On The Air: New Signals from the First GPS IIF Satellite

Recent launch of the first GPS Block IIF satellite brought new GNSS signals on the air. Researchers at the German Aerospace Center and Stanford University provide an early analysis of the signals' performance.

STEFAN ERKER, STEFFEN THOELERT, MICHAEL MEURER
GERMAN AEROSPACE CENTER (DLR)

LIANG HENG, R. ERIC PHELTS, GRACE XINGXIN GAO, GABRIEL WONG, TODD WALTER, PER ENGE
STANFORD UNIVERSITY

With the launch of the Delta IV rocket on May 27 from Cape Canaveral Air Force Station the first satellite (space vehicle number 62 or SVN62) of the latest GPS generation Block IIF (F, for "follow-on") was carried into earth orbit — a major step with roots in the past.

Eight years ago in August 2002 the United States decided in coordination with the International Telecommunication Union (ITU-R) to transmit a new civil signal on a third frequency known as L5.

This new signal is part of the IIF modernized signal filing, which also includes the military signal (M-code) on L1 and L2 frequencies and the new civil signal L2C. Because the IIF satellite generation couldn't finally be completed

lites are planned for launch within the next few years to modernize and replenish the existing constellation.

With L5 GPS features a completely new signal transmitted on a center frequency of 1176.45 MHz. Besides the legacy L1 signals, the new L5 signal is the second GPS signal located in the Aeronautical Radio Navigation Services (ARNS) band — a section of the radio frequency spectrum that is also populated by the Galileo E5a signal and ground navaids such as DME and TACAN.

Together with the legacy L1, the availability of L5 signals allows for the first time the elimination of the influence of ionospheric refraction errors by using GPS signals of the ARNS bands only. Therefore, the L5 signal is intended especially for safety-critical applications like aircraft navigation, but will, of course, be available for all civil users. (See the accompanying article, "Evaluating the GPS Block IIF-1 Satellite Signals for Aviation Users.") This makes L5 a valuable third civil GPS signal complementing the C/A and L2C signals.

New Satellite, New Signal

The structure of the operational GPS L5 signal has two components. Both components — in-phase (I) and quadrature-phase (Q) — will have the same signal power level, according to the L5 interface specification document (IS-GPS-705). The minimum received power is defined with −157.9 dBW, which is 0.6 dB more than the legacy L1 C/A code signal.

Both components carry different but nearly orthogonal and synchronized pseudorandom noise (PRN) codes. The register structure used to generate the code is the same for both channels, but different initial states are used in one of the registers. The Q-channel of the L5 signal carries no data, transmitting only a pilot signal modulated with the specific satellite PRN 25 code, which is useful for long coherent integration times. On the I-channel the signal is modulated by the navigation message and carries 100 data-symbols per second (sps).

Usage of two different PRN codes for the I and Q components allows possible tracking biases to be minimized,

as both channels are only dependent on the same carrier phase, which is typically provided by the atomic frequency standards of the space vehicle. The L5 signal uses a chipping rate of 10.23 MHz which is 10 times that of the C/A and L2C codes and a code period of 10,230 chips. The signal is coded by a Neuman-Hoffman synchronization code. With the chipping rate the signal has a 20.46 MHz null-to-null bandwidth, which is exactly the same as the legacy P(Y)-code signal.

The new signal offers several new and beneficial features, which underlines the intention of L5 to play an important role for future safety critical applications. The aim of this article is to perform a first analysis of the new signals offered by SVN62 and to assess whether the signals fulfil the high expectations for them. For that purpose dedicated measurement and analysis campaigns have been performed.

Facilities and Measurement Equipment

To verify the signal quality and performance of this new GPS generation the signals of IIF SVN62 are captured and analyzed continuously from the beginning by independently using GNSS monitoring and evaluation facilities at the German Aerospace Center (DLR) and Stanford University in the United States.

The Stanford team uses the Stanford GNSS Monitor System (SGMS) to capture the SVN 62 transmission. SGMS has a 1.8 m steerable parabolic dish antenna with an L-band feed as shown in the accompanying photograph. The antenna has approximately a seven-degree beamwidth and provides about 25 decibels of gain over conventional patch antennas.

The motor of the antenna can be driven by satellite tracking software, so that the dish can automatically point to and track the new IIF satellite. The signal from the feed of the antenna goes through a low noise amplifier, a band pass filter, and is collected by a vector signal analyzer (VSA) as shown in **Figure 1**. The VSA can down-convert the RF

(above inset) DLR´s 30-meter high gain antenna at Weilheim, Germany
(left inset) Stanford GNSS monitor station antenna

in time, a Block IIR-M satellite, SVN49, was selected to fulfil this task and carry a L5 demonstration payload into the earth orbit.

