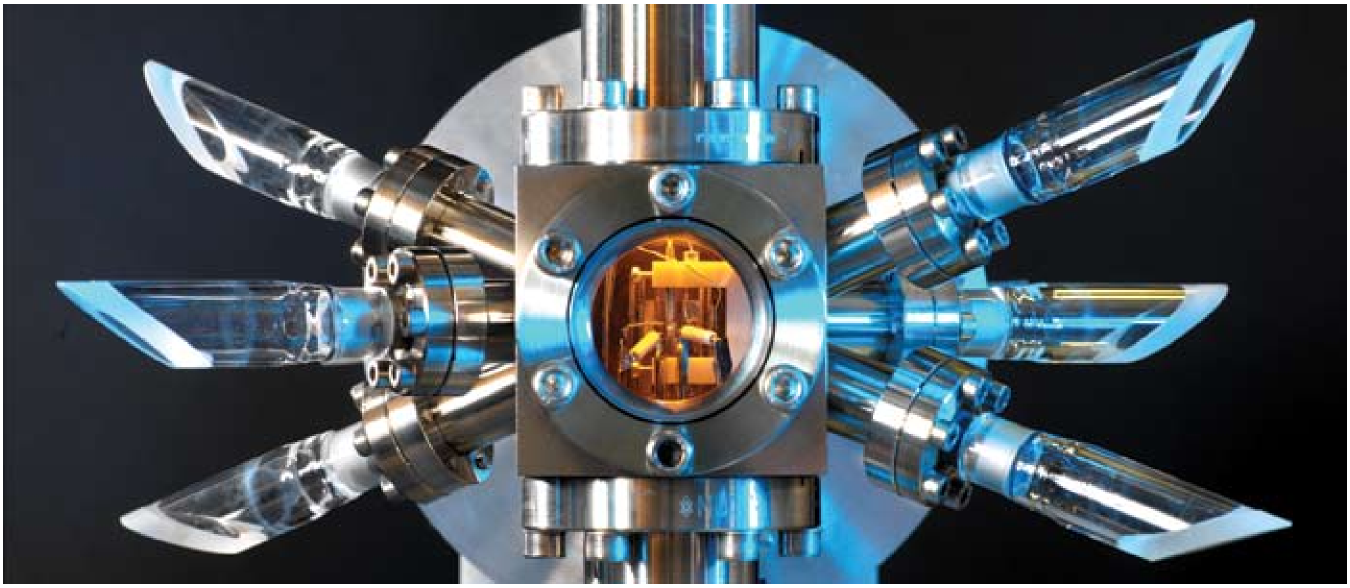
Future Time

Opportunities for Using Optical Clocks in GNSS Systems



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(above) A strontium ion trap used to provide an optical frequency reference-shown inside a 70mm vacuum cube. Courtesy of H. Margolis, NPL

At its core, the performance of a modern GNSS system depends on the quality of its timing. Galileo's GIOVE-B satellite is flying the first space-qualified passive hydrogen maser, and active hydrogen masers are part of the ground control segment that will generate Galileo system time. This column discusses the overall timing operation of the current Galileo architecture and points to the possibility of an even more accurate time source for GNSS systems in the future: optical frequency standards.

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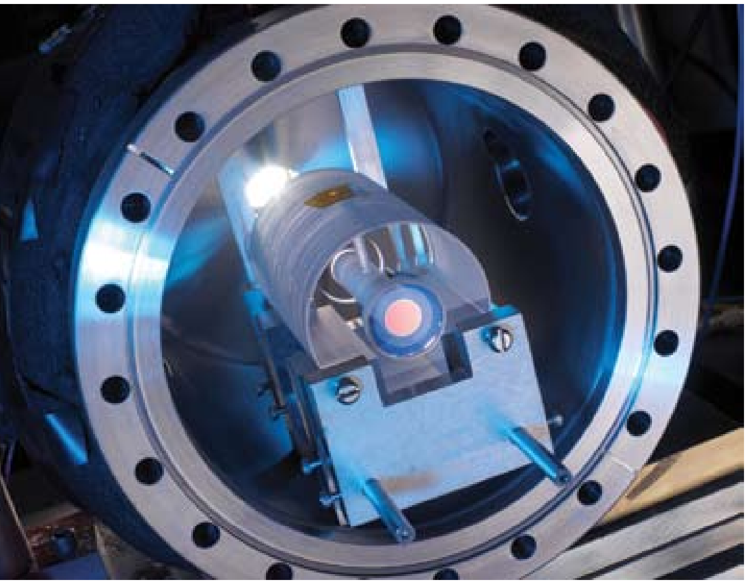
Existing GNSS systems use clocks based on microwave radio frequency (RF) standards operating at frequencies of up to 10^{10} Hz (10 GHz). This article examines the potential improvements and advantages of using clocks based on optical frequency standards, which have much higher natural frequencies of around 5×10^{14} Hz.

