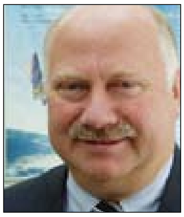
GNSS Interoperability:

Achieving a Global System of Systems or "Does Everything Have to Be the Same?"

"Working Papers" explore the technical and scientific themes that underpin GNSS programs and applications. This regular column is coordinated by Prof. Dr.-Ing. Gunter W. Hein, a leading expert in GPS, Galileo, and GLONASS.

This first article introduces the three global navigation satellite systems — GPS, GLONASS, and Galileo — and addresses the issue of their compatibility and interoperability with each other. For users, these represent crucial aspects of the relationship among GNSSes, affecting such matters as cost of equipment, ease of use, and practical applications.

Part of the rationale for building additional GNSS systems, in addition to the motive of political sovereignty, is the argument that a single system is not able to meet all the requirements for use in challenging application environments such as large cities and mountainous terrain. In the end, our answer to the question of GNSS compatibility and interoperability also answers the question of whether GNSSes are complementary or competitive and mutually exclusive systems.



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During the 1980s, Hein formed a research group that did pioneering work in the field of real-time kinematic GPS positioning and GPS-INS integration. He has served as a visiting professor and scientist at a number of universities and organizations internationally. He has contributed to more than 185 articles, papers, and presentations on geodesy and navigation and been awarded more than 100 research grants.

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With Europe's decision on March 26, 2002, to build up its own global satellite navigation system (GNSS), a new era began in this high-tech field. Although China is joining the European Galileo system — the third global system in addition to the American GPS and the Russian GLONASS — one could hear at recent international symposia in China that we probably do not have long to wait before China starts developing another (fourth) independent global system. Meanwhile, Japan is developing a regional satellite navigation system, the Quasi-Zenith Satellite System (QZSS). India is proceeding with its GPS And GEO Augmented Navigation (GAGAN) system.

While a 24-to 30-satellite constellation may satisfy many user communities, it is not sufficient to fully support some applications in urban areas and mountainous regions. A seamless worldwide navigation service for all kinds of users requires a "global system of systems" assuming interoperability and compatibility among the systems.

How Different Are the GNSSes?

Table 1 compares some key parameters distinguishing the various GNSS systems. At the very first glance only three major differences appear: The FDMA access of GLONASS, the planned civilian-only (so far) use of Galileo, and the planned public-private funding scheme of Galileo. Considering that Galileo is still in the development phase and the concession contract is not yet signed, we are left with the FDMA problem of GLONASS, which hinders its full integration into a future Global Navigation Satellite System of Systems.

TABLE 1. GNSS System Parameters

	GPS	GLONASS	GALILEO	QZSS
Number of Satellites	21+3 nominal 28 (27 Dec 2005)	21+3 nominal 13 (27 Dec. 2005)	27+3 nominal	3 IGSO
Number of Orbital Planes	6 (Trend to 3)	3	3	3
Satellite Life Time	GPSIIR:10 yrs	GLONASS: 3yrs GLONASS-M: 7yrs GLONASS-K: 10-12 yrs	> 12 yrs	12 yrs
Satellite Mass	GPS IIR ca. 2000 kg	GLONASS and GLONASS-M: 1415 kg GLONASS-K: 850 kg	ca. 700 kg	?
Signal Access Scheme	CDMA	FDMA	CDMA	CDMA
Number of Frequencies	3 L1, L2, L5(=E5a)	One per two antipodal satellites	4 L1, E6, E5a(=L5), E5b	4 L1, L2, E6 (experim.), E5a(=L5)
Number of Codes	One per service and satellite	One per service and frequency (band)	One per service and satellite	One per service and satellite
Orbit Altitude	ca. 20,200 km above earth	ca. 19,100 km above earth	ca. 23,200 km above earth	ca. 36,000 km above earth
Intersatellite Links	Yes	GLONASS: No GLONASS-M, - K: Yes	No	No
Inclination	55^0	$64,8^0$	56^0	45^0
D – Dual Use C - Civilian	D	D	C (D PRS)	C
Commercial Service	No	No	Yes	Yes
Integrity Transmission	No (GPS III – Yes)	No (GLONASS-K – Yes)	Yes	Yes
Funding	Public	Public	Public/Private	Public

Political Acknowledgment

Fortunately, even the politicians have recognized the need for compatible and interoperable GNSSes. An early (February 1999) Communication of the European Commission (EC) stated: "Galileo must be an open, global system, fully compatible to GPS, but independent of it …"

The EU-US Agreement on the Promotion, Provision and Use of Galileo and GPS Satellite-Based Navigation Systems and Related Applications signed June 26, 2004, in Dublin, Ireland, has set up the models and methodology for the radio frequency compatibility of satellite navigation systems, in particular between GPS and Galileo.

