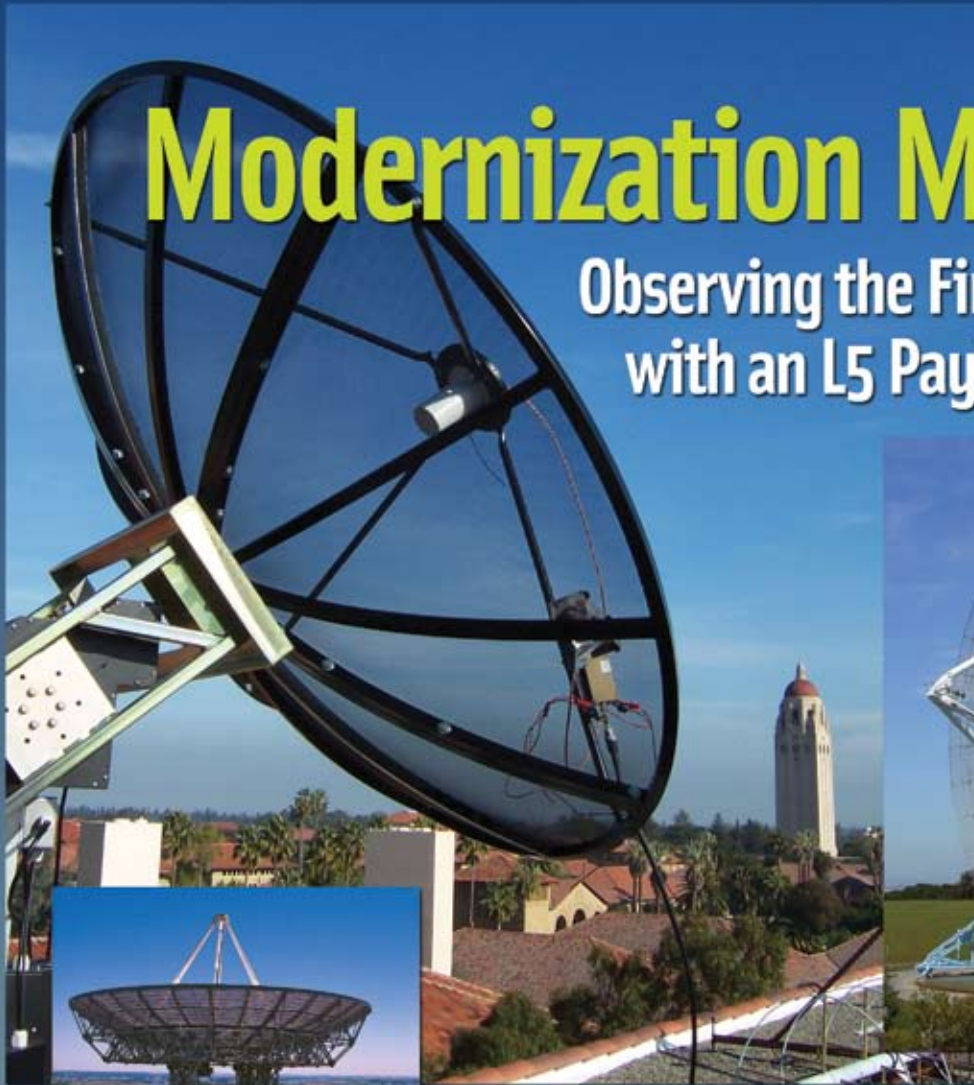


# Modernization Milestone

## Observing the First GPS Satellite with an L5 Payload



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After a lengthy delay in satellite launches caused by a variety of technical problems, the new civil GPS signal – L5 – began transmitting a demonstration signal on April 10. Using a modified navigation payload on a GPS Block IIR-M satellite placed in orbit only two weeks earlier, the U.S. Air Force switched on the eagerly awaited, modernized signal. The article reports the initial observations of L5 broadcasts by researchers in California and Colorado, including the appearance of an anomaly in SVN49's L1 signal.

*Above, left to right: The 1.8-meter dish antenna of Stanford GNSS Monitoring Station (SGMS), Stanford, California; ITS 18-meter parabolic antenna, Table Mountain, Colorado; SRI International's 45.7-meter radio telescope antenna in the Stanford hills, Stanford, California.*

**A**t 5 a.m. PDT (Pacific Daylight Time) on April 10, 2009, GNSS reached a new milestone as the first GPS L5 signal was turned on and transmitted from a GPS satellite. Eagerly anticipated, this is the first broadcast of a GPS signal in a frequency band dedicated *solely* for civilian use.

The latest signal represents the first step into a new era for GNSS users, particularly for safety-of-life applications. The L5 signal gives these users two civil signals (L1 being the other) in a protected aeronautical radionavigation services (ARNS) band. This allows for ionospheric corrections using only ARNS bands.

