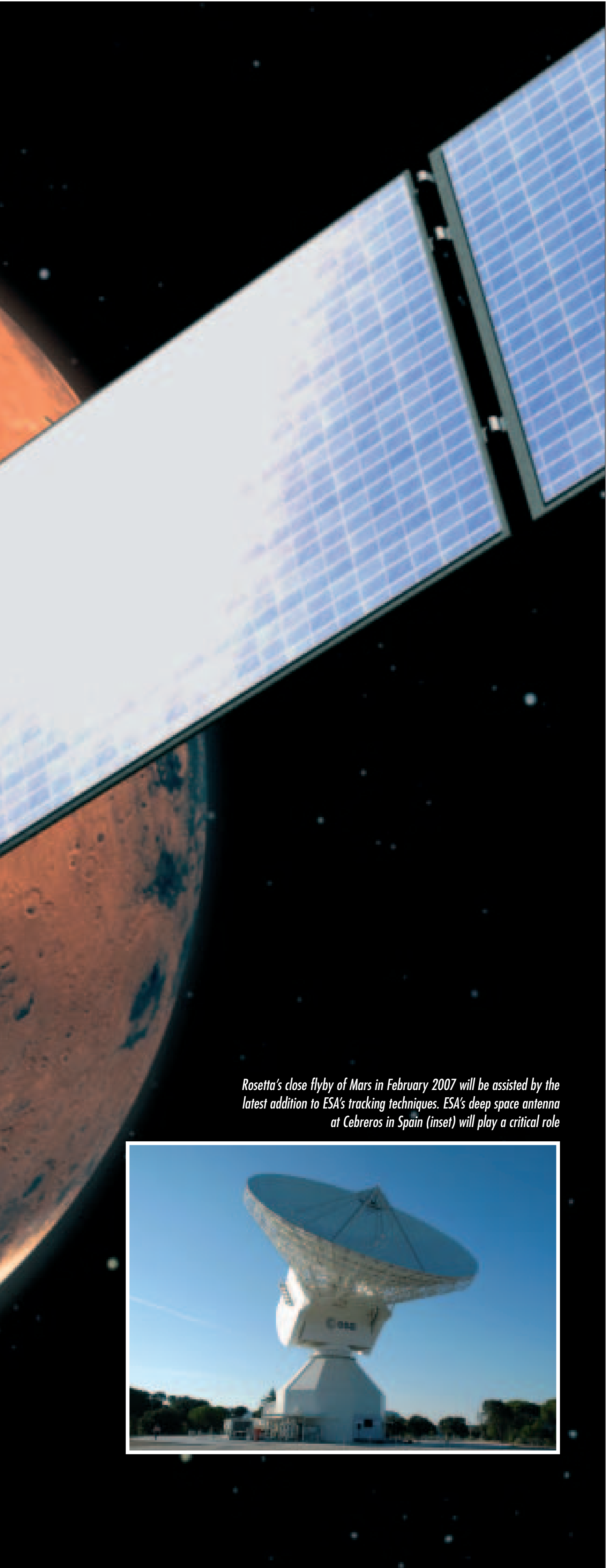
Delta-DOR

A New Technique for ESA's Deep Space Navigation



Rosetta's close flyby of Mars in February 2007 will be assisted by the latest addition to ESA's tracking techniques. ESA's deep space antenna at Cebreros in Spain (inset) will play a critical role

