US Air Force

First Look

GPS L5 Observing the Test Transmission from SVN49 Using Software Radio Processing

Using a commercial antenna and a modified software GPS receiver of their own design, researchers at Ohio University tracked the new L5 signal from the latest Block IIR-M GPS satellite. Among other things, they discovered that the test signal being transmitted from SVN49 has some different characteristics than the signal specifications defined for the operational L5 signal.

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The much-anticipated first GPS satellite with an L5 test payload was launched from Cape Canaveral on March 24, 2009. On April 10, at approximately 11:58 UTC, the L5 test transmission was turned on by the GPS Control Segment.

This event marked a significant milestone for GPS: 31 years after the launch of NAVSTAR 1 (space vehicle number 1 — or SVN01), GPS SVN49 is now transmitting on a completely new, third navigation frequency; something the GPS "forefathers" probably could never have imagined back in February 22 of 1978 when that Atlas 64F rocket carrying NAVSTAR 1 lifted off the launch pad.

Arguably even more significant is the fact that a U.S. Department of Defense (DoD) program developed primarily for military use during the Cold War era is now transmitting a signal dedicated for civil use; free of any military signal modulations.

Times have changed.

The GPS L5 transmission, like L1, is allocated in the internationally protected aeronautical radio navigation services (ARNS) band, clearing one more hurdle for GPS-based dual-frequency systems to be certified for safety-of-life services such as aviation. The L5 transmission also demonstrates the final prong of the three-pronged approach to GPS modernization: transmit stronger signals; implement longer, faster, and more sophisticated pseudorandom noise (PRN) codes; and add frequency diversity to make GPS more robust and resistant to interference for civilian and military users alike.

The implementation of the GPS modernization program started in September of 2005 with the launch of the first Block IIR-M satellite SVN53, which gave civil users direct access to L2 for the first time via the L2C code — not to mention the sophisticated M-code on L1 and L2 for military users.

Significance aside, an operational GPS L5 constellation won't exist for yet a few more years until a significant number of Block IIF satellites replace the existing constellation. For the GPS Wing, the event of April 10 meant that the US won't lose its International Telecommunications Union (ITU) filing status for L5, which came uneasily close to an August 26, 2009, deadline due to launch delays.

For the thousands of individuals who comprise the community of researchers and equipment manufacturers that use (or cater to users of) GPS for aviation and other safety-of-life, atmospheric studies, space weather monitoring, RTK, and countless other applications, it means the first-time availability of an unrestricted *wideband* civil GPS signal-in-space to help bring their research to fruition.

Certainly, GPS researchers at the Ohio University Avionics Engineering Center are among these thousands. During the past 18 months we upgraded our instrumentation-quality L1/L2 GPS software receiver to include L5. April 10, 2009 will forever be etched in our minds as that Good Friday we collected terabytes of data and spent an entire gorgeous Easter weekend stuck indoors, unrelentingly processing and processing till we finally saw the L5 correlation peak from GPS SVN49. What follows is our first look of the signal from Athens, Ohio.

GPS L5 Signal Structure

The most complete description of the GPS L5 signal can be found in the interface specification IS-GPS-705, referenced in the Additional Resources section near the end of this article. What follows is a quick summary for the purposes of this article.

In general, the L5 transmission received at time t with power level P_{L5} from the i^{th} GPS satellite can be described as:

$$S_{i,L5}(t)=\sqrt{2P_{L5,i}}D_{5,i}(t)NH_I(t)G_{I,i}(t)\cos\left[2\pi\left(f_{L5}+f_{D,i}\right)t+\phi_{L5,i}\right]+\sqrt{2P_{L5,i}}NH_Q(t)G_{Q,i}(t)\sin\left[2\pi\left(f_{L5}+f_{D,i}\right)t+\phi_{L5,i}\right]+n(t)$$

Where f_{L5} is the L5 carrier frequency of 1176.45 MHz, f_D is the carrier frequency offset due to satellite line-of-sight motion and satellite-and-receiver combined clock frequency error, ϕ_{L5} is a phase offset and $n(t)$ is the received noise.

As shown, the L5 transmission is quadrature BPSK (bi-phase shift keying) modulated, with the in-phase component containing an SV-specific 10,230-chip long PRN code G_I chipping at a rate of 10.23×10^6 chips/sec, a 10-bit Neumann-Hoffman code NH_i at 1000 chips/sec, and a rate 1/2 convolution–encoded C-NAV data stream D_5 at 100 symbols/sec.