In general, high-precision clocks used to provide time in GNSS systems are based on three elements: a reference "frequency standard," an oscillator, and a counter to count the oscillations.

Over the last two decades, the stability and accuracy of optical frequency standards based on trapped ions and atoms have improved to a point where their performance now exceeds that of microwave standards. (The articles by P. Gill listed in the Additional Resources section provide a good introduction to the principles and current state of optical clock design.)

The accompanying photograph shows an example of a UK National Physical Laboratory (NPL) strontium ion end cap trap. By trapping a single strontium ion and laser cooling it to a few milli-Kelvin, the 674-nanometer "clock transition" can be interrogated using an ultra-narrow and stable (Hz-level) laser, which provides the optical oscillator. The laser in these optical oscillators is stabilized by locking it to a special vibration-insensitive cavity made of ultra-low expansion (ULE) glass (see accompanying photo).



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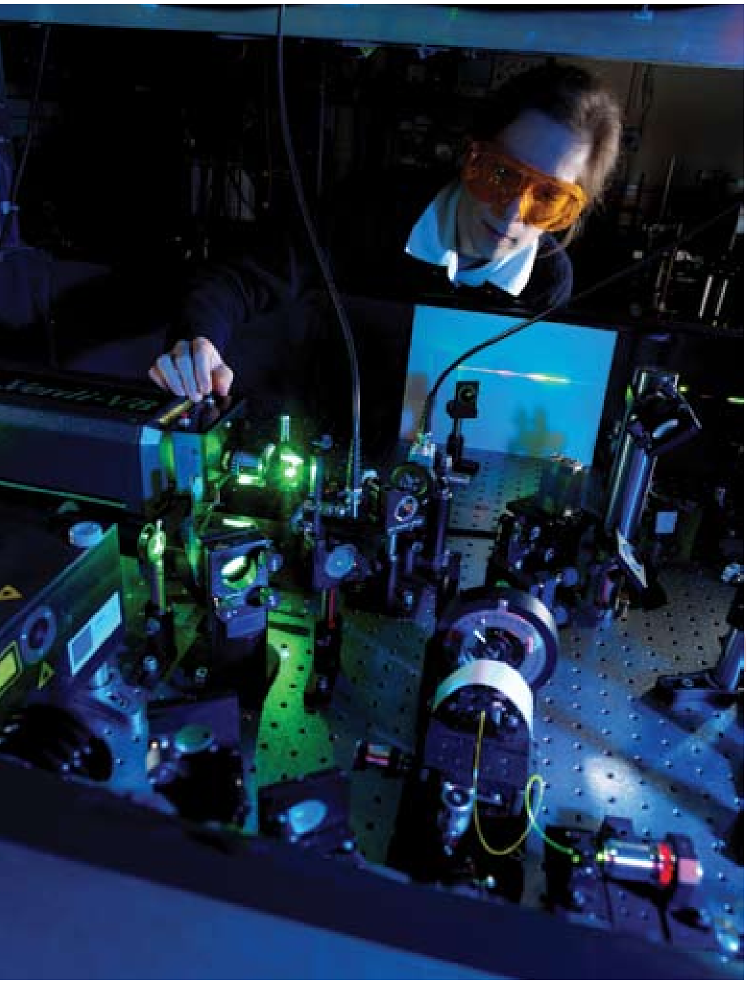

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(top) A 100-millimeter long ultra-low expansion (ULE) vibration-insensitive cavity used to stabilize a 674-nanometer laser – the oscillator for a strontium ion-based optical clock .
(bottom) An octave spanning femtosecond comb laser used to "count" optical frequencies

The last element of any clock is a counter. The development over the last decade of a special optical frequency measurement system known as an "optical frequency comb" has made possible the practical realization of optical clocks. Based on octave-spanning, femtosecond mode-locked lasers (see accompanying photo), such frequency combs can relate different stable optical frequencies with each other and with microwave frequencies with unprecedented relative frequency accuracy at the level of up to a part in 10^{19}.

