionosphere become predominant.

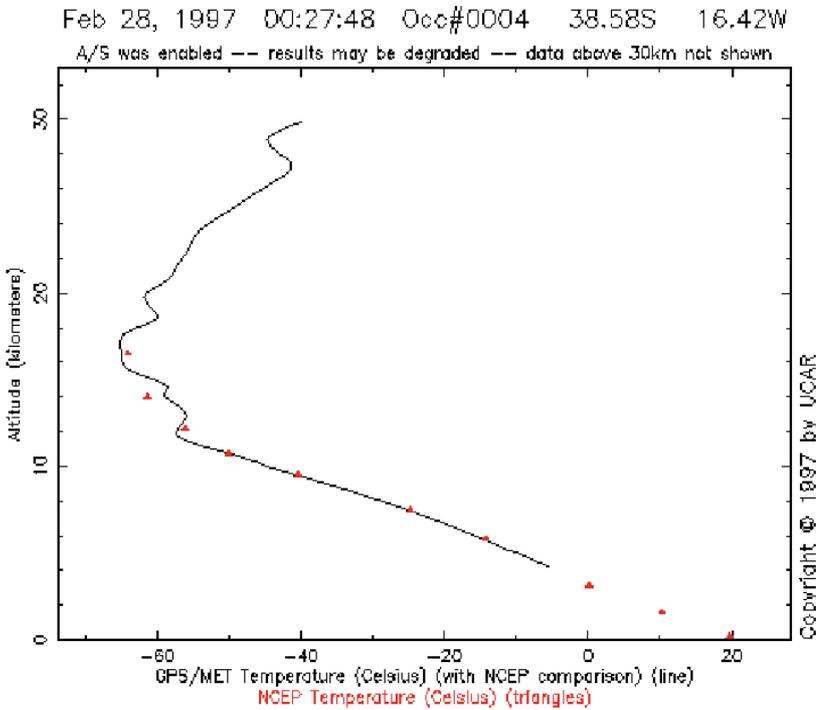


Figure 8. GPS/MET temperature soundings (courtesy of UCAR)

The DSP chip itself (TSC 21020E) has been developed by European space industry under an ESA contract. Its role within the GRAS instrument is to support the Instrument Control Unit software as well as the data-processing software (measurement, signal tracking, navigation solution and time management). The Spacecraft Interface (SCIF) board provides the interface between the DSP bus, the satellite OBDH bus and the Formatting and Multiplexing Unit (FMU) of the Payload Module.

An oven-controlled crystal oscillator is used as a reference oscillator with very stable frequency (Allan variance of 10^{-12}) in order to retrieve

The horizontal resolution of the radio-occultation technique is limited by the limb-sounding approach itself, and is of the order of 100 km in the troposphere and 300 km in the stratosphere.

A GPS/MET temperature sounding is plotted in Figure 8. The temperature profile retrieved with the geometrical-optics approximation technique is in good agreement with the radiosonde profiles provided by the NCEP and within 1 K from 16 to 5 km altitude, where the receiver stops tracking the signal. GRAS should provide better performances both in the high stratosphere and in the low troposphere, since the antenna gain of the occultation channels has been set at over 10 dB, while for GPS/MET it was only 3 dB.

Accurate retrieval of atmosphere parameters requires the implementation of several corrections. First of all, the positions and velocities of the GPS and Metop satellites have to be determined with accuracies of 1 m and 0.1 mm/s, respectively. This will be done using the navigation signals delivered by the instrument. In addition, a clock error correction needs to be implemented in order to correct for the dithering of the GPS clock, called selective availability (SA), and the long-term drift of the crystal clock onboard the GRAS receiver. For this correction, a double differential technique will be implemented using a network of 12 to 30 tracking ground stations. ESA already controls six tracking ground stations equipped with GPS receivers as part of the International GPS Service for Geodynamics (IGS) network. The occultation data will also need a clock correction to mitigate the GPS clock dithering signals (SA). This will be done using a single-differential technique, which is preferable to a double-differential approach if GRAS's master oscillator is stable over 100 sec. It will also be better in terms of its effect on the variance of the signal by root square of two, whilst the GPS

satellite clock bias and drift errors will also be cancelled.

The effect of the ionosphere can be seen as an extra signal path length of the order of 50 to 80 m, depending on the frequency, solar activity and diurnal cycle. A fine correction will be achieved in the classical way using the bi-frequency capability of the receiver. Unfortunately, the codeless mode, which is less sensitive than a single channel, will lose track at an altitude of around 10 km, leaving the receiver to operate with only one frequency. At this altitude, the extra path length due to the atmosphere is already of the order of 130 m, and a less accurate ionospheric correction is good enough. This correction will be performed by extrapolation of the ionospheric data (Total Electron Content, TEC) measured during the sounding of the stratosphere. Multipath due to appendages on the Metop spacecraft has been minimised. GRAS antenna accommodation has been carefully optimised, but a residual effect will remain which will be part of the total bending-angle error budget.

