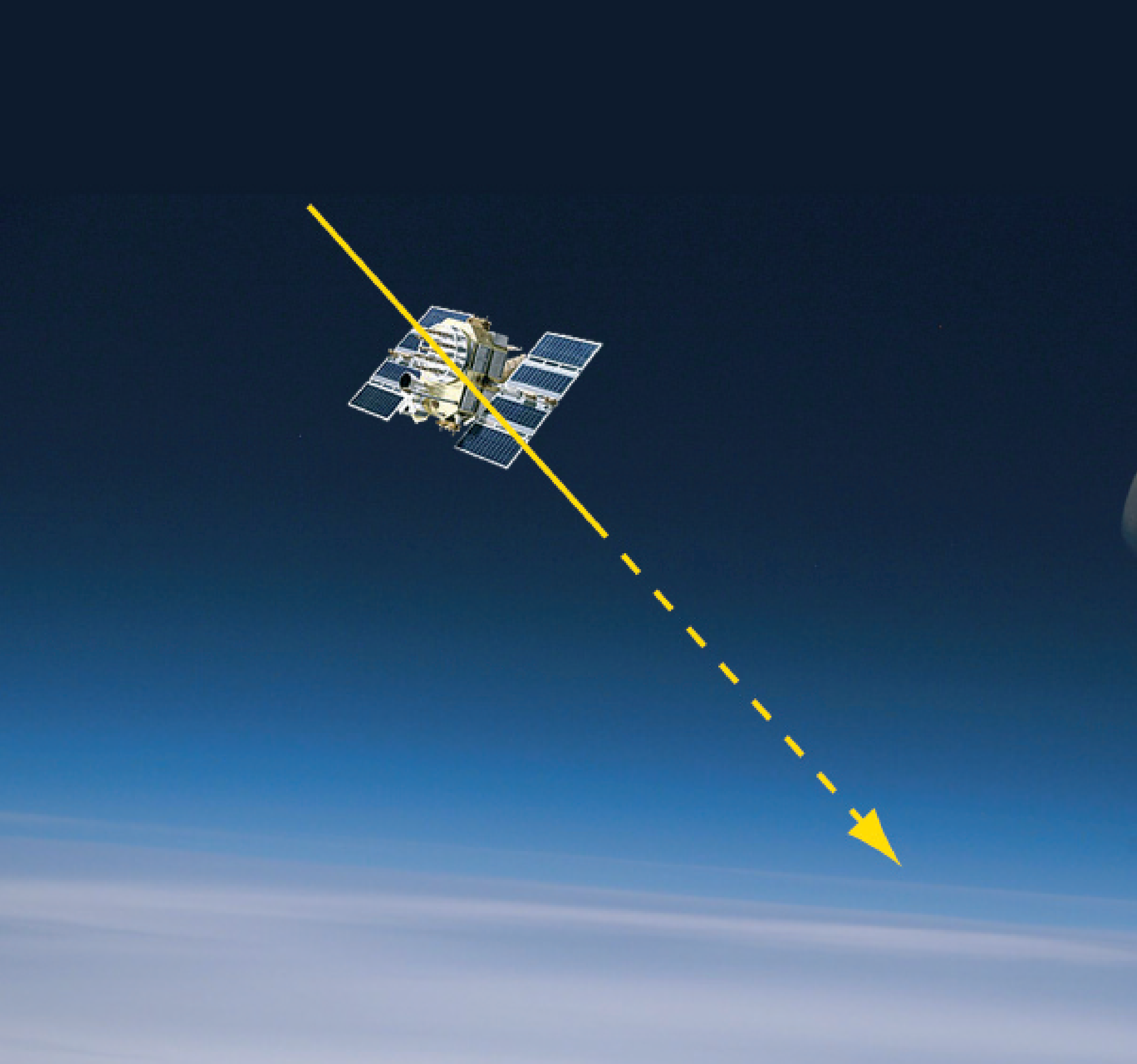


Sounding the Atmosphere

Ground Support for GNSS Radio-Occultation Processing

As seen from a low-orbit satellite, the GPS satellite disappears below the horizon (motion indicated by the yellow arrow). The radio signal is affected as it slices through the atmosphere. The case shown here is a 'setting occultation'

