Envisioning a Future GNSS System of Systems

Part 2

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For reasons of political sovereignty, technological competition, policy differences, operational control, and perhaps just plain old national prestige, the planet Earth may have four complete global navigation satellite systems within five or six years. Let's assume that happens. Are users and manufacturers destined to work through a labyrinth of competing technical specifications and management regimes in order to take advantage of the rich GNSS signal resource coming into existence? Or can we shape a better world of GNSS interoperability and cooperation?

A GNSS System of Systems? We began our discussion in the previous column (January/February 2007 issue) with an exploration of the current status, plans, similarities, and differences among GPS (United States), GLONASS (Russia), Galileo (European Union), and Compass (People's Republic of China).

Consider the similarities: All four are global systems accessible by users worldwide. They have one or more radio frequency bands in common where they broadcast open signals free of charge. They have comparable atomic time and geodetic coordinate frames.

Three of them have a common signal technology — code division multiple access (CDMA) — and the other system is considering adopting it as well. They all predominately use middle Earth orbiting (MEO) satellites with constellations (current or planned) of between 24 and 30 space vehicles each.

As we concluded in the last column, the basis for a GNSS system of systems seems strong, building on infrastructure, operations, and policies that are already in place or under development. Now we will turn to some concepts further outside the realm of the expected — some speculative possibilities based on innovative ideas, but which nevertheless are within the realm of the possible.

And nowhere is there more room for innovation than in the domain that underlies GNSS technology itself: time.

Innovations in Clocks

If there is an area where revolutionary developments could occur in the next few years, then it is in the field of clocks. The atomic clocks placed on board the satellites are probably the most crucial single element to achieve a high-performance GNSS.

Because the development cycle in clock technology is about 7 years, these newest generation technologies might be available on orbit in a timeframe of 20 years. This would considerably alleviate the challenge of generating predicted satellite clock corrections. Furthermore, one might speculate that, since orbit prediction already works quite well today, differential correction service for GNSS systems could become obsolete with the availability of improved satellite clocks. Let us now look in more detail at what future clocks might look like.

Importance for TOA-Based Systems. GPS, GLONASS, Galileo, and other GNSSes are designed to operate on the basis of the principle, "one-way time of arrival (TOA) ranging." Each satellite emits its ranging signals together with a navigation message that tells the user's receiver from which satellite, from which orbital position, and at what time it was broadcast.

By comparing the time of a signal's arrival with the time of its transmission, a pseudorange can be calculated. This one-way TOA principle allows an unlimited number of users to use a GNSS.

We can expect that over the next 20 years or so the advances in timing accuracy characteristic for the past – namely, to improve the stability by a factor 10 per decade – will continue.

However, this method assumes that all GPS satellite clocks involved in a position solution are fully synchronized with each other and with the International GPS time (or some equivalent reference). Moreover, it requires extremely precise information about the satellite's position in a well-defined reference frame.

The current standard for all GNSS satellites is to have three to four clocks on board each spacecraft — one of them being the master clock and the others, redundant units. Currently those clocks are of rubidium and/or caesium types.

Galileo will eventually also use a hydrogen-maser clock, if tests on the second Galileo In-Orbit Validation Experiment (GIOVE-B) satellite employing this technology turn out to be successful. Hydrogen masers have superior short-term stability compared to other frequency standards, but lower long-term accuracy due to changes in the properties of the clocks' microwave cavity over time.

Atomic clocks are also installed at ground stations of those GNSS systems. GPS clocks in space and on the ground are in some way synchronized to the International Atomic Time (TAI), which is the world's continuous and stable time scale. Alternatively (or additionally), the clocks are also tied to the civil Coordinated Universal Time (UTC). Derived from TAI, but synchronized with the passing of day and night on the basis of astronomical observations. These time scales and timing systems result from the cooperation of about 60 timing laboratories around the world, which continuously contribute to the realization of UTC.

UTC rarely differs from the international average by more than 10 nanoseconds. NIST is one of four laboratories worldwide operating the highest primary frequency standards to determine the frequency of UTC.

Improved Clocks – So What?

What kind of progress and alternative architecture could one invent, if GNSS receivers' oscillators had a frequency/phase stability orders of magnitudes better than the present ones? Moreover, what would be the practical effect if GNSS satellites could transmit signals for which the uncertainties in GNSS time were not counted in nanoseconds (with 5 ns corresponding to 1.5 meters in ranging error), but rather in femtoseconds (fs): one billionth of one millionth of a second (with 5 fs corresponding to 1.5 millimeter ranging error)?

It would certainly open a lot of new research topics for scientific applications. In the near future, we can expect that discussions among GNSS service providers and metrologists will begin on this subject, and numerous proposals concerning applications and design concepts will arise as a result.

The present achievement of 10-nanosecond accuracy is already an astonishing result of many decades of research and developments (see Figure 1). However, even that achievement still leaves much room for further scientific progress. We can expect that over the next 20 years or so the advances in timing accuracy characteristic for the past — namely, to improve the stability by a factor 10 per decade — will continue.

Before we discuss this point further, it seems appropriate to judge the present performance from a different perspective: that 10-nanosecond time resolution corresponds to three meters considering the propagation of light. At present, the GPS clock stability in space is still of this same order of magnitude. Meanwhile, the absolute values of the GPS satellites' real-time orbital position coordinates are on the order of one meter.

