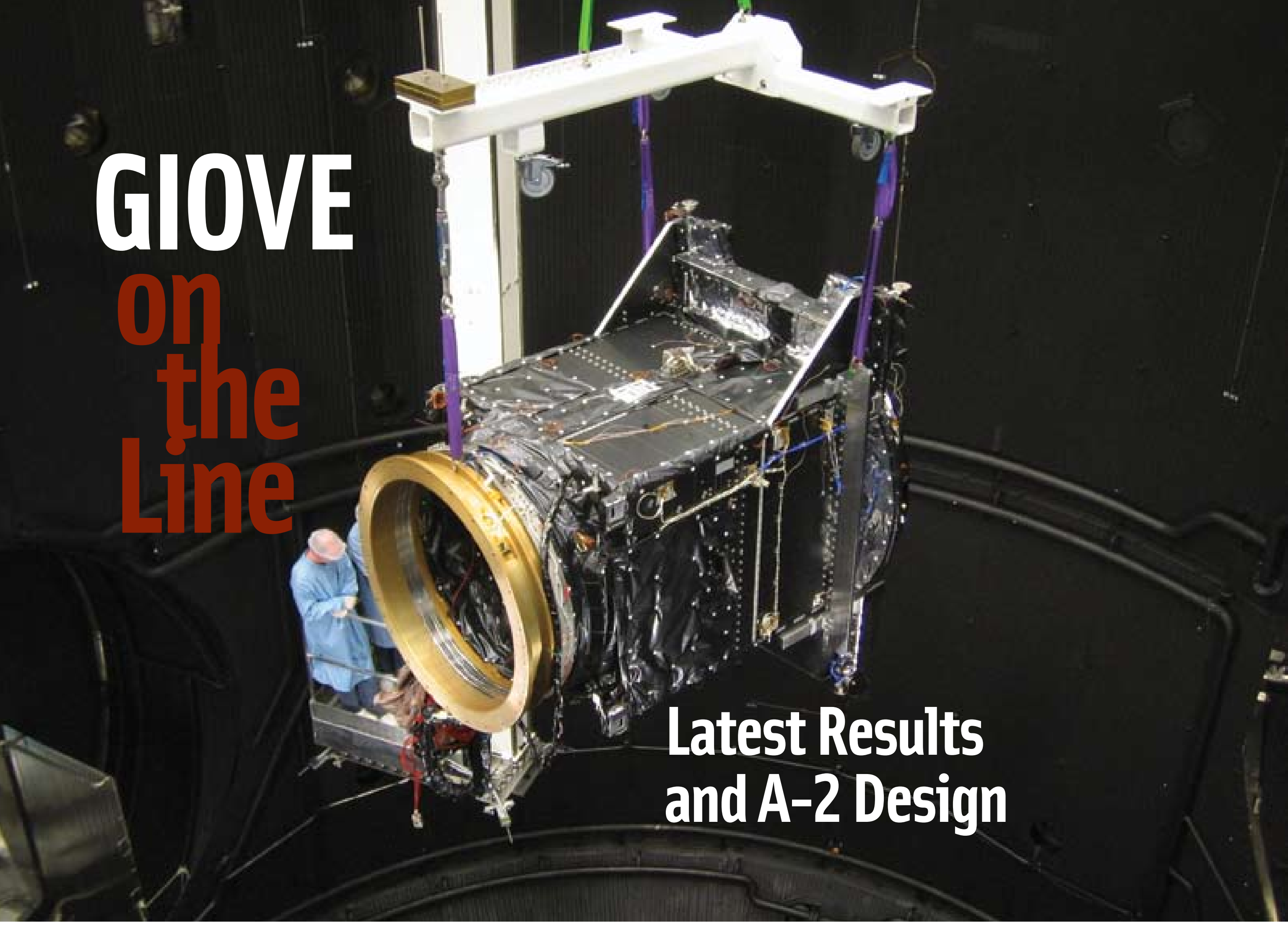

GIOVE on the Line

Latest Results and A-2 Design

The sole spacecraft in the Galileo constellation, GIOVE-A (which will be getting company soon), has been transmitting experimental signals for the past two years. During that time, a series of tests have led to refinements in payload operations. This article by engineers at GIOVE-A's manufacturer and the European Space Agency describes the signal and clock experiment results as well as the plans for a new version of the satellite, GIOVE-A2.

