Earth-Observation Applications of Navigation Satellites

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Satellite navigation systems, such as the US Global Positioning System (GPS) and its Russian counterpart GLONASS, were initially established to provide accurate positioning information. They have, however, also led to a great variety of unforeseen applications, many of which are in fields that at first sight are unrelated to navigation. One of the most successful examples is the development of observation techniques of interest for the Earth sciences.

On going developments, such as the advent of the European navigation system Galileo, will enhance the use of these techniques for ocean and atmosphere remote sensing.

Introduction

The development of Earth-observation techniques based on the use of navigation signals can be traced back to the use of GPS in geodetic applications to provide astonishing precision, such as the determination to within a few centimetres of the relative positions of points on the Earth's surface separated by several thousand kilometres. This ultra-precise positioning of fixed GPS receivers is now routinely used as a tool for studying the dynamics of the Earth's crust (e.g. plate tectonics).

In the course of the development of the related models and data-analysis techniques, new geophysical applications have emerged. Meticulous modelling work has shown how phenomena that were initially considered as measurement perturbations for the original application can later become the observations of interest for new applications. For geodetic positioning, the presence of water vapour (humidity) along the signal propagation path in the troposphere (Fig. 1) is an unavoidable nuisance, because it causes a propagation delay equivalent to a significant additional path (~ 0.4 m in humid regions). On the other hand, it is possible to derive this water-vapour content to about 1 kg/km^2 from the excess-path estimates, which can be determined via the geodetic analysis with about 1 mm accuracy. This provides an opportunity to acquire data that are useful, for instance, for detecting weather fronts in the regions where the receivers are deployed and, more generally, for improving weather forecasts if the information is properly processed in numerical weather-prediction systems. Several regional and global networks of ground GPS receivers are in place today providing data for both geodetic and meteorological applications (see Table 1; not exhaustive). As an example, Figure 2 shows the German SAPOS (SAtelliten-POSitionierungdienst) network, data from which is used for various precise positioning applications and will soon be used for tropospheric water-vapour determination also.

Table 1

Network	No. of receivers	Goals
EUREF, Europe	> 100	Geodesy, tectonics,meteorology
GSI, Japan	> 1000	Tectonics, meteorology
SAPOS, Germany	> 150	Positioning, surveying, geodesy, meteorology
South California Net, USA	> 250	Tectonics, meteorology
CORS + NOAA/FSL, USA	> 100	Meteorology
International GPS Service	> 200	Geodesy, tectonics, meteorology, ionosphere
Suominet	> 100	Meteorology, ionosphere

ESA contributes to the International GPS Service (IGS) network with six receivers at various tracking stations, and with the routine determination of precise orbits and geodetic parameters at its European Space Operations Centre (ESOC) in Darmstadt (cf. 'Satellite Navigation Using GPS' in ESA Bulletin No. 90, May 1997, which also provides an overview of GPS).

Additional information is provided by the correction for ionospheric effects realised with the reception of navigation signals at two frequencies (the ionosphere is a dispersive medium and so the propagation paths depend on frequency). The information retrieved is the total content of electrons along the propagation

