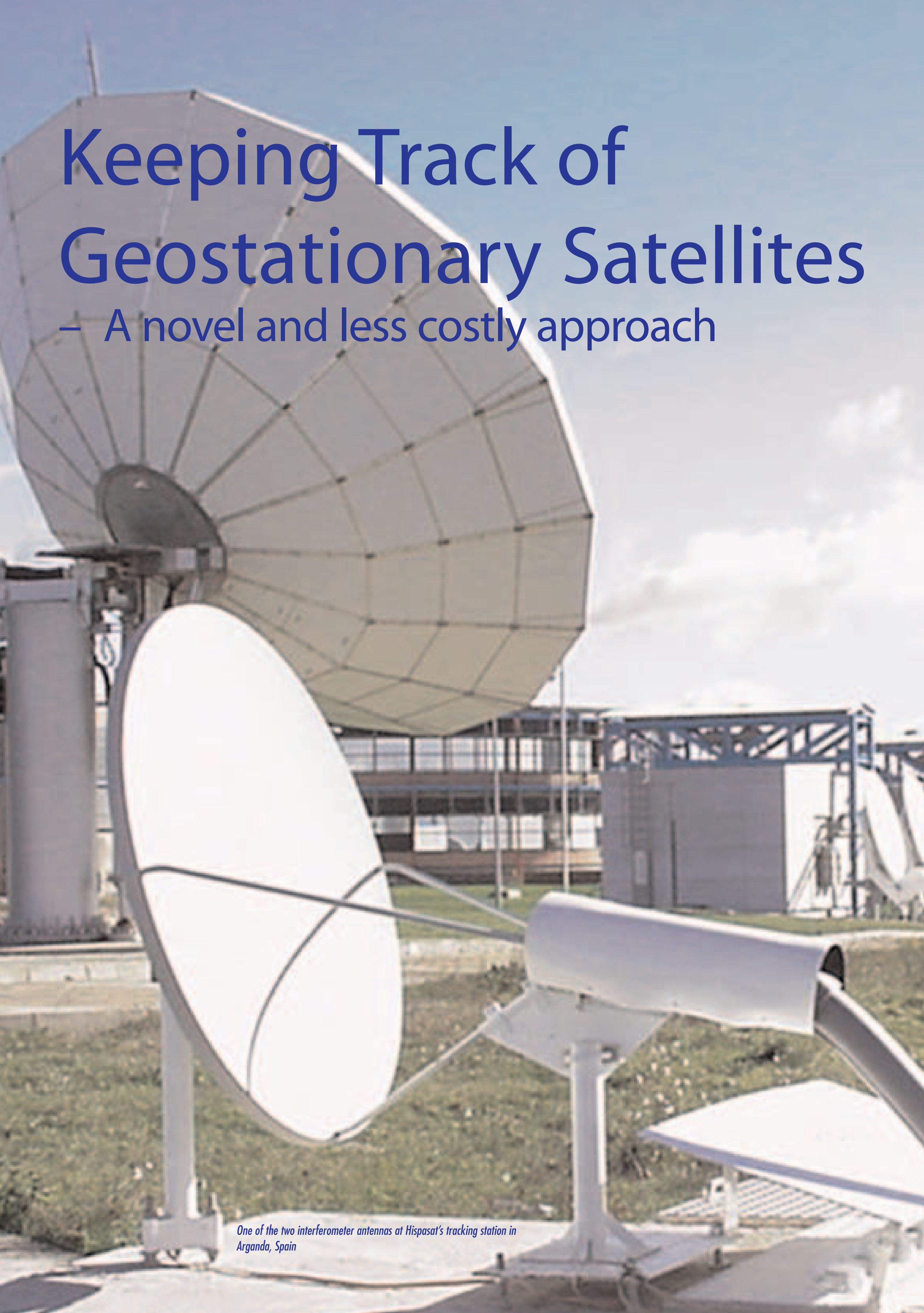
Keeping Track of Geostationary Satellites

– A novel and less costly approach



One of the two interferometer antennas at Hispasat's tracking station in Arganda, Spain

