Satellite Laser-Ranging Campaigns

GIOVE's Track

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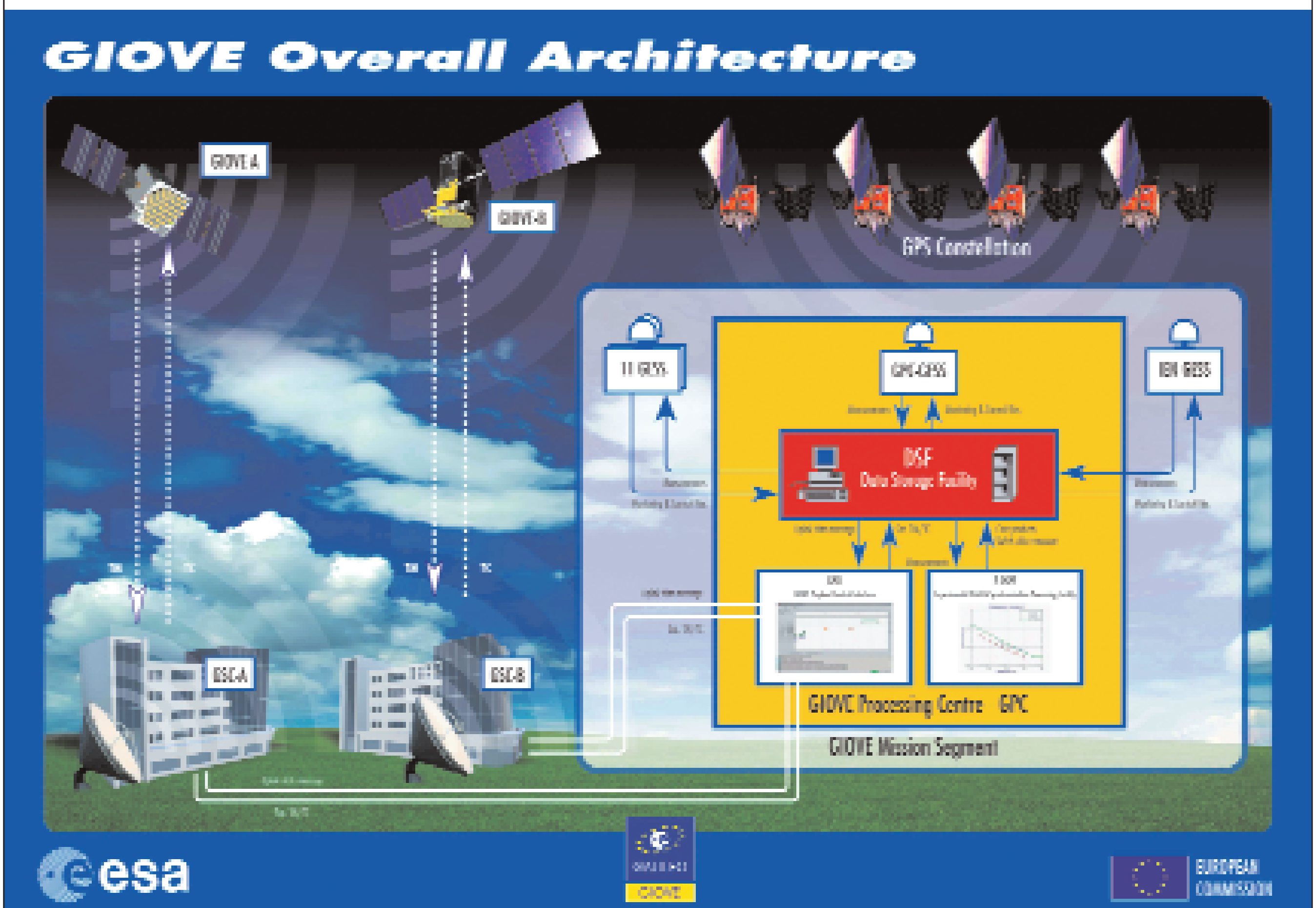
In preparation for the deployment of the Galileo system, the European Space Agency (ESA) began development in 2003 of two Galileo In-Orbit Validation Element (GIOVE) satellites: GIOVE-A and GIOVE-B. The objectives of the deployment of these two satellites are to:

- secure use of the frequencies allocated by the International Telecommunications Union (ITU) for the Galileo system
- verify the most critical technologies of the operational Galileo system, such as the on-board atomic clocks and the navigation signal generators
- characterize the novel features of the Galileo signal design, including the verification of user receivers and their resistance to interference and multipath, and
- characterize the radiation environment of the medium-Earth orbit (MEO) planned for the Galileo constellation.

GIOVE-A and -B were built in parallel to provide in-orbit redundancy and to secure the mission objectives. They provide complementary capabilities.

