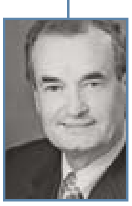
GNSS Solutions:

Atomic clocks on satellites and mitigating multipath

"GNSS Solutions" is a regular column featuring questions and answers about technical aspects of GNSS. Readers are invited to send their questions to the columnists, **Professor Gérard Lachapelle and Dr. Mark Petovello,** Department of Geomatics Engineering, University of Calgary, who will find experts to answer them.



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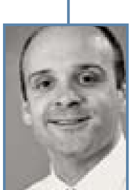

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"GPS satellites used to carry two cesium and two rubidium atomic standards on board. Subsequently, GPS switched to all rubidium clocks. Galileo plans to use hydrogen masers instead. What are the relative merits of these clocks for use in navigation satellites?"

It is well recognized that the space-qualified atomic clocks in the GPS satellites are an enabling technology, if not the enabling technology for the system. However, they are also one of the more difficult technologies to acquire.

The first GPS satellites, known as the Block I generation (Navstar Space Vehicles 1–11), initially used three newly developed rubidium clocks. Development of a space-qualified cesium clock subsequently resulted in one of the latter types being added to the satellites' clock suite, beginning with Navstar 4.

Over time, the GPS development programs for these space-qualified clocks led to the mixture of the different types of clocks used in the satellites. The rationale for their development and use in the GPS system provide answers to the relative merits of the technologies.

We should recognize that space-qualified atomic clocks are unique in the clock technology area. The electronics used in these clocks are one of the biggest differences from their ground-based counterparts. The key cost driver is that they are comprised of space-qualified electronics (Class S or equivalent), which must not only survive the launch environment but also the operational environment (thermal, radiation, etc.) with the objective of remote operation for design lifetimes of 5 to 7.5 years.

As an example, a number of commercial rubidium clocks are on the market today. Their performance varies widely for good reason: the electronics implementation and their associated cost determine the performance expected from the unit. The performance variability is driven more by the electronics making up the internal and output signals than by what would be expected from the atomic-level physical processes driving the oscillator. For GPS, the space-qualified versions were developed to provide the highest performance possible, particularly in frequency stability — the time error accumulating as a function of the interval after an update. High performance and the space qualification attributes are required to maintain the system and satellite-to-satellite synchronization for operational lifetimes of many years.

This combination of requirements leads to unique units and specialized means of manufacture. They must be capable of producing a stable short-term (~100 seconds), low-noise signal for user receivers to integrate the received signals over long intervals, and yet stable and predictable enough to maintain long-term (~1 day) signal synchronization for precision range measurement.

Following the two Navigation Technology Satellites (NTS-1 and NTS-2), the Block I satellites intended for GPS system concept demonstration were developed by Rockwell International and represented the first deployment of space-qualified rubidium clocks in significant numbers. The space-qualified cesium development followed the initial prototype in NTS-2. Preproduction versions were delivered as government equipment for the first spaceflights before being acquired in numbers for the operational system deployment.

Rubidium units were originally favored because of the quiet short-term noise performance that they provided. However, their temperature sensitivity and inherent high frequency drift uncertainty limited their long-term stability and, most importantly, predictability.

Predictability is important because it directly contributes, along with the orbit prediction errors, to the GPS space component error; the so-called signal-from-space user range error. For a standalone GPS receiver, the satellites' orbit and clock errors are inherently inseparable (i.e., they manifest themselves in the same way from a position computation point of view).

Both errors must therefore be determined to commensurate levels of accuracy – a few meters or better in the case of GPS. However, because the clock error information is broadcast to the user in the form of predictions from previous satellite uploads by the control segment, predictability is considered the third most important oscillator characteristic following short-term noise performance and reliability.

During system deployment, space-qualified cesium units were expected to be the technology of choice and were the preferred unit because they were primary standards, had very low frequency drift, and little thermal sensitivity. The short-term performance (1 to 100 seconds) of cesium standards is dependent on the type and quality of local oscillator used because the cesium interrogation time constant could be as long as 100 seconds and still satisfy the overall system performance expectations.

Future space clock development was expected to be in hydrogen maser technology, which would embody both superior short and long term performance. Original GPS expectations of the in-orbit update interval with space hydrogen masers was on the order of 14 days. GPS space clock development was in that direction.