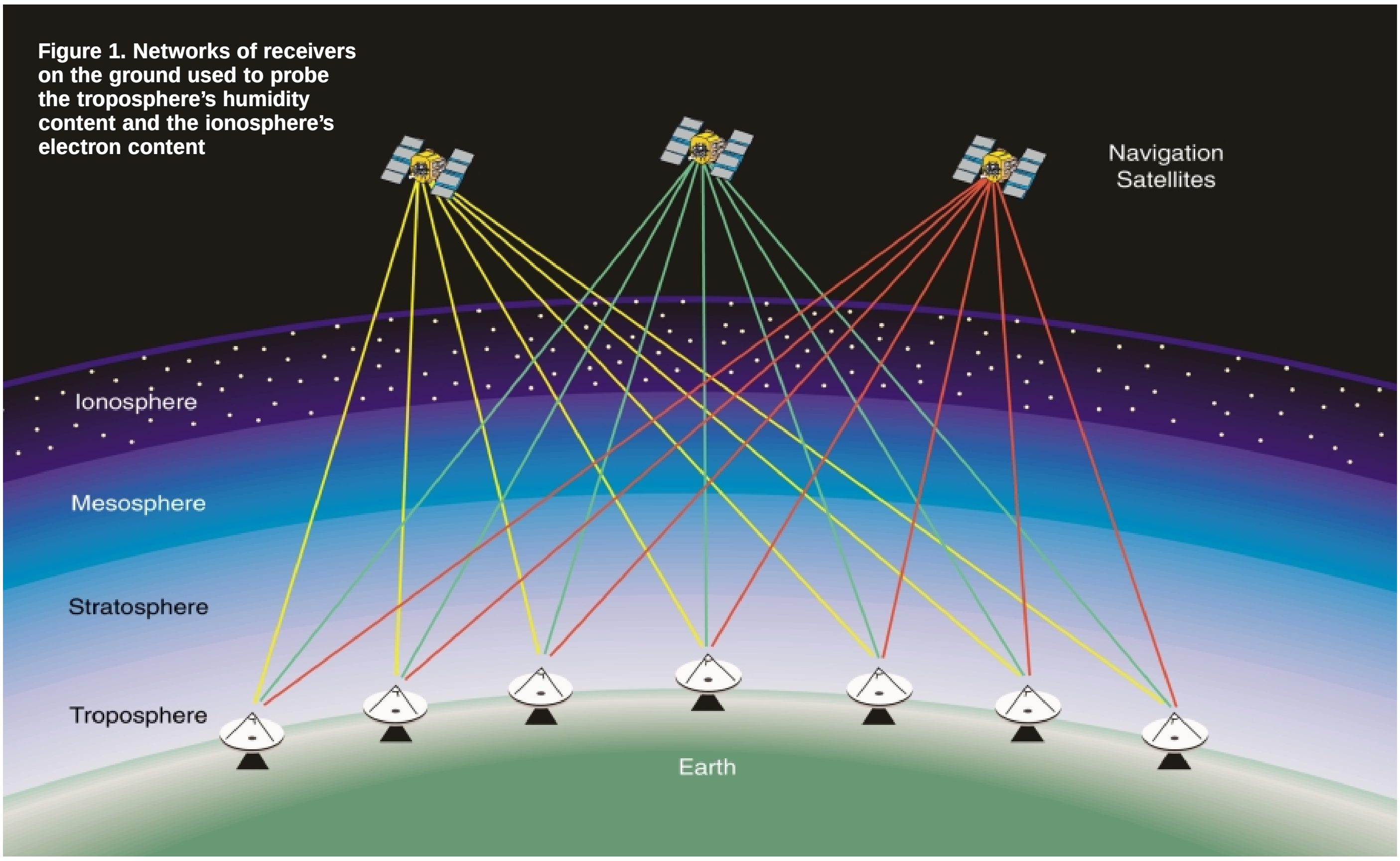


Figure 1. Networks of receivers on the ground used to probe the troposphere's humidity content and the ionosphere's electron content

