More Compass Points

Tracking China's MEO Satellite on a Hardware Receiver

WIM DE WILDE,
FRANK BOON,
J-M SLEEWAEGEN,
AND FRANK WILMS
SEPTENTRIO N.V.

On April 14 China launched its first medium-Earth-orbit (MEO) satellite code-named Compass-M1, the first in a planned constellation with global coverage based on the same principles as GPS and Galileo. In order to investigate the space vehicle's characteristics and data structure, researchers modified a GPS/Galileo hardware receiver so as to track the Compass MEO satellite. This article tells how they did it and presents the first results of their efforts.

In 2000 China deployed the Beidou-1 navigation system. Originally this S-band system provided ranging information via geostationary satellites that operate as transponders. This system design required bulky two-way radios, had a limited capacity, and coverage was restricted to East Asia.

Currently, China is developing the successor to this system, called Beidou-2 or Compass. The Compass Navigation Satellite System (CNSS) will consist of 30 medium-Earth-orbit (MEO) satellites broadcasting code division multiple access (CDMA) signals in the L-band. Unlike the relatively large user equipment of Beidou-1, Compass will support global navigation by means of small handheld receivers.

This explains the burst of research activity after launch of the first Compass satellite (Compass-M1) in April this year, particularly because China didn't disclose any details about its operation. In an article published the May/June issue of *Inside GNSS*, researchers at CNES, the French space agency, presented dish-antenna measurements of the Compass-M1 signal and unveiled the main code properties. Subsequently, a Stanford University (SU) team undertook complementary measurements and worked out the spreading code parameters, which are outlined in an article elsewhere in this issue.

The information published by CNES and SU is sufficient to build a hardware receiver able to track the signal through a normal hemispherical antenna. Rather than building a receiver from scratch, we found we could reuse a generic GNSS platform developed by our company.

After a software-modification, this GPS/Galileo receiver supported tracking of the E2 and E5B BPSK(2) signals of Compass-M1. This provided a lot of information about signal strength and ranging quality. Because the receiver is capable of logging navigation symbols, we were able to figure out the main data structure properties of Compass-M1 as well.

Receiver Fundamentals

The receiver we used to track Compass is the commercial version of the receiver used in the monitoring stations of the first Galileo satellite, the Galileo In-Orbit Validation Element–A (GIOVE-A). The articles by W. De Wilde et al and Andrew Simsky *et alia* listed in the Additional Resources section near the end of this article provide additional details about our receiver technology mentioned here and later in this discussion. Figure 1 shows an overview of the receiver. Its front-end receives all Galileo and GPS navigation bands (L1/L2/E6/E5).

After splitting and conversion to an intermediate frequency, the L1 and L2 signals are routed to a CA/P-code dual-frequency GPS baseband processor ASIC (application specific integrated circuit). The intermediate frequency (IF) signals of the Galileo bands (L1/E6/E5) enter a field programmable gate array (FPGA) after digitization for baseband processing.

This FPGA contains eight generic tracking channels. These channels consist of a mixer for removal of the carrier, two multicorrelator banks for concurrent despreading of data and pilot components, and two code generators that provide associated spreading codes. The channels were designed to support all GIOVE-A signals (including AltBOC), all open Galileo-signals, GPS L1 CA-code, GPS L5, GPS L2C, and all GLONASS signals.

Because most Galileo and modernized GPS signals have a significantly longer spreading code than GPS CA, the search space grows. To support acquisition in a reasonable amount of time, we implemented a parallel acquisition unit (PAU) in the FPGA. This unit uses a combination of a matched filter and an FFT (fast Fourier transform) algorithm supporting the same signals as the tracking channels.

The FPGA connects to a large SDRAM (synchronous dynamic random access memory) intended for logging of digitized IF samples. The logged samples can be downloaded over Ethernet and used for post-processing. This functionality was very useful to find out the Compass-M1 signal was actually available at the antenna.

