GNSS Solutions:

eLoran and signal reception under snow

"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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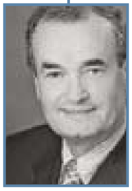

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How well can GPS signals penetrate avalanche snow?

Surprisingly, GPS signals penetrate avalanche snow very well.

Because snow is in part composed of frozen water, many people assume that snow has signal attenuation properties similar to liquid water. Tests have shown that even a high sensitivity GPS receiver cannot track through more than 1 to 2 millimeters of water where the majority of the GPS signal is reflected at interfaces between materials. Two such interfaces exist: an air-water interface at the surface of the water and the water-air interface around the submerged receiver antenna, which reflects what remains of the signal. Some of the attenuation is due to dielectric losses, but the majority is due to the air-water reflection.

What happens, however, when the GPS signal encounters snow?

In terms of reflection, the loss is approximately 11 dB lower for snow than with liquid water. Smaller angles of incidence of the signals improve their penetration (i.e., less reflection); thus, reflection losses are highest with low elevation satellites and satellites upslope of an avalanche slide.

Next, the signal that penetrates the snow surface is attenuated by dielectric losses, scattering, and fading as it passes through the snow. High water content in the snow will cause significant portion of the signal to be lost to scattering as the signal is reflected by particles of water and ice within the avalanche debris.

Overall, then, the amount of signal attenuation in avalanche snow relates directly to its water content. Dry snow with a density of 0.3 g/cm^3 (33 percent ice, 67 percent air) has a penetration depth (i.e., the depth at which half the power/energy is lost) of approximately 400 meters at 1.5 GHz. In comparison, wet snow with a similar density but having a liquid water content of 1 percent by volume (that is, 32 percent ice, 1 percent water, 67 percent air) only has a penetration depth of approximately 3 meters.

For GPS to be used to locate an avalanche victim, the signal must penetrate avalanche debris made up of snow packed to a much higher density than undisturbed snow. Freshly fallen snow will have a density ranging from 1 to 25 percent that of water. In recent tests in the Rocky Mountains, measured avalanche snow debris densities of 45 to 50 percent that of water were found, indicating a significantly higher ice content and, therefore, higher signal attenuation.

How much avalanche snow does GPS have to penetrate? To be an effective rescue tool, the GPS signals need to reach a victim buried under at least 2 meters of snow. For signals normal to the avalanche slope, this means that the signals must penetrate 2 meters. For signals with higher angles of incidence, this can translate into needed snow penetrations of up to 15 meters to reach a victim.

Figure 1 shows the histogram of L1 carrier-to-noise density ratio (C/N_0) values measured by one surface receiver and three subsurface receivers buried in avalanche snow at depths of 1.3, 2 and 2.7 meters, as a function of snow penetration. The total number of observations were counted in bins of 1 meter by 1 dB-Hz and plotted in the three-dimensional graph.

The high sensitivity GPS receivers used during the test were able to receive signals through 15 meters of avalanche snow, with an average attenuation of 2 to 3 dB per meter of avalanche snow.

During avalanche tests in the spring 2006, an average L1 signal attenuation of 12 dB at a receiver buried under 1.3 meters of avalanche snow and 15 dB attenuation under 2 meters was observed. **Figure 2** shows the C/N_0 for GPS satellite PRN19 measured by three receivers with high-sensitivity designs buried at various depths beneath the avalanche snow along with values collected by a similar surface receiver. Values for the subsurface receivers vary widely, from 12 to 35 dB-Hz, while the surface receiver can track the same satellite with a C/N_0 of 40 dB-Hz.