Additionally, the higher chipping rate on L5 enables more precise code phase measurements than available on other civilian GPS frequencies.

This article will trace the history of L5's origin within the GPS program modernization initiative, the signal's characteristics as designed, and the results of observations of the initial transmission of L5 and other GPS signals from three research facilities.

## A Short History of L5

Development of the L5 signal has its roots in the increasing use of GPS by civil users, particularly in aviation. As the system approached full operational capability, GPS system managers and user communities recognized that a second civil frequency would provide great benefits. Eventually, a second civilian signal became part of GPS modernization planning in the late 1990s.

In fact, a select panel of GPS experts recommended that two additional civil frequencies be broadcast, L2C and L5. An anecdote from that period characterizes the recommendation as arising from a debate over strategy: the civil L2 signal was thought to pose a lower risk approach to getting Department of Defense (DoD) buy-in, as there was already a GPS P(Y) broadcast on L2 (at 1227.6 MHz). However, a civil signal on L5 (centered at 1176.45 MHz), located in an ARNS band, would be more useful to safety-of-life users.

Rather than deciding to ask for one or the other, the panel recommended both new signals. After discussion and analysis, the DoD adopted these recommendations along with the proposal for two new military (M-code) signals. On March 30, 1998, Vice-President Al Gore announced that two new signals would be implemented.

At the time, the U.S. Air Force had a number of GPS replenishment (Block IIR) satellites yet to be launched and elected to modify eight of these (the IIR-Ms) to add both the new civil L2 signal as well as new military signals (L1M and L2M). Seven IIR-Ms are now on orbit and broadcasting.

The Air Force was also developing

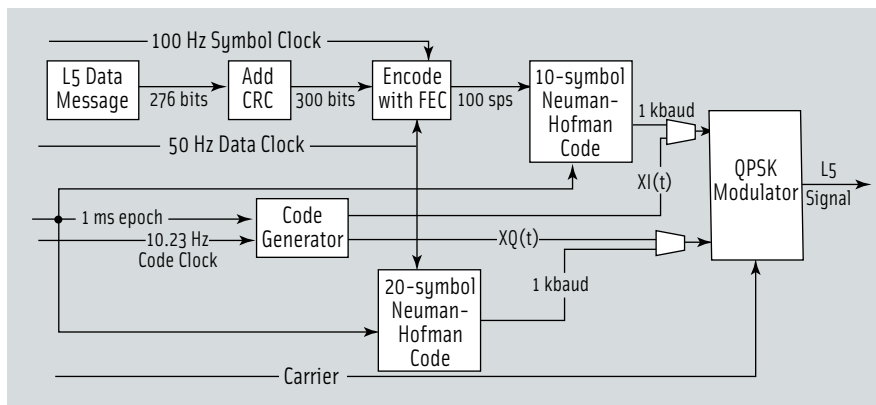


FIGURE 1 GPS L5 signal modulation

GPS L5 signal	Modulation	Chip rate	Nav Data?	Secondary code
In-phase component	BPSK	10.23 MHz	Yes	10 bit Neuman-Hofman code
Quadrature component	BPSK	10.23 MHz	No	20 bit Neuman-Hofman code

TABLE 1. GPS L5 inphase and quadrature signal comparison

the next generation of GPS spacecraft, designated IIF (follow-on). The IIF procurement added both military signals, the new civilian signal L2C as well as the L5 signal.

With the L2C signal now being broadcast, attention has shifted to L5. In recent years schedule delays on the Block IIF program (the first satellite of which was originally scheduled to launch in January 2005) brought great anxiety over the fate of L5. The U.S. radio frequency filing for L5 at the International Telecommunications Union (ITU) would expire in August of 2009 unless a continuous use of that frequency could be demonstrated.

With the launch of the Block IIF slipping to late 2009 and a Chinese filing for the L5 frequency in place, the status of the GPS civil L5 signal was indeed in danger. The GPS Wing (under its commander Col. Dave Madden) was very sensitive to the issue. Madden created an insurance policy against further delays in the launch of Block IIF by having the GPS Wing contract early in 2007 for the inclusion of an L5 demonstration payload on the Block IIR(20)-M satellite, the seventh modernized Block IIR satellite.

Fortune favored GPS as the Block IIR(20)-M satellite, designated Space Vehicle Number (SVN) 49, was successfully launched on March 24, 2009.