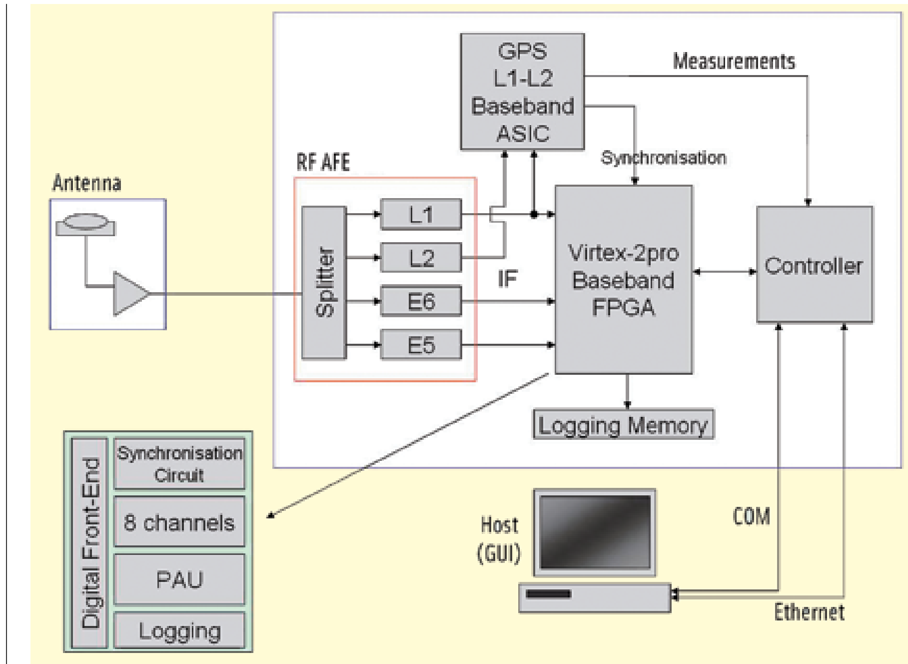


FIGURE 1 GPS/Galileo Receiver Block Diagram

Band				
Centre Frequency (MHz)	L1	E6	L2	E5
	1575.42	1278.75	1227.6	1191.795
Bandwidth (MHz)	40	40	25	55
Front-end Type	Dual conversion heterodyning			
Base-band Clock	56 MHz			
Number of GPS CA/P channels	9			
Number of Flexible Channels	8			

TABLE 1. GNSS Receiver Parameters

We logged the L1 IF signal of the front end on four random moments because we didn't have access to the two-line element set of the Compass satellite. After post-processing in a Matlab software receiver, two out of the four log-files clearly showed correlation peaks after correlation with the codes available from the SU website. This encouraged us to go ahead with the development of real-time tracking software.

To conclude the description of the GNSS receiver, Table 1 shows its main functional parameters.

Enabling Compass-M1 Support

Our modification of the receiver for tracking Compass-M1 focused on the E2 and E5B BPSK(2) signals that are believed to be the open service signals. As discussed in the CNES research mentioned earlier, these codes have a 2.046 Mcps chipping rate and a primary code length of 2,046 chips.

Stanford University figured out this code is an 11-bit shift register truncated Gold code. The overlaying secondary code is 20 bits long, resulting in a 50 Hz data rate. Both frequencies have the same primary and secondary code.

These concepts have much in common with GPS and Galileo:

- The chipping rate is a multiple of the 0.5115 Mcps, just like the rates of all GPS and Galileo signals.
- The concept of a truncated Gold code has already been introduced in GPS L5 and Galileo, though with other parameters.
- Secondary codes are defined for GPS L5 and several Galileo signals.

It turned out that all Compass-M1 signal characteristics were already supported in the generic channel design of our receiver.