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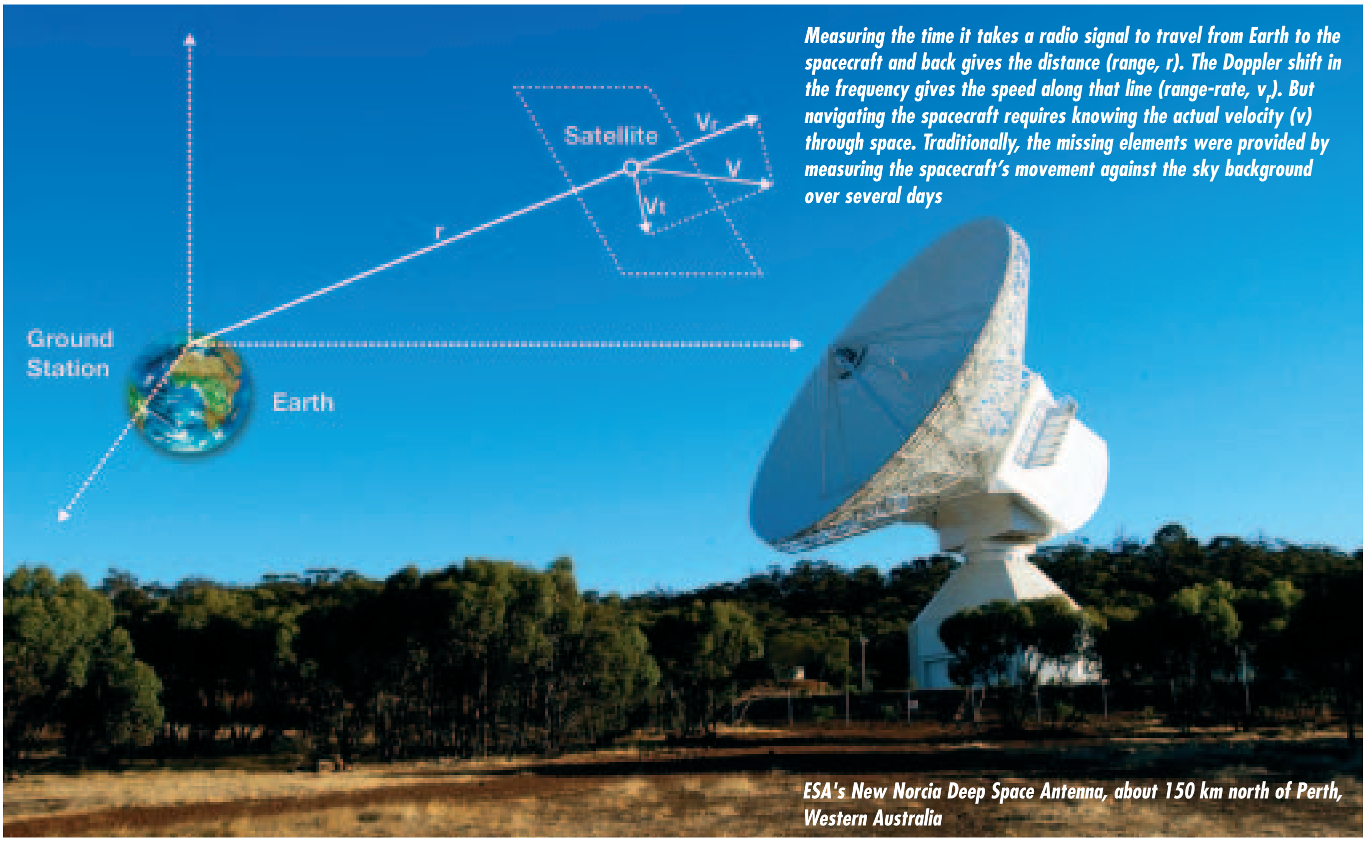
When ESA's second deep space antenna became available in late 2005 Cebreros in Spain, the Agency could begin using a powerful new navigation technique particularly important for interplanetary craft: delta-DOR. Delta-DOR contributed to the successful orbit insertion of Venus Express around the planet in April 2006, and it is expected to be a fundamental tool for navigating all of ESA's current and future interplanetary missions.