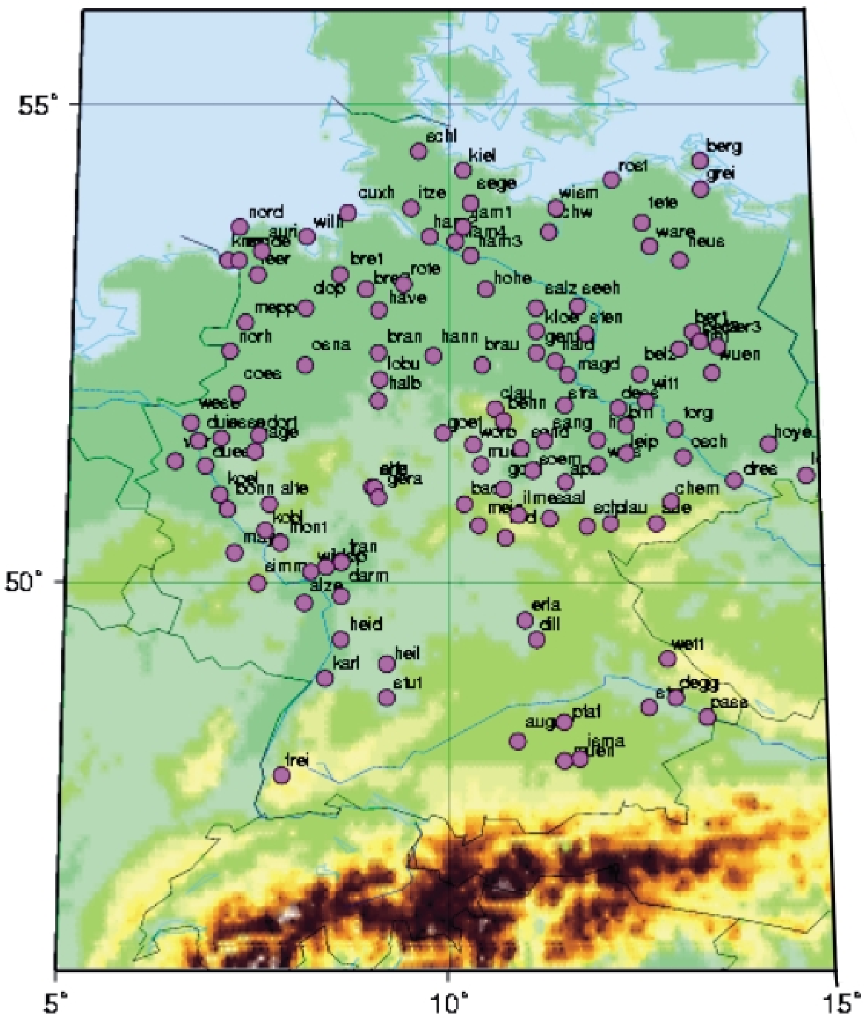


Figure 2. The SAPOS GPS receiver network of the German land surveying agencies

path in the ionosphere. This is used in various space and ground applications, as well as in studies of ionospheric dynamics.

The spaceborne applications

Earth-science applications are no longer limited to the exploitation of ground receiver data. If a high-quality receiver is installed on a satellite in low Earth orbit, it is possible to determine that satellite's orbit to an accuracy of a few centimetres with respect to a network of ground receivers (fiducial stations). The flying receiver can measure very precisely and continuously the changes in the distances to several transmitters. From these data, it is possible in a ground-processing step to reconstitute both the satellite trajectory and various geophysical parameters, such as the variations in the Earth's gravity field.

The performance of the technique has been demonstrated on the US-French Topex-Poseidon mission dedicated to ocean altimetry, where an accuracy of 2–3 cm has been achieved for the satellite height. The concept can be considered an extension of that of geodetic positioning of ground receivers: the orbit of a satellite is very smooth and highly predictable (unless the satellite is manoeuvring or in a re-entry phase!) and this allows the orbiting receiver to provide measurements of the same quality as the ground receivers. Optimal estimation techniques are applied in the ground-processing step and also provide estimates of orbit perturbations of a geophysical nature. The technique will therefore be used in future missions aimed at improving our knowledge of the Earth's gravity field, such as the Gravity and Steady-state Ocean Circulation Explorer (GOCE) selected in October 1999 as the first ESA Core Earth Explorer mission for launch in 2005 (cf. 'Probing the Earth from Space: the Aristoteles Mission', ESA Bulletin No. 72, November 1992, and 'The Gravity and Steady-State Ocean Circulation Explorer', ESA SP-1233 (1)). Several other altimetry and land-topography mapping missions also rely on GPS-based precise orbit determination.

Active atmospheric sounding by radio occultation

The exploitation of the radio-occultation technique using navigation signals as the transmitters of opportunity probably represents the most important development for the Earth sciences. Well-known in Solar System missions where it has been applied since 1964 with the first observations of Mars' atmosphere, this technique uses radio signals passing through the atmosphere in a so-called 'limb-sounding geometry' to sense atmospheric properties. When applied to the Earth, it can provide data of great value for meteorology and climatology, particularly because of its excellent geographical coverage, accuracy, vertical resolution and all-weather capability.

Our understanding of the Earth's atmosphere and our capabilities for modelling and forecasting its changes are currently hampered by our limited knowledge of the temperature and humidity fields. Reliable weather forecasts require an accurate description of the initial state of the atmosphere, because small initial-state errors can grow rapidly in the forecast. On longer time scales, climate models predict a global surface temperature increase of about 1 K (1°C) over the next 20 to 30 years, accompanied by an increase in humidity and a cooling in the upper part of the atmosphere, namely the stratosphere, extending from about 15 to 50 km height. Climate studies depend critically on the availability of accurate observations of long-term consistency, which is what the radio-occultation measurements from navigation satellites can provide.