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Europe commenced the space element of its Galileo more than two years ago with launch of the GIOVE-A (Galileo In-Orbit Validation Element-A) demonstration satellite (also known as the Galileo Satellite Test Bed-V2/A).

Along with its larger sibling, GIOVE-B, now due to launch in April 2008, GIOVE-A precedes introduction of the four IOV satellites, scheduled for launch in 2010. Built by Surrey Satellite Technology Ltd (SSTL), based in Guildford, the United Kingdom, GIOVE-A was launched in December 2005 and has been broadcasting prototype Galileo signals to the world since early 2006.

During this period, much has been learnt from the experimental campaign and the measurements taken on the ground. The signal-in-space (SIS) specification has been brought into the public domain on European Space Agency's (ESA's) website, where the GIOVE-A SIS Interface Control Document (ICD) can be downloaded. (See the Additional Resources section at the end of this article for the website URL.)

Recent activities include the detailed investigation into the end-to-end Galileo signal channel. A payload test-bed at SSTL has been used by ESA and Surrey Satellite for comparison with the signals received from orbit.

Following the success of GIOVE-A, and to assist with contingency planning prior to IOV launch, ESA awarded a further contract to SSTL in March 2007 to begin procurement of another satellite, GIOVE-A2, largely based upon the GIOVE-A design. GIOVE-A2 incorporates minor design improvements based on lessons learnt from the first satellite.

Design commonality will permit SSTL to manufacture the satellite to a very tight timescale, to be ready for launch, if requested, as early as mid 2009.

ESA and SSTL are investigating the capability of modifying GIOVE-A2 to broadcast multiplex binary offset carrier (MBOC) designs to permit early experience with the new MBOC-based signals in anticipation of the operational Galileo system.

This article will describe the current status of the GIOVE-A satellite and the achievements that have been made during the operational phase of the mission. We will then summarize briefly the current status of GIOVE-A2, concentrating on the main differences in the payload and signal-in-space from the earlier satellite.

From the Beginning

GIOVE-A was launched from the Baikonour cosmodrome in Kazakastan on December 28, 2005. Its main mission objectives were to protect the Galileo frequency filings, provide early in-orbit validation of the Galileo payload units, measure the MEO radiation environment, and enable signal-in-space (SIS) experimentation.

GIOVE-A's signal-in-space is fully representative of the operational Galileo system in terms of radio frequency and modulations, as well as chip rates and data rates. However the spreading codes differ from those planned for the operational satellites. Furthermore, the navigation message is not representative from the perspective of structure and contents and is used for demonstration purposes only.

Following a successful launch and early operations phase (LEOP) and platform commissioning, the payload units were commissioned in early January 2006. Planned operations to commission the payload and perform the initial in-orbit testing (so called Payload COP/IOT) lasted a period of almost 2 months. Following that, the extended IOT (E-IOT) measurement campaign started for a period of three to four months before the routine operations phase commenced. **Figure 1** presents an overview of the initial GIOVE-A operations.