Introduction

Routine navigation of a spacecraft around the Solar System relies on two tracking methods: ranging and two-way Doppler. Precisely measuring the time it takes radio signals to travel to and from a spacecraft gives the distance from the ground station ('two-way range'), while measuring the signal's Doppler shift provides the craft's velocity along that line-of-sight ('range-rate'). The other two position coordinates, against the sky background, are obtained only indirectly from the motion of the ground station as the Earth rotates. This imposes a daily sinewave oscillation



Measuring the time it takes a radio signal to travel from Earth to the spacecraft and back gives the distance (range, r). The Doppler shift in the frequency gives the speed along that line (range-rate, v_r). But navigating the spacecraft requires knowing the actual velocity (v) through space. Traditionally, the missing elements were provided by measuring the spacecraft's movement against the sky background over several days

ESA's New Norcia Deep Space Antenna, about 150 km north of Perth, Western Australia

on the range and range-rate data related to the position of the spacecraft. These position components, though, can only be deduced to much lower accuracy. Also, when the spacecraft is close to the celestial equator, the calculations struggle and the north-south position is very poorly determined. The craft's velocity components in the plane-of-sky are not measured and can only be found from how the position changes from day to day. This means that tracking over several days is necessary and calls for very high-fidelity modelling of the spacecraft's motion.

The tracking system at ESA's 35 m-diameter deep space antennas (DSAs), at New Norcia in Western Australia and Cebreros near Madrid provides very accurate measurements. Typically, the random errors on range are about 1 m and on the two-way range-rate less than 0.1 mm/s. Nevertheless, the limitations described above mean the accuracy of resulting orbit determination may not be good enough for navigation during critical stages of a mission. This is especially the case on approaching a planet before landing, performing a swingby or insertion into orbit. However, ESA can now augment the conventional tracking by measurements known as 'Delta Differential One-way Range' (delta-DOR).

NASA's Deep Space Network (DSN) has provided delta-DOR data since 1980 and has aided the navigation of ESA missions since 1986.

In 1992, the navigational accuracy of Ulysses on its approach to Jupiter was improved by the addition of delta-DOR measurements. In the second half of 2003, 56 delta-DOR measurements from the Goldstone (California, USA)-Madrid baseline and 49 from the Goldstone-Canberra (Australia) baseline were processed at ESOC for Mars Express. For the release of Beagle-2 and insertion into Mars orbit, this provided a 7-fold reduction in the navigation uncertainty compared with the standard method.

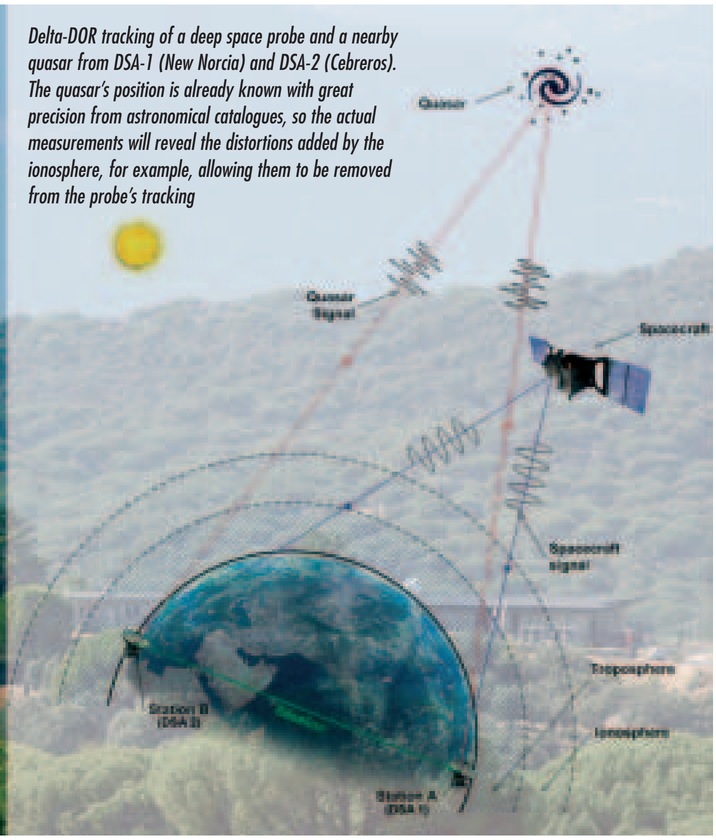
The ESA Delta-DOR Concept

The delta-DOR technique for navigating interplanetary spacecraft is based on a simple but effective concept. It uses two widely separated antennas to simultaneously track a transmitting probe in order to measure the time difference ('delay time') between signals arriving at the two stations. The technique of measuring this delay is named Differential One-way Range (DOR).