These statistics make it quite obvious that many interesting effects of nature are still hidden inside the GNSS error budget, and metrology should aim to detect and exploit such surprising phenomena. Scientists dealing with solid Earth research and with fundamental

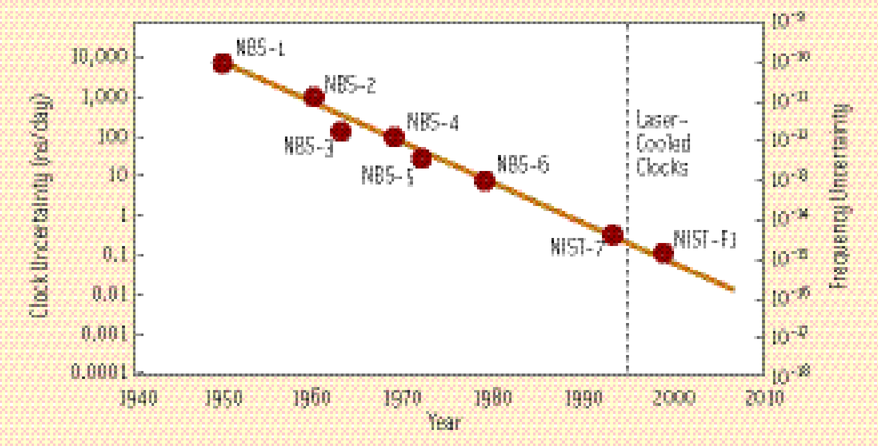


FIGURE 1 Accuracy of terrestrial caesium atomic clocks at the National Institute of Standards and Technology. The NIST-7 is an optically pumped, thermal atomic-beam, microwave caesium spectrometer and the NIST-F1 is a caesium fountain atomic clock

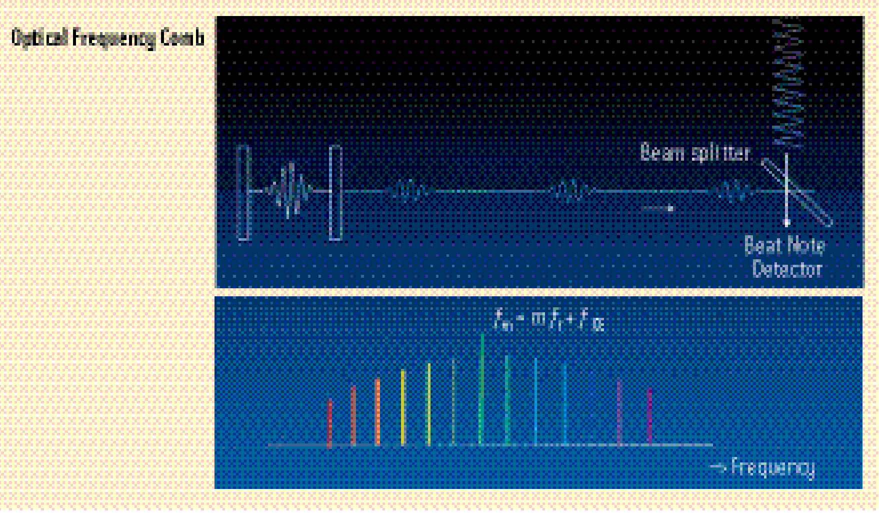


FIGURE 2 Color scheme of femtosecond laser frequency comb-synthesizer (Courtesy of Prof. T. W. Hänsch. For more details refer to the Nobel Lecture in the Additional Resources section)

relativistic issues, for example, offer highly interesting possibilities for further accuracy improvements.

Certainly, users dealing with practical applications will follow. We can anticipate this likelihood from the experiences of the past: In the 1980s, when intercontinental time synchronization was only possible to the order of a microsecond and better timing resolution was requested from scientific community, almost no "practical user" was interested in such an improvement. Nowadays the nanosecond technique is standard in metrology!

As one practical advantage of an improved time and frequency reference, system operators might be able to dispense with satellite clock corrections entirely. This could also reduce the need of corrections in the orbit prediction to very few cases, which would simplify the whole issue of GNSS control.

Space-Borne Atomic Clocks

The atomic clocks on board GNSS satellites are space-qualified samples of terrestrial units. Specific design features of the spaceborne clocks take into account the well-known effects and constraints concerning the environmental conditions, power and weight problems, and so forth. However, in principle, one can assume that the development results of the frequency standard institutes for ground-based clocks will become available for space applications a few years later with approximately the same performance qualities.

In fact, scientists emphasize that atomic clock in space will actually eliminate some of the perturbations that generate problems for fountain clocks on earth. Microgravity, less influence from the Earth's magnetic field, and other phenomena provide advantages for the performance improvements.

For example, on Earth, gravity causes an atomic clock's caesium atoms to fall away from the detector almost immediately. This makes it more difficult to determine the center of the atom's oscillations. In microgravity caesium atoms move 5 to 10 times slower.

PARCS and ACES. NASA's Primary Atomic Reference Clock in Space (PARCS) program intends to demonstrate such influences with its experimental package on board of the External Facility of the Japanese Experimental Module section of the International Space Station (ISS). Meanwhile, the ESA project ACES (Atomic Clock Assembly in Space), planned to start on the ISS in 2010, will also study the benefits that might result from future space-borne clocks.

