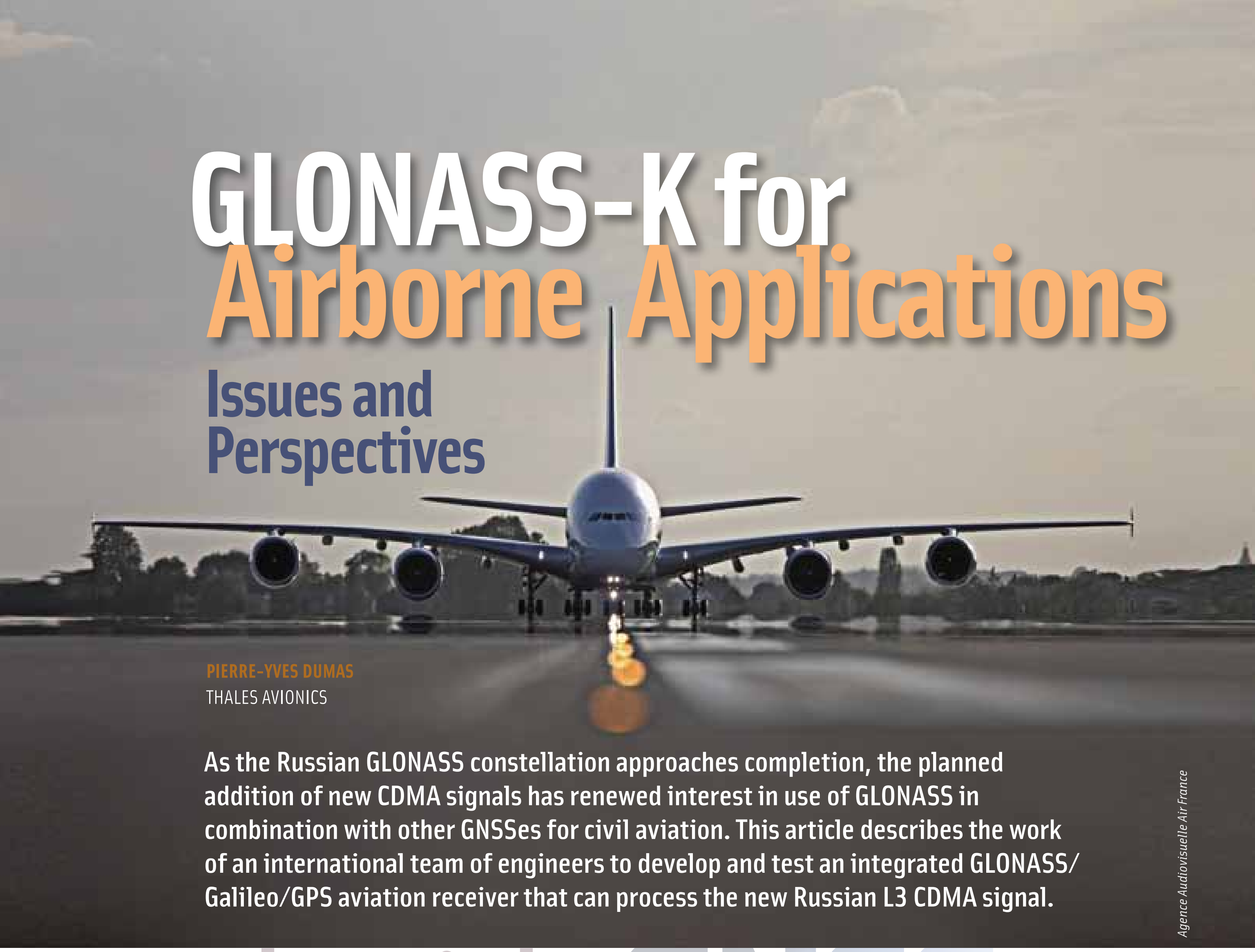

Agence Audiovisuelle Air France

GLONASS-K for Airborne Applications

Issues and Perspectives

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As the Russian GLONASS constellation approaches completion, the planned addition of new CDMA signals has renewed interest in use of GLONASS in combination with other GNSSes for civil aviation. This article describes the work of an international team of engineers to develop and test an integrated GLONASS/Galileo/GPS aviation receiver that can process the new Russian L3 CDMA signal.