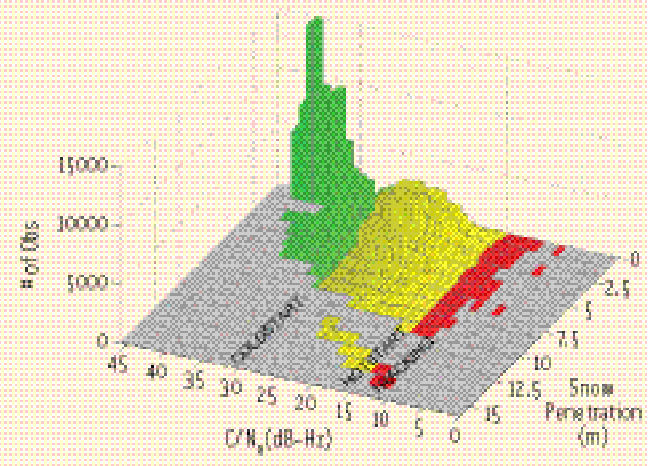

FIGURE 1 Histogram of C/N_0 Measured versus Snow Penetration

With this level of attenuation, a marked increase in pseudorange measurement noise is observed from 3.2 meters RMS on the surface to 6.3 meters RMS at the receiver buried 2 meters down. In turn, the increased pseudorange noise is reflected in the positioning statistics, with 9 meters RMS horizontal positioning accuracies beneath 2 meters of snow, while the surface accuracies are 3 meters.

Now, 9-meter single-point positioning accuracies would certainly slow down the search for avalanche

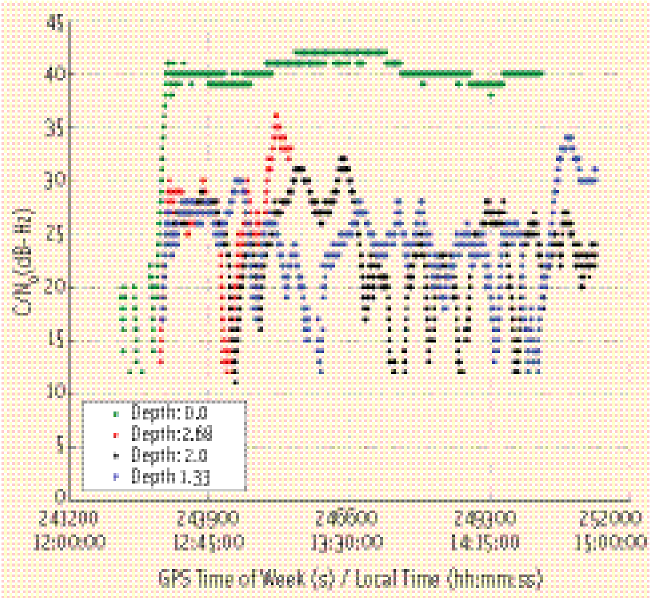

FIGURE 2 PRN 19 C/N_0 Measured in avalanche debris

victims. Because our victim isn't moving, however, and the errors are fairly random, something as simple as averaging can significantly improve positioning accuracies. If GPS were to be used for this application, a data link that also operates under avalanche snow would have to be used to report positions to rescuers.

Manufacturers The avalanche field tests described here used GPS receivers with SiRFstarIII chipsets from **SiRF Technology**, San Jose, California, USA.

Further Reading Schleppe, J., and G. Lachapelle (2007), "GPS Tracking Performance under Avalanche Deposited Snow. *GPS Solutions*, Springer, Published online, DOI 10.1007/s10291-007-0060-1

JOHN SCHLEPPE

John Schleppe is team leader of software receiver development at Calgary, Alberta. Canada–based NovAtel Inc. Prior to joining NovAtel in November 2006, John spent three years as a senior research engineer in the Department of Geomatics Engineering at the University of Calgary where one of his projects was to perform GPS tracking experiments in avalanche snow. John has been active for more than 26 years in the navigation industry with 9 years field operations experience along with 17 years experience in research and development.

What is eLoran and how is it different from Loran-C?

Simply, *eLoran* (or enhanced Loran) is the latest generation of the venerable and time-tested Loran navigation system. Enhanced Loran improves upon previous Loran systems with updated equipment, signals, and operating procedures.

These changes allow eLoran to provide better performance and additional services when compared to Loran-C. Most importantly, the improvements enable eLoran to serve as a backup to satellite navigation in many important applications. At the same time, it still remains compatible with most Loran-C receivers.