Two of the most modern atomic clocks, the space hydrogen maser (SHM) and the cold caesium-clock shall be tested in the microgravity field of the ISS. The two very different types of instruments will be synchronized by means of a specifically developed "Frequency Comparison and Distribution Package" (FCDP), and the results shall be transmitted to ground by two datalinks, a laser- and a Ku-band link.

This experiment will distribute a stable and accurate time base for space-to-ground and ground-to-ground time and frequency comparison. Institutes worldwide will participate in comparing their ground-based atomic clocks with the ACES clock signal. Analysis of the scientific data will seek to shed light on fundamental relativistic issues, as well as for time and frequency metrology, geodesy, gravimetry, precise orbit determination, and Earth monitoring by means of the very long baseline interferometry (VLBI).

The ACES project may also provide insight into the question of whether, in the far future, the world's timekeepers would be better off using a space-based time and frequency reference system as the primary standard or retaining the primary reference network on Earth.

In this aspect, the GNSS community should also investigate which other phenomena might play a role in combination with time and distance. For example, space–based VLBI could prove to be extremely important for the definition of coordinate reference frames, for UTC issues, and for astrophysics in general.

Femtosecond Lasers. Optical frequency standards have been based on laser-cooled atoms and ions for a long time (see Figure 2). These systems promised superior stability over existing microwave standards. However, dividing down the very fast optical oscillations to a countable frequency has proved to be extremely complicated until recently.

New frequency dividers based on mode-locked femtosecond lasers and microstructure optical fiber provide convenient, robust, accurate means of phase-coherently linking optical frequencies to standards in the microwave domain. This breakthrough has opened the door to a new generation of atomic clocks based on optical transitions.

Atomic Clocks: Not Just for Satellites

Improved timing in GNSS receivers is technically already possible today. However, the development of good, stable and at the same time extremely cheap reference oscillators has not kept up with progress achieved in other aspects of GNSS receiver chip design. Consequently, all types of GNSS receivers still use crystal oscillators for their timing reference.

Consider, for example, one very interesting development: in 2004 the U.S. National Institute of Standards and Technology (NIST) demonstrated a chip-scale atomic clock (CSAC) about the size of "a grain of a rice" and stable enough at 10^{-9}. The CSAC's volume is less than 10 cubic millimeters (1.5mm × 4mm) with power requirements for battery driven applications of 75 milliwatts.

A complete atomic clock based on the CSAC would be about one cubic centimeter in size according to NIST. (For details, see <http://tf.nist.gov/ofm/smallclock/index.htm>.)

This development alone could stimulate new inventions and alternative designs for GNSS receivers. Such products might not compete with the various existing and successfully used GPS receivers of the civil mass market, but they could instead lead to new developments in science and technology as well as applications in professional, commercial, and military realms.

Today GPS is already often combined with other sensors such as inertial measurement units or dead reckoning devices. Because such integrated solutions are often the only possibility in poor GNSS signal environments to allow positioning, we expect that this trend will gain even more in importance.

Development Trends of Atomic Standards. Since the U.S. National Bureau of Standards (the predecessor of NIST) developed the first atomic clock in 1949, the frequency stability and the time stability have been improved every decade by one order of magnitude, as shown in Figure 1. NIST is one laboratory among the 60 timing laboratories around the world that contribute to the determination of the UTC.

The NIST-F1 ensemble consists of six hydrogen maser and four caesium-beam clocks. It is as accurate that it would neither gain nor lose one single second in more than 60 million years!

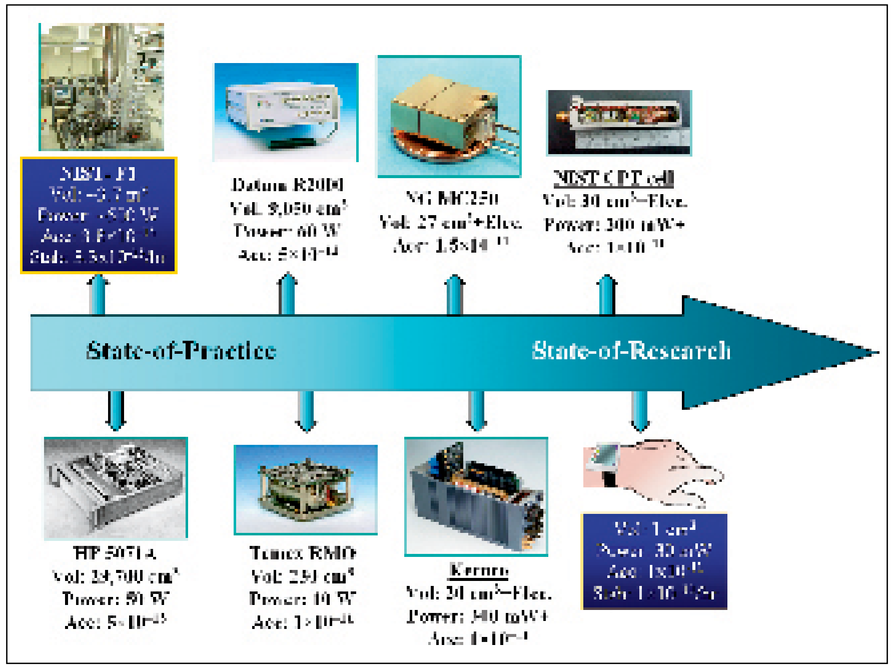


FIGURE 3 Atomic Clock Technology Progression of CSACs. Figure courtesy of DARPA by Clark Nguyen (see Additional Resources citation for more details)