As navigation signals pass through the atmosphere, either through a descending propagation path (so-called 'set event') or an ascending one ('rise event') when observed by an orbiting instrument, they are retarded and refracted (bent) through an angle determined by the gradients of refractivity along the path, as depicted in Figure 3. The main refraction effect is caused by the vertical gradient of refractivity in the lowest atmospheric layer crossed by the path. The effect results in an excess path and in a decrease in the observed signal Doppler shift compared to a path in vacuum. The path can be precisely determined from the phase and amplitude measurements of the received signals and used to determine the refraction-angle profile through a rise or set event. The refractivity gradients depend on the gradients of air density (and ultimately temperature), humidity and electron content. In the region above about 8 km (upper troposphere and stratosphere, up to 40 – 50 km), the humidity is negligible and the refractivity is due mainly to vertical temperature gradients, so that temperature profiles can be retrieved. Below this, the humidity effect dominates and, if a temperature estimate of moderate accuracy is available, the humidity profile can be retrieved. Vertical profiles of electron density in the ionosphere can also be reconstituted.

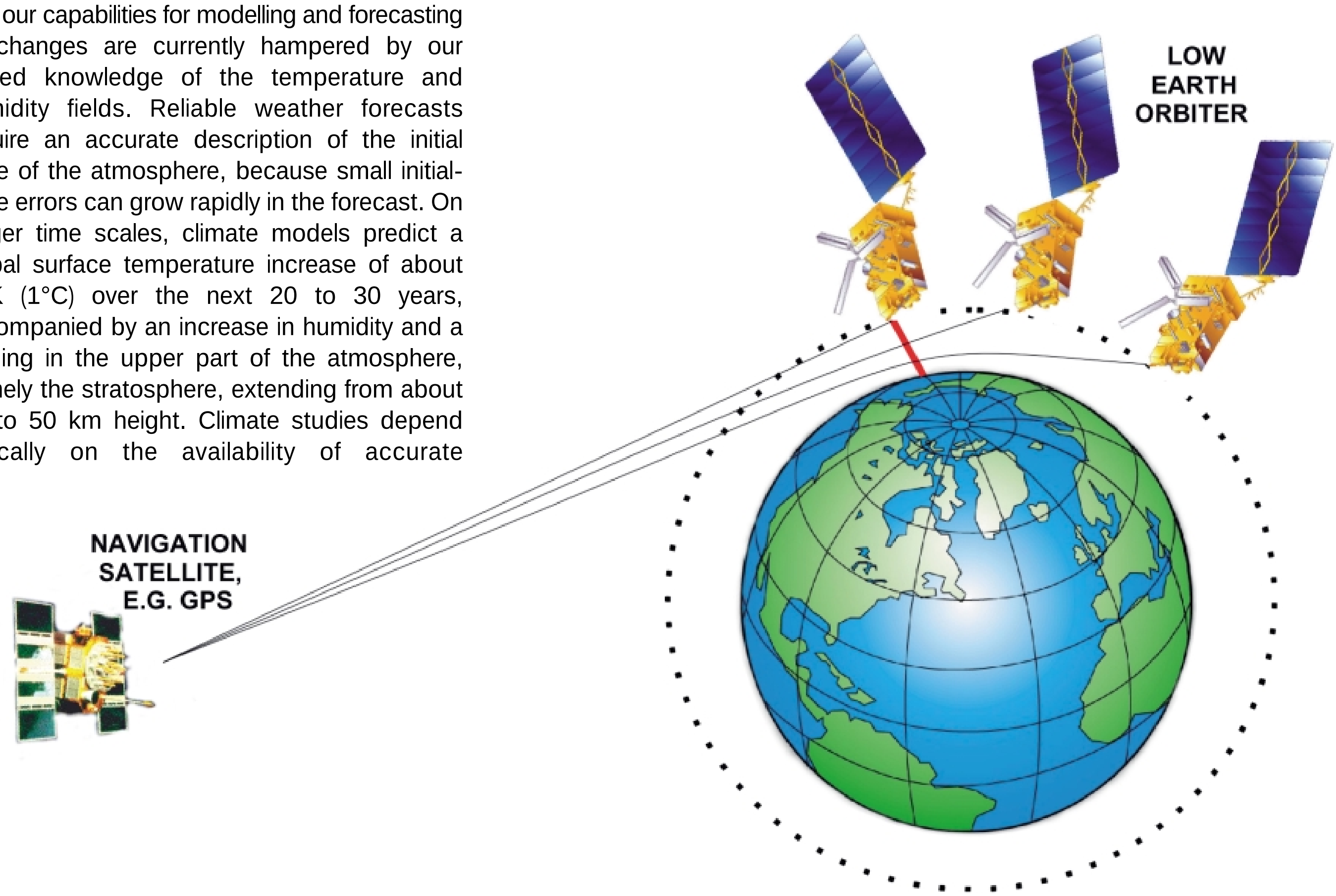


Figure 3. Principle of radio occultation using navigation signals: the signal is received on a low-Earth orbiting satellite, and the propagation path is observed to bend because of atmospheric refraction

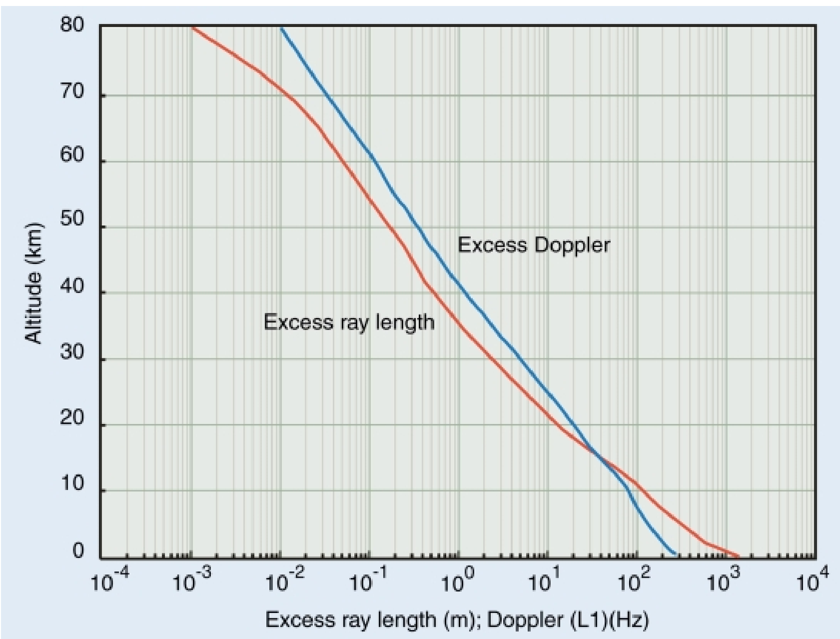
The first proposal to use GPS signals for radio occultation measurements was advanced by Russian scientists in 1987, shortly followed by a US proposal that led to a proof-of-concept with the GPS/MET experiment launched in April 1995 on the MicroLab-1 small satellite. Following extensive GPS/MET data analysis and research into the retrieval process, a significant part of which was conducted in Europe through ESA studies, it is now widely accepted that radio occultation with navigation signals