Enhanced Loran is the result of a confluence of two development streams: 1) the modernization of the Loran-C system and 2) the realization that satellite navigation has tangible vulnerabilities. The second point is especially important as many components of critical economic and safety infrastructure have come to depend profoundly on position navigation and timing (PNT) services currently provided by GPS and other satellite navigation systems. Future developments in global navigation satellite systems (GNSS) will only mitigate, not eliminate, some of the vulnerabilities.

eLoran is the result of a confluence of two development streams: the modernization of the Loran-C system and the realization that satellite navigation has tangible vulnerabilities.

These new systems will likely increase our usage and dependency on satellite navigation. The vision of eLoran's advocates seeks to use the modernized Loran infrastructure in such a way as to provide a navigation system that complements satellite-based PNT by limiting the effect of GNSS's vulnerability. In other words, use the modernized equipment and other reasonable changes to Loran-C to provide a Loran system that can be a GNSS-independent means of providing many PNT services that are vital to global economic and critical infrastructure.

Although eLoran can provide PNT redundancy to GNSS in general, its particular focus is on services to critical systems where no other backup is commonly available. Therefore, although no detailed specifications have been written for eLoran as of May 2007, the following general definition of the system, "Enhanced Loran (eLoran) Definitions Document," has been written by a panel of international Loran and navigation experts and presented to the International Loran Association (ILA) for comments:

> "the accuracy, availability, integrity, and continuity performance requirements for aviation non-precision instrument approaches, maritime harbor entrance and

approach maneuvers, land-mobile vehicle navigation, and location-based services, and is a precise source of time and frequency for applications such as telecommunications."
Enhanced Loran Definitions Document, version 0.1

Modernization and other changes are necessary because many of the desired applications are not supported by the current performance level of Loran-C. Enhanced Loran is designed to use the existing Loran system, modernized equipment, and a minimal amount of changes to achieve the required performance to support the applications mentioned in the eLoran definitions document.

Differences from Loran-C

One way of describing the details of eLoran is in terms of its differences from Loran-C. These changes from Loran-C, as outlined in the Federal Aviation Administration's (FAA's) 2004 Loran evaluation report (see editors' note at the end of this article), come in four major areas: radionavigation policy, operational doctrine, system equipment, and user equipment. European and other international Loran stations conforming to eLoran standards will have equivalent equipment performing similar functions.

Some of the major changes from Loran-C and their significance will be briefly discussed. A summary of changes is given in Table 1.

Government-Provided Propagation Delay Information. Loran propagation delay is the time difference due to traversing the actual, non-uniform terrain rather than an ideal path. These delays can be separated into two components: 1) spatial (often termed *additional secondary factor* or ASF) and 2) temporal delay.

Databases accounting for the spatial term at various locations throughout the desired coverage area will be published. Additionally, the Loran data channel (see next item) will provide