René Zandbergen & John M. Dow
Navigation Support Office, Ground Systems Engineering Department, Directorate of Operations and Infrastructure, ESOC, Darmstadt, Germany

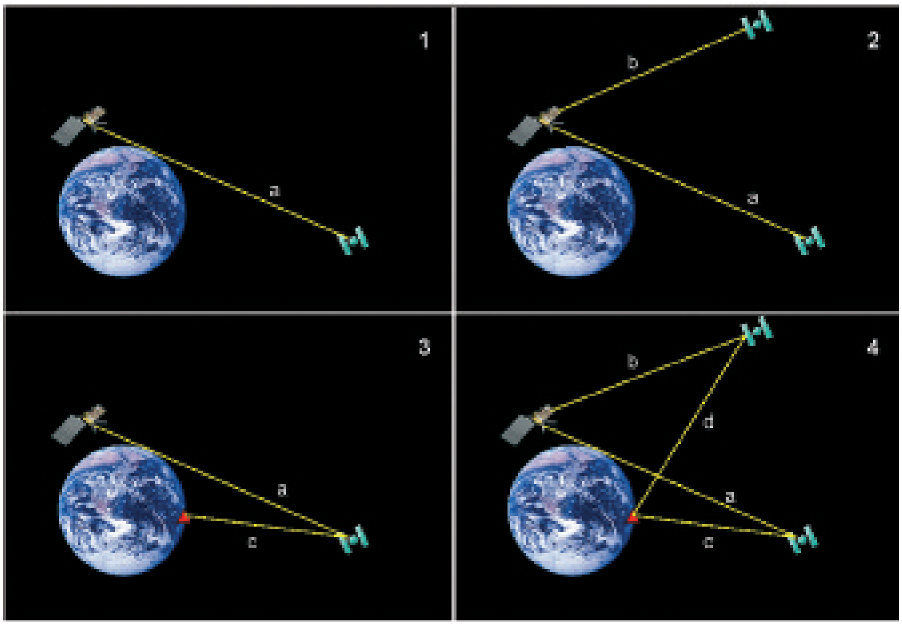
The conditions in Earth's upper atmosphere are important for predicting the weather but they are difficult to monitor. The region can be probed by measuring the effects on radio signals slicing through it from navigation satellites. ESOC's Navigation Support Office is contracted by Eumetsat to provide crucial supporting data to allow the analysis of the signals received aboard Europe's new MetOp polar-orbiting weather satellites, due to debut in 2006.

Introduction

Earth-orbiting satellites have been equipped with Global Positioning System (GPS) receivers for many years now, mostly as an aid for orbit determination. The receiver processes the signals from visible GPS satellites through one or more antennas mounted on the satellite. For GPS satellites that appear to the receiver to be close to the Earth's horizon, the signals travel through the Earth's atmosphere and are therefore less useful for orbit determination. However, such signals can be exploited for sounding the upper atmosphere by measuring how they are affected.

MetOp-A, the first satellite to be launched as part of the ESA/Eumetsat MetOp polar system, in mid-2006, is

The geometry of undifferenced (1), single-differenced (2 and 3) and double-differenced (4) occultation data processing. By computing the difference [a-b, a-c, (a-c) – (b+d)] between several signals, the uncertainties in the atomic clock offsets are eliminated



equipped with a receiver to be used for atmospheric sounding. Its data will be converted in near-realtime to atmospheric products that can be fed into numerical weather-forecasting models at European meteorological institutes. The creation of these products requires significant amounts of near-realtime supporting data, including the very precise orbits of the GPS satellites. Eumetsat has awarded the Navigation Support Office at ESOC a contract to set up the system for the generation and delivery of such data.

Atmospheric Sounding

Atmospheric sounding is based on signals from Global Navigation Satellite Systems (GNSS) that pass through the atmosphere. GNSS includes the American GPS, Russia's GLONASS and Europe's Galileo. The GPS constellation consists of 28 active satellites orbiting the Earth at an altitude of 20 000 km, transmitting navigation signals at 1575 MHz and 1228 MHz.