Chip-Scale Atomic Clocks

As shown by Bill Klepczynski during the 46th CGSIC meeting on September 26, 2006, atomic clock technology is progressing very quickly. As we see in Figure 3, the state of practice at the moment stems from the NIST-F1 prototype. With accuracies on the order of 3.8×10^{-15} and stability values ranging 3.3×10^{-15}/hr, the physical dimensions and power consumption are not so encouraging because a volume of 3.7 cubic meters and power consumption of 500 watts are currently needed. Such characteristics are impractical for receiver applications.

Nevertheless, although this is the current state of the art, the atomic clock technology progression is moving quickly toward significant reductions in the required dimensions. CSACs could be a reality in the foreseeable future. If CSAC development succeeds, the target timing accuracies of 10^{-11} with stability values around 10^{-11}/hr could be achieved in small devices of only 1 cubic centimeter with power consumptions of only 30 milliwatts.

Having such accurate clocks the size of a wristwatch would open a new world of amazing applications. The clear motivation for CSACs is to enable ultra-miniaturized and ultra–low power time and frequency references and broaden the associated applications as much as possible.

At the moment, five groups are working on this promising technology divided in two main programms. In the Defense Advanced Research Projects Agency (DARPA) program we can find NIST, Symmetricom, Honeywell, and Rockwell Scientific while in the Office of Naval Research program, Kernco is the main actor. Figure 4 shows the CSAC concept.

One of the main and most interesting applications for CSACs would be to attain rapid re-acquisition. Indeed, as we know, the choice is between more correlators and a good clock and as shown by Klepczynski, reducing the frequency instability from 10^{-7} to 10^{-11} would be

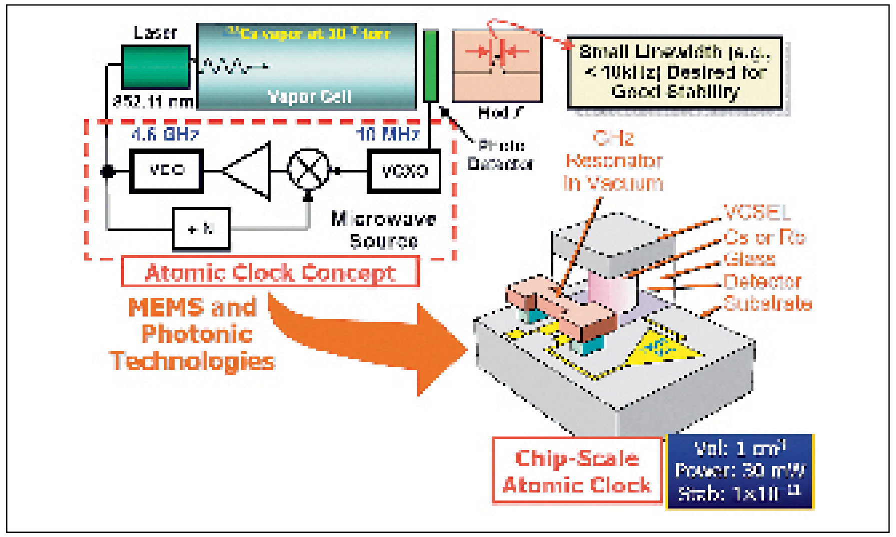


FIGURE 4 Anatomy of a chip-scale Atomic Clock. Figure courtesy of DARPA by Clark Nguyen (see Additional Resources for more details)

possible using CSACs. The result would be a reduction of the Time To First Fix (TTFF) from 93 seconds to only 5 for a similar correlator size of 6000 correlators. This means that the improvement brought by good clocks is equivalent to that of increasing the number of correlators, regardless of the real costs of both. In fact, new CSACs would have to be priced very low to compete against correlators.

"Nugget" of Synchronization. The integration of chip-scale atomic clocks into new GPS receivers is by no matter a far-future technology. Last year the U.S. Navy Space and Naval Warfare Systems Center San Diego announced their "Navigation Nugget" receiver (*Inside GNSS*, April 2006).

The Navigation Nugget consists of a software-defined GPS receiver and an inertial measurement unit (IMU), both coupled to the onboard atomic clock. The design enables highly precise positioning and navigation also in highly impaired and threatened GPS terrain.

Coupling of GPS, IMU and atomic clocks is going to assist users in positioning in jammed and shaded environments as well as in the critical area of transition between indoor and outdoor. A Navigation Nugget of enlarged scale is expected to be field-tested within months.

Time, Coordinates, and Orbits

From the users' perspective, common GNSS time and coordinate reference systems are needed to simplify the simultaneous use of different GNSSes. For political and technical reasons, however, the various GNSS systems should not be overly similar or depend on each other.

Given this premise, the most that seems achievable is use of a common standard to define the reference systems, but allowing each GNSS to employ different realizations (frames) of the given standard (system). This goal has been achieved between GPS and Galileo. Both broadcast satellite positions in a reference frame based on the International Terrestrial Reference System (ITRS).