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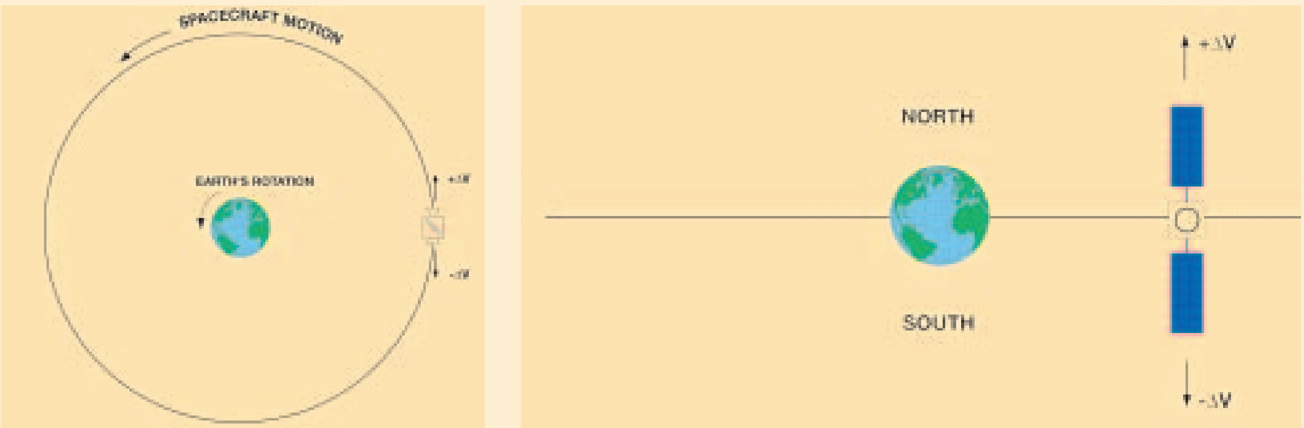
The Nature of the Problem

The usual way to establish a satellite's orbit is based on measuring the distances between it and so-called 'ranging antennas' on the Earth at different times. These distances are determined by measuring the time needed for a radio signal to make the round trip between the ranging antenna and the spacecraft. If this distance is measured at several different times, and possibly also using several antennas at different geographical locations on the Earth's surface, the spacecraft's orbit can be uniquely identified. Parameters affecting the spacecraft's motion, such as the solar radiation pressure or imperfectly known equipment parameters like delays in the spacecraft's transponders and/or in the ranging equipment on the ground, can be identified/determined as part of this process. Determining these additional parameters makes the mathematical modelling more precise and therefore also increases the accuracy with which the spacecraft's true orbit can be established.

The Geostationary Orbit

Most telecommunications and many weather satellites are operated in what is known as a 'geostationary orbit'. This is a circular orbit high above the Earth's equator with a radius of 42 164 km (about 6.6 Earth radii). This is the radius for which the time taken by the satellite to complete one orbit is the same as that taken by the Earth to rotate once around its axis, namely one day. This is consequently the altitude at which the 'centrifugal force' caused by the rotation of the Earth is equal to its gravitational attraction. As the satellite in geostationary orbit always appears to be at the same point in the sky when viewed from a given point on the Earth's surface, it means that a fixed antenna on the ground can be used to communicate with it. Millions of private households all over the World use such a fixed (dish) antenna to receive TV and radio programmes broadcast via satellite.

In practice, the gravitational attractions of Sun and Moon, the solar radiation pressure and the slight misalignment between the centrifugal force and the Earth's gravitational force disturb the sought-after 'equilibrium'. To compensate for these disturbing effects, an orbit-maintenance strategy has to be worked out, consisting of 'tangential burns' and 'out-of-plane burns' of the satellite's onboard thrusters to continuously adjust the actual orbit and keep it as ideal as possible. In order to design the necessary correction burns optimally, the satellite's real orbit has to be determined very accurately.



The geostationary orbit and the concept of tangential and out-of-plane burns

Accurate orbit determination for geostationary spacecraft poses particular problems for the very same reason that these orbits are used, namely the geometry of the spacecraft relative to Earth-fixed objects does not change and so the orbit cannot be determined by making ranging measurements from a single ground station at different times. The most common way to overcome this conundrum is to combine the ranging measurements with pointing data from a high-gain antenna. This antenna must then be controlled such that it automatically finds the pointing direction for which the strength of the signal from the satellite is a maximum (this is known as the 'auto track' mode). This 'best' pointing direction (azimuth and elevation) is then used as additional data for the orbit determination.

