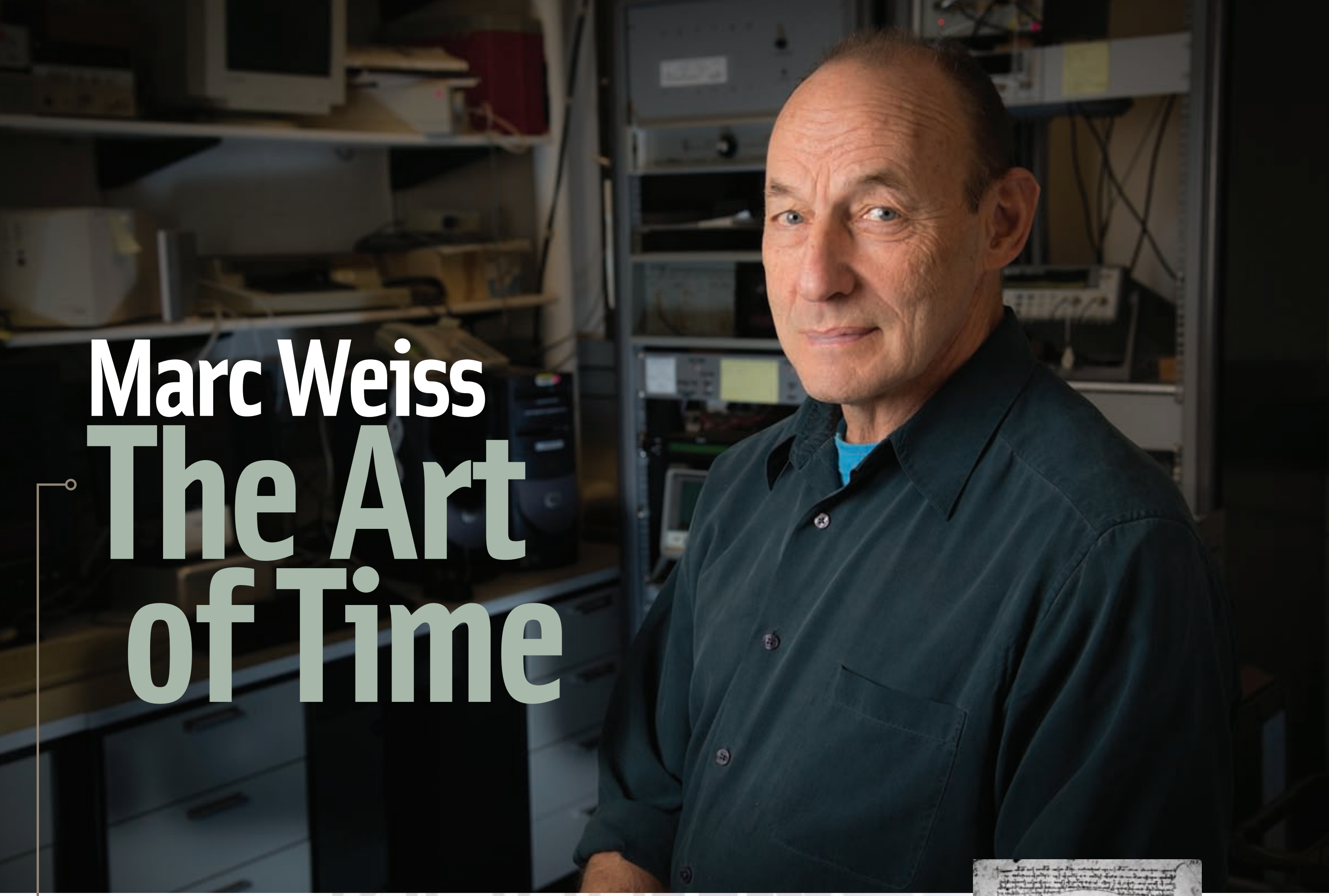

Marc Weiss
The Art of Time

How the pursuit of Beauty led a physicist to a professional life in GNSS.

STORY BY **RICHARD THOMAS**

In a career spanning nearly the entire history of GNSS-enhanced metrology, Marc Weiss has been a key participant in projects that laid the foundation for accurate synchronization of atomic clocks around the world.

As a mathematical physics Ph.D. student at the University of Colorado–Boulder, Weiss began working with then nascent GPS technology in the late 1970s. Fast-forward 35 years, and Weiss is still in Boulder, until recently as a career mathematician at the National Institute of Standards and Technology's (NIST) Time and Frequency Division. NIST is the United States' measurement standards laboratory, and the site of the NIST-F1 atomic clock, which serves as the United States' primary time and frequency standard.