Ultimately, optical clocks will offer accuracies and stabilities at the level of a part in 10^{17} or better. Such devices are likely to find both terrestrial and space applications, in scientific and environmental fields as well as navigation. Eventually, the second will probably be redefined in terms of an optical reference, rather than the current standard of a 9.2 GHz cesium hyperfine transition. **Figure 1** illustrates the stability of microwave and optical clocks. This article focuses on potential opportunities for the use of optical frequency standards in GNSS systems.

Synchronization Aspects of Galileo

Clock synchronization is a crucial issue for satellite navigation systems. Offsets of the satellite clocks are measured against the reference time scale, the so-called GNSS system time. These offsets are modeled on a continuous basis, with updates of the model parameters being broadcast to users in the satellite signal's navigation message. Because GNSS systems measure the satellite-receiver distance based on elapsed time of transmitted signals, clock prediction errors directly contribute to the overall ranging error of navigation users and thus to the uncertainty of user positioning.

In the present architecture of Galileo, the ground segment performs both generation of the system time and estimation of clock parameters. In fact, estimation and prediction of satellite orbits and clocks is a combined process performed by the orbitography and synchronization processing facilities (OSPFs). Current specifications require that the clock model shall remain valid for 100 minutes and the satellite clock prediction error is kept below 1.5 nanoseconds (1σ) over this period.

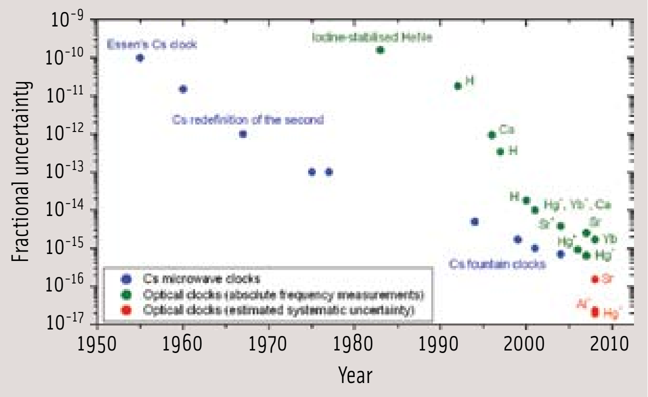


FIGURE 1 **Evolution of uncertainty of microwave and optical clocks Photo: NPL, H. Margolis)**

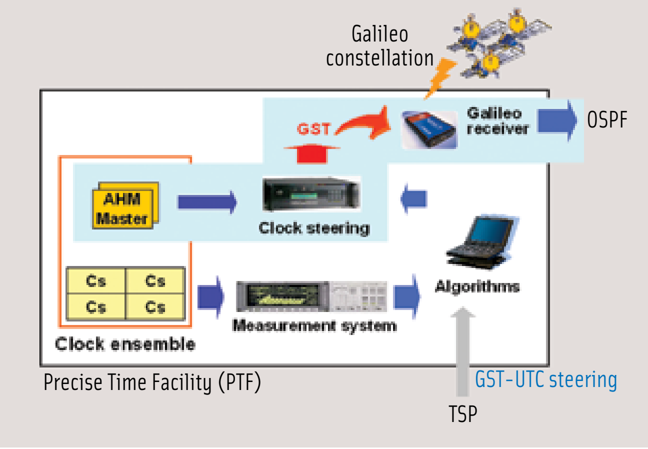


FIGURE 2 High-level architecture for Galileo precise time facility (PTF)