This methodology is now also being used to address the compatibility considerations between the Japanese QZSS and Galileo. Working Group A on Compatibility and Interoperability, one of four working groups established under the EU-US agreement, has further elaborated and discussed between the two partners in several meetings since then.

In similar fashion, the new U. S. Space-Based Positioning, Navigation and Timing (PNT) Policy signed December 8, 2004, addresses the global compatibility and interoperability of future systems with GPS. Russian representatives of GLONASS mention in all their talks the interoperability between the three systems: GPS, GLONASS and Galileo.

Defining Terms

But what do *compatibility* and *interoperability* really mean? The new U. S. Space-Based PNT Policy defines these terms as follows:

- Compatibility refers to the ability of U.S. and foreign space-based PNT services to be used separately or together without interfering with each individual service or signal, and without adversely affecting navigation warfare.
- Interoperability refers to the ability of civil U. S. and foreign space-based PNT services to be used together to provide better capabilities at the user level than would be achieved by relying solely on one service or signal.

Compatibility means, then, that GNSS systems do not interfere with each other, and that non-military (and non-governmental) signals can be jammed without adversely affecting those signals. The previously mentioned models and methodology to compute the level of interference are set up in one of the annexes of the 2004 EU-US agreement. The navigation warfare aspects of compatibility, although also an annex to this agreement, remain classified.

Interference computations themselves would fill a large technical note. In general, we differentiate between intra-system and inter-system interference. Intra-system interference can actually be much larger than the inter-system interference.

We often focus only on the interference between different GNSS systems — as is the case in the annex to the 2004 EU-US agreement. However, other in-band interference — for example, the distance measuring equipment (DME) interference in E5a and E5b — as well as spurious or out-of-band interferences might be even a more serious problem. Here we should mention the ultra-wide band problem and the matter of GNSS re-radiators for indoor use.

As an example, **Figures 1** and **2** show the intersystem interference on the L1 frequency between GPS and Galileo in both directions. **Table 2** outlines the underlying assumptions and param-

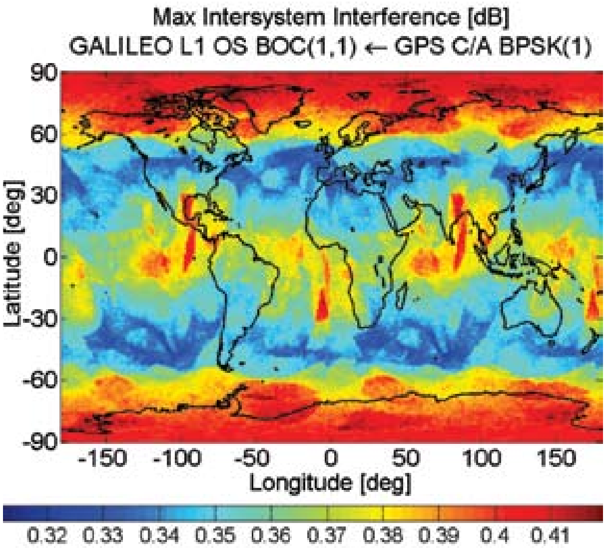

FIGURE 1. Interference in [dB] of GPS L1 C/ABPSK(1) on Galileo L1 OS BOC(1,1)

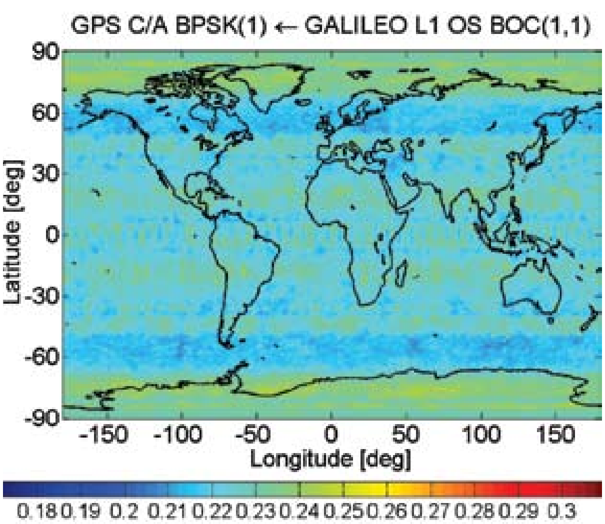

FIGURE 2. Interference in [dB] of Galileo L1 OS BOC(1,1) on GP S L1 C/A BPSK(1)