As of January 1, Weiss became a NIST associate and contractor with the ability now to consult with industry. He shares a key patent in the precise timing field, has received prestigious awards for his pioneering research, and continues his work in the areas of telecommunications synchronization and the use of relativity in GPS.

But at its heart, his professional journey has been a pursuit of Beauty.

HUMAN ENGINEERING

"I was interested in math as an art form first. When I was a kid, my father got me into this as a way of appreciating pure forms of beauty," Weiss says. "I wanted to do everything, and decided to study Math and Theater: math got me in touch with all sciences and theater, with all arts."

Early on, Weiss was influenced by a short book titled *The Education of T.C. Mits* [an acronym for "the celebrated man in the street"] — a popular treatise on mathematical thinking written by Lillian Rosanoff Lieber in 1942 and illustrated by her husband, Hugh Gray Lieber.

"It postulated that pure mathematics was a garret at the top of a tower of various kinds of math, physics, and engineering, where mathematicians and artists together explored new forms that eventually turn into technology," Weiss recalls. "It was one of the reasons I wanted to study pure mathematics."

After getting into the Ph.D. program in the CU math department, Weiss realized that he "wanted to help write new theories at the foundations of physics. It wasn't until I got a job at NBS that I got connected to anything applied."

From Pure to Applied Physics: Building the First Timing Receiver

The genesis of Weiss's career in GNSS and timing was one of fortuitous opportunities rather than preconceived planning.

"The only jobs I could have imagined [at that time] were teaching," Weiss says. He describes a "series of falling-in-love events," beginning in 1978, that led him to apply his interest in the elegance of pure math to the budding interdisciplinary field of GNSS.

Weiss began working with Dave Allan, originator of the Allan Variance measure of frequency stability, as a graduate student. This work was carried out at the National Bureau of Standards (NBS), the precursor to NIST. At NBS, Allan became Weiss's group leader and they started working on a GPS receiver in 1979. Their goal was to build a receiver optimized for time transfer.

"While there were already GPS receivers available," Weiss says, "they would not support nanosecond-level time transfer."

Time transfer is a method of synchronization based on comparing timing data from multiple sources with a common reference. Weiss explains that in navigation receivers, the time delay of signals from the antenna through the receiver is canceled since position fixes are computed from differences between satellite signals. For a GNSS timing instrument, however, the delay must be directly accounted for in order to produce an accurate time.

In 1981 the project team succeeded in achieving time transfer with unprecedented accuracies. Through a partnership with Allen Osborne Associates, Inc., two dozen GNSS timing receivers were initially manufactured and distributed to timing labs around the world to support time transfer over large distances.

This innovative technique directly led to a dramatic improvement in the accuracy of International Atomic Time (TAI), the weighted average of atomic clocks around the world that serves as the basis for Coordinated Universal Time (UTC), the primary standard for precise time globally. Their efforts earned the project team the NBS Applied Research Award in 1981. At this point, Weiss was still a Ph.D. student, and says that he still "had no idea" he would stay at NBS (later NIST) for a career.

After the deployment of the receivers in laboratories, Weiss had the opportunity to work on a calibration campaign in 1986. This activity led him to timing labs all over Europe and galvanized his interest in the GNSS field.

Compass Points

GNSS Event that most signifies for you that GNSS has "arrived"

GNSS receivers in cell phones were a shock. I always knew that electronics could be shrunk almost forever, but the physics of the antenna, and the tiny signal, seemed to necessitate at least a quarter-wave in size, and clear exposure to the sky. We had visions in the 1980s where we would speculate "by the year 2000 (which seemed forever far away) receivers (which at the time cost many 10s of thousands of dollars and weighed 10s of kilograms) would cost under $100, weigh less than one kilogram, and take up less space than a VCR tape drive."

Engineering Mentor

If I have to pick one, it would be David Allan. He brought me into the field of time and time transfer, just as GPS was nascent. He was always very supportive and encouraging.

Patents Held:

Along with Dave Allan, Judith Levine, and Dick Davis, patent #5,274,545 issued in 1993 for "Device and method for providing accurate time and/or frequency." Published as an article, "Smart Clock: A New Time," in the December 1992 issue of *IEEE Transactions on Instrumentation and Measurement*.