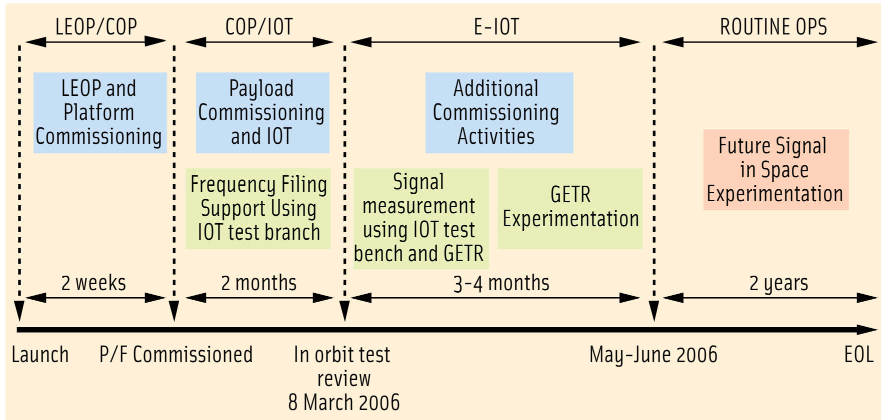

FIGURE 1 **GIOVE-A operations**

The results from the successful IOT campaign were presented publicly at the ION GNSS 2006 conference (see the article by M. Falcone et alia in Additional Resources.)

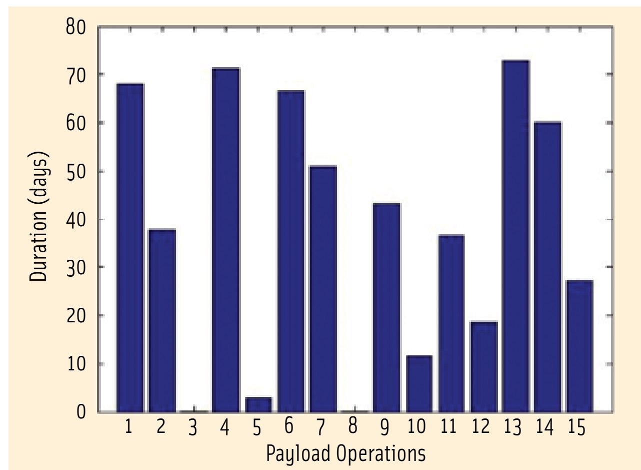

FIGURE 2 **GIOVE-A payload operations**

Payload Operations

During the IOT campaign in early 2006, various signal modes were transmitted from GIOVE-A to confirm the correct functionality and performance of the payload in orbit. These broadcasts also enabled ESA to gather sufficient data to support its claim that the Galileo frequency filings had been brought into use as required by the International Telecommunications Union (ITU).

GIOVE-A has three signal generators in the navigation payload. All of these initial activities were performed on the nominal payload A chain. Once the frequency filing activities were complete, the two redundant payload chains were then commissioned.

At the end of the commissioning activities and following an outage for anomaly resolution and platform maintenance, the satellite entered a more stable operating regime on May 17, 2006, using the nominal payload A chain. Since this time, payload operations have been continuous except for outages for platform maintenance or anomaly resolution. At all times, outages are minimized to maintain the availability of navigation signal transmissions.

From May 17, 2006, to January 13, 2008, (a total of 607 days) the payload has been operational for 454 days — an availability figure of more than 93 percent. Some 15 payload operations have taken place during this period, separated by outages of varying duration, as shown in **Figure 2**. Five of these outages were to perform planned maintenance activities onboard the satellite. Other outages were due to operations switching from one payload chain to another as well as some occasional glitches in the telemetry monitoring that caused the payload to be switched off.

The monitoring operations were reconfigured slightly in early December

2006, which resolved this issue and there have been no subsequent outages. Since this fix, the availability of the payload transmissions has increased to more than 95 percent.

A second in-orbit test campaign was performed during June and July 2007. Although several signals were generated during this campaign, we consider it a single test operation as the payload units operated continuously throughout the period. When the satellite is changing from one signal mode to another, the signal transmissions are turned off. However, these periods are very brief, typically only 15–20 minutes.

In the months of stable operations between the IOT campaigns, the GIOVE-A satellite broadcasts one of two nominal dual-frequency signal modes: E5 ALTBOC/E2L1E1 Interplex or E6 Interplex/E2L1E1 Interplex. GIOVE-A cannot broadcast all three frequency bands at once; therefore, operations alternate between the E5 and E6 signals as required for each of the experimentation activities. Typically, E5 – L1 signals are preferred for clock characterization experiments.

Second In-Orbit Test

A second comprehensive in-orbit test campaign was carried out on the GIOVE-A navigation signals during June and July 2007. This test campaign made use of the 25-meter dish at the Chilbolton Observatory, owned and operated by the Science and Technology Facilities Council (STFC) in the UK.