As is well known, Galileo will become the European complement to the U.S. Global Positioning system.

But what about Russia's GLONASS?

Although this constellation has been in operation for nearly three decades, the limited number of available satellites along with an uncertain governmental commitment to GLONASS performance until recent years had seriously restricted its use for aviation.

However, the ongoing and planned modernization of the GLONASS space and ground segments, as well as an increasing number of satellites in orbit, will lead in the mid-term to an attractive additional constellation for airborne receivers.

Moreover, international regulatory agreements already allow the use of GLONASS L1 receivers onboard civil aircraft. Standards and recommended practices (SARPS) for GLONASS L1 receivers have been published for several years by ICAO (International Civil Aviation Organization). In addition, a recent Russian regulation mandates the integration of a GLONASS receiver onboard Russian-manufactured aircraft.

So, why don't we take a fresh look at this GNSS system and assess its potential benefit for aviation? This article will examine the utility of the GLONASS, particularly its new signal plan initiated with the K-generation of satellites, in the context of a multi-constellation receiver development project.

Using Multiple GNSSes

Multi-constellation receivers are considered by all aviation actors as the future of airborne navigation. Taking advantage of an increased number of satellites and multi-frequency capability, such receivers will benefit simultaneously from an improved satellite signal availability and better positioning, velocity, and timing (PVT) accuracy.

A lot has been done regarding combined GPS/Galileo aviation equipment. Standards have been discussed for years and are currently developed in the leadership of working groups of the European Organization for Civil Aviation Equipment (EUROCAE) and RTCA Inc. (formerly Radio Technical Commission for Aeronautics).

However, until now, standards have not been achieved to support Galileo/GLONASS capability for civil airborne receivers, mainly due to the fact that no obvious signal compatibility and spectrum commonality exists at the receiver level. The frequencies and types of modulations of the two GNSS systems

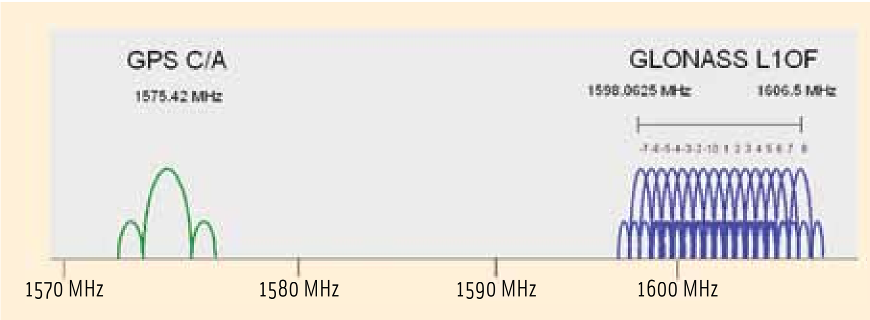


FIGURE 1 GPS/GLONASS L1 frequency band

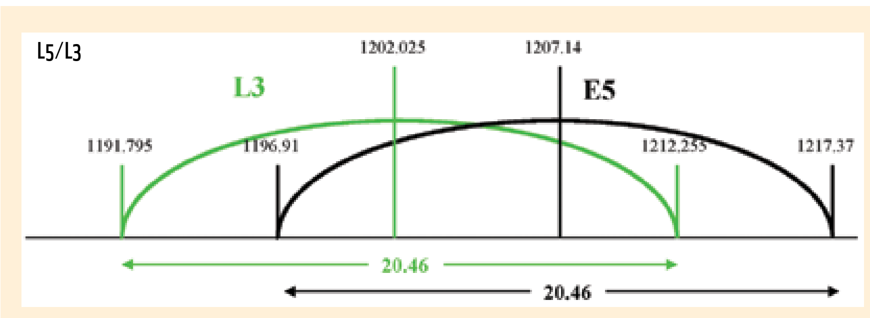


FIGURE 2 GLONASS-K L3 modulation

are indeed different and require two separate RF chains for L1 to comply with interference rejection–mask requirements (see **Figure 1**).