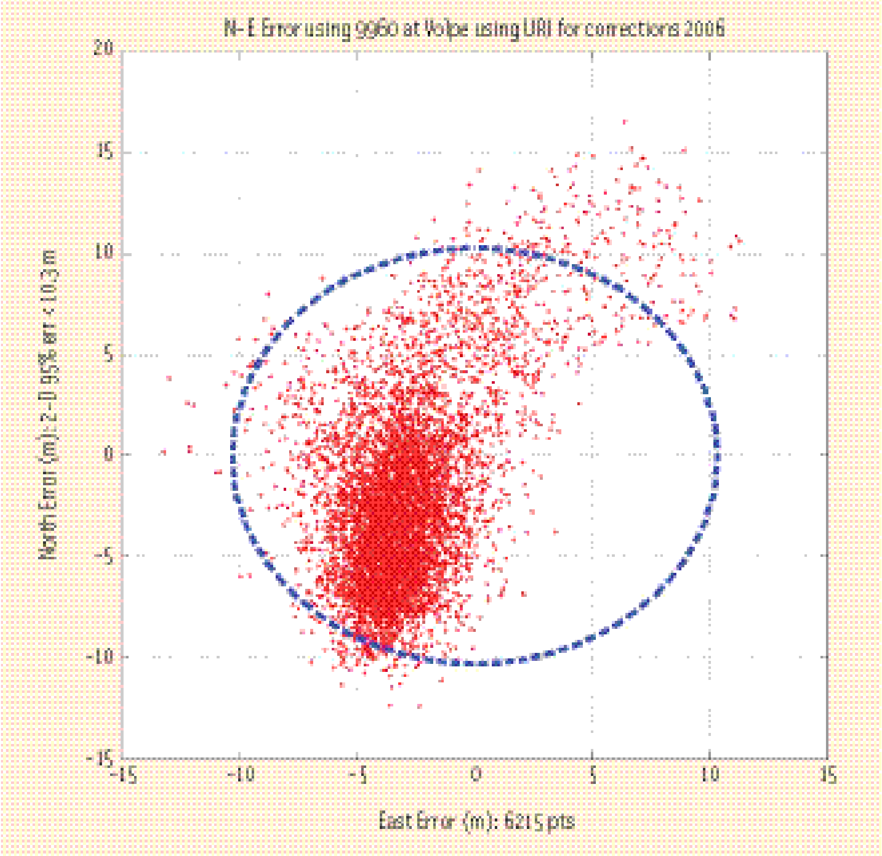

FIGURE 1 Plot of error in the horizontal plane at Volpe National Transportation System Center using University of Rhode Island measurements as corrections (The dotted blue line represents the 95 percent accuracy circle.)

Area	Major Change
Radionavigation policy	Airport survey to generate ASF database for NPA/enroute
	Harbor entrance survey to generate ASF database for HEA
Operational Doctrine	Time of transmission (TOT) control
	Off air to indicate out-of-tolerance conditions at station
	Continuous phase changes to correct timing errors at stations
	Long-term synchronization to UTC using at least one non-GNSS dependent means
System Equipment	All stations use solid state transmitters (SSX)
	New uninterruptible power supplies and antenna coupler
	New timing and frequency equipment (TFE) to control timing
	New cesium clocks (three per station)
	Improved monitor network using existing sites
	Loran data channel (ability to add digital data to the Loran signal)
	Installation of transmitter control set (TCS) and remote automated integrated Loran-C (RAIL) equipment allows for the monitoring and control of all station equipment
User Equipment	Ability to incorporate propagation delay tables for specific applications
	All-in-view capability (use all available stations regardless of chain)
	Improved cross rate interference mitigation
	Improved impulsive noise mitigation
	Ability to demodulate ninth pulse communications
	Antennas (H field) to mitigate precipitation static (when necessary)

TABLE 1. Summary of eLoran changes from Loran-C

corrections for the temporal component at certain locations. These are necessary for aviation nonprecision approach (NPA) and maritime harbor entrance approach (HEA) requirements. They aren't needed — but are still beneficial — for other users.

Loran Data Channel. A data channel on Loran will be used to provide differential Loran, station identification, aviation warnings, and other messages. Differential Loran corrects for the temporal or time varying component of propagation delay. Station identification provides information to identify station and determine precise time. Aviation warning messages provide timely warnings of propagation hazards that affect the safe use of Loran for landing approach.

Other messages may be broadcast, including an authentication message that provides antispoofing capabilities through source verification of the signal. In this United States, the data channel will use the ninth pulse communications (NPC) whereby pulse(s) modulated using pulse position modulation (PPM) are added to the end of the nominal Loran eight-pulse sequence.

Time of Transmission (TOT) Control. Station broadcast times will be steered to an international standard, Coordinated Universal Time (UTC), instead of using the current system area monitors (SAMs). TOT ties the transmission of each station back to UTC allowing for better performance when using stations from different Loran chains ("cross chain").