The Galileo test station also used the Chilbolton dish during the initial IOT campaign following the GIOVE-A launch with the same types of measurements taken during both campaigns. However, prior to the start of the latest testing a number of upgrades were performed on the station drawing on the experience of the first campaign. These upgrades included:

- fabrication and installation of a new L-band feed. This led to an improved noise floor and provided better cross-polar discrimination.
- relocation of the measuring equipment from the control room to the radio cabin. This improved the reliability of the measurements by removing several hundred metres of cable and two amplifier units from the signal path through the receiver chain.
- a better calibration procedure was used to derive the system noise temperature (Tsys), antenna sensitivity (G/T), and thus the antenna gain, G.

The Chilbolton test station calibration prior to the first IOT campaign followed a method that used ESA Artemis telecommunications satellite pilot signal as a reference at Artemis frequency and inferred gain across the band using G/T measurements from the Cassiopeia A extrasolar radio source. Using this approach made it necessary to assume either constant system temperature across the band or constant antenna efficiency across the band. We assumed a constant system temperature for this initial calibration exercise.

Assuming a constant temperature, however, led to an unrealistically high efficiency figure during the system calibration prior to the new campaign. On the other hand, if the efficiency determined at the Artemis frequency was used across the band, more realistic gains result.

To resolve this issue, we employed an alternative method for determining the antenna gain. The paper by N. Roddis cited in Additional Resources includes several references on the subject as well as the procedure that we followed in calculating the gain.

Two antenna noise figures (Y-factors) were extracted from measurements. The first is the ratio between cold sky measurements and those obtained with microwave absorber material placed in front of the feed. The second is the ratio between cold sky measurements and Cassiopeia measurements.

FIGURE 3 Antenna dish calibration measurements at Chilbolton

Signal Type	Measurements
Modulated signals	In-band spurious (IBUS) Out-of-band spurious (OBUS)
CW signals	EIRP In-band spurious (IBUS) Polarisation Purity

TABLE 1. Key measurements

The Y-factors are used to derive TSYS and G/T respectively, and hence G. **Figure 3** shows the tests that employed the absorber taking place on the dish.

The performance of the Chilbolton station during the initial IOT campaign proved to be very good and generated high-quality results to support both the frequency filing exercise and the initial commissioning and IOT measurements. The upgrades performed on the station for the recent campaign were an attempt to refine the system to improve the reliability and quality of the results even further, and also to increase the efficiency of the operations and data capture.

IOT Campaign

SSTL controllers directed GIOVE-A to broadcast a number of different signal modes during the in-orbit test campaign that enabled a wide range of measurements to be taken. **Table 1** lists the key parameters measured for each of the modulated and continuous wave (CW) signals. These parameters were measured during the initial IOT campaign

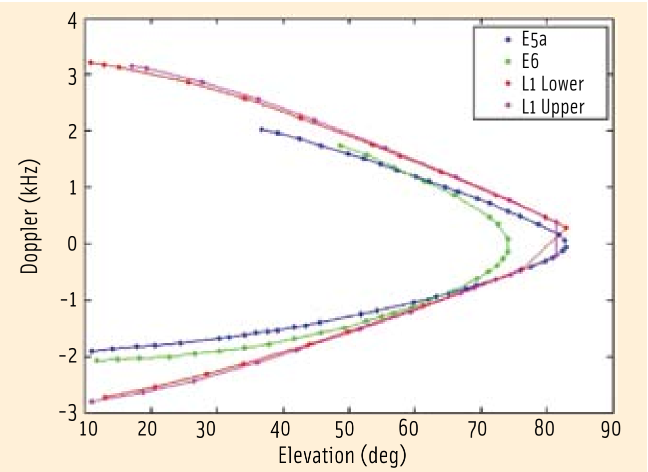

FIGURE 4 Measured Doppler on CW signals

and were repeated during the 2007 tests to look for any degradation in the performance of the payload in the 16 months between the two campaigns.