However, the recently introduced GLONASS-K modulation scheme creates new opportunities for synergy between Galileo and GLONASS.

GLONASS Constellation Roadmap and GLONASS-K

The current GLONASS constellation comprises 22 operational GLONASS-M satellites and one experimental GLONASS-K satellite.

As shown in the GLONASS roadmap proposed by Russian authorities (**Table 1**), several additional civil signals should be broadcast by next-generation satellites on L1 (1575.42 MHz), L3 (1202.025 MHz), and L5 (1176.45 MHz) frequencies.

The first experimental GLONASS-K satellite actually launched on February 26, 2011, will broadcast a new type of civil signal on L3. Although an official GLONASS-K interface control document (ICD) is not expected to be available before end of this year, some L3 signal characteristics have been made public.

The L3 frequency considered for GLONASS-K is located at 1202.025 MHz, only five megahertz away from the E5b central frequency, as shown in **Figure 2**. A classical code division multiple access (CDMA) modulation common to all other GNSS systems is implemented instead of the frequency division multiple access (FDMA) modulation used on legacy GLONASS L1 and L2 signals. This modulation, a bi-phase shift-keying (BPSK) 10.23 MHz with pilot and data components, closely resembles the GPS and Galileo signals located on L5/E5 band.

Future GLONASS signals are also expected to use CDMA modulation to ease interoperability with GPS and Galileo. Moreover, the GLONASS roadmap shows a plan to broadcast a navigation signal on L5 beginning in 2015.

The assessment of the new L3 signal and its interoperability with Galileo from a civil-aviation point-of-view was the motivation for the GAGARIN project launched two years ago and co-funded by the European Commission (EC). GAGARIN (standing for Galileo And GLONASS Advanced Receiver INtegration) aims at developing a receiver mock-up in parallel with an RF constellation simulator to assess the interest in a bi-constellation Galileo/GLONASS-K scheme. Studies regarding airborne GLONASS-K/Galileo antenna; positioning, velocity, and time (PVT), and integrity have also been conducted.

Led by Thales Avionics, the GAGARIN project involves the following partners: NAVIS, a GNSS receiver manufacturer (Russia, Ukraine); GosNII Aeronavigatsia, an aviation certification authority (Russia); Cobham Technology, antenna manufacturer (United Kingdom); and DLR, national space agency research lab (Germany).

Thanks to a preliminary GLONASS-K L3 ICD provided by Russian authori-

Roadmap of GLONASS modernization

Satellite Series	First Launch	Current Status	1602 + n×0.5625 MHz (L1, FDMA)	1575.42 MHz (L1, CDMA)	1246 + n×0.4375 MHz (L2, FDMA)	1242 MHz (L2, CDMA)	1202.025 MHz (L3, CDMA)	1176.45 MHz (L5, CDMA)
GLONASS	1982	Out of service	L1OF, L1SF	-	L2SF	-	-	-
GLONASS-M	2003	In service	L1OF, L1SF	-	L2OF, L2SF	-	-	-
GLONASS -K1	2010	Construction	L1OF, L1SF	-	L2OF, L2SF	-	L3OC	-
GLONASS -K2	2013	Design Phase	L1OF, L1SF	L1OC, L1SC	L2OF, L2SF	L2SC	L3OC	-
GLONASS -KM	2015	Research Phase	L1OF, L1SF	L1OC, L1SC, L1OCM	L2OF, L2SF	L2SC, L2OC	L3OC, L3SC	L5OC