## Overview of the L5 Signal

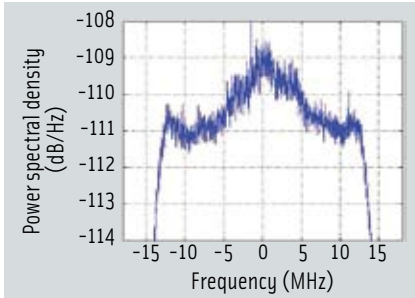
The L5 signal consists of two carrier components, in-phase and quadrature. Each carrier component is a binary phase shift keying (BPSK) signal with a chip rate of 10.23 MHz.

The in-phase component is modulated by a bit sequence of the modulo-2 sum of a primary code, a secondary code for synchronization, and navigation data, while the quadrature component is only modulated by a primary code and a secondary code, without navigation data. The secondary codes for the in-phase and quadrature channels are 10-bit and 20-bit Neuman-Hofman codes, respectively.

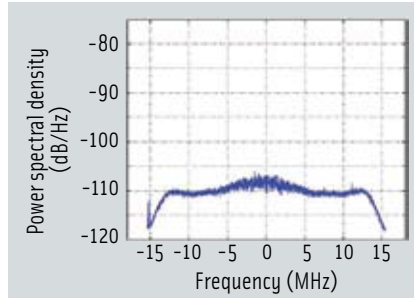
The modulation of GPS L5 signals is shown in Figure 1. Table 1 summarizes the in-phase and quadrature signal features.

The L5 frequency band is within the frequency band of the existing aeronautical system pulsed emitters, namely Distance Measuring Equipment (DME) and Tactical Air Navigation (TACAN) systems. DME provides distance measurements between an aircraft and a ground station, while TACAN — a military system — provides additional azimuth information to aviators. The DME and TACAN systems transmit pulses paired 12 microseconds apart, each pulse lasting 3.5 microseconds.

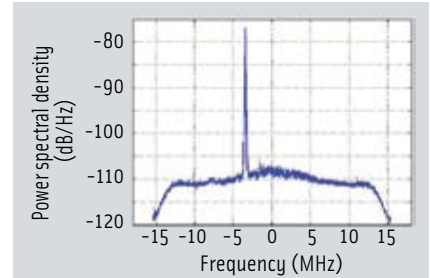
The L5 and DME/TACAN signals can co-exist, obviating any need to move



**FIGURE 2** The very first snapshot of the L5 spectrum of GPS SVN 49 satellite, captured at 5:00 a.m. PDT on April 10, 2009, at Stanford, California. Satellite elevation was 64 degrees and azimuth was 305 degrees. The Woodside DME was arranged to be off.



**FIGURE 3** The L5 spectrum of GPS SVN 49 satellite, captured at 5:40 a.m. PDT on April 10, 2009, at Stanford, California. Satellite elevation was 74 degrees and azimuth was 256 degrees. The Woodside DME was off.



**FIGURE 4** The L5 spectrum of GPS SVN 49 satellite, captured at 5:40 a.m. PDT on April 11, 2009, at Stanford, California. Satellite elevation was 74 degrees and azimuth was 249 degrees. The satellite elevation is identical to that in Figure 3, to ensure that the antenna pattern and the received L5 signal power are the same. The Woodside DME was on. Clearly visible in the spike around -4 MHz is the DME signal captured through a side lobe of the 1.8-meter parabolic antenna gain pattern.

the DME center frequencies permanently. However, arrangements were made to turn off the nearby Woodside, California, DME in the early morning of April 10, 2009, until an hour after SVN 49 began broadcasting the L5 signal. This enabled researchers at the Stanford facility to capture pristine satellite data on the first day of transmissions.

### Facilities for Capturing SVN 49 Transmission

We used three facilities in California and Colorado for the data capture. One is the 1.8-meter dish antenna of the Stanford GNSS Monitoring Station (SGMS). The second is the 18-meter dish located at Table Mountain, Colorado. The third one is SRI International's 45.7-meter dish antenna located in the hills above Stanford.

The three dish antennas, shown on the opening page of this article, have been previously used to observe GPS, Galileo GIOVE, and Compass satellite transmissions.

As described in earlier *Inside GNSS* articles (see the Additional Resources section near the end of this article), a vector signal analyzer is used in the Stanford GNSS Monitoring Station to down-convert the radio frequency signal to baseband and record the data. The Stanford SGMS dish connects to a band pass filter, but the Colorado dish does not.

### Observations through the 1.8-meter Dish Antenna

We will first discuss the observations made by the dish antenna at Stanford University.

**L5 Signal Measurements, with the Woodside DME On and Off.** At Stanford, we observed the L5 initial broadcasting at 5 a.m. PDT. **Figure 2** shows the very first snapshot. We verified the center frequency of the L5 signal to be 1176.45 MHz and the chip rate to be 10.23 MHz.