During occultation of the transmitting satellite by the Earth's horizon, a large part of the signal path traverses the atmosphere. This slightly reduces the speed of the radio waves compared to the speed of light in vacuum, apparently increasing the measured distance between the GPS satellite and the receiver aboard the low Earth orbit (LEO) satellite. The effect is greatest at the point where the signal is nearest to the Earth. As a result of the relative motion of the two satellites, the altitude of this point will decrease (in the case of a setting occultation) or increase (in the case of a rising occultation).

While this atmospheric effect on the signal is a source of error when the data are used for precise positioning or orbit determination, it can yield useful information about the the upper atmosphere, such as temperature and pressure. Tracing the effect with time generates an atmospheric profile. For the case of MetOp, orbiting at an altitude of around 820 km, the profile will be generated in up to 100 sec.

MetOp satellites are equipped with a GPS receiver called 'GRAS' (GPS Receiver for Atmospheric Sounding), which can process data received through its three antennas. One antenna on the zenith side (pointing away from Earth) receives signals that are hardly affected by atmospheric effects, so they can be used for precise orbit determination. The other receivers are mounted on the fore and aft sides of the satellite, facing in the direction of motion and against it, respectively. Each of these antennas monitors only radio occultations, and can track up to two occulting GPS satellites at the same time.

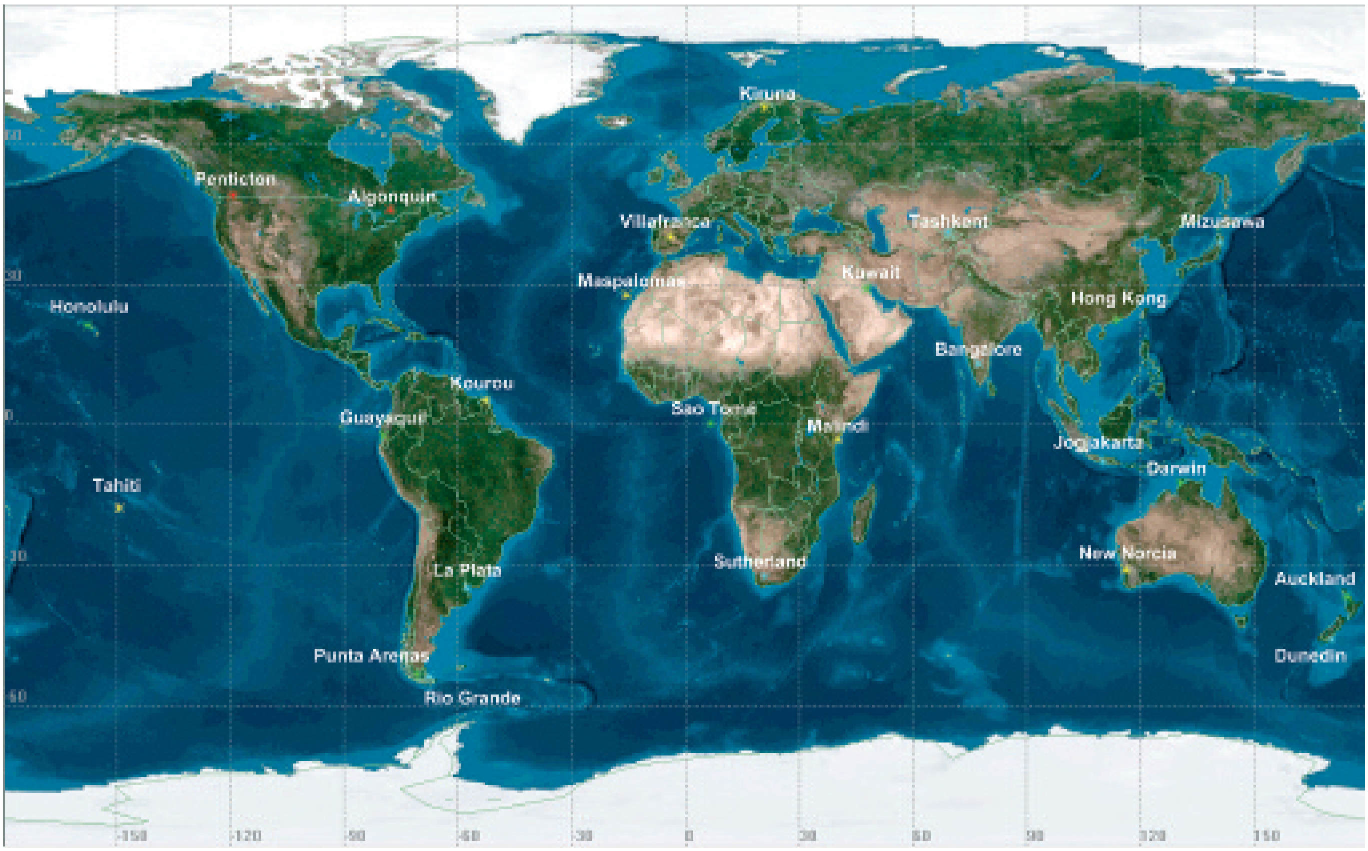
Through the geometry of the MetOp and GPS orbits, some 500 radio occultations will be observed on an average day – making around 500 atmospheric profiles available to meteorological scientists daily.