Space-qualified rubidium and cesium clocks on board the Block I spacecraft experienced a number of performance problems, including phase and frequency jumps, thermal sensitivities, changing frequency drift

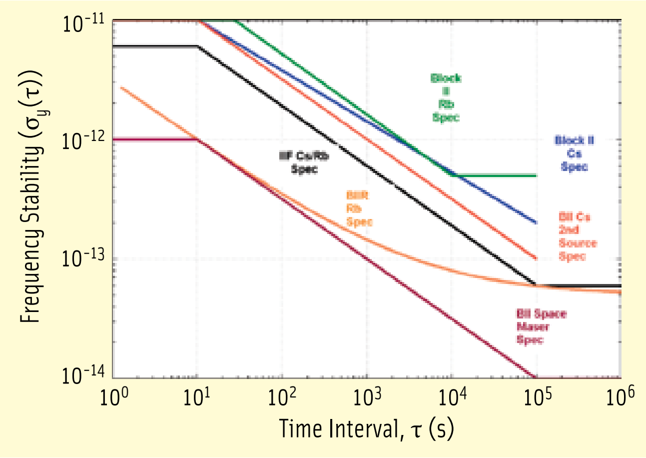

FIGURE 1 Space clock stability specifications for GPS. They are expressed in terms of frequency stability (), which represents the time error accumulating as a function of the interval after update.

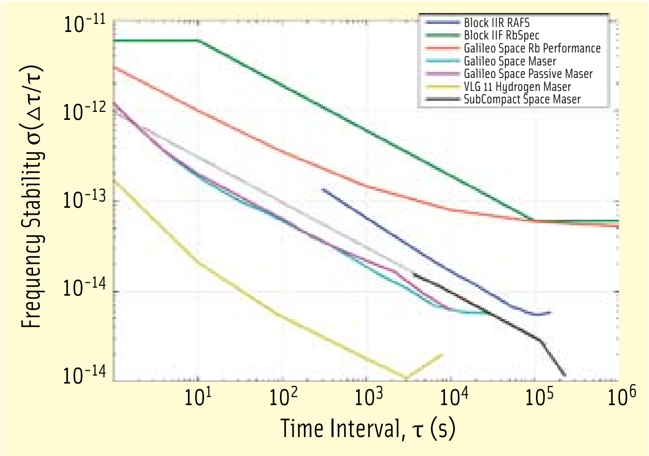

FIGURE 2 Stabilities of the various clocks used in GPS or yet to be used in Galileo. All except the specification lines are based on data taken at NRL or published for Galileo.

characteristics and outright failures. The need for reliable, long operating life became a driving development requirement. During Block II operational deployment, the Rockwell/Efratom rubidium clocks were improved, thermally stabilized, and finally performed successfully. The cesium units developed during Block I were likewise improved and made more reliable for successful operation.

The specifications for the stability of space-qualified clocks during Block II and successive generations of satellites are illustrated in **Figure 1**.

Multiple efforts were undertaken, primarily by the Naval Research Laboratory (NRL), to develop alternate industrial sources for GPS space clock technology as well to demonstrate the on-orbit performance of these space-qualified rubidium and cesium clocks. Another major concern was ensuring an industrial source's capability to produce the clocks in sufficient numbers for system use.

EG&G, now Perkin Elmer Optoelectronics, became the alternate source for space-qualified rubidium clocks. After the Block IIR satellite contractor's space cesium unit development failed, EG&G rubidium units became the sole clock on board the satellites. Block II space-qualified atomic clocks, both rubidium and cesium, went out of production following the release of the Block IIR contract and are no longer available.

Several different groups contributed to the technologies needed to produce a small high-performance space qualified hydrogen maser in the NRL program for the GPS system. Hughes Space & Communications Division built a prototype compact space maser for the Block II/IIA satellites, which was tested at the NRL. Hughes' Research Laboratories developed a subcompact design and built several experimental units as part of the GPS program.

That subcompact GPS maser design is similar to that being used for the Galileo GNSS satellites. The developers of Galileo recognized the difficulty of producing space-qualified atomic clocks and began development early in their program. A comparison of the stabilities of these different units is shown in **Figure 2**.

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and in 1984 became the head of the Space Applications Branch and the NRL GPS Clock Development Program. He is the Navy member of the Reliance Frequency Control Panel; chair of the ITU-R Special Rapporteur Group on the future of the UTC Time Scale; and international chairman of ITU-R Working Party Group 7A, Precise Time and Frequency Broadcast Services.

Correction

An item in the GNSS Solutions column in the July/August issue of *Inside GNSS* (page 21) incorrectly stated the business relationship associated with the common technology IP for two related GNSS chips: Topcon Positioning Systems' G3 Paradigm chip and the Javad Navigation Systems' (JNS) GeNiuSS chip.