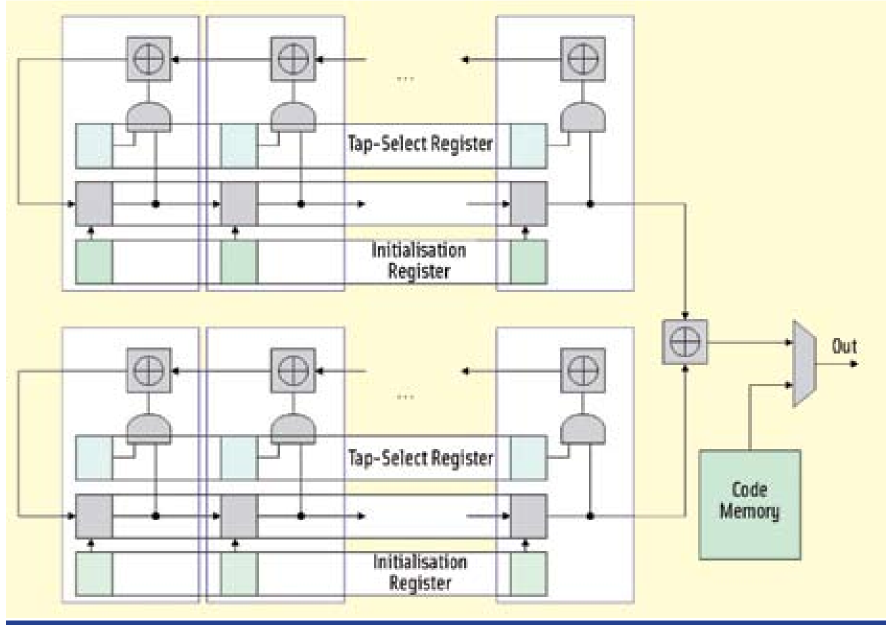


FIGURE 2 Generic Code Generator

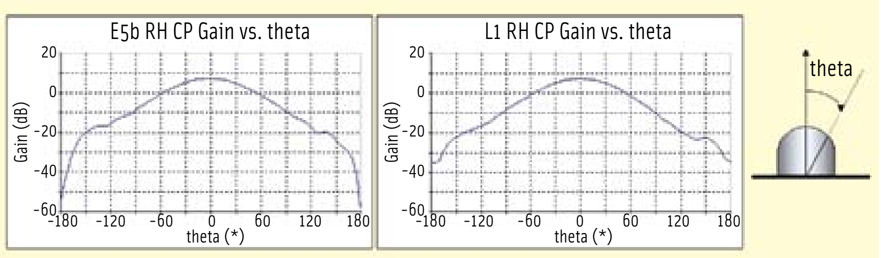


FIGURE 3 Antenna Gain at E5B and L1

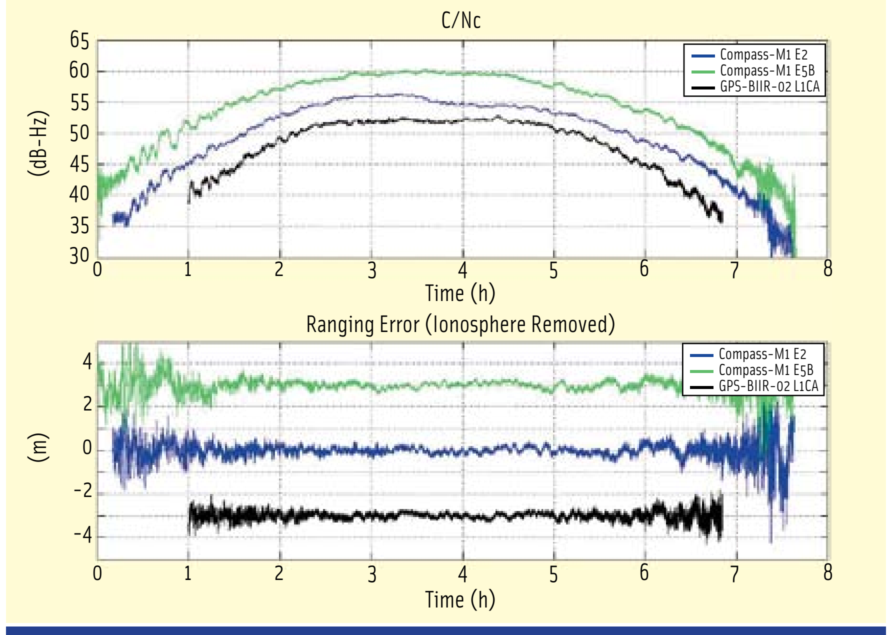


FIGURE 4 Compass-M1 C/No and Ranging Error Compared to GPS

The receiver's channel and PAU have two code-generation options (see Figure 2). The first option is a generic Gold code generator. The feedback taps and initialization vectors can be programmed by software. Alternatively, the spreading code can be sourced via a memory, as required for the non-Gold-code L1BC and E6BC Galileo signals.

We chose to use the Gold-code generator option because this uses the hardware more efficiently, envisaging later implementation in an optimized product currently in development.