Sounding Data Processing

The radio occultation data will be collected aboard MetOp and downlinked to the ground once per orbit, for analysis at Eumetsat. To compute the effect of the atmospheric refraction, the processing software requires highly precise knowledge of the true distance between MetOp and the occulting GPS satellite, and a highly precise measure of the signal delay. The first is obtained from orbit determinations of MetOp and GPS, and the second from the time difference between transmission and reception of the signal. This relies on a very precise determination of the offsets of the atomic clocks used by the satellites; these offsets are measured with respect to the GPS reference time, which is accurately maintained with respect to coordinated universal time (UTC).

The quality of the products from this process depends on the accuracy of the GPS orbit and the clock offset data that are fed into it. The atomic clocks must be extremely stable: clock offset and their accuracies are measured in nanoseconds (10^{-9} s). The radio signals travel about 30 cm in 1 ns; the most advanced processing centres can now achieve accuracies of the order of 0.1 ns.

If the atomic clocks are not stable to this level over several tens of seconds (the duration of an occultation), slightly more complicated alternative processing techniques may be employed. These compute range differences, such that the variations of one or more atomic clocks



The receiver sites of the GRAS Ground Support Network. ESOC sites are indicated in yellow, GFZ in light blue, Fugro Seastar in green and NRCan in red (only the prime sites are shown)

with respect to the reference time are eliminated from the calculations. The data-processing scheme described earlier is known as 'undifferenced' processing. If it is suspected that MetOp's clock is not stable enough, it can be eliminated from the calculations by computing the difference between the ranging signals coming from the occulting GPS satellite and an unocculted GPS satellite received through the zenith antenna, and using this in the occultation processing. If the clock of the occulting GPS satellite is suspect, it can be eliminated by computing the difference between the range from this satellite to MetOp and the range from this satellite to a ground station. We can even eliminate all clock offsets by computing a double difference.

Support Data

Through more than 10 years' participation in the International GNSS Service (IGS), ESOC's Navigation Support Office has become one of the most experienced producers of high-precision GPS orbit and clock offset data. The IGS makes available its data (GNSS ground receiver data from a global network comprising several hundred sites) and products (orbit and clock solutions from seven analysis centres) freely to the user community. From this, it is known that the most precise orbit solutions that can be made available are of the order of 3 cm, with a corresponding clock offset accuracy of the order of 0.1 ns. This type of accuracy is sufficient for the support data needed by the radio occultation data processing. There are, however, some constraints put on the support data by Eumetsat, namely:

– the radio occultation data are to be fed into near-realtime numerical weather simulations, so they must be available within 3 hours of the occultation;
– clock data should be available at the highest possible rate (ideally 50 Hz) during occultations;
– the support data should be provided with a guaranteed availability for up to 15 years (covering the first three MetOp missions).

In 2001 the Navigation Support Office completed a study on a system that could deliver the required support data against the strict requirements on accuracy, timeliness and availability. The primary support data required include:

– near-realtime GPS orbit and clock offset solutions, available within 60 minutes. The driving accuracy requirement is a 0.5 ns clock offset accuracy for each supported GPS satellite;
– for single difference processing: near-

realtime ground station clock offset solutions with the same accuracy and timeliness as the GPS clock offset solutions.
– also for single difference processing: GPS ground receiver data (one measurement set per second) for each occulted GPS satellite, during the occultation event. These data should be available within 60 minutes of the occultation;
– off-line orbit and clock offset solutions with enhanced accuracy, which are of interest for climatological research.