JNS has an exclusive license from Topcon to use the chip in products sold into all application markets except for a set of "Precision Markets" identified in an agreement between the two companies. In turn, under the agreement Topcon is prohibited from selling outside of those "Precision Markets."

What receiver technologies exist for mitigating GNSS pseudorange and carrier phase multipath?

Pseudorange and carrier phase multipath errors are the last dominant errors in differential positioning and assume significance in high precision positioning applications. The multipath errors can range from a few meters to a few tens of meters in pseudorange and up to a few centimeters in carrier phase measurements.

Receiver manufacturers have invented various multipath mitigation schemes with varying degree of successes. In general, more research work has been done to mitigate pseudorange multipath errors than those associated with the GNSS carrier phase.

One of the earliest methods of reducing pseudorange multipath errors calls for smoothing the pseudorange measurements with carrier phase measurements. This technique is popularly known as the "Hatch Filter." The underlying theory of this method is that pseudorange measurements are noisier and more substantially affected by multipath than are the more precise carrier phase measurements.

Carrier phase measurements, however, do not provide absolute ranging information due to integer cycle ambiguity. In the absence of a cycle clip, carrier cycles can be used in conjunction with the raw pseudorange to calculate the smoothed pseudorange. Several popular smoothing techniques exist to accomplish this, although consideration should be given to the effect of code/carrier divergence due to the ionosphere. Carrier smoothing tech-

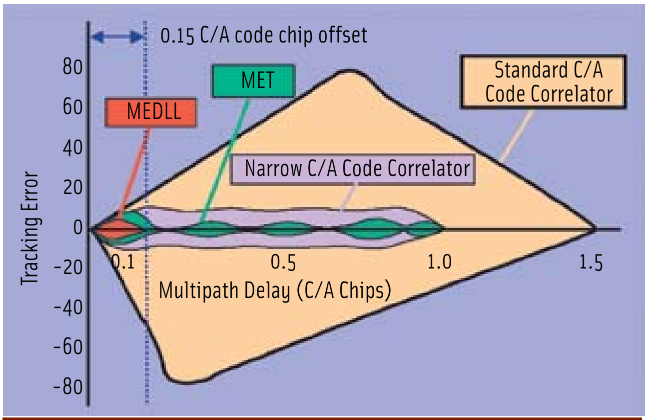

FIGURE 1 **Different pseudorange multipath mitigation schemes, including narrow and standard code correlators, Multipath Elimination Technique (MET), and Multipath Estimation Delay Lock Loop (MEDLL)**

niques are common in almost all high precision GNSS receivers.

The first major breakthrough in pseudorange multipath mitigation came with the introduction of the so-called "Narrow Correlator" design. The primary difference in this correlator compared to its predecessors is that it employs narrow spacing between the "early" and "late" arms, compared to the standard wide spacing correlator. The latter employs "early" and "late" arms with a spacing of 1 C/A code chip or nearly 1 microsecond whereas a narrow spacing correlator has arms with a typical spacing of only 0.1 C/A-code chip or nearly 100 nanoseconds.

The reduction in correlator spacing not only makes the pseudorange measurements 10 times more accurate, but multipath error is also reduced to approximately 1/10 in magnitude, especially the multipath error due to long delay replicas. To take advantage of this narrow spacing, the intermediate frequency (IF) bandwidth is also increased from about 2 MHz in standard correlator to more than 10 MHz in a Narrow Correlator. **Figure 1** shows the multipath error envelopes for a standard and a Narrow Correlator without band limitation.

The figure clearly reveals that employing narrow spacing correlators significantly reduces the long delay multipath but provides no relief to the short delay multipath. Further, the long delay multipath is not completely eliminated. So, room remains for further improvements.

The narrow correlator technique makes the hardware quite complex due to a large IF bandwidth and corresponding large sampling frequencies. This makes it unsuitable for large volume, mass-market applications. Low cost receivers typically employ simple multipath mitigation schemes. One such scheme is to use the correlation values in the "early," "prompt," and "late" arms to estimate the multipath error coefficient by comparing these values with the expected theoretical correlation values in those arms and thereby estimate the pseudorange multipath errors.

Further improvements to the narrow correlator technique in multipath mitigation are achieved by employing more than the early, prompt, and late correlators. Adding two correlators, one each on the early and late sides of the prompt correlator, achieves more effective multipath mitigation.