Table 2 lists the nominal signals designated for investigation during the measurement campaign. These consisted of the three primary signals broadcast during nominal operations. In addition, a CW signal was broadcast in each frequency band to confirm the effective isotropic radiated power (EIRP) of the payload transmissions.

Long-duration passes were selected for the CW signals so that power measurements could be taken over a large range of elevation angles. For all CW passes, alternate co- and cross-polar measurements were taken. At least two in-band spurious (IBUS) signal measurements were interspersed with these power measurements to provide in-band spectral plots.

During each pass dedicated to modulated signal measurements, at least two IBUS plots were taken of each signal being broadcast along with at least two full sweeps of the defined OBUS bands. Experience from the initial IOT campaign highlighted the benefit of having two independent measurements for each band of interest to help identify external inference sources.

EIRP and Received Power

We used the measurement of received power at Chilbolton to assess the EIRP of the satellite. Within the measurement accuracy, the EIRP estimate agreed well with the results from the initial IOT campaign.

In general the recent results are marginally lower than those taken in 2006. The reason for this is considered to stem from an improved value of antenna gain rather than any degradation in output power from the payload.

From a user perspective, received power is a more important parameter than EIRP, and **Table 3** presents the minimum received power in each frequency band. The results are within a dB of the requirements set out in the SIS ICD. It should be noted, though, that the transmitted power requirements on the GIOVE satellites are lower than for the IOV satellites.

CW Frequency

We measured the frequency of each of the transmitted CW signals in order to generate the Doppler shift at each point. (See **Figure 4**.) Because the E2L1E1 CW signal is a BOC(15,0), two CW-like signals are offset by 15 * 1.023 MHz on either side of the L1 center frequency.

We measure the frequency of each lobe separately. The Doppler results for the E5 and E6 signals are continuous smooth curves, as the station was able to track the signals throughout the pass. The elevation of the E2L1E1 pass was 84 degrees, however, which is above the limit of the dish. This break in the tracking of the E2L1E1 signal caused the discontinuity in the L1 lobes visible in Figure 4.

IBUS and OBUS

We performed IBUS measurements for both CW and modulated signals by executing a spectral sweep of the frequency band while a signal was being broadcast. An analysis of the IBUS for each of the CW signals detected no anomalies.

Signal Type	Measurements
Modulated signals	E5 ALTBOC E6 Interplex E2L1E1 Interplex
CW signals	E5a CW E6 CW E2L1E1 BOC(15,0) CW

TABLE 2. Nominal signals

Frequency	Minimum Received Power (dBW)
E2L1L1	-156.6
E5a	-154.4
E6	-154.1

TABLE 3. Minimum received powers

Designation	Frequency Band (MHz)
GPS L2	1215.60 – 1239.60
GLONASS L2	1237.8275 – 1252.2220
GLONASS L1	1592.9575 – 1610.0000
SAR	1544.2 – 1544.8
RA9	1330.00 - 1427.00
RA10	1610.60 - 1613.80
RA11	1660.00 - 1670.00

TABLE 4. OBUS bands investigated during IOT

These results were very similar to the previously reported results obtained in the initial IOT campaign Similarly, the spectral plots obtained for the modulated signals were consistent with the measurements from the initial IOT campaign, indicating that no degradation has occurred in payload performance.

The OBUS bands investigated during IOT were limited by the receiving bandwidth of the Chilbolton, which covers the band from 1100 MHz to 1700 MHz. The OBUS bands contained within this frequency span are listed in **Table 4**.

The noise floor of the Chilbolton measurements prohibited an in-depth investigation of spurious signals down to the level of the specifications. Therefore, these in-orbit tests were limited to looking for gross errors in the transmissions and confirming that the performance was comparable with the results obtained in 2006.