GIOVE-A was launched on December 28, 2005, into an MEO with an altitude of 23,260 kilometers. Carrying a payload of rubidium clocks, signal-generation units, and a phase-array antenna of individual L-band elements, GIOVE-A started broadcasting on January 28, 2006, securing the frequencies allocated by the ITU for Galileo.



▲ **FIGURE 1** GIOVE overall architecture

GIOVE-B, to be launched in 2007, will complement the first satellite with an additional passive H-maser clock and will transmit the Galileo signal on three separate carriers simultaneously: E1, E5, and E6.

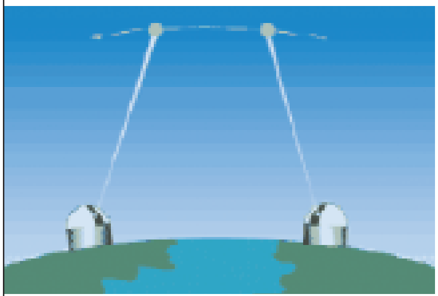
The GIOVE mission segment consists of a global network of Galileo Experimental Sensor Stations (GESSes) and a GIOVE Processing Centre (GPC), located at ESA's European Space Research and Technology Centre (ESTEC) in Noordwijk, the Netherlands.

The GPC computes precise orbits and clock offsets of the GIOVE satellites based on measurements collected by a global network of GESSes on Galileo and GPS satellites at a 1 Hz sampling rate. Navigation messages generated by the GPC are uplinked to the satellites through each of the satellite control centers: GSC-A at Guildford, United Kingdom, for GIOVE-A, and GSC-B at Fucino, Italy, for GIOVE-B (see **FIGURE 1**).

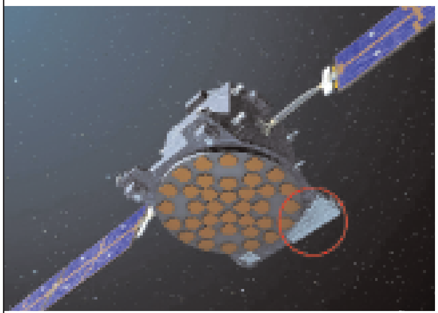
Satellite Laser Ranging

Performance of the on-board atomic clocks, antenna infrastructure, and signal properties is evaluated through precise orbit determination, supported by satellite laser ranging (SLR), an independent high-precision technique for orbit determination (see **FIGURE 2**) based on a global network of stations that measure the round-trip flight-time of ultra-short laser pulses to satellites equipped with laser retroeflector arrays (LRAs). SLR provides instantaneous range measurements of millimeter-level precision which can be compiled to provide accurate orbits.

GIOVE-A is equipped with an LRA with 76 corner cubes (see **FIGURE 3**), which provides a return energy about 40 percent higher than the GPS reflectors. Only a fraction of the SLR stations are capable of ranging (mostly at night) to the GIOVE and GPS satellites due to the high altitude and the relatively small size of the LRAs (see **FIGURE 4**).



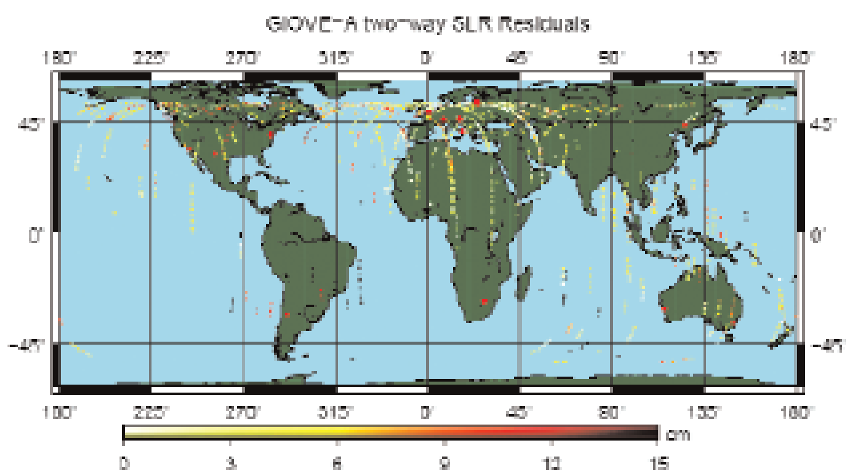
▲ **FIGURE 2** SLR provides two-way range measurements from laser stations to satellites carrying laser retroreflector arrays



▲ **FIGURE 3** GIOVE-A and its laser retroreflector array

In order to separate clock and orbit effects, the GIOVE mission segment simultaneously measures ranges using the GIOVE-A radio navigation signals and ranges using SLR. The radio ranges include the effects of the clocks while the laser ranges do not. The geographical distribution of SLR data provided enough accuracy to the orbit determination, helping to separate the clock offset in the radio navigation signal from the orbit dynamics, and, therefore, observing the clock behavior.