As mentioned earlier, the DME transmitter site closest to Stanford is in Woodside, located at latitude 37.39278 N, longitude 122.28194 W with a site elevation of 675 meters. The DME transmits at the 1173 MHz frequency. Due to the site's proximity to the Stanford receiving antenna and the high elevation, Woodside DME is the major operational aeronautical signal in the L5 band in the Stanford vicinity.

**Figures 3 and 4** compare the L5 spectra with the DME turned off and on, respectively. **Figure 3** was plotted at 5:40 a.m. on April 10 when the Woodside DME was still off. **Figure 4** is an observation from the following day at the same time (April 11, 5:40 a.m.) when the Woodside DME was back on the air.

The two plots were intentionally taken when the satellite elevation was the same to ensure that the antenna pattern and received signal power were identical for both observations. For ease of comparison, the scales of **Figures 3** and **4** are set to be the same.

As shown in **Figure 4**, Woodside DME is a strong narrowband spike in the L5 frequency band, whose peak power spectral density is 30 decibels above that of the GPS L5 signal. Operationally this is not a problem as L5 receivers can detect and blank the L5 pulses with little impact on the GPS L5 signal reception.

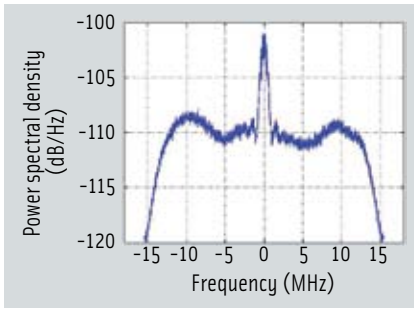
### Other SVN 49 Signal Observations.

Besides the L5 signals, we also observed signals in other frequency bands broadcast by satellite SVN 49, namely L1, L2, and even L3 for a short period of time. Centered at 1381.05 MHz, the L3 signal provides the communications link for the Nuclear Detonation (NUDET) Detection System (NDS) payload on board GPS satellites designed to detect nuclear detonations and other high-energy infrared events.

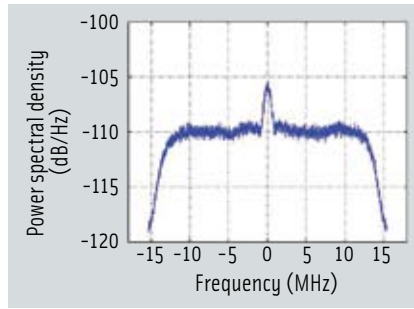
**Figure 5** shows the spectrum of the L1 signal centered at 1575.42 MHz. Again, the spectrum is already down-converted to the baseband. The spectrum shows the 1.023 MHz C/A signal, the 10.23 MHz P(Y) signal, and the binary offset carrier (BOC) (10,5) M-code signal.

**Figure 6** shows the spectrum of the L2 signal down-converted to the baseband. The spectrum shows the 1.023 MHz C/A signal, the 10.23 MHz L1 P(Y) signal and BOC(10,5) M code signal. Although the satellite was at a higher elevation when the L2 spectrum was captured compared to the L1 spectrum in **Figure 5**, the received L2 signal power is lower than the received L1 signal power, because the peak of the power spectral density (PSD) is lower.

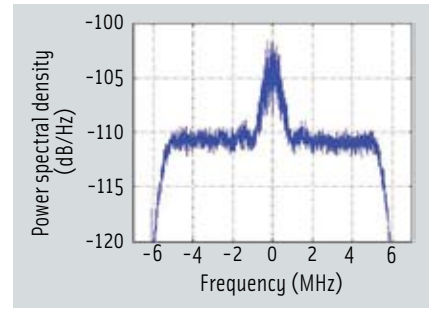
The unexpected observation of the L3 signal at center frequency 1381.05 MHz for a few minutes around 5:50 a.m. PDT on April 10, 2009, is shown in **Figure 7**. The authors assume that the short



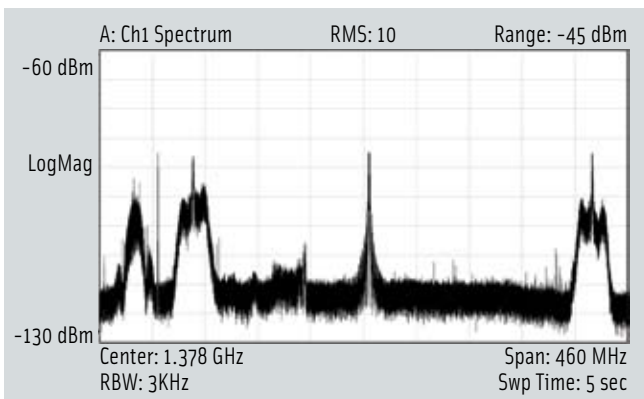
**FIGURE 5** The L1 spectrum of GPS SVN 49 satellite, captured at 4:20am PDT on April 10, 2009, at Stanford, California. Satellite elevation was 46 degrees and azimuth was 314 degrees. The spectrum shows the 1.023 MHz C/A signal, the BOC(10, 5) M code signal, as well as the 10.23 MHz L1 P(Y) signal.