However, the pointing data obtained in this way only has an accuracy in the order of ± 0.01 deg – the larger the antenna, the narrower the beam and the better the accuracy. This accuracy is certainly good enough for the basic orbit-maintenance strategy for a single spacecraft, but with many 'co-located' spacecraft occupying the same nominal position on the geostationary ring, more accurate orbit determination is needed for the implementation of an additional 'collision-avoidance' strategy. Most operators with several spacecraft at the same geostationary position therefore have a second ranging antenna at a remote location. Hispasat, for example, which is a Spanish commercial satellite operator, has its control centre in Arganda close to Madrid and an additional ranging station on the Canary Islands.

The Novel ESA Solution

The problem of orbit determination for geostationary spacecraft was analysed at ESOC in considerable detail about 10 years ago by the late Mattias Soop. He found that, provided that the longitudes of the spacecraft and the ground station were significantly different, it is not necessary to have both azimuth and elevation data from an antenna to be able to determine the satellite's orbit accurately; it is sufficient to have only one of these parameters determined as a function of time. He called this a 'One-and-a-Half Tracking System' (presented at the Conference on Space Flight Dynamics in Toulouse in June 1995). Furthermore, it is not even necessary to ascertain the parameter directly, but it is enough to know the variation in the parameter over a sufficiently long time interval. This led him to propose the novel solution of using an interferometer for the orbit determination of geostationary spacecraft.

The interferometer technique relies on measuring the interference between the radio signals from the spacecraft as received by two antennas (see figure). The direct output of such an interferometer would only be the phase difference as a fraction of a wavelength. If, for example, this difference were 0.3 of a wavelength, one cannot know a priori if the difference in distance to the spacecraft for the two antennas is -1.7, -0.7, 0.3, 1.3, 2.3, etc. It is therefore not possible to determine the azimuth directly. But as this shift changes only slowly (the basic cycle has a period of one day), and as this shift can be monitored continuously, the change in azimuth can be determined unambiguously and with a very high accuracy – in fact orders of magnitude better than the pointing accuracy obtained from an antenna in 'auto-track mode'. The resulting orbit determination is even accurate enough for co-located clusters of spacecraft that require a collision-avoidance orbit-control strategy, making a second, costly, and remotely located ranging terminal unnecessary.

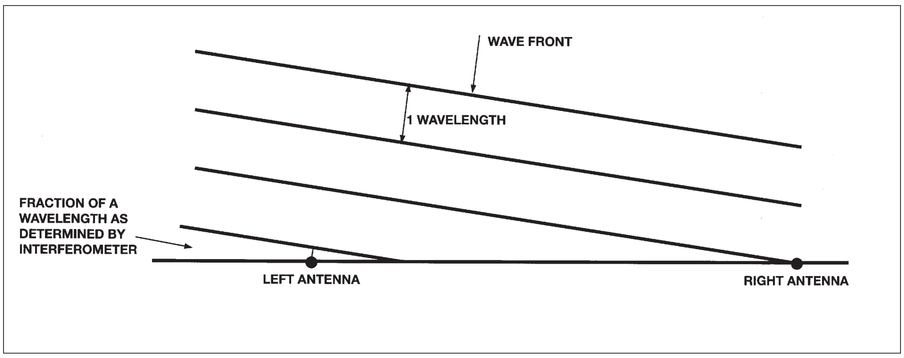
Now, 10 years later, such an interferometer has been built and tested at Hispasat's tracking station in Arganda, Spain. Developed by the Spanish company CRISA under an ESA contract, it consists of two identical parabolic antennas sited just 250 metres apart. Signals received at both antennas are transmitted to a central electronics rack by means of wide-band phase-stable optical fibres that can handle frequencies of up to 20 GHz (see accompanying panel).