The quadrature component is modulated with a different 10,230-chip long SV-specific PRN code G_Q and a 20-bit Neuman-Hofman code NH_Q with chipping rates the same as the I-channel: C_P, C_Q, NH_P, NH_Q, and $D_5 \in \{1, -1\}$, NH_I = [1 1 1 1 - 1 - 1 1 - 1 1 - 1 - 1}, and NH_Q= [1 1 1 1 1 - 1 1 1 - 1 - 1 1 - 1 1 - 1 1 1 - 1 - 1 - 1 1]. The 10.23 MCPS code chipping rate results in a null-to-null bandwidth of 20.46 MHz: identical to the bandwidth of the legacy P(Y) code modulation on L2.

The Neuman-Hofman codes effectively lengthen the 1-millisecond, periodic L5 PRN codes to 10 and 20 milliseconds for the in-phase and quadrature-phase channels, respectively, to provide improved cross-correlation performance.

Referred to as the pilot channel, the quadrature-phase component contains no data modulation and, hence, enables long coherent integration by the user equipment — integration that is primarily limited by dynamics estimation errors (i.e., inertial drift) and the stability of the receiver's (and to a lesser extent the satellite's) reference oscillator. The L5 pilot channel thus allows the implementation of robust and certifiable high-sensitivity and anti-jam processing.

The GPS L5 transmission from SVN49 has significant deviations from the specification of IS-GPS-705 [because] the primary goal of integrating an L5 demonstration payload into a Block IIR-M satellite was to satisfy the ITU's "bring into use" deadline.

According to IS-GPS-705, the guaranteed minimum received signal power $P_{L5,\,min}$, to a user at the surface of the earth measured at the output of a 3 dBi linearly polarized antenna from an SV at elevation above five degrees is stated as -157.9 dBW: 0.6 dB stronger than the -158.5 dBW minimum specified for the legacy L1 C/A code signal.

Assuming the said antenna is at the standard ambient temperature of 295K, the guaranteed received minimum carrier-to-noise ratio (C/N_0) measured at the output will be 46.9 dB-Hz. However, C/N_0 values measured by a GPS receiver connected to a typical circularly polarized antenna would be three to six decibels lower due to the antenna gain pattern and receiver implementation losses.

The L5 Test Transmission

It is important to realize that the GPS L5 transmission from SVN49 has significant deviations from the specification of IS-GPS-705. As the article by T. Powell et alia discusses (Additional Resources), the primary goal of integrating an L5 demonstration payload into a Block IIR-M satellite was to satisfy the "bring into use" deadline of August 26, 2009, a date which was set when the United States filed with the ITU Radiocommunication Sector (ITU-R) to transmit on the L5 frequency.

The following is a listing of these deviations:

- SVN49 transmits only the dataless quadrature component of the L5 signal specification. (i.e., in the L5 signal equation presented in the previous section, $G_{I,i}(t) = 0$).
- It is 'hardwired' to generate only one PRN code on L5: L5-Q PRN63. This applies no matter what PRN is assigned to SVN49's primary GPS mission. (Currently, the primary mission assignment is PRN1.)
- Most likely, the transmitted power on L5 is lower than required to meet the guaranteed minimum received signal strength specified in IS-GPS-705. This is because the demonstration payload is occupying the auxiliary payload capability of the Block IIR-M spacecraft, which is probably not designed to handle the power requirements of an additional transmission at full-spec.
- Most likely, the antenna gain pattern of SVN49's L5 transmission may not be optimal for full earth surface coverage because the L5 demo mission is secondary to the IIR-M vehicle's primary mission of sustaining the GPS constellation.

The first two factual constraints mean that the L5 test transmission is non-operational, but allows acquisition and tracking as an experimental signal — good enough to meet the conditions of the ITU filing and to enable basic research on triple-frequency GPS. The latter two deviations in the preceding list are "educated guesses" based on the authors' initial observations of the L5 signal.

L1/L5 RF Front-End and Data Collection System

In anticipation of the first L5 signals in space, the Ohio team upgraded its Transform-Domain Instrumentation GPS Receiver (TRIGR), described in the article by S. Gunawardena et alia (2007), to include L5. TRIGR represents a breakthrough set of GPS receiver technologies that had been developed at the Ohio University Avionics Engineering Center during the last six years.