Slight coordinate differences at the millimeter level might exist due to the use of different realizations of the same standard, but those differences are not significant for the navigation user. In contrast, GLONASS coordinates are based on the PZ-90 reference system, making the coordinate conversion more cumbersome.

Similarly, all time systems of GPS, GLONASS, and Galileo are based on UTC, but using individual realizations of UTC. "Spending" one satellite's observations enables a GNSS receiver itself to solve for the time offset between two different satellite systems. Up to now Europe and the United States have agreed on broadcasting the Galileo-GPS time offsets mutually.

If GLONASS and the upcoming GNSS systems, including augmentations, follow this approach (for example QZSS plans to do so), we can also consider the issue of a common time reference to have been resolved. One just has to keep in mind that the number of broadcast offset values increases as the square of the number of compatible systems operating under such reciprocal agreements.

If future ground segments had multisystem navigation receivers installed at monitoring sites and reference stations, they could make a great contribution to the very precise definition and subsequent maintaining of a global time and coordinate reference frame.

Satellite Operations & Opportunities

Satellite operations — signals, frequencies, payloads, communications — offer a number of opportunities for cooperation among the GNSS system operators to improve the collective robustness of a system of systems while greatly improving the users' experience.

CDMA or FDMA? GPS, Galileo, and China's planned Compass system employ code division multiple access (CDMA) techniques in their systems' design. On the other hand, GLONASS has used and still uses frequency division multiple access (FDMA) technology.

As long as a common technique is not used by all GNSS services, we cannot say that the systems will be fully interoperable, as users would desire. During the GPS/GLONASS Working Group 1 meeting in December 2006, both sides emphasized the benefit to the worldwide GNSS user community a common approach concerning FDMA/CDMA would bring. The Russian side announced that they will come to a decision about possible addition of or conversion to CDMA technology by the end of 2007.

CDMA technology allows for a great separation between signals that share the same band. Given its great robustness against all sources of potential interference, all systems are expected to finally adopt CDMA in the future.

New RNSS bands? The radionavigation satellite service (RNSS) portion of the RF spectrum is overcrowded. This is especially true on the L1 band. Nevertheless even those bands that have not been used yet will certainly be shared by many systems in the near future. Thus, the search of other free frequency resources is something that will occur with a high probability in the next years.

As we know, the Galileo program obtained authorization to use a C-band assignment for radionavigation. The technical complexities, however, have made it impossible for the first generation of Galileo to take advantage of the C-band allocation.

Indeed, phase noise problems, the higher free space attenuation (related to the use of omni directional antennae) and the strong signal attenuation due to rain knocked down all the proposed solutions. But in some decades, things could have changed; thus could maybe the C band be an alternative? What about adding lower frequencies to contribute towards a more effective indoor use of GNSS? We will return to this subject in Part 3. There, we will depict an imaginary scenario where C-Band would be reserved for military/governmental applications leaving the L band alone for civil users (or vice versa?). This would have very interesting benefits to both types of user and important consequences.

Inter-satellite Links? Inter-satellite links could be something quite common in not so many years. The Galileo program has studied the possibility but for financial reasons did not employ them in the first generation. GPS has carried out first tests with inter-satellite links. GLONASS and GPS will implement them on one of the next generations.

Without doubt, for achieving shorter times-to-alarm for integrity purposes, inter-satellite links are the only way to go. Moreover, one can even envision these links supporting applications of atmospheric sounding (GNSS occultation) for tracing global atmospheric humidity maps, contributing to improved global weather forecasting.

Multi-Mission Concept? Satellite missions are expensive, and consequently the trend is to put many missions together. If we take a look at GPS III, we can see proposals of equipping the satellites with weather sensors, nuclear detectors (already on board existing generations of GPS satellites), earth observation, and atmospheric sensors. The objective is to extend the payload capability to the maximum to spread costs across multiple missions, and the trend will remain in the future.

For some time QZSS was expected to offer a communication service together with navigation. Although the idea seems to have been abandoned, similar approaches could be revisited again in coming years.

Additionally, GNSS could also be used not to only position on the ground but also in space. Why not to use GNSS to position geostationary satellites? Today GEOs are placed into their intended orbital locations with accuracies of around 1 degree. But if GNSS were used here, too, the tolerance cold be reduced to lower values of for example 0.2 degrees, thus allowing for a denser network of geostationary satellites and a more efficient exploitation of the limited space resources in that specific orbit.

Dedicated Indoor-GNSS?

The present and planned GNSSes are definitely the primary positioning resource when line-of-sight signals from the satellites can be received. Over the last decade product designers and manufacturers have considerably increased GPS receiver sensitivity (by nearly 30 dB). Today satellite navigation even works with attenuated signals, for example, inside a vehicle's glove compartment or on the upper floors of buildings.

Notwithstanding those facts, GNSS is definitely still not a dedicated or autonomous means for indoor positioning. Can this performance be improved and, if yes, how?

Although we have no definitive answer about this, we can point out some major aspects that could help improve satellite navigation reception in signal-challenged environments. For instance, increasing the transmitted signal power would definitely help. One could imagine that it might be possible to increase satellite signal power by only a few decibels. A further increase in received signal power might become possible using directional transmitting antennas (similar to the GPS spot beam mode planned for military signals) giving, perhaps an additional 20 decibels of received power.