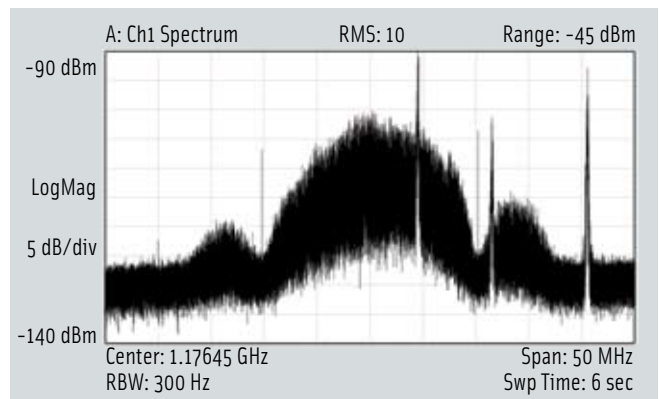
**FIGURE 6** The L2 spectrum of GPS SVN 49 satellite, captured at 4:31a.m. PDT on April 10, 2009, at Stanford, California. Satellite elevation was 51 degrees and azimuth was 313 degrees. The spectrum shows the 1.023 MHz L2C signal, the BOC(10, 5) M code signal, as well as the 10.23 MHz L2 P(Y) signal.



**FIGURE 7** The L3 spectrum of GPS SVN 49 satellite, captured at 5:51 a.m. PDT on April 10, 2009 at Stanford, California. Satellite elevation was 73 degrees and azimuth was 237 degrees. The L3 signal disappeared a few minutes later.



**FIGURE 8** The full spectrum captured by the 18-meter parabolic antenna at 5:46 a.m. PDT at Table Mountain, CO. Because the facility does not use a bandpass filter, all GPS bands (from left to right, L5, L2, L3, and L1) are shown. The GPS signal spectrum from this antenna is boosted higher above the noise floor than the Stanford SGMS antenna, due to the higher antenna gain provided by the larger antenna parabolic reflection area.



**FIGURE 9** A close look at the L5 spectrum captured by the 18-meter parabolic antenna. The L5 spectrum is consistent with the Stanford 1.8-meter dish observation, but the DME environment is different.

appearance of the L3 signal was for test purposes.

## Observations at Table Mountain, Colorado

Because the facility does not use a bandpass filter, the observations through the 18-meter parabolic antenna at Table Mountain show all GPS bands in **Figure 8**. From left to right, the frequency bands are L5, L2, L3, and L1.

The GPS signal spectrum from this antenna is cleaner than the Stanford SGMS antenna, due to the higher antenna gain provided by the larger antenna parabolic reflection area.

**Figure 9** presents a close look at the L5 spectrum through the parabolic antenna. The spectrum is consistent with the L5 signal definition and the spectrum seen from the Stanford 1.8-meter dish.

Table Mountain is different from that at Stanford and no DME transmitters were arranged to be turned off, the L5 spectrum in **Figure 9** shows three DME/TACAN signals appearing on the right-hand portion of the spectrum.

## Observations from SRI Dish Antenna

The cleanest L5 spectrum among the three facilities we have access to was captured by SRI International's 45.7-meter dish antenna in the Stanford hills. The large-diameter parabolic reflection area of this antenna provides a 52-decibel antenna gain for L-band signals.

The high antenna gain boosts the L5 signal above the noise floor in the frequency domain, and, thus, the main lobe and the side lobes of the L5 spectrum are clearly shown in **Figure 10**.

Because the DME/TACAN environment at

## Acquiring and Tracking the First SVN 49 Transmission

Immediately after the data recording, we loaded the collected SVN 49 data collected by our 1.8-meter dish into our multi-signal all-in-view GNSS software receiver.

We have used this software receiver to acquire and track GPS, Galileo GIOVE, and Compass transmissions, reported in earlier *Inside GNSS* articles.

With the observed SVN 49 data loaded into our receiver, we successfully acquired and tracked the L5 signal. The acquisition results are shown in **Figure 11**. The L5 signal is present only in the quadrature channel and not the in-phase channel.