The technology encompasses instrumentation-quality RF front-ends, high-fidelity wideband multi-bit–sampled intermediate frequency (IF) data collection and post-processing, and high-performance realtime transform-domain GPS baseband processing engines implemented on field programmable gate array (FPGA) processors.

The current version under development represents the third generation of TRIGR technology and is being targeted for a variety of next-generation multi-channel and multi-frequency GNSS applications. **Figure 1** shows the block diagram and frequency plan of the L1/L5 RF front-end used for L5 signal analysis.

Figure 2 shows a close-up view of the L5 section of the front-end. The performance of the L5 section of the front-end was verified previously using L5 signals-in-space from WAAS PRNs 135 and 138. Results of this work and additional details of the front-end are covered in the article by S. Gunawardena et alia (2008).

As shown in Figure 1, the L1/L5 signals downconverted to the 70 MHz IF are bandpass sampled at 56.32 MSPS to yield a digital baseband signal with its IF centered at 13.68 MHz. To maximize options for high-dynamic range GNSS signal processing (such as in the midst of interference), the analog IF is sampled at 14-bit resolution without the use of automatic gain control circuitry. For data collection purposes, these 14-bit samples are then reduced to 8, 4, 2 or 1-bit per sample inside the FPGA and subsequently streamed to a RAID storage array.

The ability to stream 8-bit L1/L5 samples continuously (~113 MBytes/sec sustained transfer rate) and to do so for up to five hours continuously (storage limit of the array) enabled us to capture pristine sets of L1/L5 data for the morning and afternoon visibility periods of SVN49. We postprocessed the data to produce the results presented in this article.