Parameter	GPS ← Galileo	Galileo ← GPS
Simulation Period	10 days	10 days
Time Resolution	180 sec.	180 sec.
Grid Resolution	Lon. 1°, Lat. 1°	Lon. 1°, Lat. 1°
Elevation Angle	10°	10°
Front End Bandwidth	24.552 MHz	24.552 MHz
Emission Bandwidth	GPS 30.69 MHz Galileo 40.92 MHz	GPS 30.69 MHz Galileo 40.92 MHz
Received Power [dBW]	GPS $-158.5<C_j<-155.2$ Galileo $-156<C_j<-154$	GPS $156.3<C_j<-153$ Galileo $-157<C_j<-155$

TABLE 2. Assumptions and Parameters for the Interference Computations (see Figures 1 and 2)

As for the definition of interoperability given earlier, this is a very general explanation; therefore, we need to clarify what it means. One can split the general term up into system interoperability — where different GNSS systems provide the same answer, within the specified accuracy of each individual system, and signal interoperability — in which different GNSS systems transmit signals allowing to combine them in a "simple" receiver for a combined PNT solution.

In a presentation to the Civil GPS Service Interface Committee last September entitled "GNSS User Assessment of GPS/Galileo Interoperability," A.J. Van Dierendonck characterized the latter term also as "optimized system interoperability." And, in fact, some kind of optimization process must take place in order to define signal interoperability.

The level of interoperability is certainly the (weighted) result of several factors:

- compatibility of the GNSS systems
- simplicity of user segment (receiver design)
- market situation/economic aspects
- independence of countries
- (national) security
- vulnerability of the combined PNT solution

Different governments and owners of GNSS systems may emphasize one or another topic more than others. Consequently, optimizing interoperability involves not merely technical considerations but also involves political and military decision processes — in particular, when looking at the dual-use character of (almost all) the systems.

How Much Similarity?

Two immediate conclusions are possible. First of all, in terms of system interoperability all GNSSes (GPS, GLONASS, Galileo, QZSS) are interoperable. Secondly, a solution of signal interoperability or optimized system interoperability cannot be that all GNSS signals would be the same.

No doubt, commercial worldwide trends would like to see that happen. However, common mode failures would make such a combined PNT solution extremely vulnerable. Creating diversity and at the same time ensuring signal interoperability is the way to go. Looking more into those aspects, would it not be advisable to define GNSS signals in such a way that we can still compute in a "simple" manner a combined solution but with the smallest degree of vulnerability?

The present signal interoperability between GPS and Galileo to enable combined use of the systems for better performance at the user level was guided by the following considerations:

Signals-in-Space. Signal structure, waveforms, codes, and data messages are implemented as software in a receiver; differences among them cause no problem.

Different frequencies may introduce frequency biases and degrade accuracy. Multiple front-ends (or ones with a larger bandwidth) are necessary. High-precision real-time solutions using carrier phase observations are not possible (at least not without approximations which lead to a degradation of accuracy).

Requirement: Common center frequencies are needed for signal interoperability (combined processing of observations)

Coordinate Reference Frame. In satellite navigation practice, the so-called Reference Frame represents an important element. A Reference System is the conceptual idea of a (time or coordinate) system,