can provide useful profiles of density, pressure and temperature in the middle atmosphere and the colder troposphere, as well as humidity profiles in the tropical and mid-latitude regions of the troposphere. The features that make this technique so interesting for meteorology and climate studies include the global coverage (about 1000 profiles per day can be obtained for each instrument on a polar low Earth orbiter, with 48 navigation satellites), the all-weather capability (no blockage by clouds, unlike classical satellite sounders), the high vertical resolution (varying from some 1.5 km in the stratosphere to some 0.2 km in the troposphere), the retrieved temperature accuracy (about 1 K up to 35 km), and the long-term consistency. This latter quality stems from the fact that the measurements are essentially time-interval observations, which can be referred to fundamental metrological standards (atomic time).

In addition to measuring the precise phase and amplitude of the carrier signal from each navigation satellite occulted by the atmosphere, the instrument also measures other signals that do not cross the atmosphere so as to determine precisely its own velocity and position. These are needed to compute the (large) Doppler shift caused by orbital motion and derive the excess Doppler caused by the propagation in the atmosphere. The required accuracy, particularly for the along-path velocity component, is high (order 0.1 mm/s), which makes it mandatory to use differential positioning techniques, supported by a global ground network of receivers. The use of differential techniques also allows the correction of transmitter and receiver oscillator errors, which might otherwise be confused with the atmospheric contribution. When the gradients of refractivity in the atmosphere are small over spatial scales of the order of the signal wavelength (0.2 m), the processing can be based on geometric optics, so that the propagation paths can be treated as well-localised rays. The excess-Doppler profile can be transformed into a refraction-angle profile, which in turn enables one to derive a refraction-index profile.