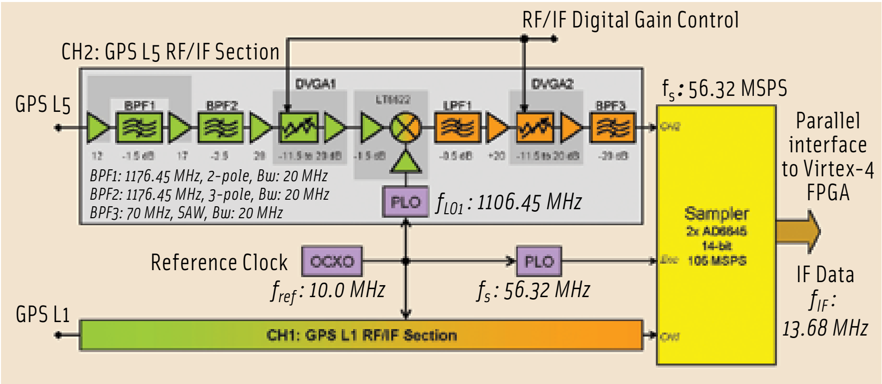


FIGURE 1 L1/L5 RF front-end and frequency plan

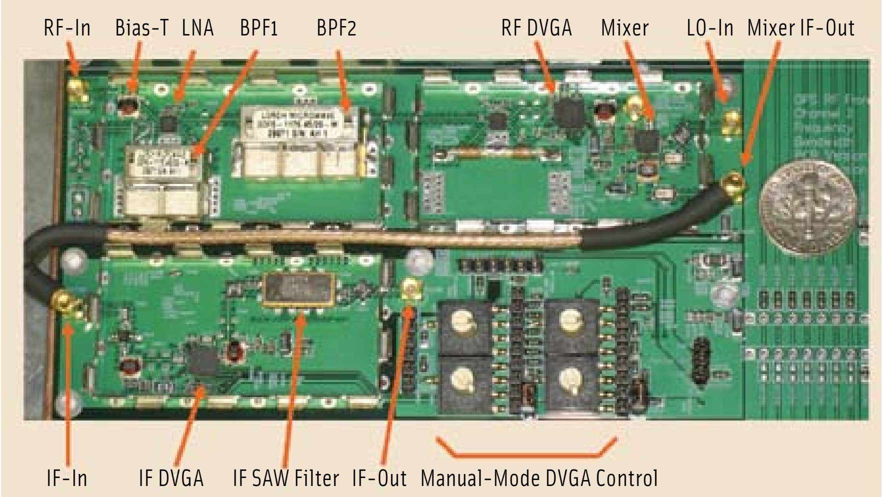


FIGURE 2 L5 channel of TRIGR RF front-end

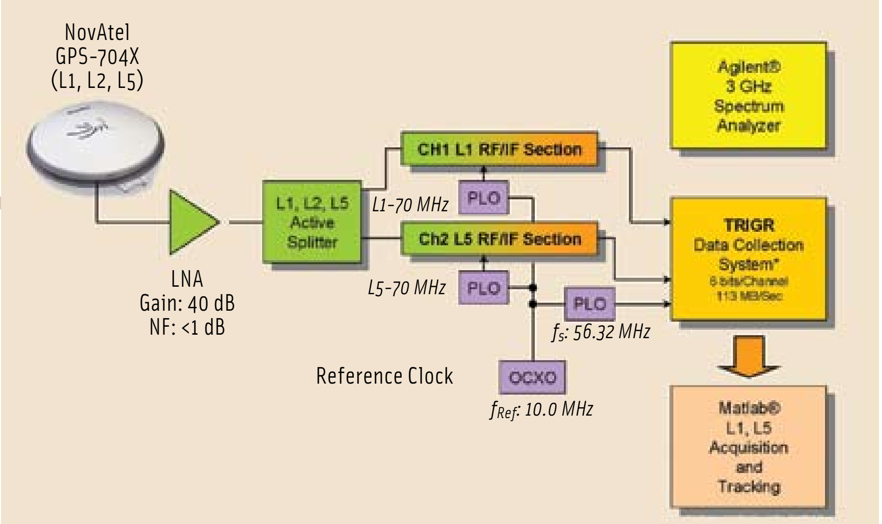


FIGURE 3 Test setup for live GPS L1/L5 RF data collection and spectrum analysis

Data Collection Setup

Figure 3 shows the test setup that was used to collect live L1/L5 data for the results presented in this article.

We used a commercial antenna that covers the L1, L2 and L5 bands. Because this model is a passive antenna, we incorporated a high-quality low noise amplifier (LNA) with a noise figure below 1 decibel and approximately 40-decibel gain. The LNA is placed as close to the antenna port as possible to obtain the lowest possible system noise figure. The RF signal is fed to each front-end channel via an active splitter built into the four-channel RF front-end.

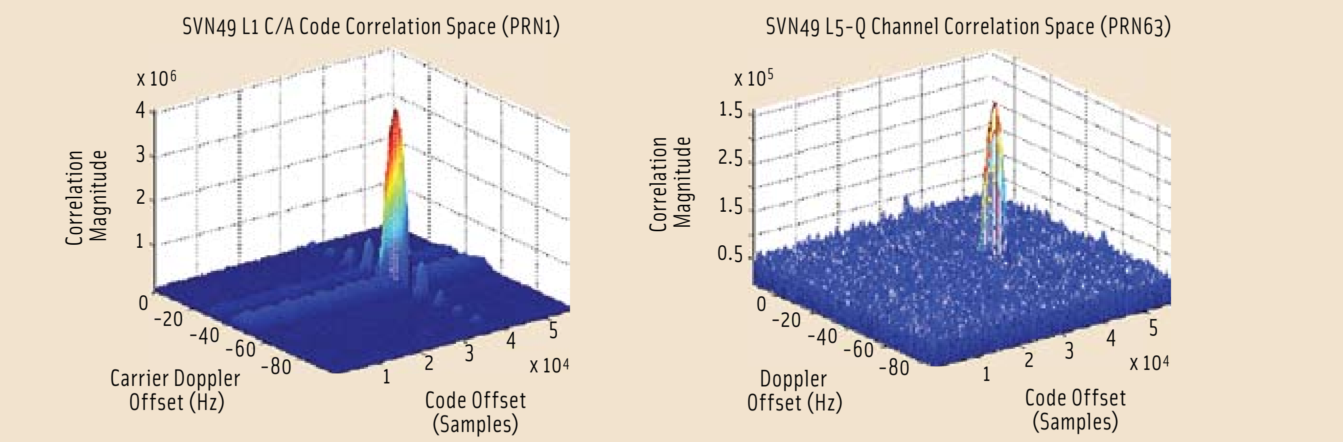


FIGURE 4 Left: SVN49 L1 C/A code correlation space computed using 100milliseconds of coherent integration (includes 5-bits data wipeoff). Right: Correlation space of L5 pilot channel computed using 100-millisecond coherent integration.

Acquiring the GPS L5 Signal

As described previously, the L5 test transmission may not necessarily adhere to the guaranteed minimum received signal level of -157.9 dBW (~47 dB-Hz). Even though we suspected it, the necessity for more care when acquiring the L5 signal (relative to the "easy" acquisition of L1 C/A) was not immediately apparent.