Another idea would be to choose a frequency that is better suited than an L-band signal to penetrate buildings. One recalls, for example, that Loran-C signals are known to provide rather good reception inside buildings. However, Loran-C is also known to exhibit different problems regarding interference, and a space-borne signal might not be able to penetrate through the ionosphere.

On the other hand, many signal reflections occur within buildings; so, a wide bandwidth signal might help separate direct and multipath signals. One could imagine that the satellites broadcast ultrawideband (UWB) signals for that purpose. This involves frequencies in the range of 3-10 GHz. Naturally, the code pseudorange noise would be extremely small combined with excellent multipath mitigation capabilities.

Apart from these rather hypothetical options, a future GNSS system should

Erratum

The authors would like to mention that in the January/February issue the two following erratas were found:

1. As noted by Grace Pazos made us note, the first GPS Block IIR-M (SVN 53/PRN 17) was launched on September 26, 2005. December 16, 2005, was actually the date it was set usable for operational purposes.
2. As correctly noted by Christian Tiberius, Table 3 mentions 64 E for one of the GEO-longitudes of one of the EGNOS satellites. In fact, this is the old ESTB satellite (PRN 131) and the current EGNOS PRN 126 is much closer to Europe, at 25 E.

Moreover, we would like to thank Christian Tiberius and Grace Pazos for their helpful comments in finding these errors.

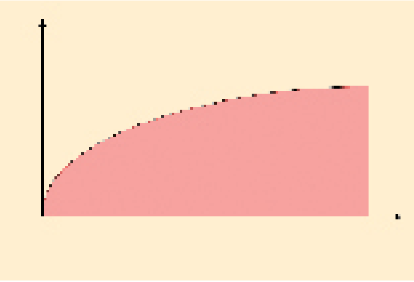


FIGURE 5 Qualitative analysis of the expected marginal gain as a function of the number of GNSS satellites

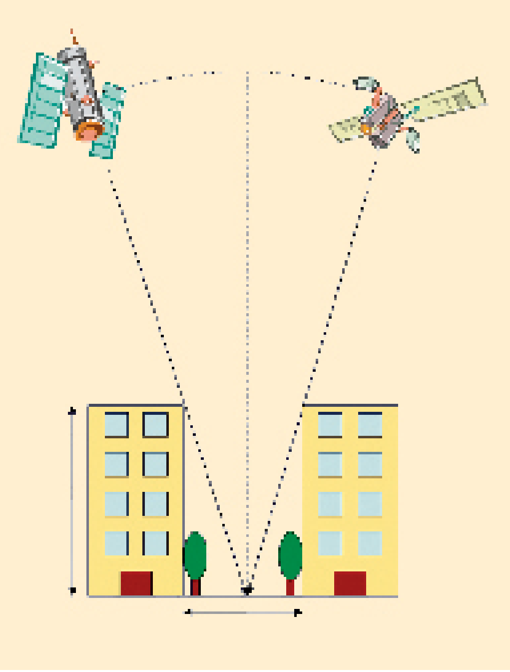


FIGURE 6 Example of GNSS satellite density could be selected

generally provide an optimized signal structure for high sensitivity receivers to allow easy acquisition and reliable tracking. For example an intelligent mixture between short PRN codes for easy acquisition and long PRN codes in case when cross-correlations are important would be desirable. Furthermore, it should provide long-term predictions for satellite orbit and clocks.

Satellite navigation will also do a good job in helping other indoor navigation systems. Among the latter, ultra-tight GPS/INS integration, wireless network positioning, RFID, and terrestrial UWB, are promising candidates.

The concept of pseudolites also could be of interest, if they are cheap and extremely simple to operate. A local service provider can place them relatively easily in locations where satellite navigation signals can not be received. Just imagine a pseudolite in the form of a light bulb operating completely autonomously. Of course, this area requires a lot of standardization work in order to control the mutual interference of pseudolites and GNSS signals and to allow GNSS receiver manufacturers to process those signals.

GNSS beyond the earth for space exploration?

Why should we limit ourselves to the Earth? We hear everywhere about U.S. plans to return again to the moon and start from there with the human exploration of other planets in the solar system.

Putting antennas pointing towards the space is something that could become a common practice within only a few decades. GNSS would then still give us a position and a time, but what time? With respect to the earth? In a lunar or solar coordinate system?

Perhaps we already should begin thinking about implementing solar system time such as a NASA speaker announced in the 2006 Munich Satellite Navigation Summit.

The GNSS System of Systems

As we have seen from our previous discussion in the January-February 2007 issue of *Inside GNSS*, four global navigation systems might be fully operational within two decades providing, an excellent coverage of most of the locations on the earth.

Today, with GPS alone an average of approximately 10 satellites can be seen at any point of the earth. When GPS, GLONASS, Galileo, and COMPASS are operational — assuming they would be fully interoperable — four times more satellites may be available for navigation, positioning, and timing.

Locations that now have poor coverage might no longer need a regional augmentation, and then the natural question arises: what is the added value of using regional systems when all the planned global systems are already delivering the accuracy that we need?

Are so many satellites really necessary?