The atmospheric parameters of interest are linked by a simple mathematical relation to the refraction index, which enables one to reconstitute them with the help of the known gas and hydrostatic equilibrium laws. The refraction-angle profiles can also be used directly in numerical weather-prediction models in order to combine them with other atmospheric measurements in an optimal estimation approach, which is routinely done in operational meteorology. These prediction models can provide temperature estimates with good accuracy (2 – 3 K) over the humid regions, where radio-occultation data can therefore be used to retrieve humidity with about a 10 – 20% accuracy.

Figure 4 shows a typical profile of the excess path. This is clearly a substantial effect if compared to the millimetric accuracy with which one can measure it. The profile has been generated with a complex software simulator developed under an ESA study in order to analyse the end-to-end performance of the technique, and currently in use at various European institutes and companies. Figure 5 shows an example of temperature and water-vapour pressure retrievals from actual data collected in the GPS-MET experiment and compared to similar retrievals from numerical weather-prediction systems using a large set of conventional measurement systems (radiosondes, satellite radiometers, etc.). The total refraction angle reaches about 1 deg at grazing incidence and can be determined from the data to an accuracy of better than 0.01% of a degree. Because of the limb-sounding geometry, the horizontal resolution of the measurements is between 100 and 300 km, which is sufficient considering the atmosphere's stratified structure and assuming proper data treatment in weather and climate models.

Figure 4. Typical excess-path and Doppler-shift profiles through a radio-occultation event



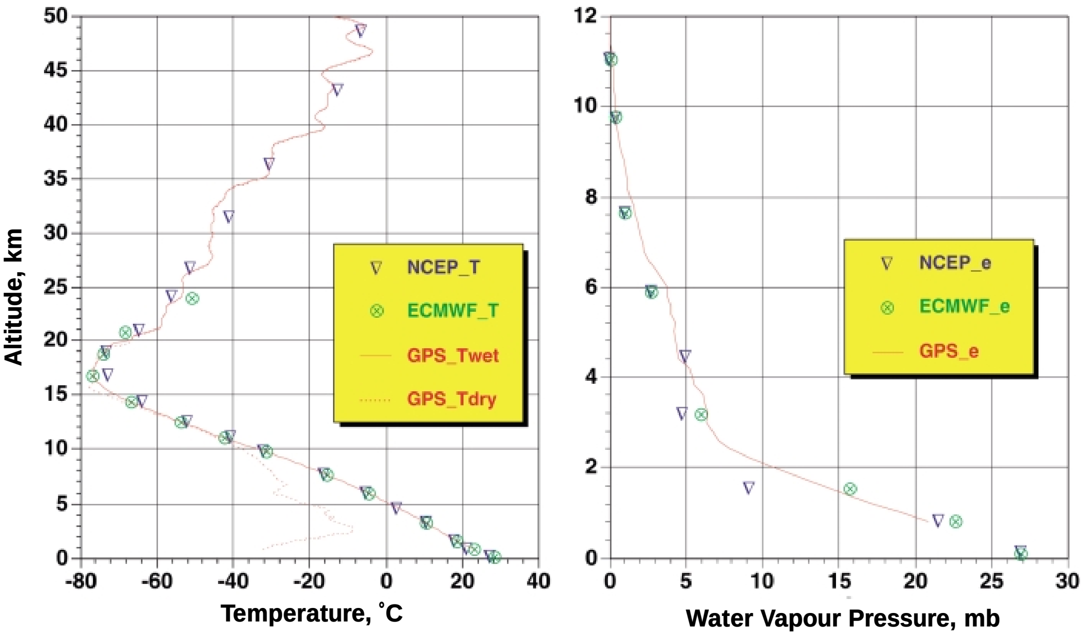


Figure 5. Example of temperature and water-vapour-pressure retrievals from data collected in the GPS-MET experiment, showing the agreement with similar retrievals from numerical weather-prediction systems that use a large set of conventional measurement systems. The GPS_Tdry retrieval neglects the presence of humidity and results in an underestimate of temperature
(Data courtesy of the UCAR GPS-MET Project, the National Center for Environmental Prediction (NCEP, USA) and the European Centre for Medium-Range Weather Forecasts (ECMWF, UK))