The L5 signal specification (IS-GPS-705) defines the pseudorandom noise (PRN) code of the SVN 49 L5 signal as the L5 code in the code set of PRN 63. Each code set of a certain PRN number in the GPS signal

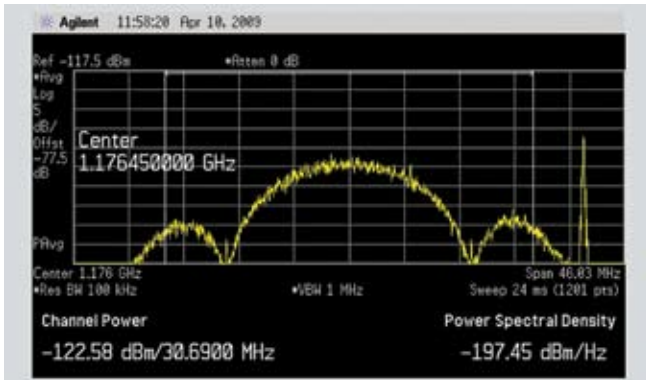


FIGURE 10 The L5 spectrum captured by the SRI 45.7-meter dish antenna. The large size of the dish reflection area provides an antenna gain as high as 52 decibels, which boosts the L5 signal high above the noise floor in frequency. A clear L5 spectrum with the main lobe and two side lobes are shown. Figure courtesy of Mike Cousins and John Ciboci, SRI International.

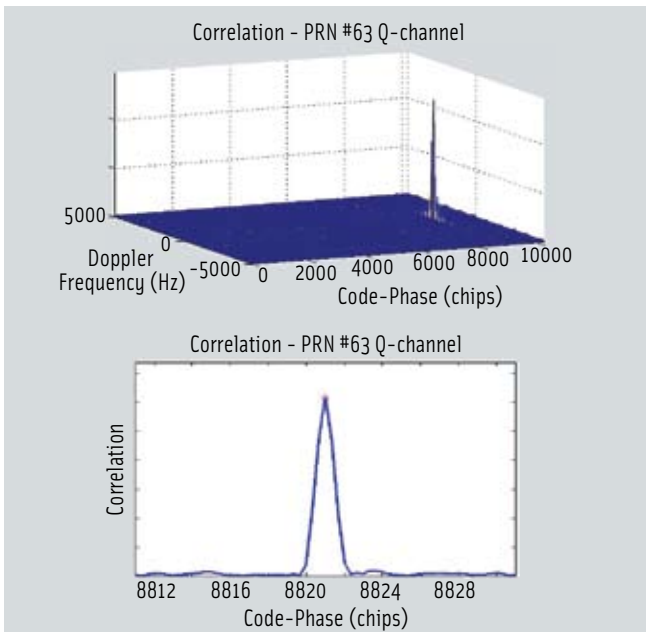


FIGURE 11 Acquisition plot of SVN 49 L5 signal with five milliseconds of coherent integration. The data used in the plot were logged at 5:30 a.m. PDT on April 10, 2009. The triangular correlation peak clearly visible in the right-hand panel verifies the BPSK modulation of the signal. Only the quadrature channel contains signals, not the in-phase channel.

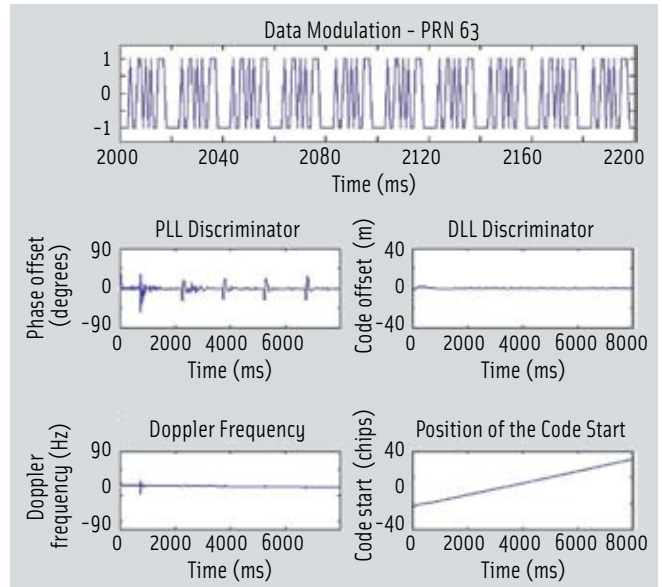


FIGURE 12 L5 tracking results. The data modulation on the top shows a 20-bit Neuman-Hofman code modulated on the primary PRN code, which is consistent with the L5 Q-channel signal definition. The phase lock loop shows jitter every 1.5 seconds, which indicates a periodic carrier phase scattering.

The phase lock loop (PLL) output shows jitters every 1.5 seconds in the time domain, which indicates a periodic carrier phase scattering of the PRN 63 L5 test signal.