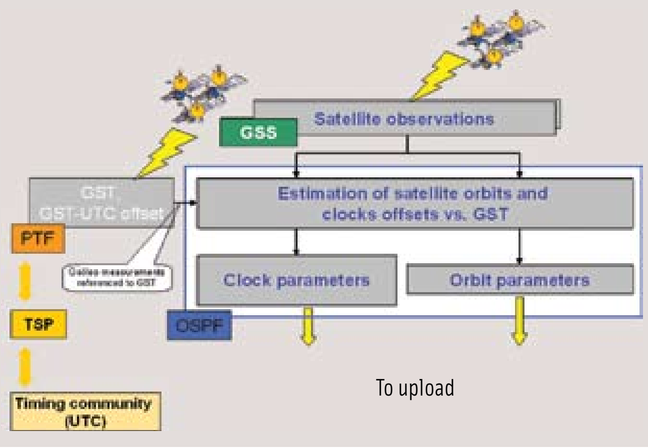


FIGURE 3 Synchronization in Galileo

The Galileo architecture currently relies on state-of-the-art microwave atomic clocks. An active hydrogen maser at the Galileo Precise Time Facility (PTF) will generate Galileo System Time (GST), with the maser's output steered on a daily basis to the international time-scale UTC — or Coordinated Universal Time — (modulo 1 second) using the data from the Galileo Time Service Provider (TSP).

This physical signal from the PTF hydrogen maser is fed into the Galileo receiver collocated at the precise timing facility. The satellite observations from this receiver are further provided to the OSPF to link all system clocks to GST.

UTC is produced as the joint effort of the international timing community. The Bureau Internationale des Poids et Mesures (BIPM, or International Bureau of Weights and Measures) computes a postprocessed, weighted average of about 200 atomic clocks world-wide that is further adjusted to match the definition of the SI second. This latter product is called International Atomic Time (TAI). After TAI's coordination with the Earth rotation, UTC is obtained.

The role of TSP is to establish an interface between the Galileo core infrastructure and the timing community, that is, to link GST to the international time standard represented by UTC. This is done through measuring GST offset with respect to real-time UTC realizations, called UTC(k), generated at selected European laboratories. The TSP will also compute an intermediate time-scale based on data from atomic clocks in European timing laboratories.

In case of a TSP link failure, the maser output will be steered to the ensemble of cesium clocks at PTF (four commercial high-performance clocks). Presently, TSP has to predict the GST-UTC offset over six weeks because of the rate of UTC computation. In case of a TSP link failure, PTF must be able to maintain specific autonomy performance requirements over 10 days.

There will be two PTFs operating in hot redundancy. One PTF will be placed in the Fucino control center and another one at Oberpfaffenhofen. **Figure 2** shows the high-level PTF architecture.

Each Galileo satellite will carry four clocks: two space passive hydrogen masers (SPHMs) and two rubidium atomic frequency standards (RAFS). More information on Galileo onboard clocks is available at the ESA website <www.esa.int/galileo>. Key requirements for on-board clocks, in addition to frequency stability, are reliability for extended period of time (12+ years) and predictability.

The overall synchronization in Galileo is presented in **Figure 3**.

The following part of the article deals with an assessment of the benefits of introducing optical clocks into a GNSS system considering the present Galileo architecture.

Clock Prediction Accuracy for Navigation

As mentioned in the previous section, there are three key prediction intervals in the present Galileo architecture:

- 100 minutes for prediction of satellite clocks versus GST
- 10 days for prediction of GST-UTC offset in autonomy (in the case of a TSP link failure)
- 6 weeks for prediction of GST-UTC offset in the nominal operational mode (TSP-linked).

The first interval is important for accuracy of user positioning; the latter two are mainly of interest with respect to metrological issues.

With respect to the effect on user positioning, we studied the clock prediction error for two basic scenarios of utilization of optical clocks in the present Galileo architecture: on the ground as the source of the system time and on board the satellites. We performed extensive clock simulations considering both state-of-the-art RF atomic clocks and the emerging optical clocks.

The clock data were simulated with the help of the DLR simulation tool NavSim. **Figure 4** shows the relative frequency instability (Allan Deviation) of satellite and ground clocks assumed for these simulations. The optical clock was assumed to run continuously, with the assumption of a conservative limit of the long-term stability $1 \cdot 10^{-16}$.

OSPF estimates of satellite clock offset versus system time are not noise-free. Simulations were made with a noise level of 0.45 nanosecond (1σ) — the present Galileo specification

— and 50 picoseconds (1σ), which is close to the best results demonstrated by the International GNSS Service (IGS). We also studied a noise-free scenario was also studied. The satellite clock prediction accuracy was estimated for the prediction intervals of 100 minutes.