Often the geometric (ray) optics description is no longer valid in humid regions, because the complex geometry of the humidity field can cause rapid fluctuations in refractivity. Such fluctuations cause multiple propagation paths and significant diffraction effects. In this case, the probed region behaves like a focussing rather than a defocussing lens, and the sensor measures a rapidly varying signal. In terms of rays, it is as if the instrument is measuring the result of the interference of an unknown number of rays (Fig. 6). To handle such effects correctly, the data processing must be based on wave optics (physical optics). A satisfactory method has been elaborated in the course of various studies, based on the concept that the rays can be 'disentangled' by propagating the received signal backwards until it is reconstructed on a virtual surface (auxiliary plane in Fig. 6) where the effects are negligible. Once this is achieved, the retrieval can be carried out as before, starting with the derivation of the excess Doppler shift. The method requires one to measure also the amplitude of the received signal. An added advantage of the method is that it allows the vertical resolution to be sharpened further and makes it possible to observe vertical features in the atmosphere with sizes below 100 m. All of the retrieval methods have been verified by means of the end-to-end performance simulation software mentioned and will be used in the data processing for forthcoming missions.

Other studies have addressed the accuracy of the GPS/MET retrievals compared with other sensors, e.g. radiosondes providing in-situ measurements of comparable accuracy, and with various weather-prediction models. The results show that temperature errors are below or close to 1 K, although the comparison becomes difficult for regions where the errors of existing sensors and models are above this value. This is the case for a large part of the Southern Hemisphere, where the limitations in the existing data are particularly strong.

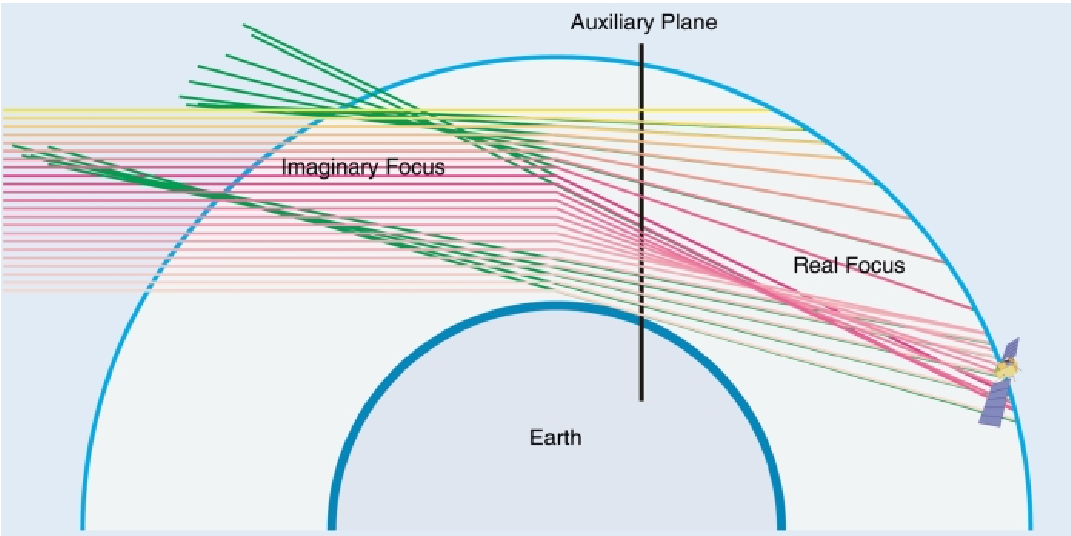


Figure 6. Illustration of multiple propagation effects in radio occultation caused by large atmospheric refractivity gradients. The effects are removed by processing the received data so as to propagate the paths backward up to a (virtual) auxiliary plane