With these additional correlators, the slopes of the early and late sides of the correlation triangle can be measured and their intersection point can be calculated. This subsequently led to in the "Multipath Elimination Technique (MET)" and "Pulse Aperture Correlator (PAC). This new correlator improved the long delay multipath mitigation performance with regard to the Narrow Correlator and is also shown in Figure 1.

Another type of correlator that makes use of the additional two arms is the "Strobe Correlator," which employs a double delta discriminator. In this correlator, there are two pairs of "early" and "late" correlator arms, with each pair spaced at typically 0.1 and 0.2 of a C/A-code chip. Typically in a receiver the early-minus-late correlation value is used as an input for the code tracking loop. In the Strobe Correlator, however, the differences of the early-minus-late correlation values between the two pairs of correlators are used in the code tracking loop.

This has somewhat comparable performance with respect to MET for multipath mitigation as shown in **Figure 2**. Further improvements in the Strobe Correlator technology is achieved in the Advanced Strobe Correlator (**Figure 3**).

Extending the concept of having additional correlator arms for better multipath mitigation, more correlators can be employed to get information of the entire correlator function. For example, 10 – 15 correlators spaced at narrow intervals spread across a C/A-code chip could give enough information about the entire correlation triangle that the correlation triangle can be recreated instantaneously.

With this information, one can estimate the multipath parameters and, thereby, the multipath errors. This is the principle behind the "Mul-

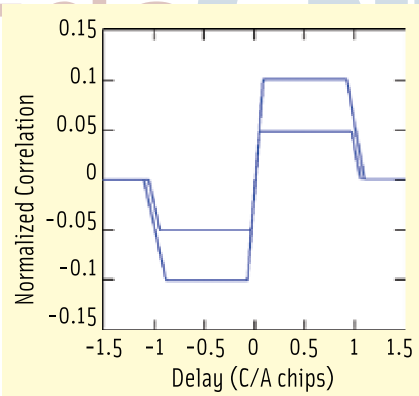

FIGURE 2 **Narrow correlators 100ns and 200ns delay spacing**

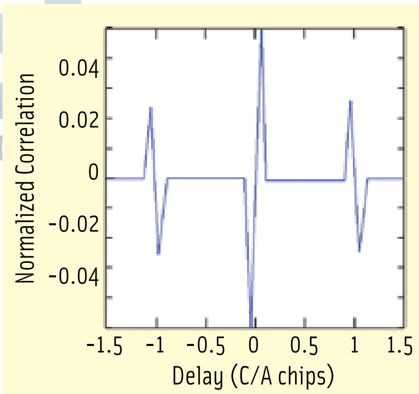

FIGURE 3 **Correlation pattern for the Strobe correlator with 200 ns delay spacing**

tipath Estimation Delay Lock Loop or MEDLL," which is one of the most complex and advanced multipath mitigation techniques. The major advantage of MEDLL is that it almost eliminates long delay multipath errors resulting in a multipath error envelope comparable to that of the GPS P-code.

All the techniques described so far employ some modifications in the correlator to mitigate multipath errors. A new technique named the Vision Correlator does not modify the correlators. Instead, it measures the phase transitions of the received GNSS signal radio frequency characteristics in the time domain by filtering all the transitions over a period of time. This technique is particularly useful for reducing short delay multipath.

In comparison with pseudorange multipath, only a limited number of carrier phase multipath mitigation techniques are available today. Unlike pseudorange multipath effects, the carrier phase multipath does not have a strong signature in the GNSS signal observables and, therefore, are difficult to mitigate. Furthermore, the maximum carrier phase multipath error does not exceed one-quarter of a carrier cycle or 4.75 cm for the L1 carrier.

The fundamental way to reduce both code and carrier multipath effects is to increase the chipping rate. For example, if the C/A code chipping rate can be increased to the level of P code chipping rate, then the multipath error will reduce by almost an order of magnitude.

This property is exploited in the "Gated Correlator." Here, a fraction of the C/A code chip is used for correlation; in other words, a "gated" C/A-code is used. As a result, the carrier phase multipath error reduces in proportion to that fraction, because long delay replicas are no longer affecting the carrier. The downside of this technique is a loss of correlation values due to the fractional correlation, which reduces the sensitivity of the receiver.

"Advanced Strobe Correlator" and "enhanced MEDLL" also appear capable of further reducing carrier phase multipath errors. However, reduction of carrier phase multipath errors in the receiver is still a challenge to be completely overcome.

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