"O": open signal (standard precision), "S": obfuscated signal (high precision); "F": FDMA , "C":CDMA; n=-7,-6,-5,...,6

TABLE 1. GLONASS constellation roadmap

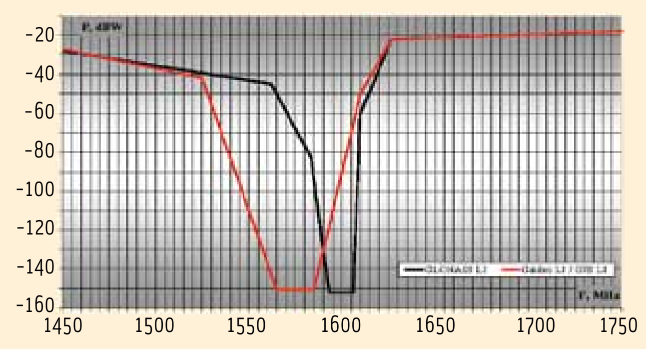


FIGURE 3 L1 interference masks at preamplifier input

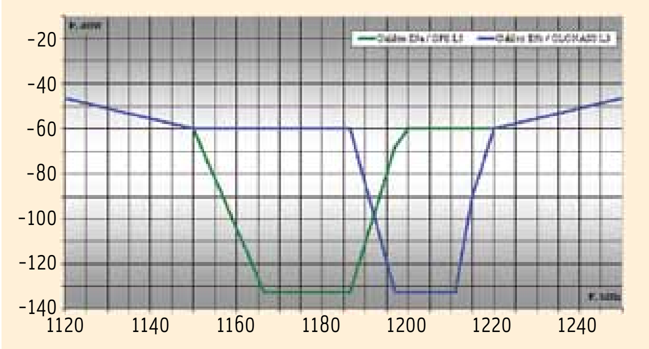


FIGURE 4 Galileo E5a/E5b interference masks at preamplifier input

ties, the GAGARIN consortium managed to work efficiently and to deliver in the expected timeframe a receiver mock-up and a constellations simulator compatible with the ICD.

Interference Rejection Masks

The main challenge in the receiver mock-up RF design is linked to the compliance with standardized rejection masks. The GPS L1 and GLONASS L1 figures for these masks were standardized a long time ago and are well known to aviation manufacturers. They are provided in the ICAO SARPS Annex 10.

Figure 3 shows the interference-rejection mask at a preamplifier input for GPS L1 and GLONASS L1. The steep rejection required on the upper side of the GLONASS L1 band is due to the proximity of Iridium and satcom transmitters. This is one of the major difficulties when designing a GLONASS L1 RF chain because achieving such a steep rejection requires numerous filtering stages.

Standards for Civil Aviation

The development of an airborne receiver for civil aviation is ruled by compliance to specific standards. To be used onboard an aircraft, a GNSS receiver must obtain a TSO (technical standard order) from the U.S. Federal Aviation Administration or the European Aviation Safety Agency. This TSO guarantees that the receiver can achieve performance levels as defined in documents called minimum operational performance specifications (MOPS), complies with specific hardware and software development assurance levels, and withstands aeronautical-grade temperature, vibrations, and humidity conditions.

The MOPS document provides very detailed and stringent requirements describing receiver development, performance, test procedures, and internal algorithms. MOPS are discussed and elaborated by RTCA and EUROCAE technical working groups

After a MOPS document is issued (usually by RTCA and EUROCAE together), it can be used as a basis for ICAO SARPS redaction. Once ICAO members (186 countries) adopt SARPS, their application becomes mandatory for receiver manufacturers.

Galileo rejection masks were discussed and adopted in the frame of the EUROCAE standardization group some years ago. **Figure 4** shows the required rejection mask for E5a and E5b bands. Airborne receivers will process E5a and E5b as two separate BPSK signals to increase interferences robustness and limit the ADC (analog/digital converter) sampling frequency.