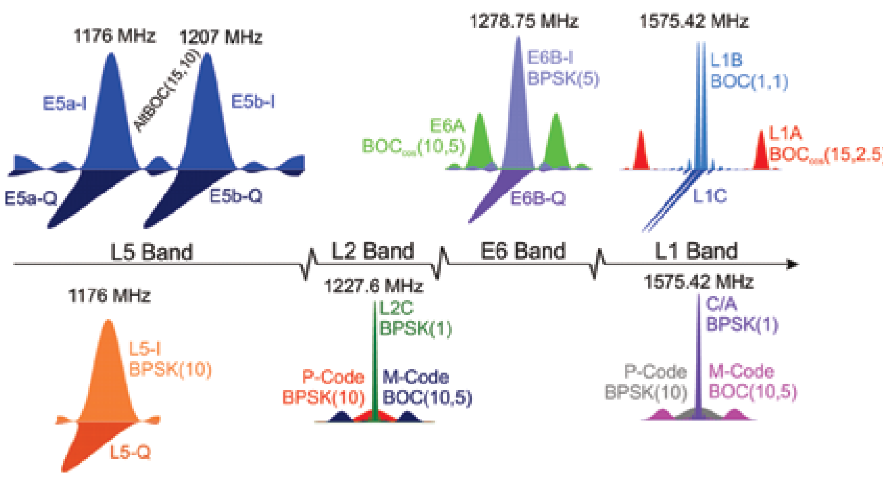

FIGURE 3. Interoperability between GPS and Galileo Open Service on L1 and L5/E5a. From the technical point of view interoperability also exists between the GPS M-Code and the Galileo PRS on L1.

including the fundamental theory and standards.

In contrast, a Reference Frame is the realization of a reference system through observations and a set of station coordinates and time within the control segment, and it is this frame that provides the basis for positioning.

Even if GNSS system operators could agree on using the same coordinate reference system, the (different) ways of realizing these systems would result in differences of a certain accuracy level between the two reference frames.

For various reasons the realization of a particular GNSS system's coordinate reference frame should be based on stations different from those of other GNSSes. These reasons include ensuring the independence of both satellite systems, enabling a second satellite navigation system to be used as a backup solution, reducing the vulnerability of a satellite navigation system to single-mode failure, and so forth. The international civil coordinate reference standard is the International Terrestrial Reference Frame (ITRF).

Differences in coordinate frames have to be at least smaller than the specified absolute (single receiver positioning accuracies. For differential GNSS users, differences between reference frames do not play any role since they cancel out in the differential computations.

The GPS coordinate reference frame (WGS84) is realized by the coordinates of the GPS control stations. Differences between ITRF96 and WGS84(G1150) amount to less than two to three centimeters (well beyond the necessary accuracy).

The present goal for the Galileo Terrestrial Reference Frame (GTRF) is to realize it within less than three centimeters (two sigma) with respect to ITRF.

Conclusion: For (almost) all positioning and navigation users, WGS84 and GTRF are equal to ITRF.

Time Reference Frame. Galileo System Time (GST) as well as GPS time will be different real-time realizations of UTC (Universal Time Coordinated)/TAI (Atomic Time), which is the international civilian time standard.

The remaining very small offset between the two realizations of the same standard at the nanosecond level can be determined in a combined receiver with very high accuracy at the cost of using one satellite observation for this extra unknown in the PNT computations.

Moreover, the United States and the European Union have agreed to have their satellites broadcast the GPS-Galileo time offset in the future.

Conclusion: The GPS-Galileo time offset can be easily determined or received by the user receiver.

CDMA VS FDMA. As a consequence of the signal-in-space interoperability requirement (identical center frequencies of interoperable signals), only CDMA (Code Division Multiple Access) satellite systems can fulfil it. This is not the case with the GLONASS system, which is a FDMA (Frequency Division Multiple Access) system. Thus, GLONASS is not "signal interoperable" to GPS or Galileo, but it is "system interoperable," according to the definition given earlier.

GPS and Galileo are "signal interoperable" with regard to the L1 and the L5/E5a frequencies and both open (and free) services (see **Figure 3**). Galileo does not use GPS L2 because it does not have an Aeronautical Radio Navigation Service (ARNS) designation. QZSS plans to be signal-interoperable to GPS and Galileo on the same frequencies. The military GPS M-code and the Galileo Public Regulated Service (PRS) have signalinteroperability on L1.

Additional questions regarding the level of interoperability among GNSS systems will undoubtedly be further discussed in Working Group A under the 2004 US/EU agreement as well as in other international fora. However, the trade-off between the threat by common mode failures on the one hand and the degree of simplicity of the user receiver still has to be carefully considered.

Conclusions

Interoperability and compatibility are the two driving mechanisms by which to achieve a Global Satellite Navigation System of Systems. At the same time, however, the independence of single systems also provides greater reliability and integrity of the GNSS utility for users and guarantees a certain competition among the systems. In the future, this competitive situation will be driven by the market and no longer solely by political decisions – unless interoperability is given up. An ideal situation for the PNT user of the future! IG