The E5B and E2 frequency bands are both within the bandwidth of the receiver's analog front end. Here we need to remark that the E2 center frequency happens to be at 1561.098 MHz, rather than 1561.1 MHz as stated in earlier papers. This is exactly equal to the GPS center frequency minus 14 times 1.023 MHz and perfectly symmetrical to the E1 band. This may suggest CNSS will support AltBOC(14,2) modulation.

The E2 offset with respect to L1 was well within the pulling-range of the oscillators in the tracking channel. We concluded the the receiver's hardware didn't need to be modified in order to be Compass-M1–compliant. Enabling Compass-M1 reception only required an upgrade of the embedded software and of the graphical user interface.

Tracking Compass-M1

We hooked the receiver up to a GPS/Galileo/GLONASS choke ring antenna. Figure 3 shows the gain profile of this antenna. The receiver acquired Compass-M1 straightaway via the PAU, proving the versatility of the platform.

We logged the signal strength and pseudoranges during a complete high-elevation pass on July 5. The ranging accuracy was investigated by subtracting the precise but ambiguous carrier-based pseudorange from the code-based pseudorange. The ionospheric effect (around 10 meters) was removed via a curve-fit.

We did this for both frequencies and compared the results to similar data obtained from the GPS satellite Block IIR-02 (PRN13) through the same setup. This data was recorded during a pass through zenith. The resulting graphs are shown in Figure 4. The ranging errors have been shifted apart for clarity. Actual ranging errors are shown in Table 2.

Our first observation is that the Compass-M1 satellite is sending a lot of power. Conversion into received isotropic power results in -153 dBW for E2 and -150 dBW for E5B, compared to -157 dBW for GPS L1CA. This enables acquisition at very low elevations and offers new perspectives for indoor navigation.

The second observation is that the Compass ranging quality is similar to GPS. In the 2 hour to 5 hour time frame in Figure 4 we found a ranging error standard deviation as indicated in Table 2. The contribution due to thermal noise is displayed in the table as well.

These data clearly show that the performance is limited by multipath, and we see a similar behavior in this area for both systems. This indicates that the higher chipping rate doesn't have much influence on the ranging performance. This is as could be expected, because most multipath has a delay much shorter than the 500-nanosecond Compass chip length.

Our receiver has a built-in correlation peak monitoring function. Figure 5 displays the E5B correlation peak. The E2 peak looks very similar.

Compass-M1 Data Structure

The GNSS receiver can output the data symbols received from the satellite. We logged the Compass E2 and E5B data during the satellite pass. To find out the data structure we calculated the autocorrelation functions of the logged data (Figure 6). This clearly shows a periodicity of 30 seconds.

A close-up view of the 30-second interval reveals small peaks at a spacing of 6 seconds. This suggests 30-second frames and 6-second subframes. Note that a very high correlation exists for a 12-minute shift. This may indicate that the Compass navigation message has a 24-frame period.

Because the same format is detected at both Compass frequencies, we found it interesting to calculate the cross-correlation function between E2 and E5B data, which shows perfect correlation. Further investigation indicates that the satellite is sending the same data message simultaneously at E2 and E5B.

We need to underline the fact that the subframe and frame periodicity are exactly identical to that of GPS CA-code. An obvious thing to do was to try to route the received symbols to the GPS CA navigation data decoder. Unfortunately, the decoder didn't synchronize. Apparently the navigation message preamble is different from the GPS preamble.

We detected the correct preamble by looking for a pattern that was repeating every six seconds. By reorganizing the data, we came to the structure presented in Figure 7. This figure shows the data received during three succeeding frames.