Our initial analysis of the dataset containing the L5 turn-on event yielded no discernible correlation peak. This had us puzzled: was the L5 turn-on event postponed? Did we have a bug in our L5 code generator? Our initial method used one millisecond of coherent integration (to sidestep having to perform NH_Q code wipeoff) and a handful of non-coherent integrations (to increase signal-to-noise ratio at the expense of squaring loss).

Soon we realized this would not work if the signal were significantly weaker than expected. Further, what if the NH_Q code transition happened close to the middle of our one-millisecond data blocks? This would kill most of the correlation energy and yield no peak. A bit of refinement was in order!

Because we had recorded both the L1 and L5 coherently sampled data streams in the same file, we could initialize the L5 processing by first acquiring SVN49's L1 C/A-code signal (PRN01) and use it to determine both the Doppler frequency offset at L5 ($f_{D,L5} = (f_{L5}/f_{L1})f_{D,L1}$) and, more importantly, the 20-millisecond L1 C/A navigation data bit epochs. The latter, by definition, are the same as the 20-bit NH_Q code epochs (ignoring the few samples offset due to hardware and atmospheric relative delays).

While we were at it, we also aligned our one-millisecond data block to coincide with the start of the C/A-code (i.e., code phase zero alignment). With the code-phase and Doppler frequency offsets nailed, we tried 100 milliseconds of coherent integration with NH_Q code wipeoff. (The carrier frequency needs to be within 10 Hz for 100-millisecond coherent integration).

The resulting L5 correlation peak was a sight to behold! **Figure 4** shows the acquisition results. Animations of the L5 correlation space can be viewed at <http://www.youtube.com/user/sanjeevg123>.

Observed Strength of L5 Test Signal

As of the time of this writing, at least two groups from Europe have reported GPS-L5 received signal strength being stronger than expected. (See Septentrio and Javad GNSS news releases cited in Additional Resources.) This may be due to the fact that SVN49 reaches higher elevations in Europe.

In the U.S. Midwestern region SVN49 peaks at elevations of approximately 37 and 34 degrees during it's two daily passes. At the peaks of these passes, the observed signal strengths are approximately 35 dB-Hz; relatively weak compared to the guaranteed minimums of IS-GPS-705.

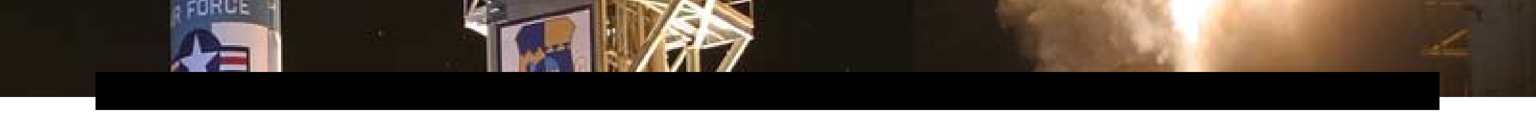
As alluded to earlier, the test payload's L5 antenna beam pattern appears to have a narrow main beam. Observations at multiple locations would aid in inferring the antenna pattern, which would be useful for numerous research applications.

We are presenting the carrier-to-noise (C/N_0) versus time and elevation profiles from our initial observations of the L5 test signal from Athens, Ohio, (N 39° 12' 33.14520", W 82° 13' 25.93487") as a first step towards inferring the actual gain pattern of the L5 test signal. We trust this information will be especially helpful for those researchers who plan to use regular L1/L5 GPS antennas (i.e., standard patch-types as opposed to high-gain dish antennas) to get a sense of the signal strengths to expect from a location similar to ours.

For the results shown in this article, the L1 and L5 front-end channels were sampled at an effective resolution of four bits per sample and continuously streamed to the TRIGR RAID array for about four hours, generating files of approximately 850 GB each for the two passes.

Because it's prohibitively slow to postprocess the entire files with the software we were using (requiring about 30 minutes to process a second of data on a fast desktop computer), observations were made every five minutes for a duration of one second per observation.