None of the OBUS results indicated any unexpected anomalies, and the plots were all in good agreement with the initial IOT results. So, again, no evidence of any degradation in payload performance

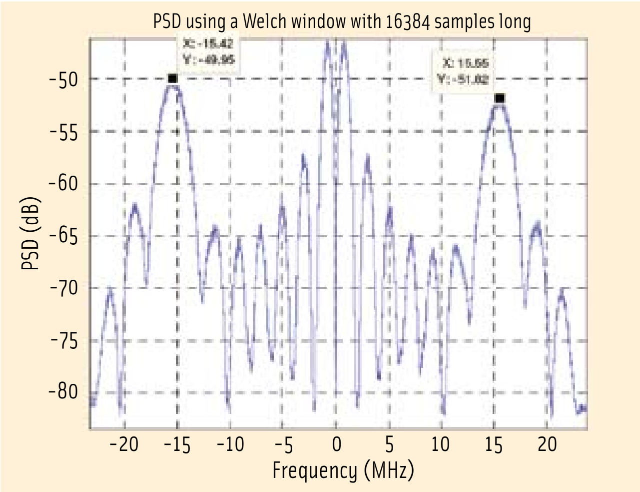

FIGURE 5 E2L1E1 interplex uncompensated spectral plot

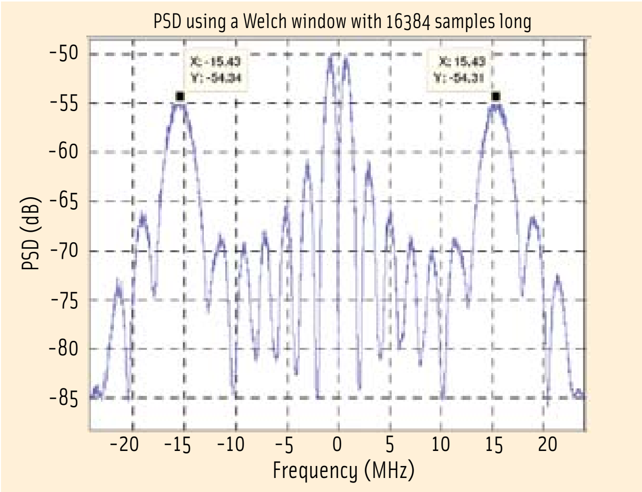

FIGURE 6 E2L1E1 interplex compensated spectral plot

or functionality emerged in these latest tests.

Payload Asymmetry

Since GIOVE-A was launched in December 2005 it is well known that the transmitted E2L1E1-A BOC(15,2.5)-C signal was asymmetrical in terms of spectral properties. Over the past number of months considerable time and effort has been spent in trying to assess and fix this asymmetry. The fix was successfully applied to the broadcast signal on July 19, 2007.

As reflected in **Figures 5** and **6**, the uncompensated spectrum has a 1.87 dB difference in the BOC(15,2.5)-C major lobes whereas after the fix the difference is 0.03 dB. Please note although these plots appear to show that the fix has lead to perfectly symmetrical lobes in fact there is still a difference between the lobes because the amplitude response of the Chilbolton station needs to be taken into consideration when interpreting these results. There is still about 0.7 to 0.9 dB asymmetry in the signals. These are preliminary results which will be refined in due course.

Future Work with GIOVE-A

The design life for GIOVE-A was 27 months with the nominal operation phase due to end in March 2008. In the remaining time, further experimentation activities are planned:

- a further short IOT campaign at Chilbolton scheduled January/February 2008 to confirm stability of key SIS parameters such as EIRP and IBUS
- continuing clock characterization experiments
- additional laser tracking campaigns using the International Laser Ranging Service.

In summary, no signs of degradation have appeared in any of the onboard systems, either platform or payload; so, we are confident that GIOVE-A will continue to operate through the end of its nominal mission and beyond.

GIOVE-A2 Mission

In early 2007, ESA awarded a new contract to SSTL for the follow-on GIOVE-A2 satellite. Given the current launch date for GIOVE-B, there may not be any overlap in operations between GIOVE-A and GIOVE-B, unless the mission of the former is extended.

GIOVE-A2 will serve as a backup for GIOVE-B to help provide continuity in broadcast Galileo navigation signals in case any launch or in-orbit problems occur with GIOVE-B.