The preamble of each subframe is followed by a subframe counter that

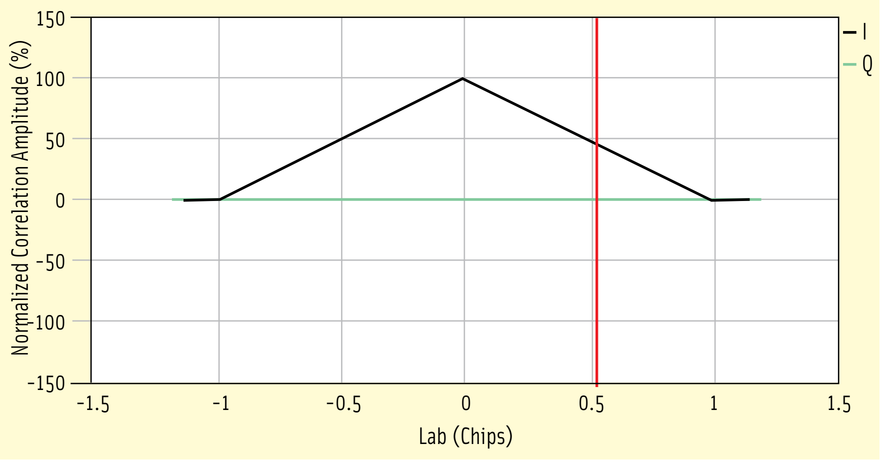


FIGURE 5 Compass-M1 Correlation Peak E5B

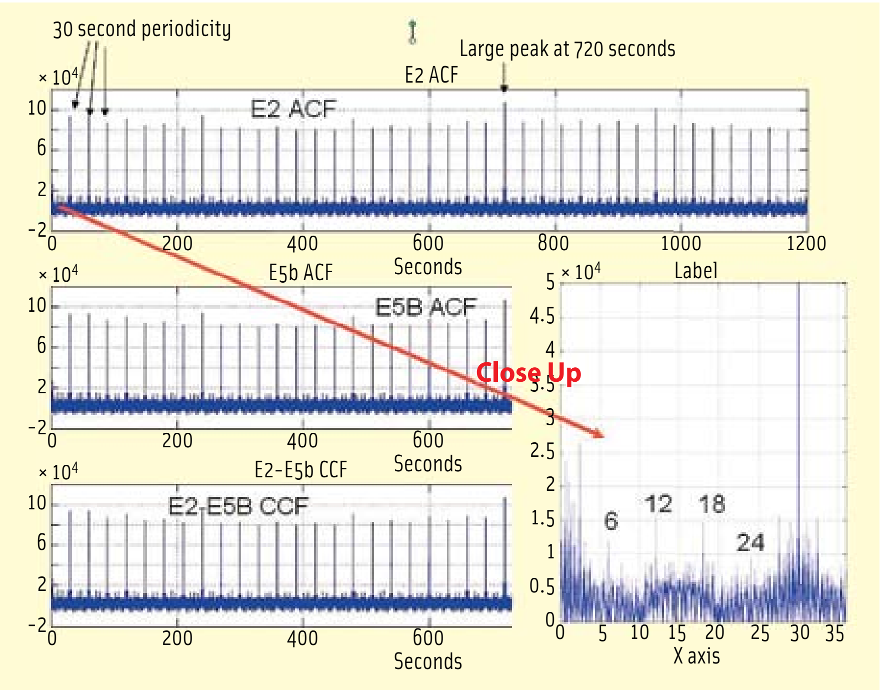


FIGURE 6 Navigation Data Correlation

Satellite	Compass-M1 E2	Compass-M1 E5B	GPS PRN13 L1
C/No	55.5 dB-Hz	60 dB-Hz	52 dB-Hz
Antenna Gain	7.2 dBi	7.5 dBi	7.2 dBi
System NF	2.4 dB	1.4 dB	2.2 dB
Isotropic Power	-153 dBW	-150 dBW	-157 dBW
Ranging Error	13.5 cm	13.4 cm	11.9 cm
Thermal Noise Contribution	2.4 cm	1.7 cm	3.7 cm

TABLE 2. Comparisons of Selected Compass and GPS Signals

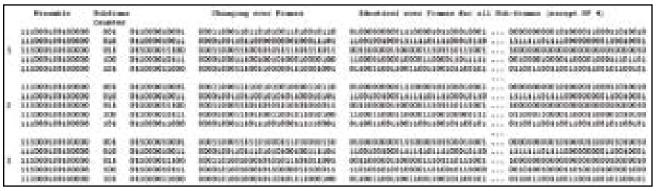


FIGURE 7 Compass-M1 Navigation Data

and E5B. The framing structure is similar to GPS CA-code, but the field ordering is different.