In Figure 4, one can observe that the E5b mask is not exactly centered on the Galileo E5b central frequency (1204.03 MHz). This is due to the fact that part of the E5b signal band is located outside of the aeronautical reserved RF band due to frequency allocation constraints. The adjacent band, allocated to military radars, may strongly interfere with the Galileo signal and eventually prevent the receiver from computing its position

To address this issue, EUROCAE has decided to only use a 14-megahertz sub-band of the E5b signal that is located inside the aviation band.

To meet the rejection mask requirements, new RF surface acoustic wave (SAW) filter technology can be used in the first stage of the RF chain. These filters offer much steeper filtering performance than regular ceramic filters and require a more limited footprint on the board.

As no GLONASS-L3 rejection mask is standardized yet for aviation, the project team decided, for GAGARIN receiver development, to process the L3 frequency through the same RF channel as E5b, (see **Figure 5**). The degradation due to the offset between the filter central frequency and the signal central frequency is similar to that obtained when processing E5b signal and is fully acceptable. This architecture allows us to limit the number of GAGARIN RF chains and, thus, the receiver complexity.

Receiver manufacturers and standardization groups would probably go for this specific architecture instead of developing an expensive additional RF channel for future Galileo/GLONASS-K receivers.

Pulse Mitigation Technique

One of the issues linked to the use of aeronautical E5/L3 band is the overlapping presence of ground and on-board emitters dedicated to distance measuring equipment (DME) used for aircraft positioning (**Figure 6**). The power of these emissions can reach significant values at the antenna port and, as a result, may considerably degrade the signal-tracking performance of GNSS receivers.

Indeed, the EUROCAE MOPS has defined a geographical point near Frankfurt (Germany) where an aircraft cruising at 40,000 feet could receive in the E5 band a maximum number of DME pulses coming from 119 visible

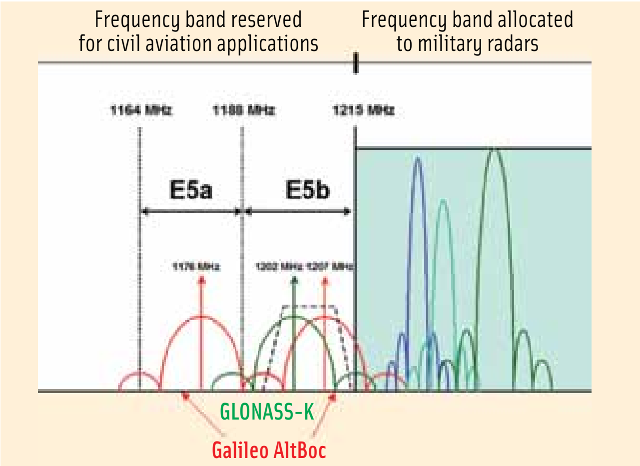


FIGURE 5 Frequency allocation in E5 band

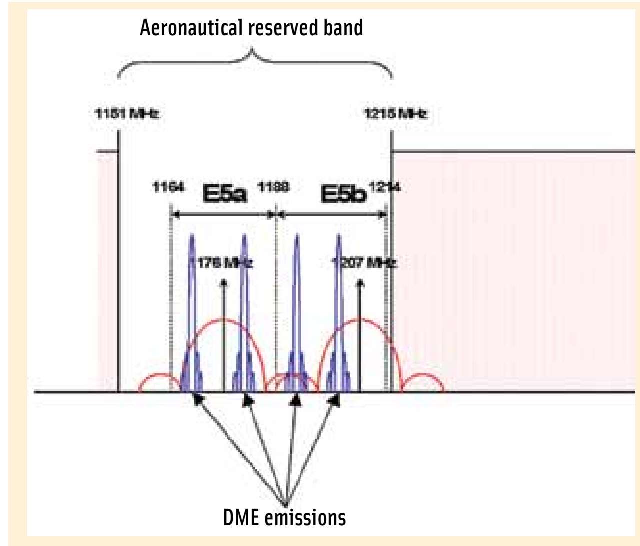


FIGURE 6 DME emissions in E5 band

GAGARIN receiver mock-up

ground stations. Previous theoretical studies had concluded that a pulse mitigation technique should be implemented on E5a/E5b GNSS receivers to avoid loss of tracking.