Other auxiliary products are also included in the support data to be delivered.

As a result of this study, ESOC was awarded a contract to develop, validate and operate a GRAS Ground Support Network for all three MetOp satellites. The network must also be extendable to support similar missions.

The ESOC Navigation Facility, hosting the GRAS GSN

The GRAS Ground Support Network (GSN)

The feasibility study concluded that, to be able to deliver receiver data for all GPS satellites being occulted, and to compute sufficiently accurate near-realtime GPS orbit and clock offset solutions, a dedicated ground receiver network with redundant global coverage was required. At that time, ESOC operated seven GNSS receivers, deployed at the ESA ground station sites worldwide, with some overlapping visibility. The required network needs at least 25 well-distributed receivers, even before allowing for redundancy.

The data from these receivers are routed continually, either as a realtime data flow or in frequent batches, to a processing centre at ESOC, where automated procedures pre-process, edit and select the data, generate all required products and deliver them to Eumetsat. Significant parts of the highly complicated software required for this processing were already available in the Navigation Support Office, through its participation in the IGS, but modifications and additions were made to make the system satisfy the customer's requirements.

For the receiver network, contracts were established with the German GeoForschungsZentrum (GFZ) in Potsdam and the Norwegian commercial operator Fugro Seastar, who both operate their own global networks of GNSS receivers. A contract with the Canadian government institution Natural Resources Canada (NRCan) allowed the inclusion of some important sites in North America. In addition, Météo-France agreed to deploy a GPS receiver on their site in Tahiti. There is a scarcity of sites in the Pacific, so it is a key element in the GRAS Ground Support Network.

Each network operator is responsible for collecting the data from its own receiver sites. Permanent data lines have been established between ESOC and the three operators, and all the data are delivered in files covering 15 minutes of 1 Hz data, delivered within 5 minutes of the last observation in each file. Data from all 40 sites (44 receivers) are collected at a new facility in ESOC.

With these, GPS satellite orbits are computed and predicted in near-realtime every 3 hours. Based on these orbit solutions, high-rate clock offsets are computed every 15 minutes for all active GPS satellites and for all GSN stations.

Based on daily predictions from Eumetsat, indicating which GPS satellites have radio occultations at which times, ground receiver data for single-difference processing are selected and prepared for delivery to Eumetsat fully automatically.

All near-realtime products are delivered to Eumetsat as soon as they have been computed or prepared, and are stored in parallel on a file server at ESOC. These, and a number of additional products, such as the offline enhanced products, are kept online for 6 months, after which they are archived. A procedure for restoring archived data has been agreed with Eumetsat.

The entire GRAS GSN, including the network of receivers, the processing centre at ESOC and all software involved, was developed and deployed in the period from September 2003 to March 2005. It went through a validation phase from May 2005 to December 2005, and on 15 February 2006 it was officially declared 'ready for operations'. The network can support two MetOp satellites in parallel, and was designed to be easily adaptable to support other missions with similar requirements.

The GSN Processing Centre

The high availability requirements placed on the GRAS GSN made it necessary to operate it from a secure environment with built-in redundancy. Plans existed for a dedicated Navigation Facility as part of ESOC's operations infrastructure, and it became clear that the GRAS GSN would become its first major project.

The Navigation Facility was first used in May 2005. All hardware is divided into two independent chains ('A' and 'B'), which are physically separated such that the loss of one chain will still allow full operability of the system.

Connectivity to the outside world, a critical component of the GSN owing to the large amount of data being continually retrieved, is based on a relay system through a demilitarised zone, making it impossible for unwanted traffic from the internet to reach the operations infrastructure.

The Navigation Facility was inaugurated on 17 February 2006. The six operator positions are not all used by the GRAS GSN, which is a fully automated system requiring only minimal manual intervention. Other projects will be operated from this facility in the near future.

Since the GRAS GSN was completed some months before the first MetOp launch, ESOC and Eumetsat agreed that the project should go into hibernation for about 3 months. Operations will start up a month before the MetOp-A launch, which is planned for mid-July 2006.

Acknowledgements

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