GIOVE-A2 is based largely upon the GIOVE-A satellite design but incorporates minor design changes based on lessons learnt from the first satellite. The GIOVE-A2 project is split into two tasks. Long lead item (LLI) procurement and required design changes to the satellite comprise the first task on which SSTL is currently working. Task two —the assembly, integration and test phase of the project — is expected to kick off in early 2008.

The start date for the second task depends on the progress and status of both the GIOVE-A and GIOVE-B satellites. If any problems are encountered on either of these, then GIOVE-A2 is likely to be built, tested, and launched on a rapid schedule to provide continuity of the Galileo signal-in-space.

The baseline schedule is to launch GIOVE-A2 fourteen months after the kick-off of task two, and current planning indicates a launch date in the second half of 2009. However, if the first two satellites continue to operate successfully, then more development time may be available in the schedule, which could create an opportunity to increase the scope of the GIOVE-A2 satellite. To this end, ESA has awarded SSTL a feasibility study to look at additional payload capability or further experiments that can be embarked on if sufficient development time becomes available.

GIOVE-A2 Nav Payload

The baseline design for the GIOVE-A2 satellite is largely unchanged from GIOVE-A. As the navigation payload, in particular, on GIOVE-A has worked extremely well there are no hardware design changes planned to correct or improve functionality.

One enhancement that is being implemented, however, is the inclusion of a navigation signal generator capable of producing the new MBOC signal.

SSTL is redesigning part of its signal generator to support MBOC. In addition, ESA is pursuing options that may enable an ESA-developed signal generator to be developed that includes MBOC in time to be embarked on GIOVE-A2.

On GIOVE-A the SSTL signal generator was developed to mitigate the risks of schedule delays on ESA-developed signal generator units. Even though the main payload units were delivered in time to be flown on GIOVE-A, the SSTL chain was also placed on board because the satellite bus had enough room to house both signal generator chains.

The SSTL signal generator was designed to be just sufficient to generate the signals necessary to protect the frequency filings. Therefore, it had reduced functionality and performance compared to the ESA payload units. For example, the SSTL chain can generate the E2L1E1-A BOC(15,2.5) and the BOC(1,1) signals individually but cannot generate combined interplex signals.

The MBOC signal implemented on the SSTL signal generator is the composite BOC or CBOC(6,1,1/11) signal, which is a linear combination of BOC(1,1) and BOC(6,1) sub-carriers. The BOC(6,1) component contains 1/11 of the channel power of the overall signal. (For a further description of MBOC, see the article "The MBOC Modulation: A Final Touch for the Galileo Frequency and Signal Plan," by Jose-Angel Avila-Rodriguez et alia, in the September/October 2007 issue of *Inside GNSS*.)

On GIOVE-A2, the MBOC signal is of interest for experimentation purposes rather than frequency filing. The requirements are therefore rather different because more use may be made of the signals. As a result, the SSTL signal generator on GIOVE-A2 will be able to generate an interplex signal on E2L1E1 comprised of the BOC(15,2.5)-C and CBOC(6,1,1/11).

The modulation schemes on the other frequency bands remain unchanged. Therefore, the signal generator will still be unable to generate an E6 interplex or the E5 ALTBOC signal. Given the rapid development schedule required for the mission, the decision was taken to constrain any additional functionality within the existing unit designs.

The modulator, frequency generator and upconverter unit (MFUU) is the module in the SSTL signal generator chain responsible for generating the spreading codes, modulating the codes with the navigation data, and upconverting the signals to L-band. An engineering model of the MFUU is currently under test at SSTL to verify its functionality and performance. The modulation schemes are implemented within a field programmable gate array (FPGA), and a baseline version of the FPGA's VHSIC hardware description language containing the new CBOC interplex signal has already been developed.