In parallel with a regular temporal blanking technique associated with a patented automatic gain control (AGC) design, Thales developed a specific *frequency domain adaptive filtering* (FDAF) technique. This method uses an advanced filtering module to selectively remove the jammed frequency band instead of zeroing the whole signal.

The performance of these mitigation techniques had already been evaluated on previous Galileo receiver prototypes and could also be assessed with the GAGARIN receiver.

A digital synthesizer was loaded with a baseband I/Q (in phase/quadrature) file configuring the environment to simulate the DME hotspot during receiver tests.

Tests have been conducted on hardware with an RF constellation simulator. The simulator used an Altboc modulation for the Galileo E5 band and a BPSK10 modulation for the GLONASS L3 band. The tests have concluded that over the hotspot environment on E5 band, without mitigation techniques, the C/N_0 was decreased by 17.5 decibels, leading to loss of data demodulation. The C/N_0 decreased by 7 decibels with temporal blanking technique and only 3 decibels with FDAF method.

Receiver Mock-Up

The GAGARIN program developed a mock-up of a multi-constellation receiver, shown in the accompanying photo, that is fully representative of a future airborne multi-constellation receiver with a form and fit factor that complies with the ARINC Characteristic 743 specifications for an airborne GPS receiver. The hardware and the PVT software have been developed by NAVIS while the signal-processing was designed by Thales.

The receiver includes 48 generic channels and 10,752 pilot/data complex correlators. Each channel is capable of processing GPS L1, Galileo E1 or E5b, and GLONASS L1 or L3 signals.

The mock-up's digital processing is based on a hardware automatic acquisition engine, which drastically reduces the acquisition time. It outputs bi-frequency PVT and includes a standard RAIM algorithm.

Based on robust and proven hardware architecture for digital as well as RF parts, the receiver embeds state-of-the-art digital signal processing algorithms and FDAF interference mitigation technique. Provisions for forward-compatibility with GPS L5 and Galileo E5a have been taken in the receiver.

Tests of GPS L1 and GLONASS L1 have been conducted with real satellite signals, while Galileo signal capability could only be assessed with a specific RF multi-constellation simulator developed in the frame of GAGARIN project by NAVIS. Based on a Galileo simulator that was upgraded to generate GLONASS L3 signals, the GARGARIN simulator has the capability to work with GPS L1/L5, Galileo E1/E5a/E5b and GLONASS L1/L3 signals.

GLONASS-K capability was tested using the simulator then validated in real conditions with the first GLONASS-K satel-