New Cesium Clocks and Timing Suites. The new equipment and control upgrade improves nominal timing performance of Loran broadcasts to always be within 100 nanoseconds of the expected broadcast time UTC. This level of performance could not be achieved with acceptable availability using earlier equipment. As a result the threshold for declaring the Loran station out of tolerance was set at 500 nanoseconds. Hence, although Loran accuracy is generally better than this, 500 nanoseconds is a bound on the timing rather than the accuracy. The goal for eLoran is to reduce that number to 100 nanoseconds.

Benefits to the User

The improvements offered by eLoran result in many benefits to users. It yields many performance enhancements in all the traditional areas of concern for PNT: accuracy, integrity, availability, and continuity. Additionally, eLoran can enable numerous applications previously unavailable on Loran and enhance the robustness of the system with the addition of authenticated navigation information.

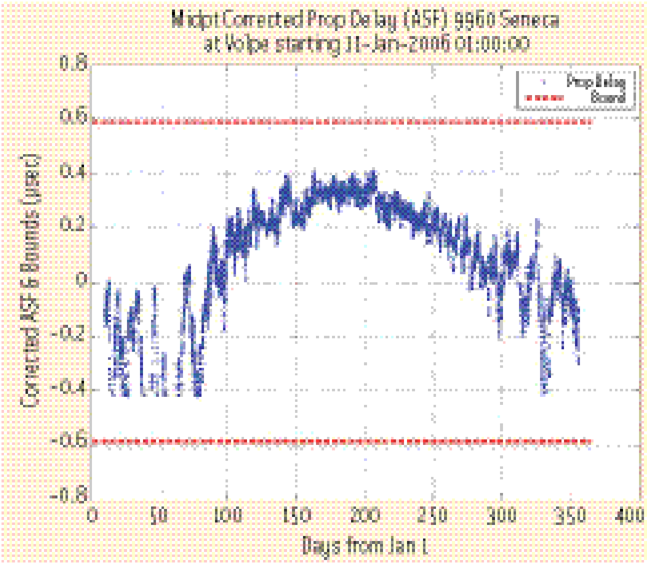

FIGURE 2 Propagation Delay and Bound at Volpe Center from Seneca, New York, transmitter (472 km)

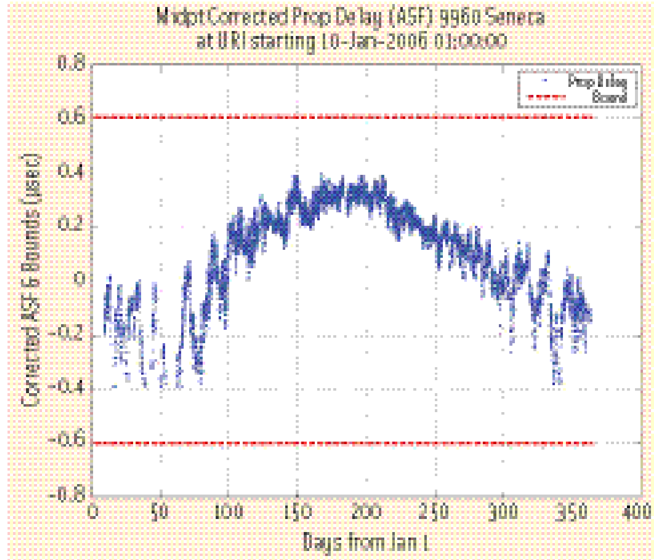

FIGURE 3 Propagation Delay and Bound at University of Rhode Island from Seneca, New York, transmitter (458 km)York, transmitter (472 km)

Significantly improved accuracy, as needed for the harbor entrance approach (HEA) application, is one of the most obvious improvements. An example of the potential accuracy benefits can be seen in **Figure 1**.

The figure shows a yearlong plot of position error at the Volpe National Transportation System Center in Cambridge, Massachusetts, USA, if differential Loran corrections from University of Rhode Island (URI) are used to correct for the temporal component of propagation delay. These two sites are separated by 104 kilometers. The 95 percent accuracy level is less than 10.3 meters.