Theoretically, the delay depends only on the positions of the two antennas and the spacecraft. However, in reality, the delay is affected by several sources of error: for example, the radio waves travelling through the troposphere, ionosphere and solar plasma, and clock instabilities at the ground station.

Delta-DOR corrects these errors by 'tracking' a quasar in a direction close to the spacecraft for calibration. The chosen quasar's direction is already known extremely accurately by astronomical measurements, typically to better than 50 *billionths* of a degree (a nanoradian).

ESA's second Deep Space Antenna, at Cebreros, Spain



Delta-DOR tracking of a deep space probe and a nearby quasar from DSA-1 (New Norcia) and DSA-2 (Cebreros). The quasar's position is already known with great precision from astronomical catalogues, so the actual measurements will reveal the distortions added by the ionosphere, for example, allowing them to be removed from the probe's tracking

The quasar is usually within 10º of the spacecraft so that their signal paths through Earth's atmosphere are similar.

In principle, the delay time of the quasar is subtracted from that of the spacecraft's to provide the delta-DOR measurement (the Greek symbol 'delta' is commonly used to denote 'difference'). The delay is converted to distance by multiplying by the speed of light.

A complication is that the quasar and spacecraft cannot be measured simultaneously. In practice, three scans are made: spacecraft-quasar-spacecraft or quasar-spacecraft-quasar, and then interpolation between the first and third converts them to the same time as the second measurement, from which the delta-DOR data point is calculated.

As two angles are required to define a direction, full exploitation of delta-DOR calls for measurements from two different baseline orientations, the closer to 90º the better. The error in the delta-DOR measurement translates into an angular error that diminishes with longer baselines. Maximising the baseline is limited by the need for the spacecraft and quasar to be mutually visible from both antennas for long enough.

During each scan, signals are sampled and recorded in the stations. The recorded data are transferred to ESOC, where they are processed to extract the delay.

A spacecraft signal is normally a sequence of frequency-spaced tones (either dedicated DOR tones produced by the transponder or harmonics of the telemetry subcarrier), each tone with its full power contained in a few Hertz of bandwidth. In contrast, quasar signals look like noise buried in the antenna's overall noise. For this reason, two different algorithms (based on the signal's characteristics) are necessary when extracting the delay in the signal arrival times at the two stations.

Also, the accuracy improves if the tones are further apart in frequency. So a wide bandwidth is important.

With the Cebreros DSA-2 antenna coming into operation in September 2005, ESA had the potential for making delta-DOR measurements for the first time. With DSA-1 at New Norcia in Western Australia, the baseline is 11 650 km. However, even with this basic infrastructure, the system had to be upgraded for delta-DOR: modifying the receivers at each station, a new architecture for the communication links from the stations to ESOC, the development of a 'correlator' to extract the delays from the raw data recorded at each station, and a flight dynamics system able to use the measurements.

The system upgrade was completed in less than 10 months, driven by the need to have an operating and tested delta-DOR capability before the Venus Express launch in November 2005. The improved system could then help to navigate the craft between the planets and into the critical orbit insertion.

The Venus Express orbit had to calculated to very high accuracy, so an uncertainty of only 1 nanosecond (a billionth of a second) was imposed on the delta-DOR time-delay measurements. This corresponds to an angular accuracy of roughly a millionth of a degree – better than 4 km on the probe's position at a distance of 150 million km.

With only two stations available, ESA can provide delta-DOR tracking with just one baseline, and can track the spacecraft only in the portion of space visible between New Norcia and Cebreros.