The processing of the occultation and the navigation data, as well as the data from the fiducial ground station, will be performed in the Level-1b ground processor. A Ground Processor Prototype (GPP) is being developed to validate the Level-1b algorithms, and to verify the end-to-end performance of the data chain. An extensive pre-launch characterisation of the instrument is planned to fully characterise its transfer function. After launch and during the satellite commissioning phase, the instrument performances will be verified and validated.

The near-real-time products

The GRAS Level-1 products (Table 1) are processed in the Eumetsat Polar System (EPS) Core Ground Segment (CGS) located at Eumetsat in Darmstadt, Germany. Level-1b products from the EPS GRAS mission will be

Table 1. GRAS Level-1 and Level-2 products

Level 1 products

- Residual phase data
- Sounding occultation table
- Navigation data
- Total bending angle as a function of the impact parameter at L1 and L2
- Ionospheric corrected total bending angle (first-order correction)
- TEC
- Auxiliary data
- Earth orientation parameters
- Observation error characteristics

Level 2 products

- Refractivity profiles
- Temperatures profiles
- Moisture profiles
- Pressure profiles
- Integrated precipitable water vapour
- Temperature and humidity retrieval parameters
- Observation error characteristics
- TEC

disseminated to the operational users of meteorological data within 2 h 15 min of the observation. All GRAS Level-1 products are to be archived and will be available to users via the Unified Meteorological Archive and Retrieval Facility (UMARF) from the EPS CGS.

Applications

Numerical Weather Prediction

Assimilation of GRAS observations into NWP models is the most important operational application for the data produced by the instrument. GRAS observations combine high vertical resolution and high absolute accuracy with global coverage and good long-term stability. These features complement the existing and planned meteorological observation systems very well.

The trend in Numerical Weather Prediction is towards using variational assimilation. This technique suits GRAS observations very well as it enables the assimilation of observation quantities that are not model variables. For GRAS data, this means that the observations can be assimilated either as Level-1 or as Level-2 products, providing an opportunity to optimise the system performance in terms of both complexity and accuracy. However, assimilation of the GRAS data into NWP models requires a deep understanding and good characterisation of the observation errors.

Because of the low horizontal resolution, GRAS observations can be expected to be most valuable in global forecasting over the short-to-medium range (1–10 days). They should also have a positive impact on regional and mesoscale forecasting by providing information over the sparsely observed ocean areas. Also, the boundary conditions from the global models to the regional and mesoscale models will be more accurate due to the impact of GRAS data on the global models.

Climate monitoring

The basis for climate monitoring is databases populated with accurate global measurements of the atmospheric characteristics over a long period of time. The 14-year EPS GRAS mission is a very good starting point for building up an archive of radio-occultation data. The long-term stability and self-calibration features of the GRAS instrument support the objectives of climate-monitoring applications.

Unfortunately, the climate-monitoring requirements are very demanding in terms of temperature resolution (0.1 K), which is one order of magnitude better than currently requested for NRT weather predictions. Recent studies have demonstrated that a constellation

of six satellites with GPS/GLONASS receivers, or 12 satellites with GPS only, is the minimum necessary in order to attain the objectives set by the climate community. GRAS on Metop might therefore be considered a first step, but many companion GPS receivers are needed in orbit in order to match the climate needs.

Other applications

Study of the heat exchange between the stratosphere and troposphere requires accurate measurements of the temperature profile across the tropopause. This phenomenon takes place at tropical latitudes and in regions where the sparse radiosonde network cannot provide enough data for the verification of theories and models. The very good temperature-measurement accuracy provided by GRAS at the locations where no permanent radiosonde or lidar measurement network exists will enable the verification and further study of many atmospheric theories and models.

Conclusions

The GRAS instrument on Metop, as part of the EPS system, will provide an unrivalled set of high-quality atmospheric sounding data with a vertical accuracy ranging from 1 km down to 100 m at low altitude. In addition, GRAS provides a unique opportunity to establish the height of the tropopause with a vertical accuracy of better than 1 km.

The GRAS instrument capitalises on the experience gained with its precursor GPS/MET, and its improved design allows it to better fulfil the mission objectives. The instrument is designed around a DSP chip and an ASIC, which have been developed under ESA contract. Their utilisation and adequacy within a GPS receiver has been validated with an instrument breadboard. Small-satellite radio-occultation missions, and in particular Champ, will pave the way for the setting up and utilisation of the ground infrastructure necessary for the clock correction and the precise orbit determination.