Several studies are under way testing the capability of differential Loran for HEA. An accuracy level of 10 meters or less seems achievable with a reasonable density of monitors. The accuracy is achieved by using the monitor corrections to remove the temporal changes in propagation delay and using the ASF database to remove the absolute delay of various locations relative to the monitor.

Figure 2 and **Figure 3** show the propagation delay at Volpe and URI from the Seneca, New York, signal. The temporal correlation is clearly visible while the spatial difference between the two has been removed. The corrections generated by the differential Loran monitors will be broadcast on the Loran data channel.

A less obvious and visible benefit is improved integrity. Some of the changes made, such as going to TOT control, allow Loran errors to be more easily modeled and predicted. For example, TOT control aids error modeling because all transmitted signals are tied to a common source (UTC). This allows for error bounds that are necessary to guarantee the integrity levels required by aviation.

The integrity bounds for the temporal variations are plotted on Figure 2 and Figure 3. These bounds are based on improved models derived from U.S. Coast Guard data. These integrity bounds clearly over-bound the errors and help result in position bounds that limit the position errors at the level required by aviation landing. These bounds would be more difficult to determine without changes such as TOT control.

Availability and continuity are improved with the addition of more reliable transmitter equipment, uninterruptible power supplies (UPS), lightning arrestors, and changes to transmitter operations. Analysis of data from 2000–2002, before these improvements were implemented at all stations, already showed tangible benefits for availability and continuity when compared to performance from the early 1990s. Availability and continuity are also improved by being able to perform cross-chain operations, which are aided by such eLoran features as station identification message and TOT control.

Finally, the eLoran program is pursuing addition of an authentication message for its data channel. The authentication will allow the receiver to verify that the source of the signal is an actual Loran transmitter. Providing a means of authenticating the Loran signal will significantly improve robustness against spoofing. This enables applications that depend on a secure and trusted source of navigation information.

Conclusion

eLoran is a significant evolutionary improvement over Loran-C. It incorporates new technology and operations to provide a system capable of offering more services.

The benefits of eLoran fall in two primary areas. First, they will allow aviators, mariners, and other users with suitable user equipment to retain much of the operational capability they had with satellite-based PNT even in the absence of GNSS. Enhanced Loran has the capability of serving applications supported by Loran-C as well as aviation landing, maritime harbor entrance and approach, and many others.

Second, eLoran will enable applications previously not supported by GNSS, Loran-C, or other navigation systems. This is partly because eLoran has room for growth if and when additional functionality such as authentication is added. These factors make enhanced Loran of great interest to many sectors that have come to rely on precise navigation or timing for safety and economic efficiency.

Editors' Note

For more information on Loran and eLoran, refer to:

International Loran Association, "Enhance Loran (*eLoran*) Definition Document", version 0.1, January 2007, <www.loran.org>

Benjamin Peterson, Ken Dykstra, David Lown, Kevin Shmihluk, "Loran Data Channel Communications using 9th Pulse Modulation," Version 1.3, October 2006, <http://www.navcen.uscg.gov/*eLoran*/9th-pulse-modulation-ldc.html>

Federal Aviation Administration report to FAA Vice President for Technical Operations Navigation Services Directorate, "Loran's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications," March 2004, <www.navcen.uscg.gov/loran/geninfo/LORAN_Tech_Eval_Final_Report_0304.pdf>

Sherman Lo, et al., "Loran Availability and Continuity Analysis for Required Navigation Performance 0.3," Proceedings of GNSS 2004 – The European Navigation Conference, Rotterdam, The Netherlands, May 2004

General Lighthouse Authorities of the United Kingdom and Ireland, "The Case for *eLoran*", May 2006, <http://www.navcen.uscg.gov/loran/geninfo/press8971_file_1_thecaseforeLoran.pdf>

For information regarding the vulnerability of GPS, refer to:

"Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System," John A. Volpe National Transportation System Center, August 20, 2001.

SHERMAN LO

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