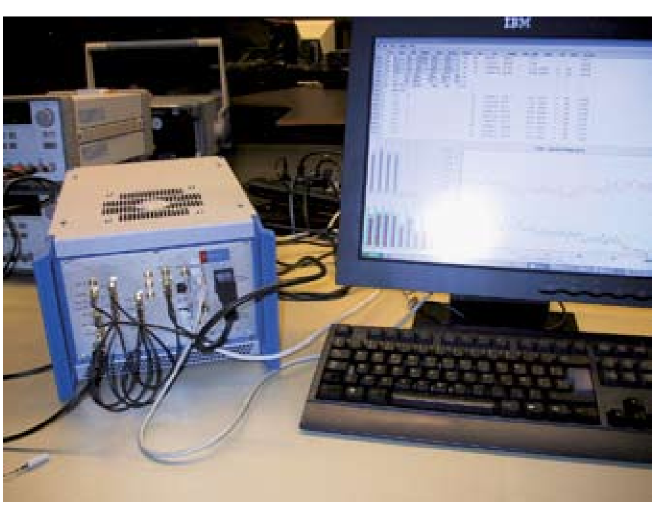
counts from 1 to 5. For all subframes except frame 4, the bits after bit 60 didn't change over similar subframes in the three frames. Because we see data switching over in repeated zero-sequences after odd multiples of 30 bits, this suggests 30-bit wording. This would be similar to GPS CA-code. However, the parity mechanism is different from GPS CA.

After support of preamble and subframe detection in the embedded software, the Compass-M1 timing was compared to GPS. The second subframe of Compass-M1 lags the first GPS subframe by exactly 14 seconds. This relationship suggests the Compass-M1 timing is UTC-based.

Conclusion

A software modification has been applied to an existing GPS/Galileo/GLONASS receiver to enable real-time Compass-M1 tracking at E2 and E5B through a hemispherical antenna. The signal strength was clearly higher than the one of GPS and exceeded 60 dB-Hz at E5B. No anomalies were observed in the ranging accuracy.

Identical data is transmitted at E2



Modified GPS/Galileo/GLONASS receiver tracking Compass-M1

Acknowledgment

We thank Orban Microwave Products (www.orbanmicrowave.com) for providing their excellent GPS/Galileo/GLONASS choke ring antenna and associated gain-plots. Part of the equipment used for this study is based on the work performed under ESA contract 18834/05/NL/MM.

Manufacturers

The GeNeRx1 GPS/Galileo receiver used to track the Compass-M1 signals is manufactured by **Septentrio N.V.**, Leuven, Belgium. The choke ring antenna is from **Orban Microwave Products (OMP)**, Leuven, Belgium.

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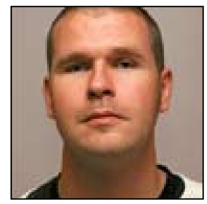
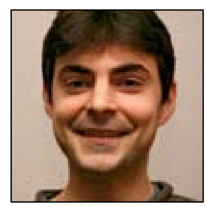
Authors

Wim De Wilde received his master's degree in electrical engineering from the University of Ghent. Upon graduation he joined the DSL research team of Alcatel Bell. Since 2002 he has been an R&D engineer at Septentrio Satellite Navigation. His areas of interest are analog and digital signal processing and system design.



Frank Boon holds a Ms. Sc. in aerospace engineering from the Delft University of Technology. He is responsible for the design and implementation of positioning algorithms in the firmware of Septentrio's GNSS receivers. His research interests include error models of GNSS measurements and optimization of positioning algorithms for high dynamic applications.



Jean-Marie Sleewaegen is currently responsible for GNSS signal processing, data analysis, and technology development at Septentrio Satellite Navigation. He received his M.Sc. and Ph.D. in electrical engineering from the University of Brussels in Belgium.

Frank Wilms has a diploma in mechanical engineering, with specialization in spaceflight technology, from the Technical University of Braunschweig. At the university's Institute of Flight Guidance and Control he worked on real-time data-acquisition systems and integrated navigation systems based on GNSS. In 1999 he was with the Navigation Section of Dornier Satellitensysteme/DaimlerChrysler Aerospace and involved in system architecture tasks within the ESA GNSS-2 Comparative System Studies. In 2000 he joined Septentrio Satellite Navigation in Leuven (Belgium) where he was responsible for GNSS receiver interface design as well as application project management. Since 2003 he has served as manager of Septentrio's Galileo projects with ESA, CDE1 Test User Segment (CDE1 TUS) and GSTB-V2 Experimental Test Receiver (GETR). Wilms is also involved in Galileo and security-related business development. IG