Figure 5 summarizes our simulation results. These indicate that to achieve a significant improvement of prediction accuracy for satellite clocks, optical clocks should be implemented on board the satellite. In fact, the contribution of the active hydrogen maser (used as the source of GST) to the prediction uncertainty of satellite clocks is negligible for both SPHM and RAFS because the active maser is by far more stable than they are.

With OSPF noise as per the present Galileo specification, optical clocks on board the satellites might improve the clock prediction accuracy by about one order of magnitude or even, with reduced OSPF noise, by about two orders. Delay variations in the ground equipment (Galileo receivers in the tracking network) and in signal chains on board the satellites need further careful study.

Clock Prediction Accuracy for Metrology

As discussed earlier, prediction of the GST-UTC offset is also important for Galileo's metrological function because it enables precise dissemination of UTC.

Figure 6 illustrates simulated prediction uncertainty at the 1 sigma level with an ensemble of 4 cesium clocks (the present PTF configuration), 25 cesium clocks (a representative example for the TSP configuration), and an optical clock. All clocks were simulated as per the stability assumptions in Figure 3.

Additionally, measurement noise was added on the GST-TAI offset of 0.35 nanoseconds (1 sigma) corresponding to the noise of a two-way satellite time and frequency transfer (TWSTFT) link. We studied two prediction intervals: 10 days (corresponds to the autonomy period) and 45 days (corresponds to the nominal UTC prediction).

Currently, Galileo requirements call for prediction of the GST-UTC offset with an accuracy of better than 13 nanoseconds (1sigma) in the nominal mode. This target seems to be achievable only with an extended ensemble of cesium clocks, potentially also including active H-masers. This ensemble by far exceeds the baseline PTF configuration; so, the requirement can presently be met only with the assistance of TSP as foreseen in the baseline.

Thus, the role of TSP to link GST with the European timing community — which operates the necessary number of clocks — is essential. However, with an optical clock at PTF, the target accuracy of GST-UTC prediction could easily be achieved with a margin of about 50 percent. In this case, the Galileo system could precisely predict the GST-UTC offset relying on the internal infrastructure.