The ideal case for delta-DOR purposes would be to have another deep space antenna at American longitudes, preferably in the southern hemisphere. This would provide a baseline almost perpendicular to the current one, completely resolving the angular position of the spacecraft.

With such a baseline, ESA could be independent of outside help for delta-DOR tracking.

Setting up the System

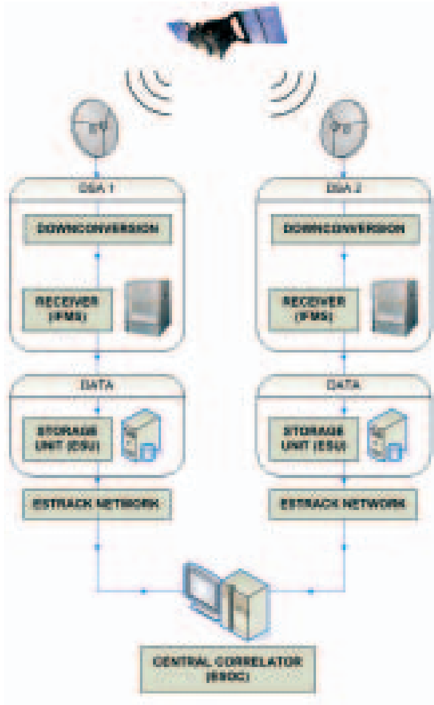
Creation of the delta-DOR system was done step by step. Several elements of the existing infrastructure had to be modified and some created *ex novo* to meet the highly demanding requirements on a very tight schedule.

Receiver modifications

The existing Intermediate Frequency Modem System (IFMS) receiver had to be modified for simultaneous reception of multiple signals and to synchronise the raw data, essential for achieving the required accuracy.

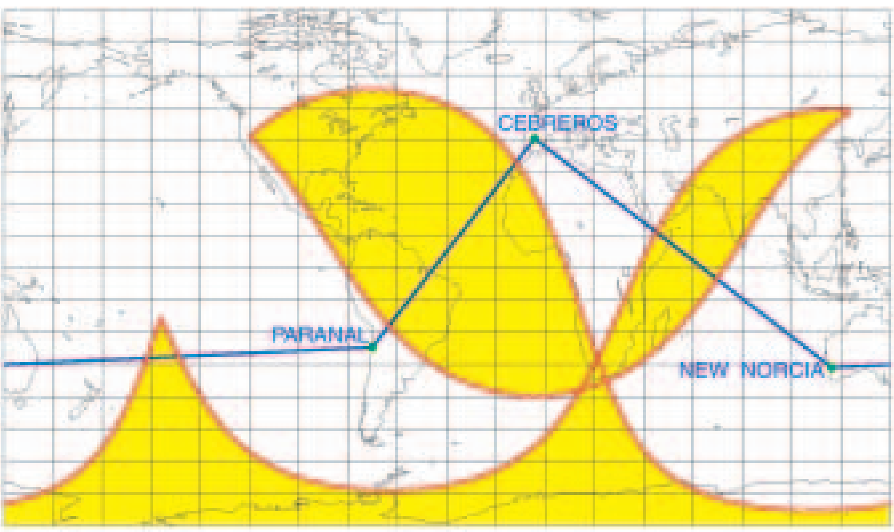
The IFMS is a multi-mission receiver developed by British Aerospace under ESA contract for a large variety of routine tracking purposes – telecommand transmission, telemetry reception, data decoding, ranging and Doppler measurements. In order to support delta-DOR measurements, the IFMS was upgraded to receive up to eight channels in different portions of the downlink spectrum with a relative time-tag synchronisation among the channels of better than 1 nsec. Remote installation of the software (another characteristic feature of this receiver) then allowed a fast upgrade of the receiving system in both antennas. For redundancy, two of the three receivers in each station were upgraded.