Having as many satellites as possible is always good. Nevertheless, every extra satellite implies an important extra cost to society and therefore we might well ask if a point is reached at which no real improvement can be observed when the size of the combined GNSS constellation increases.

Indeed, one might expect that the relative gain brought by 30 satellites when there are already 30 existing is higher than that of 30 additional satellites when there are already 60. This is equivalent to saying that the marginal gain diminishes as the size of the constellation grows. Such a conclusion should not come as a surprise, because it reflects a well known economic law that applies to most goods and services in the world.

As reflected in Figure 5, the four global satellite systems now in existence or under development will have around 110 satellites altogether. Do we really need so many? To what region of Figure 5's curve do 110 satellites correspond?

An imaginable possibility to estimate the saturation level in terms of geometry would be to calculate the number of satellites that are needed to cover a difficult urban canyon environment, such as shown in Figure 6. Indeed, if we assume a house of 25 meters height with a distance of 10 meters between two buildings, an angle of approximately 12 degrees results with respect to the satellites and the middle of the street. If we further assume the same semi-major axis as Galileo and five MEO planes, all the Earth could be covered for elevation angles higher than 78 degrees by 5 × 22 (or 110) satellites. This number, of course, corresponds to about four GNSS constellations, whose orbits are optimized with respect to each other.

In the framework of the Galileo program, various studies have been carried out in the past years to assess the effect of increasing the number of satellites of an existing constellation in which the effect of doubling the number of satellites was studied in detail. In terms of positioning accuracy, the improvement resulting from the better geometry is obvious. Indeed, the step from GPS alone to Galileo + GPS undoubtedly represents a clear gain for the final user.

Nevertheless once a reasonably dense constellation of satellites is achieved, would not the user profit more from an additional increase of power than from an increase in the number of satellites? Let us think again of our future scenario of 110 satellites. What would be better for the user: one extra satellite or an increase in the transmitted power?

The problem gains even more multidimensionality if we recall the development of the semiconductor industry in recent years. As mentioned earlier, it is not so unrealistic to think that not too far in the future pseudolites could be a cheap product that anyone could place in locations with poor GNSS coverage. These single-chip pseudolites (SCPL) could thus meet users' positioning requirements in areas where satellites signals could not be received, no matter how dense the network of satellites.

Standardization and Harmonization

Satellite navigation is fashionable. Every superpower wants to have a satellite navigation system of its own and preferably a global one. But, is there room for everyone? We saw in the previous discussion that on the other hand the real need of having multiple systems is open to question at some point from an economic perspective.

A very different issue, but one of great importance, is whether we can have so many systems coexisting together without degrading the performance of one another. The interference caused on one system by the rest is technically difficult to measure, and especially if each system would develop its own concept without taking the rest into account.

In the 2004 agreement on GNSS cooperation between the United States and the European Union an interference compatibility methodology was developed in conjunction with the NSCC following ITU standards. The bilateral Agreement, however, is only between Americans and Europeans. If new systems come into play, standardization will be needed and perhaps even multilateral agreements. Otherwise chaos will reign in the RNSS band and the law of the strongest will prevail.

Who should and could be responsible for coordinating these actions? It seems that the United Nations Office of Outer Space Affairs could play such a role — extending its efforts in sponsoring formation of the International Committee on GNSS (ICG). But transforming existing bilateral agreements into compatible multilateral agreements is not an easy task. For better or worse, the more players are involved, the more difficult it has always been to go on things.

Satellite navigation is fashionable. Every superpower wants to have a satellite navigation system of its own and preferably a global one.

GPS and Galileo are compatible and interoperable to a high degree, but are not equal. Although important common actions have occurred in recent months, there is still a long way to go. And the difficulties are compounded when we compare both systems with GLONASS or the planned Compass.

No matter what the system designers do, the fact is that the user market will explode in the next years. GNSS receivers will work better and almost everywhere, and the fusion with other communication devices is already on the threshold. International standards and certification are urgently needed and although it is true that ICAO, ITU, RTCA already provide models for certification and regulation, the market forces are stronger and demand faster reactions.

Global vs. Regional Integrity

Everybody talks about integrity — the ability to warn users about "unhealthy" — erroneous — satellite signals. Galileo will have integrity built into the system itself, and GPS III will follow this path as well. At least the two will have it. GLONASS might embrace the idea, too, and possibly Compass as well.

The only problem is that the integrity concepts developed — or under development — for Galileo and GPS are different. As a result we cannot strictly talk about global integrity as long as no harmonization exists among the methods.

What happens, then, if every system has different integrity requirements and concepts? Should Galileo assure a six-second integrity constraint but the others do not, then what use was it for Galileo to have a more stringent design than the others? Can we talk about integrity at all if each GNSS understands it a different way?

Additionally, the concept of integrity itself is also pretty open. We have the standard integrity defined for the aviation community (by the International Civil Aviation Organization or ICAO), another for maritime, land, etc. The different understanding from different communities should flow in a structured way so that in the future all the systems would be certified for use worldwide in whatever mode or operating environment, and all the systems should incorporate certified RAIM.

For other life-critical services as search and rescue common frequencies would be desirable as well as compatible modulation and code rates.

Conclusions

GNSS is already a success and, as happens with any success, everybody wants to have part of the cake. The GNSS System of Systems of the future will be the result of putting together many different navigation systems from different countries.