What popular notions about GNSS most annoy you?:

1) Some in the industry think that clocks don't matter, that they are of little importance compared to signals and satellites. GPS works so reliably *because* of atomic clocks.
2) There's a lot of confusion about the difference between signals and data. GPS is not just another piece of the information system: it is a source of a signal. A signal differs from data in that it can only be useful if measured in the present. It can't be stored, buffered, and re-transmitted without at least keeping careful track of all that.
3) Popular shows imply that GPS is tracking people; that somehow the satellites know what people are doing. Of course, the GPS satellites only transmit. They don't track anything. GPS trackers do exist — because of cell phone technology.

Favorite equation:

The relativistic frequency change in clocks:

$$\frac{\Delta f}{f} = \frac{\Delta\Phi}{c^2} - \frac{\Delta v^2}{2c^2}$$

where $\frac{\Delta f}{f}$ is the fractional frequency offset of an oscillator due to $\Delta\Phi$, the change in gravitational potential, and Δv, the change in velocity, and where c is the speed of light. Note that this uses the physics convention where Φ is negative, hence gets larger farther from the Earth. Thus, relativity says that the frequency of an oscillator runs slower as velocity increases, and runs faster as you get farther from the Earth. These combine in GPS to give a mean rate offset of 4.4647×10^{-10} faster than on Earth's geoid, which would produce a time offset after one day of 38,575 ns!

As a consumer, what GNSS product, application, or engineering innovation would you most like to see?

I'm going to plug here for a GNSS improvement, not directly a consumer product. I have been a long-time advocate of on-board monitoring of GPS clocks, running multiple atomic clocks on each satellite and measuring them against each other. The largest cause of signal anomalies is clock anomalies, which could easily be completely removed from the error budget. This would require a small amount of hardware change on-orbit. It's a technique we have used in national timing labs for years. It would allow for not only detection and removal of bad signals, but automatic fast recovery.

Professional Honors/Leadership Positions

NBS 1983 Applied Research Award "For the development of a satellite receiver measurement technique that provides cost effective international time and frequency comparisons at state-of-the-art accuracy".

NIST 2013 William P. Slitcher Award "For pioneering highly productive industry/government partnerships to advance telecommunications and data networks through precision synchronization".

Weiss at the helm during sailboat outing to San Juan Islands

"We drove from one national timing lab to another," Weiss says, "starting at OP [Observatoire de Paris] in Paris, driving to IEN [Istituto Elettrotecnico Nazionale, now part of the Istituto Nazionale di Ricerca Metrologica] in Torino, Italy, TUG [Technische Universität Graz] in Graz, Austria, PTB [Physikalisch-Technische Bundesanstalt] in Braunschweig, Germany, VSL [Van Swinden Laboratorium – Dutch Metrology Institute] in Delft, Netherlands, NPL [National Physics Laboratory] in Teddington, UK, and back to OP. I was amazed at how important this had become."

Another experience around this time led to Weiss's decision to dedicate his career to the GNSS field. "Dave Allan brought Col. Gaylord Green [director of the GPS Joint Program Office] to NBS for a show and tell," he recalls. "I was young and unsure, and I gave a talk about some estimation work I was doing, ending with what I hoped for. [Col. Green] said something like '*and that's where we'll get*.' I found it very affirming, and never forgot the feeling."

Weiss says that work remained to be done coordinating and using measurements after the GPS timing receiver had been built and distributed internationally. NBS created a service in the late 1980s that allowed customers to obtain UTC(NBS) in their labs as a reference for their own master clocks, using GPS satellites in common view between labs as a means of time transfer.

The common-view method simultaneously compares clocks located in different facilities with the time generated by the same GPS satellite's atomic clock as a shared reference. The data used to generate TAI and UTC by averaging more than 200 atomic clocks in approximately 50 laboratories across the globe are often collected and distributed using this method.

Telecom Synchronization and "The Smart Clock"

In the late 1980s, Weiss's group at NBS worked with the United States Air Force (USAF) on designing and maintaining the frequency standards for the GPS constellation. His group provided reports and studies to help advance the development of both on-orbit space vehicles (SVs) and next-generation SVs.

At this time, Weiss focused on the problem of *ensembling* clocks. His team developed a time scale algorithm that derived the best stability of all the clocks at each averaging instant in a given ensemble. This work led to Weiss's patent in 1993 for "The Smart Clock" concept, which uses an algorithm to enhance the stability of a clock or oscillator by comparing it to an external standard, such as UTC.

The algorithm automatically estimates a correction to the output of the clock and decides when external data are required to maintain the clock's accuracy. Weiss says that this work also informed NIST's consulting work on the Global Positioning System, as the Air Force had implemented its own method for ensembling all SV and master clocks to produce the GPS time scale.