▲ **FIGURE 4** World map showing geographical distribution of satellite laser-ranging stations that participated in the first GIOVE-A ranging campaign



▲ **FIGURE 5** GIOVE-A two-way SLR residuals

TABLE 1 Week-based SLR-only orbit determination results

Week	Time Span	Stations	Observations	Rejected	RMS (cm)
1	22 MAY–28 MAY	5	70	0	1
2	29 MAY–04 JUN	6	102	2	1
3	05 JUN–11 JUN	9	280	9	4
4	12 JUN–18 JUN	8	320	0	3
5	19 JUN–25 JUN	7	97	0	2
6	26 JUN–02 JUL	11	191	13	2
7	03 JUL–09 JUL	7	75	0	1
8	10 JUL–16 JUL	8	189	0	2
9	17 JUL–23 JUL	10	285	20	4

The International Laser Ranging Service (ILRS) has agreed to support the GIOVE mission by providing SLR data during tracking campaigns coordinated with the GPC at ESA ESTEC. It is especially interesting to have some SLR campaigns during satellite eclipse period when temperature changes might affect navigation performance.

First Campaign Results

The first tracking campaigns took place between May 22 and July 24, 2006, with participation from 14 globally distributed SLR stations. In addition to confirming the good health of the LRA on GIOVE-A after launch, the SLR data has been essential for a health check and a preliminary characterization of the on-board rubidium clocks.

This nine-week campaign provided abundant SLR observations in the form of normal points, which are 5-minute averages of single-shot range measurements at 4–10 Hz.

This campaign demonstrated, once more, the high quality of the SLR data. **TABLE 1** shows the results, obtained by the Navigation Office at the European Space Operations Centre (ESOC), for a week-based SLR-only orbit determination process. The table shows the number of stations and amount of data accepted and rejected in the process, and the root mean square (RMS) of the residuals (the difference between the observed laser range and the estimated orbit).

The dynamic model used for these results included an expansion of the Earth gravity field in 15 x 15 harmonic coefficients based on the GRACE-02 model; solid tides (deformation of the Earth crust due to the sun and the moon); effect of the sun, the moon, and major planets on the satellite; relativistic acceleration; solar radiation pressure on the satellite (based on CODE mode by the University of Bern) with five estimated parameters; and estimation of the state vector as three position coordinates and three velocity coordinates.

Due to the geographical location of most of these SLR stations, the best coverage occurred over Europe and Central Asia, North

America, and Indian Ocean and Australia. **FIGURE 5** shows the participating stations and the two-way (or round-trip) laser range residuals as ground tracks on a world map.

At the time of this first campaign, only part of the GIOVE mission segment infrastructure was deployed, with only two of 13 sensor stations (ESTEC, the Netherlands, and Torino, Italy) in operation: The SLR data enabled a dramatic improvement in the orbits to an accuracy of 20 centimeters and the clock to an accuracy of 1 nanosecond.

SLR Station in China

Given the importance of SLR data for the characterization of the GIOVE clocks, the People's Republic of China contributed to the Galileo program the refurbishing of a Chinese SLR station to provide GIOVE laser-ranging observations. This enhanced SLR station is located in Changchun in northeast China and was selected among the Chinese stations contributing to the ILRS because it had demonstrated strong MEO satellite tracking; collocation with an existing International GPS Service station; and good weather conditions.

At the time of this writing, refurbishing work had been finished and acceptance tests were underway. As part of this acceptance test, the observations performed by Changchun at the time of the campaign were included in the data set as the data revealed itself to be of high value for the analysis carried out. The geographical location of Changchun (see Figures 4 and 5) was of primary importance in providing better laser-ranging coverage of GIOVE-A.

Future Campaigns

Currently, deployment of the GESSes is underway; the first six stations were deployed by the end of October and the next six stations will be deployed by the end of November. Two campaigns will be organized in collaboration with the ILRS, aiming to further improve knowledge of the orbit and onboard clocks.

In 2007, at least four additional campaigns are planned to characterize and validate orbital modeling of the GIOVE-A satellite during specific conditions such as eclipses, and to support these measurements for GIOVE-B as soon as it is launched.

ESA acknowledges the important role of the ILRS in coordinating this effort and fully recognizes the activities of the SLR stations that will participate in the GIOVE-A and -B measurement campaigns.

For more information on the International Laser Ranging Service, visit *http://ilrs.gsfc.nasa.gov.*

Manufacturers

GIOVE-A was developed by **Surrey Satellite Technology Ltd.** (UK), and GIOVE-B by a European consortium including **Alcatel Space Industries** (France), **Alenia Spazio** (Italy), **Astrium GmbH** (Germany), **Astrium Ltd.** (UK), and **Galileo Sistemas y Servicios** (Spain). Laser retroreflector arrays were manufactured by IPIE of Russia.