Two External Storage Units (ESUs), each an off-the-shelf server, were added to each station to offload the storage burden from the receiver. They also permit fast formatting and long-term storage of the data.



The system updated for delta-DOR: the improved receiver, the storage units at each station, the modified wide-area network and the development and installation of a software correlator at ESOC

Areas of mutual visibility (greater than 10° above the horizon) between DSA-1 (New Norcia), DSA-2 (Cebreros) and a hypothetical station in Paranal (Chile), highlighting the advantage of having a third antenna



Data transfer

Once the data have been stored on the ESUs, they are transferred to the correlator at ESOC for processing. The quantity is substantial (up to 11 Gbyte) – mainly from the quasar observations. Furthermore, they must reach ESOC within 12 hours in order to be used for navigation within 24 hours of the observations. To cope with these restrictions and to keep the costs down (so no dedicated data links), existing resources had to be used. Both stations are connected to ESOC via a triangular network, where each side has a 2 Mbit/s capacity. For the delta-DOR data transfer, the capacity is used on a best-effort basis, on both the direct line (single hop) and the indirect line (dual hop). The busy lines, especially for New Norcia, required special data retrieval and stacking algorithms. (See also 'New Communication Solutions for ESA Ground Stations' in *ESA Bulletin* 125.

A high throughput was achieved: an average of up to 1.2 Gbyte/hour from

New Norcia and up to 1.4 Gbyte/hour from Cebreros, or up to 95% of the available bandwidth.

The correlator

The data are finally collected and processed in a 'correlator' explicitly designed for delta-DOR processing. The challenge in this case consisted of containing the costs (thus building a *software* correlator instead of the more complex and expensive hardware correlator normally used) and the very tight schedule. Defining the software requirements and identifying the interfaces with all the other elements was a demanding task, requiring the analysis of similar processors developed by NASA's Jet Propulsion Laboratory and radioastronomy systems. The Department of Aerospace and Astronautical Engineering of the University of Rome 'La Sapienza' developed this software correlator. The host machine is an off-the-shelf server with enough computational power to process the data to meet the 24-hour constraint.

Flight dynamics support

An important role during all phases is played by the ESOC Flight Dynamics team, who support the planning, execution and evaluation of delta-DOR observations by:

- identifying suitable quasars near to the direction of the spacecraft, and providing visibility information;
- providing accurate orbit predictions to the correlator, including derived quantities like expected one-way range and range-rate values for both the spacecraft and quasar for both stations;
- processing the reduced DOR data within complex software to generate the delta-DOR residual (the difference between the actual measurement and its value predicted from mathematical models) and, together with the processing of the conventional data, to determine the spacecraft orbital parameters.

Two IFMS receivers were upgraded at each ground station

Delta-DOR Operations

The two ground stations are usually remotely operated from the Ground Facilities Control Centre in ESOC. Orbit predictions required to point the antennas to the object are delivered to the stations on a routine basis. The unique delta-DOR feature is the production by the Flight Dynamics team of predictions for quasars. The operations of all ground elements supporting delta-DOR (ground stations, correlator, Flight Dynamics, communications, ESOC facilities) are scheduled according to Flight Dynamics requirements, which mesh with station usage by other missions, and in coordination with a delta-DOR observations planning team. The data recorded at the ground stations are retrieved offline via the correlator workstation during or just after the observation itself.

Based on the raw data, and on the prediction files provided by Flight Dynamics, the correlator extracts the delay between the signal arrival times at the two stations required for the orbit determination software. These are delivered to the Flight Dynamics team to calculate the spacecraft's orbit.

The Validation Campaign with Mars Express

Testing of ESA's delta-DOR system began in late 2005 using Rosetta and Venus Express. Around the same time, DOR measurements were made of pairs of quasars (one of each pair representing the spacecraft) so that the correlation of the quasar signal could be validated. In January and March 2006, test DOR data were obtained from Mars Express.