Figure 5 shows measured C/N_0 from SVN49's L1 C/A and L5 Q transmissions



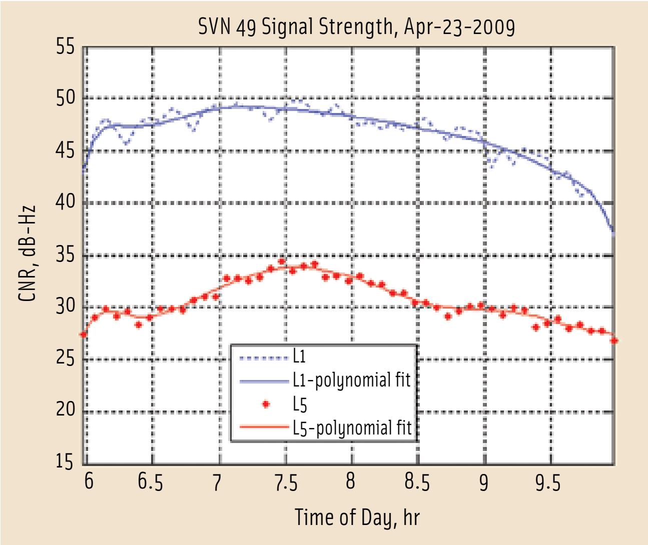


FIGURE 5 L1 and L5 received C/N0 as a function of local time (EDT) at Athens, Ohio: morning visibility period

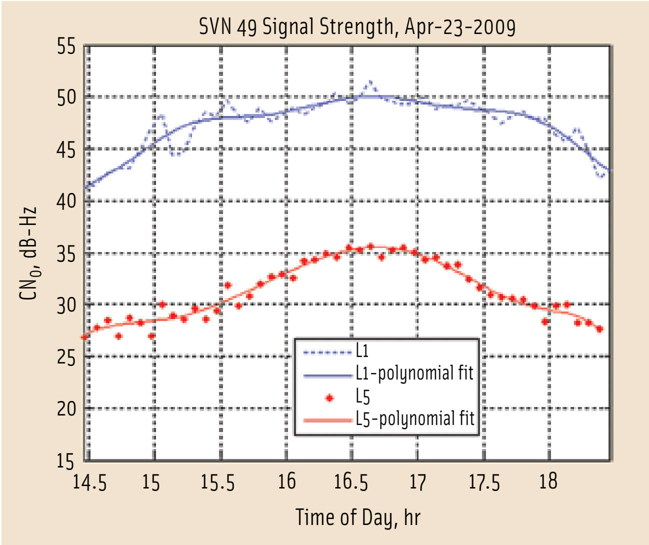


FIGURE 6 L1 and L5 received C/N0 as a function of local time (EDT) at Athens, Ohio: afternoon visibility period

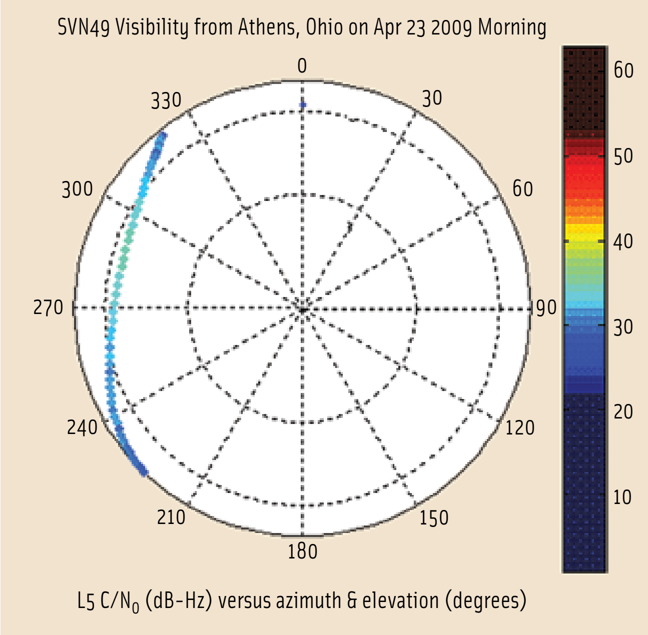


FIGURE 7 Received C/N0 from L5 test transmission as a function of azimuth and elevation at Athens, Ohio: morning visibility period