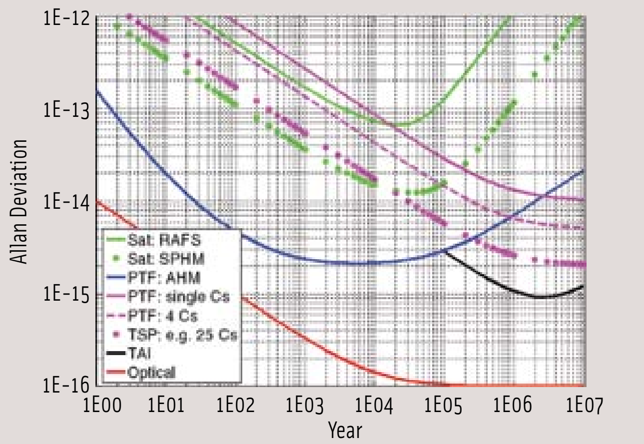


FIGURE 4 Relative frequency instability

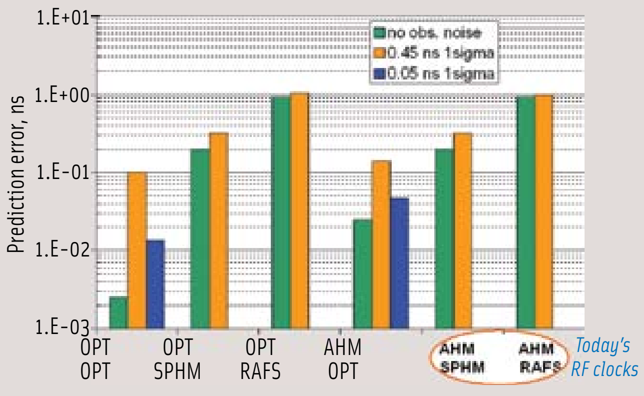


FIGURE 5 Uncertainty of satellite clock prediction

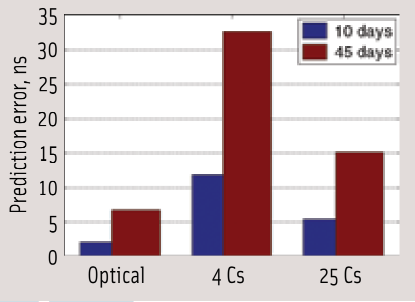


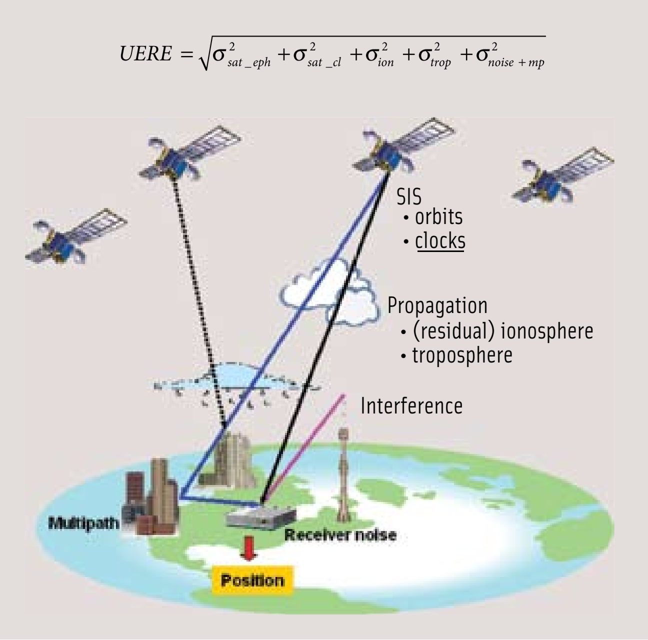
FIGURE 6 Clock prediction uncertainty

User Positioning Accuracy

Galileo services are defined for users who employ pseudorange observations to compute their position. As a part of this procedure, user receivers process the pseudorange measurements computing residuals between their modeled and measured values. The individual components of the measurement model along with the corresponding data sources in the real-time processing are listed here:

- geometrical range: broadcast ephemeris, preliminary user position
- satellite clock offset versus GST: broadcast clock correction
- ionospheric delay: broadcast ionospheric model or dual-frequency observations
- tropospheric delay: built-in tropospheric model.

The overall user ranging accuracy (driven by the uncertainties of the broadcast data and models) is typically characterized by the user equivalent range error (UERE). The UERE represents the root mean square of the sum of all error sources listed in the previous paragraph: uncertainty of satellite ephemeris and clock parameters, residual ionospheric and tropospheric



$$UERE = \sqrt{\sigma^2_{sat\_eph} + \sigma^2_{sat\_cl} + \sigma^2_{ion} + \sigma^2_{trop} + \sigma^2_{noise+mp}}$$

FIGURE 7 **UERE contributions**

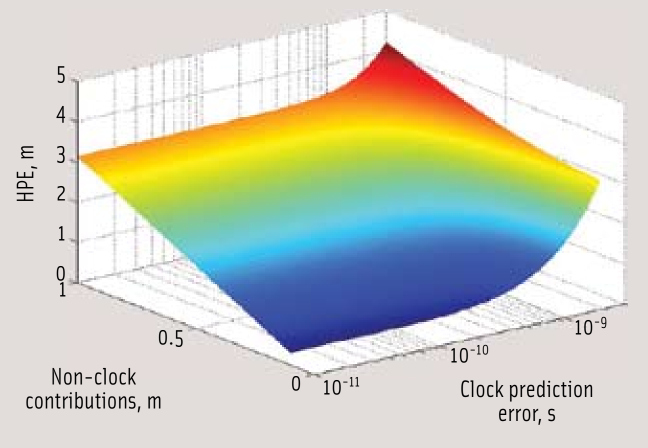


FIGURE 8 **HPE sensitivity**

errors, s unmodeled effects such as receiver noise and multipath (see also **Figure 7**):

The projected UERE for users of the Galileo dual-frequency Open Service is about 1.1 meters (1σ, global average), where the combined contribution of satellite ephemeris and clock errors is specified to be below 0.65 meter (1σ). Without the clock contribution, UERE amounts to approximately 1.0 meter (1σ).

Presently, the amount of UERE is dominated by the multipath in urban environment. Using carrier phase measurements, which are much less sensitive to multipath than the pseudoranges, can considerably improve UERE. GNSS receivers can use carrier phases either to smooth the pseudorange observations or to determine position by applying a triple- or multi-carrier phase resolution technique (TCAR or MCAR).