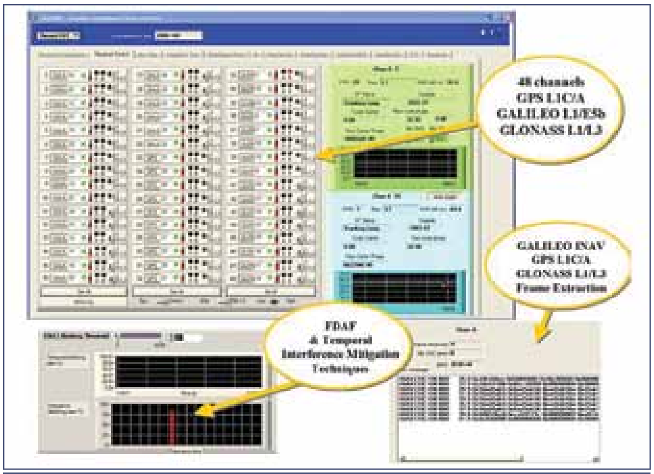


FIGURE 7 Screenshot of GAGARIN receiver graphical user interface

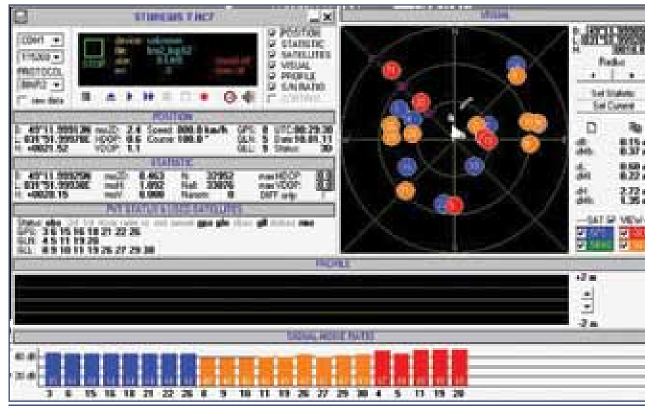
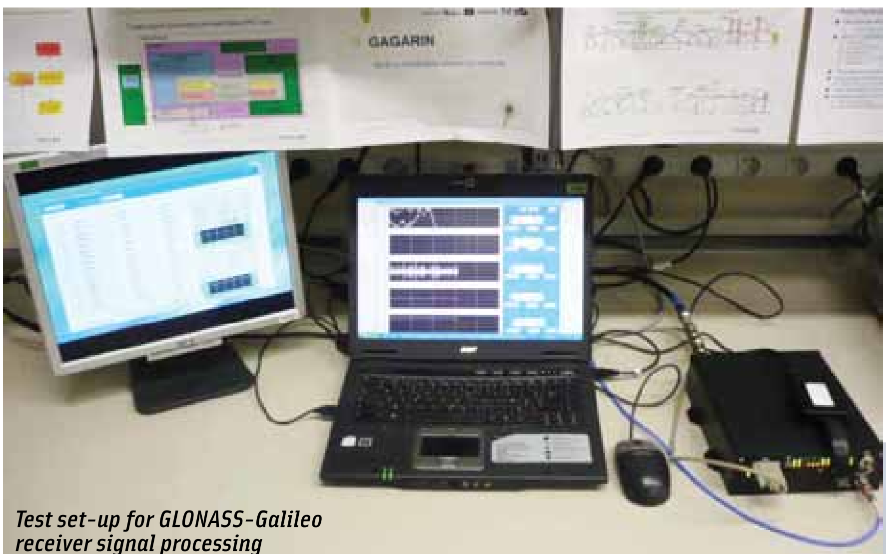


FIGURE 8 PVT screenshot



Test set-up for GLONASS-Galileo receiver signal processing

lite after its launch in February 2011. The accompanying photo shows the receiver under test.

For each signal type (GPS L1, GLONASS L1 and L3, and Galileo L1 and E5b), we determined the minimum acquisition and tracking thresholds. The consistency of the measurements was also checked as well as the correct data demodulation. **Figure 7** shows the receiver's 48-channel capability as well as some frame extraction and FDAF processing.

Regarding GLONASS-K, no recording has been done with the actual on-orbit satellite; however, tests on the simulator showed that the receiver was able to acquire the L3 signal down to 35.1 dB-Hz and to track it down to 23.8 dB-Hz. Finally, we tested the PVT software, and the capability to track simultaneously three constellations was demonstrated as presented in **Figure 8**.

Conclusions

In the frame of the GAGARIN study, we have demonstrated the feasibility of a GPS/Galileo/GLONASS-K triple-constellation receiver for civil airborne applications. Compliance with the draft Galileo MOPS and the GPS standards has been assessed, and the interest of Galileo/GLONASS-K combination has been evaluated.

The receiver mock-up embeds state-of-the-art technology at the RF and signal-processing level and provides a triple-constellation capability. At the same time, a GLONASS-K constellation simulator was developed, paving the way to future multi-constellation receiver development.

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