In the 1990s, Weiss became involved with synchronization in telecommunications. He worked with Dave Allan on modifying the Allan Variance to meet the needs of telecommunications, creating the *time deviation* (TDEV) metric that indicates the time instability of a signal source. Weiss says that synchronization has become increasingly important and challenging in telecom systems, and that international networks depend on time and frequency from GNSS. He adds that financial or technical issues can prevent precise time users from directly connecting to GNSS, and that GNSS vulnerability to interference is a big issue for this community.

Weiss with son, Jesse, and companion on post-graduation adventure

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Weiss founded a conference in 1992, the Workshop on Synchronization in Telecommunication Systems (WSTS), now cosponsored with the industry Alliance for Telecommunications Industry Solutions (ATIS). WSTS, which he considers one of the "major achievements" of his professional life has since grown to include the International Telecom-Sync Forum (ITSF), a sister conference in Europe.

The conference enables the precise timing community to address the evolving challenges of new telecom systems and techniques. For instance, he says, core telecom networks' movement toward asynchronous packet networks with a more distributed model has required new techniques for transferring time through the networks. One example to which Weiss points is the Precise Time Protocol (PTP), based on the IEEE 1588 standard, which enables precise synchronization of clocks in measurement and control systems.

Connecting the Dots and Relativity in GNSS

A common thread in Weiss's current projects is the collaborative effort to transfer time through a public network between NIST-Boulder and the alternate master clock (AMC) of the United States Naval Observatory (USNO) at the GPS Master Control Station at Schriever Air Force Base. Weiss sees this project as a first step toward a method of backing up GPS in order to provide precise time to U.S. critical infrastructures. He describes it as a linkage between his work chairing WSTS and participating on committees devoted to protecting these infrastructures from GPS vulnerabilities.

Another current project of Weiss involves supporting the GPS Directorate in developing GPS III, with a particular focus on clocks. Weiss connected the GPS Directorate with the cold-atom clock builders at NIST, which is now working on a prototype for a next generation GPS clock using cold-atom technology. Another new project closes to heart Weiss says is developing new paradigms for connecting data processing with synchronization.

"Timing is fundamentally a physical signal plus data," he says. "But the progress we have seen in computing and networking has been achieved in the context of encapsulation and layering of function. As functions and systems become removed from the physical layer, if they need sync, it arrives with poorer quality. I hope to build a large, cross-disciplinary research project to make sync a first-class citizen".

Another area in which Weiss has worked throughout his career involves the role of relativity in GPS. He is collaborating with Dr. Neil Ashby, who crafted the original relativistic terms for the Global Positioning System, on other GNSS relativity projects. These address such issues as why GPS satellites have no "noon-midnight redshift," why the rates of GPS clocks are independent of the sun's gravitational field to first order, and how to incorporate relativity factors into the European Atomic Clock Ensembles in Space (ACES)

mission that will go on the International Space Station.

But Weiss has not been indifferent to the beauty of a world outside mathematical physics — especially given his strategic location at the edge of the Rocky Mountains. Boulder sits at 5,300 feet; 10 miles due west is the Continental Divide at 12,000–14,000 feet.

"Since I came here in 1973 to go to graduate school, I've spent as much time as I can going up to the high mountains," Weiss says. "I particularly love the area above timberline, in the tundra, before you get so high that it's mostly rock. The tundra is lush with gorgeous flowers and thick grass, even though it [stays] winter there almost until summer [arrives] in July and August."

That love of the outdoors is shared by his family. Last summer, Weiss's son Jesse graduated from high school, and they took a llama trip together before he headed off to college. In 2011 he hired a sailing friend to take him, wife Pam, Jesse, and Pam's daughter Laura on a charter sailboat cruise through the Pacific Northwest's San Juan Islands.

After many years in the field, Marc Weiss remains inspired by new innovations and technical refinements."In the last decade I've been privileged to witness some of the technical reviews of new space-atomic clocks being built . . . to go into GPS IIF and GPS III [satellites]," he says. "It is absolutely amazing how the combination of advanced quantum physics flows into intensely examined engineering details, to produce one of the most excellent commercial clocks ever built."

Marc Weiss and wife, Pam

Looking back on his career in engineering and its influence on his life, Weiss makes the connection between the exercise of the scientific method and the history of science: "I am only more fascinated and amazed by what I have witnessed, what has grown out of the simple curiosity of a long lineage of scientists and engineers, from before we even knew those words." IG

Human Engineering is a regular feature that highlights some of the personalities behind the technologies, products, and programs of the GNSS community. We welcome readers' recommendations for future profiles. Contact Glen Gibbons, glen@insidegnss.com.