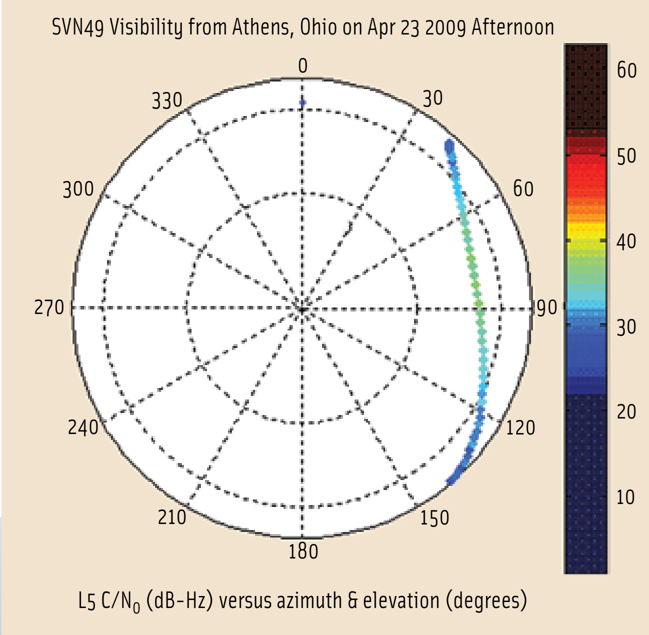


FIGURE 8 Received C/N0 from L5 test transmission as a function of azimuth and elevation at Athens, Ohio: afternoon visibility period

during the morning visibility period from Athens, Ohio, on April 23. **Figure 6** shows the same for the afternoon visibility period.

Figures 7 and **8** show the measured C/N_0 as a function of azimuth and elevation angles (i.e., skyplot) from our location for the morning and afternoon visibility periods, respectively. **Figure 9** shows C/N_0 as a function of elevation angle for both periods of visibility.

From Figures 5 and 6, it can be seen that, on average, the power differential between SVN49's L1 and L5 transmissions is approximately 15 decibels. This confirms our initial assessment that the L5 test transmission has significantly lower signal strength than the 46.9 dB-Hz guaranteed minimum specified in IS-GPS-705. The observed minimum C/N_0 from our location is closer to 27 dB-Hz.

Assuming that the L1 and L5 gain patterns of the reception antenna are consistent, as was verified from the antenna manufacturer's datasheet, the L1 C/N_0 contours from Figures 5 and 6 could be used as a baseline to deduce the L5 antenna gain pattern variation. Using this observation, the figures show two faintly distinguishable minima that may correspond to nulls in the antenna pattern. The time spacing between these nulls is approximately two hours for the morning visibility period and three hours for the afternoon.

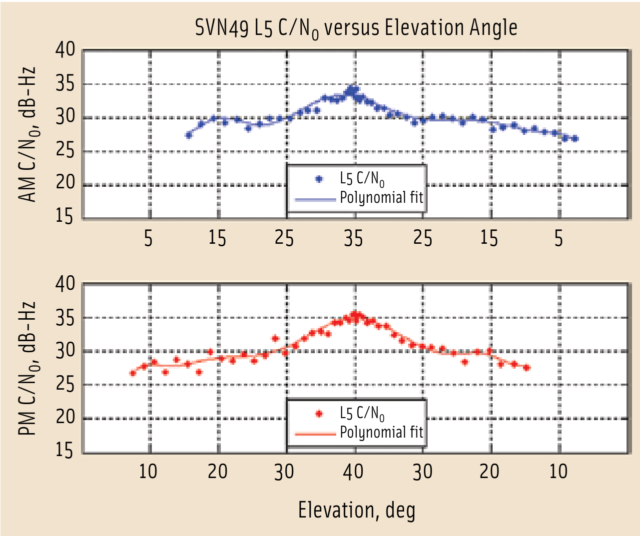


FIGURE 9 LReceived C/N$_0$ from L5 test transmission as a function of elevation angle for both visibility periods at Athens, Ohio

In terms of elevation angle, these minima correspond to an elevation of between 22 to 24 degrees, as distinguishable from Figure 9. This reinforces the notion that SVN49's antenna pattern has a narrower-than-specified main lobe. Besides this initial assessment, we plan to do more detailed analysis of the L5 test transmission during the coming months.

Data Available For Download

The Ohio University research team is making available raw L1/L5 sampled IF datasets containing the L5 transmission from SVN49 (naturally includes the WAAS GEO L5 transmissions as well). We hope this data will help other researchers to develop and test their own GPS L5 signal processing techniques.

The data can be downloaded at <www.ohio.edu/avionics/sdr>. The site contains data files sampled at 1, 2, 4, or 8 bits. In addition, file format information and a MATLAB data visualization script are also provided. Coherently sampled L1/L2/L5 datasets from our next-generation TRIGR instrument currently under development will also be made available shortly.