In addition to these receiver techniques, the orbit accuracy can be improved to the level of better than 0.1 meter (1sigma) by incorporating long-term ephemerides as the IGS has already demonstrated. With these improvements, the non-clock contributions of UERE may be reduced down to approximately 0.3 meter (1sigma).

User positioning accuracy can be characterized through UERE and the so-called geometrical dilution of precision (DOP) factor, which derives from the geometry of the satellite constellation observed by GNSS user equipment. Thus, the horizontal positioning error (the sum of the latitude and longitude error components) can be estimated as

$$HPE = HDOP \cdot UERE$$

where HPE is horizontal user positioning error (1 sigma), and HDOP is the horizontal dilution of precision factor. Presently, the Galileo requirement for horizontal positioning accuracy is four meters (95 percent).

Figure 8 illustrates the sensitivity of HPE (at 95 percent level) to non-clock UERE contributions and clock prediction uncertainty.

We can draw a few conclusions from Figure 8:

- the Galileo baseline with RAFS on board the satellites and an active H-maser in the Galileo PTF to generate the system time — corresponding to a non-clock UERE contribution of approximately one meter (1sigma) and a clock prediction error of approximately 1 nanosecond (1sigma) — leaves a fair margin (with HPE of approximately 3.4 meters (95 percent) with respect to meeting the Galileo system requirements for user positioning accuracy
- HPE sensitivity to clock prediction errors below one nanosecond (1sigma) with the present design is not significant because the error budget is dominated by other contributions
- implementation of optical clocks on board the satellites and on the ground could be beneficial in the future when non-clock contributions are reduced, e.g., down to 0.3 meter (1 sigma). This would improve the HPE by about 30 percent compared to the scenario of using microwave clocks in this enhanced design: from approximately 1.3 meters (95 percent) down to approximately 1 meter (95 percent).

Other Clock Requirements

Clock stability is important for reducing the uncertainty of clock prediction and, thus, for improving user positioning accuracy, as well as helping meet other important specifications related to integrity and operations.

From the operational point of view, Galileo specifications call for on-board satellite clocks to have a life expectancy of more than 12 years. At this stage, no theoretical limitations are known that would prevent achieving this target using optical clocks.

Weight and power consumption are another two important requirements. For RAFS and SPHM the indicative values are 3.3 kilograms and 20 watts and 18 kilograms and 60 watts, respectively. In general, it is desirable (especially considering evolution of the system design) to reduce both values. This is a challenging target. Presently, various possible development routes for space optical clocks are being considered.

Because Galileo will be employed in safety-critical applications such as air traffic control, satellite clocks need to be highly reliable. Galileo integrity processing will be able to determine adverse clock events, e.g., interruptions and signal discontinuities. However, such events may affect users' ability to determine position and, thus, the continuity of service. Consequently, reliability shall become one of the major design drivers for the future optical clocks.

Summary

Satellite clock prediction accuracy may be considerably improved with the emerging optical clock technology. To maximize the performance benefits, optical clocks should be placed onboard the satellites (and on ground to generate the system time).

Implementation of optical clocks to keep the system time could increase the accuracy of Galileo timing service (dissemination of UTC) and keep the UTC prediction function within the system. In this case, dependence on an external infrastructure such as the TSP may be reduced.

If other contributions to the error budget (mainly, the multipath) were reduced, we might anticipate further significant benefits to user positioning accuracy from improved clock technology, for instance, through exploitation of carrier phase techniques.

Placing better clocks on satellites will reduce the need for frequent updates, which will simplify the requirements on ground systems and also reduce costs. If update links were to fail for a significant amount of time, having very good clocks in the space segment would reduce the rate of degradation of the service to users on the ground.

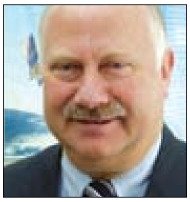
Additional Resources

[1] Gill, P., "Optical frequency standards," *Metrologia*, 42 S125, 2005

[2] Gill, P., and H. Margolis, "Optical clocks," *Physics World,* May 2005

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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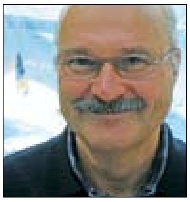
HUGH KLEIN is a principal research scientist at the UK National Physical Laboratory (NPL). He is working on developing an optical clock based on a single trapped strontium ion and has been involved in several related ESA studies.



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