The accompanying figure illustrates the basic output of the interferometer. It shows the difference in 'linear phase', which is

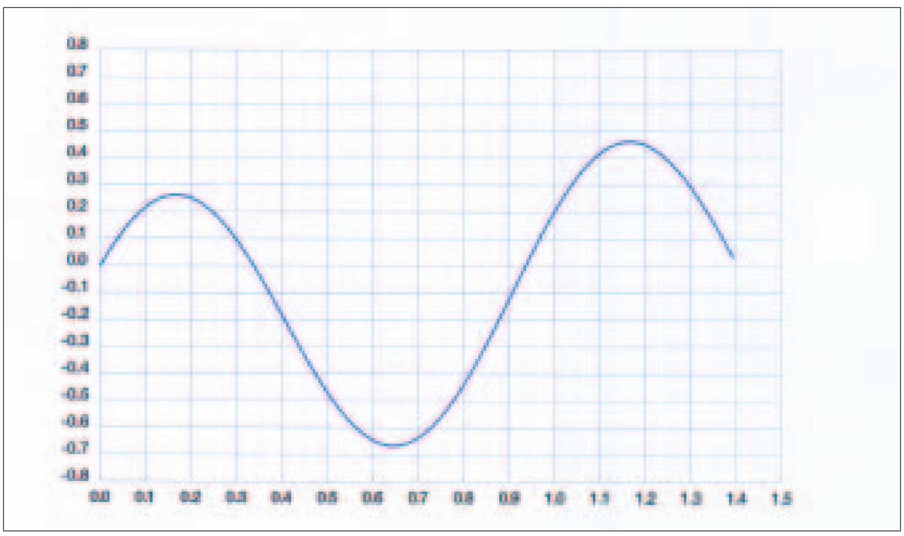
Why Use Optical Fibres?

The use of these fibres is a key element in the interferometer's performance for two reasons. Firstly, the excellent stability of the fibres as a function of temperature keeps the relative phase error between both antenna chains and the central rack within acceptable limits. Secondly, the wide-band characteristic of the fibres allows the signal transmission to the central rack to be made at spacecraft received frequencies. This removes the need for distributed down-conversion equipment, which would otherwise be a major source of phase errors in the system, and enables a centralised dual down-converter design, in which intermediate frequencies are generated directly at the central rack, thereby minimising phase errors due to local oscillator frequencies and their transmission to remote equipment.

Following the dual down-converter, both intermediate frequencies are digitised, such that their Fourier transform can be computed. This allows the relative phase difference between the two signal chains to be measured accurately over time and stored for further processing. This process is not limited to a single spacecraft and can be simultaneously performed for all satellites within view and within the receiver's frequency band.



The principle of the interferometer technique



Typical output from the interferometer essentially the difference in distance to the spacecraft from the left and right antennas. Because this phase shift is permanently monitored and its rate of change is slow compared with the sampling frequency, the change in this 'linear phase' can be computed without ambiguity (positive/negative and number of wavelengths). In the example shown, the daily variation has an amplitude of 513 mm, which corresponds to about 22 wavelengths. This variation is due to the fact that the spacecraft's orbit is neither perfectly circular nor perfectly equatorial.

The basic accuracy obtained with one set of measurements used for one Fourier Transform is about 5% of a wavelength. With a frequency of 13 GHz this is about 1.2 mm. The corresponding directional accuracy with 250 m between the antennas is then 1.2/250000 radians, or about 0.0003 deg. This compares with the approximately 0.01 deg pointing accuracy of an auto-track-mode antenna. It must, of course, be remembered that the interferometer does not directly measure azimuth direction, but only the change of this azimuth with time. However, provided the longitude of the spacecraft is significantly different from the longitude of the tracking station, the high accuracy of the interferometer more than compensates for any accuracy dilution due to having to determine this additional parameter.

The Software

The orbit-determination programs that make up the ESOC 'export package' for geostationary orbit control have been extended to accept the interferometer data. This upgraded software package has already been applied to accurately determine the orbit of the Hispasat-1A satellite, using data from a ranging antenna in Arganda (close to Madrid) provided by the Hispasat organisation, and from the CRISA interferometer also installed on this site. Used in combination with interferometer ranging, this ESOC software package (PEPSOC - Portable ESOC Package for Synchronous Orbit Control) is the ideal system for optimal and cost-efficient orbit control for either a single spacecraft, or a cluster of several spacecraft sharing a common position in the geostationary ring. esa