Instrument development

Navigation sensors, even if space-qualified, cannot be used as instruments for the applications described, since substantially higher performances and different modes of operation are needed. For this reason, the development of suitable instruments was initiated in 1994 within ESA's Earth Observation Preparatory Programme. Relevant differences with respect to navigation equipment include: a larger number of receiving channels, since both positioning and sounding must be supported; low-noise measurements at high data rates; an ultra-stable oscillator; high-gain beam-shaped antennas, to compensate for losses incurred in the atmospheric propagation; improved sensitivity to observe the weak signals during a tropospheric occultation, including a so-called 'open-loop' mode where an on-board atmospheric model aids the instrument operation when closed-loop phase locking of the signal is no longer possible. The GNSS Receiver for Atmospheric Sounding (GRAS) has been developed to provide radio-occultation measurements in an operational way. Initially proposed in 1996 as the instrument for a prospective constellation of micro-satellites (cf. 'The Atmospheric Profiling Mission', ESA SP-1196 (7)), it is now being implemented on the Metop mission following a request by Eumetsat to include it in its meteorological payload. It is worth mentioning that the experience gained with GRAS has also given European industry the opportunity to win important development contracts for similar sensors in the US market. Recently, additional activities have been started to develop a miniaturised version of GRAS for the Atmospheric Climate Experiment (ACE) mission, selected in 1999 as a potential Earth Explorer Opportunity mission and currently being studied at Phase-A level, as well as for other flight opportunities.

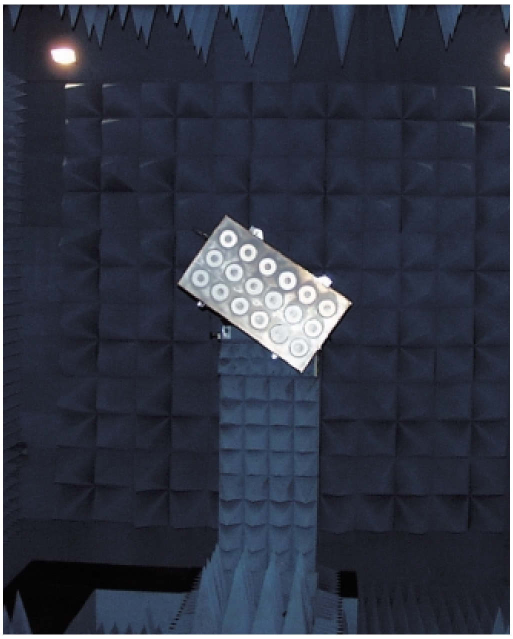


Figure 7. Anechoic chamber testing of the GRAS antenna breadboard developed within the EOPP and GSTP programmes
(courtesy of Saab Ericsson Space)

Emerging applications

The Earth-observation applications of navigation systems could soon extend to ocean remote sensing, following various proposals elaborated since the late eighties regarding the exploitation of navigation signals reflected at the sea surface. The goals are mainly observation of the sea state (waves) and surface winds, and ocean altimetry. While some successful proof-of-concept airborne experiments have been conducted (see ESA Bulletin No. 101, p. 133), studies and further experiments are now underway to assess the feasibility and usefulness of a spaceborne system. If these are confirmed, benefits similar to those of the atmospheric-sounding application could be achieved via this new use of navigation satellites as transmitters of opportunity. These include the reduced implementation effort, because of the receive-only instrumentation, and a substantial data return because of the large number of transmitters. Improved spatial and temporal sampling of both ocean and atmospheric conditions could then be achieved.

Future prospects

The advent of the European navigation system Galileo, and the planned GPS enhancements, represent promising developments for all of the applications described here, mainly because of the anticipated increases in the number of transmitting satellites, in signal power, and in the number of carrier frequencies. Future instrument developments will certainly take advantage of these advances.

On the user side, while the operational meteorology community is already working on the exploitation of ground-based water-vapour and radio-occultation data, climate scientists are becoming increasingly interested in the prospective of a long-term climate observing system based on principles very different from those of the current instruments and able to provide improved long-term data consistency. Proposals such the ACE mission mentioned above and similar ones in the USA are driven by this vision. Considering how quickly the initial concepts for using navigation satellites for Earth observation have moved from a pure research scenario to one driven by operational applications, we can expect a very healthy future for this young domain of space techniques.

Acknowledgement

The current European leadership in the exploitation of the radio-occultation technique is the result of the work and dedication of many ESA contractors, including the Danish Meteorological Institute, the University of Graz (A), the Max-Planck Institute for Meteorology (D), the Aeronomy Service of CNRS (F), the Catalan Institute for Space Studies (E), the UK Meteorological Office, the University of Leeds (UK), Austrian Aerospace, Saab Ericsson Space (S) and Terma (DK). The support of the ESA Earth Science Division is also gratefully acknowledged.