Of all these tests, those with Mars Express were the most important. While in orbit around Mars, its trajectory is determined using only Doppler data, with a resulting error in its position relative to the planet of usually less than 200 m. Our knowledge of the position of Mars itself has about the same accuracy. Mars Express could thus be used to evaluate the real accuracy of the delta-DOR measurements.

The Mars tests revealed a correlator problem that caused the delta-DOR measurements to be wrong on the order of 5 nsec. After this was corrected, processing of the six sets of DOR data showed that all but one of the delta-DOR measurements were accurate to better than 0.5 nsec (the goal was 1 nsec). The other gave 0.7 nsec; this was caused by using a quasar 15º from the spacecraft (the standard is within 10º).

The Operational Venus Express Campaign

Following these encouraging results, and although the project was still in its validation phase, it was decided to make delta-DOR measurements of Venus

Express and use them operationally. Fifteen data points derived from sessions on five occasions in March and early April 2006 augmented a total of 45 NASA measurements obtained at the same time, mainly from the Goldstone-Canberra baseline.

Pre-launch analysis had shown that, under normal circumstances, the navigation accuracy needed for insertion into orbit around Venus could be achieved with range and Doppler data only. Delta-DOR increased confidence, because it could confirm the basic correctness of these conventional orbit solutions.

Also, delta-DOR covered the contingency case of the spacecraft switching to its basic safe mode during the last few days before arrival at Venus. In that case, thrusters would fire autonomously and perturb the orbit with a velocity increment of unknown magnitude and direction and imprecisely-known timing. Delta-DOR would reveal the orbit much faster than conventional data.

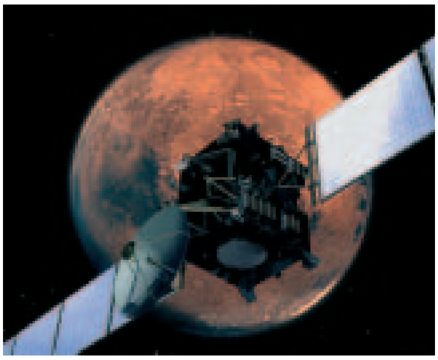
Analysis showed that the quality of these ESA measurements was only slightly inferior to those obtained using NASA's 34 m antennas. The most accurate were obtained with NASA's 70 m dishes. Although the delta-DOR data substantially reduced the navigation uncertainties, the improvement was not as marked as that for Mars Express. This was mainly due to a combination of unfavourable geometry and problems achieving consistent modelling of small accelerations from solar radiation pressure and possible outgassing from the spacecraft.

Despite this, the single most important navigation parameter, the minimum altitude above Venus at arrival, was only 3 km higher than the predicted 386 km. Even with all the information available after the event, it is not possible to distinguish entirely between small navigation errors and the small difference between the actual and expected performance of the orbit insertion.

The Future

On 25 February 2007, Rosetta will swing by Mars at a planned altitude of 250 km. Errors in the swingby are fuel-expensive to correct afterwards, so it is planned to make both NASA DSN and ESA delta-DOR measurements, mostly in January and February.

In early 2007, Rosetta will appear in Earth's southern sky, at the limit of simultaneous visibility from Goldstone and Madrid for NASA. It is expected that very few, if any, DOR measurements can be made from this baseline. This means that, in order to exploit delta-DOR capabilities to obtain complete direction information (that is, use two baselines), one must be of NASA stations and the other of ESA stations – a truly complementary arrangement between two space agencies.



ESA's delta-DOR measurements will be important for combining with NASA's information during the Rosetta flyby of Mars in February 2007

Future interplanetary ESA missions will also benefit from this technique. It is expected that it will help BepiColombo to make significant fuel savings in its correction manoeuvres. In preparation, a SMART-1 tracking campaign validated the capability of the system to record and process dedicated DOR tones transmitted by the spacecraft.

Finally, collaboration with NASA and Japan will be improved by the development of data translators to exchange data and results. This will greatly extend the number of baselines available for delta-DOR observations, benefiting everyone involved in the navigation of deep space probes. e