### SVN 49 Anomalous Behavior

Many observers have noted that the ranging performance of SVN 49 includes some anomalous behavior. An observable elevation angle-dependent shift in the L1 code delay exists that is consistent with an antenna group delay bias, although the nature and cause of the anomaly are still under investigation.

In order to observe this anomaly, we processed data from a receiver at Mauna Loa, Hawaii, which is part of the National Satellite Test Bed (NSTB) receiver network. The data set was recorded on May 5, 2009.

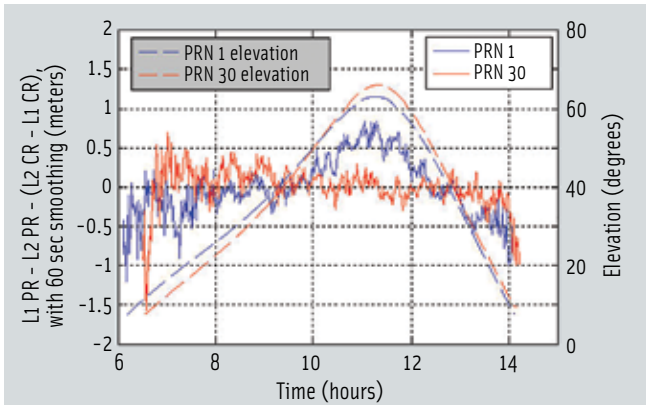
We compared the SVN 49 measurement results with those from SVN 30 (PRN 30), a GPS IIA satellite that shares the same B2 expanded orbital slot as SVN 49. Over the 24-hour observation time on May 5, the maximal elevation difference seen at Mauna Loa between SVN 49 and SVN 30 is only 4.3 degrees, and the maximal azimuth difference is only 5.8 degrees. The proximity of SVN 49 and SVN 30 results in similar ionosphere and troposphere effects at the receiver and thus provides a sensible basis for comparison.

We examined several combinations of the satellite measurements to identify and isolate the potential sources of the anomaly. The observed carrier measurements for the two satellites were very similar and displayed no obvious signs of anomalous behavior. However, the code measurements did reveal a visible discrepancy.

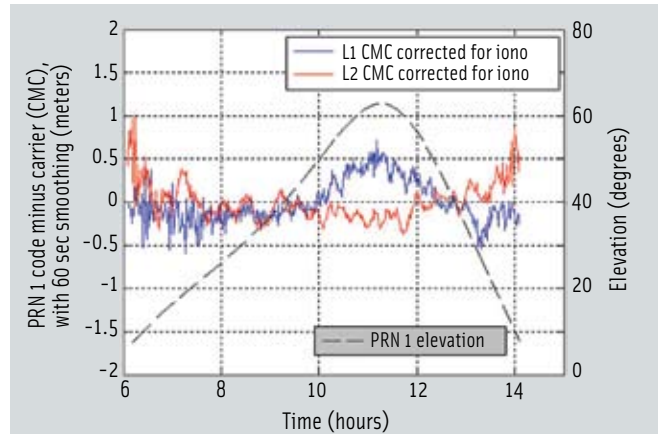
Figure 13 shows the computed L1/L2 pseudorange (PR) difference minus the L2/L1 carrier range (CR) difference. The frequency differences cancel out the common errors between

specification contains a set of the L1, L2, and L5 codes. However, the L1 and L2 PRN codes use the L1 and L2 codes in the code set of PRN 1 in the signal specification, codes from a different PRN number set. The authors assume that the absence of an L5 in-phase signal and the PRN number inconsistency indicates that the current L5 signal is a test signal.

Figure 12 shows our L5 tracking results. The data modulation plot shows the secondary code modulated on top of the primary PRN code. The secondary code of the L5 Q channel is a 20-bit Neuman-Hofman code with the bit string [0 0 0 0 1 0 0 1 1 0 1 0 1 0 0 1 1 1 0], the same as defined in the L5 signal specification.



**FIGURE 13** Comparison of PRN 1 to PRN 30 pseudorange errors where clock, orbit, troposphere, and ionosphere errors are eliminated. PRN 30 is chosen for comparison due to its orbital proximity. PRN 1 has an elevation-dependent bias with a relative shift of 0.7 meters from 20 degrees elevation to 60 degrees elevation



**FIGURE 14** PRN 1 code minus carrier measurements after applying a dual-frequency ionosphere correction. The clock, orbit, troposphere, and ionosphere errors are all eliminated. An obvious elevation-dependent bias exists in the L1 measurements.

L1 and L2, such as clock, orbit, and troposphere errors. The difference between (L1 PR - L2 PR) and (L2 CR - L1 CR) then eliminates the frequency-dependent ionospheric error.