Nevertheless, the final users are only interested in receiving signals — no matter where they come from or to whom they belong. Thus a true global system of systems would be with no doubt his desire. Today we can only imagine what it will look like, but the shape of that future system will depend on the decisions that we make today.

The time for cooperation, harmonization, and standardization is here. Nobody says that it will be an easy task, but wouldn't it be a great thing to have receivers in the near future that can receive dozens of satellites in difficult scenarios where no single system alone can offer reliable services today?

Additional Resources

[1] Avila-Rodriguez, J.A. et al. (2005), "Revised Combined GALILEO/GPS Frequency and Signal Performance Analysis", *Proceedings of ION GNSS 2005* – 13-16 September 2005, Long Beach, California,USA.

[2] Avila-Rodriguez, J.A et al. (2006), "How to optimize GNSS signals and codes for indoor positioning", *Proceedings of ION GNSS 2006*, 26-29 September 2006, Fort Worth, Texas, USA

[3] China Daily, Beijing, 13 November 2006

[4] Galileo SIS ICD 23/05/2006

[5] Hein, G.W., Eissfeller, B. (2001), "Technology Assessment for Precision Positioning and Navigation Scenarios 2005 and 2010 for Automotive Applications," prepared for DaimlerChrysler Research and Technology, 9 March 2001

[6] Hein, G. W. et al. (2006), "MBOC: The New Optimized Spreading Modulation Recommended for GALILEO L1 OS and GPS L1C", *Proceedings of ION PLANS 2006*, 24-27 April 2006, Loews Coronado Bay Resort, San Diego, California

[7] http://de.wikipedia.org/wiki/Atomic_Clock_Assembly_in-Space

[8] http://gps.losangeles.af.mil/engineering/icwg/Docs/EC%20 and%20US%20Joint%20Statement%20on%20GALILEO%20and%20GPS%20Signal%20Optimization%20-%20%2024%20Mar%2006.pdf

[9] http://gps.losangeles.af.mil/engineering/icwg/Docs/WGA%20Signed%20Recommendation%20on%20MBOC%20-%2023%20Mar%2006.Pdf

[10] http://pnt.gov//public/docs/2004-US-ECagreement.pdf

[11] http://tf.nist.gov/ofm/smallclock/index.htm

[12] http://www.glonass-ianc.rsa.ru/i/glonass/joint_statement_eng.pdf

[13] http://www.space.com/spacenews/archive05/Nigeria_0221.html

[14] Irsigler, M., and G. W. Hein and A. Schmitz-Peiffer (2004): Use of C-Band frequencies for satellite navigation: benefits and drawbacks, GPS Solutions, Volume 8, Number 3, 119-139, September 2004, Wiley Periodicals Inc., 2004

[15] Irsigler, M. and G. W. Hein, B. Eissfeller, A. Schmitz-Pfeifer, M. Kaiser, A. Hornbostel, and P. Hartl, " Aspects of C-Band Satellite Navigation: Signal Propagation and Satellite Signal Tracking" In: EUGIN [Hrsg.]: Proceedings on CD, ENC GNSS 2002, May 27–30, 2002, Kopenhagen

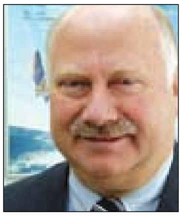
[16] IS-GPS-200: NAVSTAR GPS Space Segment /Navigation User Interfaces

[17] Nguyen, C. & Kitching, J. "Towards chip-scale atomic clocks," in *Digest of Technical Papers, ISSCC 2005*, 1, 84-85, Piscataway, NJ: IEEE, 2005.

[18] Nobel lecture: Passion for Precision (T. W. Hänsch). Review of Modern Physics 78 (2006) 1297-1309

[19] Revnivykh, S., "GLONASS Status Update", *Proceedings of 46th CGSIC Meeting*, 25 September2006, Fort Worth, Texas, USA

Authors



"Working Papers" explore the technical and scientific themes that underpin GNSS programs and applications. This regular column is coordinated by **PROF. DR.-ING. GÜNTER HEIN.**

Prof. Hein is a member of the European Commission's Galileo Signal Task Force and organizer of the annual Munich Satellite Navigation Summit. He has been a full professor and director of the Institute of Geodesy and Navigation at the University of the Federal Armed Forces Munich (University FAF Munich) since 1983. In 2002, he received the United States Institute of Navigation Johannes Kepler Award for sustained and significant contributions to the development of satellite navigation. Hein received his Dipl.-Ing and Dr.-Ing. degrees in geodesy from the University of Darmstadt, Germany. Contact Prof. Hein at <Guenter.Hein@unibw-muenchen.de>.

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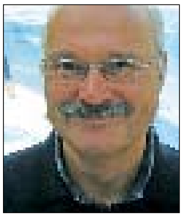

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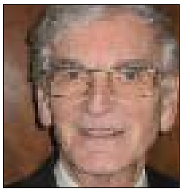
Stefan Wallner studied at the Technical University of Munich and graduated with a diploma in techno-mathematics. He is now research associate at the Institute of Geodesy and Navigation at the University FAF Munich. Wallner's main topics of interests are the spreading codes and the signal structure of Galileo and also interference and interoperability issues involving GNSS systems.



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