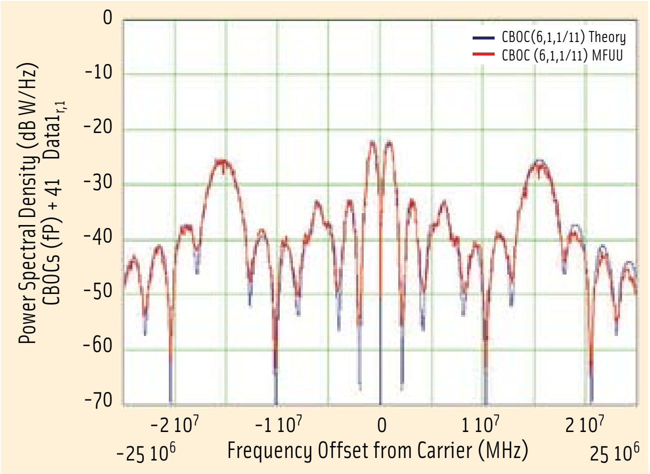

FIGURE 7 CBOC interplex signal

Figure 7 presents a CBOC interplex signal generated on a test MFUU board with the theoretical spectrum as a comparison. The plot indicates that an excellent agreement exists between the generated signal and theory, providing confidence that the signal has been implemented correctly. A slight roll-off on the upper part of the spectrum, which is thought to be due to a tight low-pass filter fitted to the test board used to generate the signal but that is not used on the actual MFUU.

Testing of the MFUU engineering unit is expected to be completed shortly. The design will then be reviewed during the GIOVE-A2 delta critical design review before manufacturing of the flight unit commences during the second task of the project.

Concluding Remarks

Over the past two years, GIOVE-A has proven to be an invaluable asset for ESA and the wider navigation community. The availability of representative Galileo signals-in-space has enabled ESA to validate their GIOVE Mission Segment and associated operating procedures and analysis algorithms, such as orbit determination and clock modelling.

This is an important step in preparing for the operation of the full Galileo ground segment. In addition, with the publication of the GIOVE-A SIS ICD, many receiver manufacturers have developed GIOVE-capable receivers and been able to verify their functionality using broadcast signals rather than simulations.

In coming months GIOVE-B will be launched to provide continuity of the Galileo SIS and allow additional clock characterization activities for an onboard passive hydrogen maser in addition to rubidium frequency standards.

GIOVE-B should then be joined by the GIOVE-A2 satellite. If both satellites operate in parallel, this will allow more scope for experimentation.

Looking to the future, SSTL welcomes the recent announcements by the European Commission to finance the deployment of a full operational Galileo system through public funding. This new procurement approach will encourage value for money by introducing competition into the project at all levels. SSTL is teaming with OHB Technology AG, based in Bremen, Germany, to bid on the contract to build the operational Galileo satellites. Together, the partnership believes it can produce Galileo spacecraft quickly and at an extremely competitive price.

OHB would build the satellites; SSTL would produce the electronic payloads.

The longer mission lifetimes specified for the full Galileo satellites mean that careful analysis of the space environment is needed before proposing unit designs that will meet these requirements while still remaining cost-efficient and compatible with a rapid development and production schedule.

Operational Galileo satellites have more stringent requirements than the GIOVE satellites, particularly much longer lifetimes, higher performance specifications, and additional services. However, the main payload units flown on GIOVE-A were pre-developments for the final constellation and are quite similar to those to be flown on the operational satellites. In addition, SSTL is still the only company with experience of operating the navigation payload units in-orbit. These activities provide SSTL with unique payload knowledge and experience that can be transferred to production of the Galileo payloads.

Galileo now has a firm technical foundation through the GIOVE in-orbit activities. Further progress with GIOVE-B, GIOVE-A2, and leading on to the IOV satellites will bring Galileo step by step towards an operational system.

Acknowledgments

The authors acknowledge the excellent ongoing work performed by both the SSTL and ESA project teams in supporting the operations and experimentation on GIOVE-A. Thanks go to the staff at STFC, TAL and CL2 for the work supporting the IOT campaign at Chilbolton.

Additional Resources

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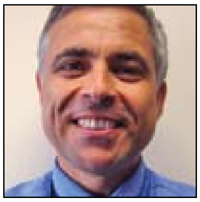

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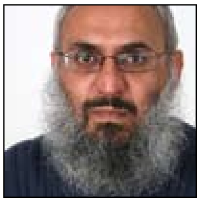

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