The elevation curves of PRN 1 and PRN 30 are also presented for comparison in Figure 13. The PRN 30 curve is flat over the whole satellite path showing no sign of an anomaly. However, the PRN 1 curve has a distinct bump of 0.7 meters at high elevation.

Figures 14 and 15 examine how the dependency affects the L1 and/or L2 bands. These figures show the code/carrier difference for a single frequency after applying dual-frequency carrier-based ionosphere error corrections. Again, clock, orbit, troposphere, and ionosphere errors are all eliminated.

Figure 14 indicates that the SVN 49 anomaly is primarily in the L1 band. Compared to Figure 15, the L1 code-minus-carrier (CMC) with ionosphere correction for PRN 1 has a bias highly correlated with the satellite elevation. Consistent with Figure 13, the bias has a relative shift of 0.7 meters from a low elevation of 20 degrees to a high elevation of 60 degrees.

The L2 CMC curve is flatter, although there could be a bias in the opposite direction. Figure 15 shows the normal case of PRN 30, where both L1 and L2 CMC curves are flat over the whole satellite path.

In summary, the SVN 49 L1 signal has a bias with a relative shift of about 0.7 meters from a low elevation of 20 degrees to a high elevation of 60 degrees, as observed in Mauna Loa, Hawaii. Similar results have been reported by other researchers at different locations.

This bias can be larger if the satellite reaches a higher elevation at other locations (e.g., up to 90 degrees in Australia). The satellite is labeled as unhealthy and will likely remain so as the anomaly is still under investigation.

## Conclusion

This article presents our first observations of the new GPS IIR(20)-M satellite, also known as SVN 49. The GPS IIR(20)-M satellite is the very first GPS satellite with an L5 payload, centered at 1176.45 MHz in a band designed solely for civilian use.

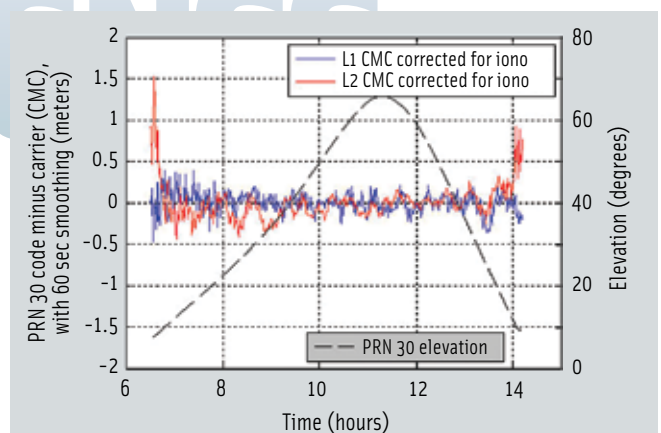
The satellite was launched on March 24, 2009, and its L5 transmission was turned on at 5 a.m. PDT on April 10, 2009. We observed the broadcast signal from SVN 49 in all frequency bands, namely L1, L2, L5, and even L3 band for a short period of time.

We acquired and tracked the broadcast L5 signal, which only appeared in the quadrature channel and carried PRN 63 as the primary PRN code and a 20-bit Neuman-Hofman code as the secondary code.

Finally, we investigated an anomaly of SVN 49 in L1 band based on data collected at Mauna Loa, Hawaii, on May 5, 2009. A measurement bias is observed in the L1 band and is dependent on the elevation. The satellite is labeled as unhealthy as the anomaly remains under investigation.

## Acknowledgment

The authors gratefully acknowledge the support of the Federal Aviation Administration under Cooperative Agreement 08-G-007. This article contains the personal comments and beliefs



**FIGURE 15** PRN 30 code-minus-carrier (CMC) measurements after applying a dual-frequency ionosphere correction. Compared to Figure 14, both L1 and L2 curves are flatter, showing no evidence of dependence on elevation angle.

of the authors and does not necessarily represent the opinion of any other person or organization.

David De Lorenzo from the Stanford GPS Lab developed the software receiver based on the integration of our own receiver code and code from the University of Aalborg, Denmark, and Dennis Akos of the University of Colorado, Boulder.

The authors would also like to thank Stuart Riley from Trimble Navigation Ltd. for valuable discussions on L5 PRN codes, and Mike Cousins and John Ciboci from SRI International for providing the L5 spectrum snapshot.

### Manufacturers

Stanford University and Colorado researchers use an 89600 vector signal analyzer (VSA) from **Agilent Technologies**, Santa Clara, California, USA, to collect signals received at either the SGMS or Table Mountain dish antennas. Stanford also used an E4440 spectrum analyzer manufactured by **Hewlett-Packard Company**, Palo Alto, California. The university's software GNSS receiver is implemented in MATLAB from the **MathWorks, Inc.**, Natick Massachusetts, USA.

### Additional Resources

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