Summary and Conclusions

At long last, after numerous launch delays and just 20 weeks before the ITU filing deadline, an L5 signal is transmitting from a GPS satellite. Even though the L5 signal from SVN49 is non-operational, it is nevertheless useful for many dual and triple-frequency research applications, receiver development, and testing.

The Ohio University research team collected coherently sampled L1/L5 software radio data from its TRIGR instrument of the L5 turn-on event as well as complete data sets for both visibility periods of SVN49 for several days thereafter. The first-look results presented here were obtained by post-processing this data.

We presented data about the visibility of the signal in terms of C/N$_0$ as a function of elevation and azimuth angles, as observed using a typical multi-frequency patch-type antenna from our location in Athens, Ohio, USA. We observed that the signal is on the average approximately 15 decibels weaker than specified in IS-GPS-705. Moreover, we showed that the signal strength varies significantly with elevation angle from our location where SVN49 peaks around 35 degrees in elevation.

Our observations contrast stronger-than-expected-signal reports from Europe where SVN49 rises near zenith. Observation of L5 C/N$_0$ minima with respect to time and elevation angle seems to indicate an antenna pattern with a narrower-than-expected main lobe.

As reported by *Inside GNSS* (see Additional Resources) on May 4, 2009, in addressing the European Navigation Conference, Lt. Col. David Goldstein of the GPS Wing indicated the presence of an anomaly on SVN49 that is responsible for elevation-angle-dependent range biases on the L1 and L2 transmissions.

The availability of long L1/L5 sampled data records from our TRIGR instrument, even days before the L5 turn-on event, enables us to perform a detailed independent study of this anomaly — and perhaps will shed some light as to what to expect for those still intending to do research using what is for now the only triple-frequency, albeit unhealthy, GPS satellite. The results of such a study will be presented in the months ahead.

Acknowledgements

The authors thank Frank Lorge of the Federal Aviation Administration's William J. Hughes Technical Center for discussions related to the L5 test transmission. Curtis Cohenour with the Ohio University Avionics Engineering Center is acknowledged for providing SVN49 orbit data used in the skyplots. Previous generations of TRIGR technology was developed under funding from the FAA LAAS and WAAS programs.

Manufacturers

The L1/L5 antenna was a GPS-704X from **NovAtel, Inc.**, Calgary, Alberta, Canada. We used a 3 GHz spectrum analyzer from **Agilent Technologies**, Santa Clara, California, USA, for initial spectrum observations. TRIGR uses FPGAs from **Xilinx Inc.**, San Jose, California, USA., and runs on the Windows XP platform from **Microsoft Inc.**, Redmond, Washington, USA. The data was postprocessed using MATLAB from the **Mathworks, Inc.**, Natick, Massachusetts, USA.

Additional Resources

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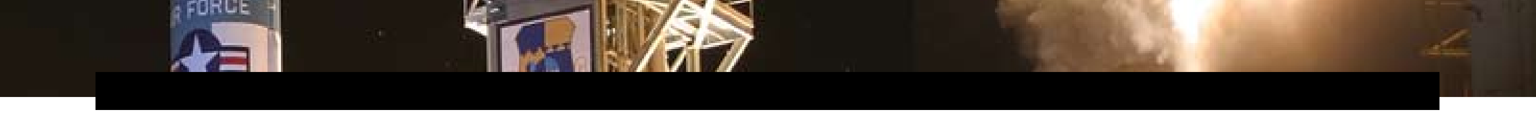

[4] *Inside GNSS* (on website), "GPS SVN49 and L5 Signal: A Success with Problems," <http://www.insidegnss.com/node/1478>, May 5, 2009

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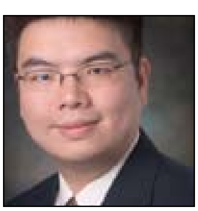

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Michael Braasch, Ph.D., is Thomas Professor of Electrical Engineering and director of the Avionics Engineering Center (AEC) at Ohio University. He was one of the pioneering researchers who investigated the application of software radio and transform-domain signal processing techniques for GPS receivers. His work also includes research in high-precision GPS positioning through differential carrier-phase processing. Braasch is internationally recognized for his work on characterizing the effects of GPS multipath on both pseudorange and carrier-phase baseband signal processing and is one of the originators of the integrated multipath-limiting antenna for GPS. In addition to GPS-related research, he has also worked on other navigation systems including INS, ILS, MLS, VOR, Loran-C, and DME. IG