SVN62 is the satellite to bring an operational L5 signal payload into orbit. The satellite incorporates a new on-orbit reprogrammable processor that is able to receive software uploads for improved system operation. A total of 12 IIF satel-

signal to baseband and save the data in computer-readable format. The SGMS has provided many observation measurements for GNSS satellites, which have been published in previous issues of *Inside GNSS*.

The DLR uses its GNSS Signal Verification and Analysis Facility (SVAF) that was established in 2005 and constantly updated to allow state-of-the-art measurements and performance analysis. The core element of this facility is a 30-meter deep space antenna located at the DLR ground station at Weilheim, Germany.

The antenna and the measurement equipment have been adapted to the requirements in the navigation field. A newly developed broadband circular polarized feed and a new receiving chain,

including an online calibration system (shown in **Figure 2**), were installed at the antenna during the preparation for the second-phase Galileo In-Orbit Validation Element (GIOVE B) in-orbit test (IOT) campaign in spring 2008.

The antenna — based on a shaped Cassegrain system — is characterized by a gain value of around 50 decibels in the L-band and a beamwidth of 0.5 degree. The calibrated facility allows very precise and detailed analysis of GNSS signals because the navigation signals are raised high above the noise floor so that individual code chips become clearly visible.

SVN62: First IIF Signal Analysis

Shortly after the launch of this new Block IIF satellite the first signal transmissions of SVN62 were received showing initial broadcast test at lower output levels — a common procedure during the commissioning phase of a new satellite payload that helps to avoid possible damages due to the heating of the equipment.

During SVN62's transition period to its final orbit position further broadcast tests were

recorded. For about one hour on June 6 (from about 13:10 PDT to 14:20 PDT), the satellite transmitted a one-zero pattern at the L1 and L2 frequencies instead of a nominal GPS PRN code, as shown in **Figure 3** and **Figure 4**. The signal was recorded at June 6, 2010, around 13:15 PDT using the Stanford SGMS with its 1.8-meter dish. During all other times on June 6, the satellite transmitted a nominal PRN 25 on both L1 and L2, including GPS legacy signals but not the M-code.

The first L5 transmission was recorded during SVN62's track on June 17 over Europe and Asia. After the satellite changed its signal configuration the transmission of the new L5 and also of M-code signal on L1 started. The team at DLR was able to record a pass of around three hours with the 30-meter high gain antenna.

This first signal transmission allows an initial analysis of the long-awaited third civil GPS signal. With an overlaid theoretical spectrum shape (black curve in **Figure 5**), we obtain a first quick look at the spectral asymmetries and deformations of the signal. We see that the signal is band limited by the front end filters used in the L5 payload, ensuring the required spectral separation from the GPS L2 frequency band.

We also note a slight asymmetry of the spectral shape between the side lobes of the signal. They differ around three decibels in their peak power level. Those asymmetries are quite common analog deformations of signals and typically result from frequency selectivity of the satellites payload components or transmitter antenna.

Since June 28, SVN62 seems to be switched to its final signal transmission scheme — L1: C/A, P(Y), and M codes; L2: L2C, P(Y), and M codes; L5, data & pilot. Thus we were able to track several complete satellite passes including the new operational L5 signal.

In order to characterize the signal quality, we compare the signals of this first IIF Block satellite (which, of course, is still set unhealthy and not intended for operational use at the moment) with one of the operational Block IIR-
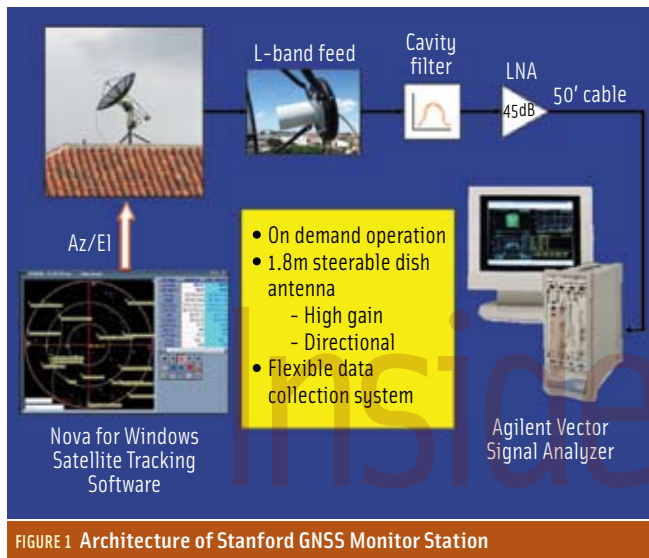

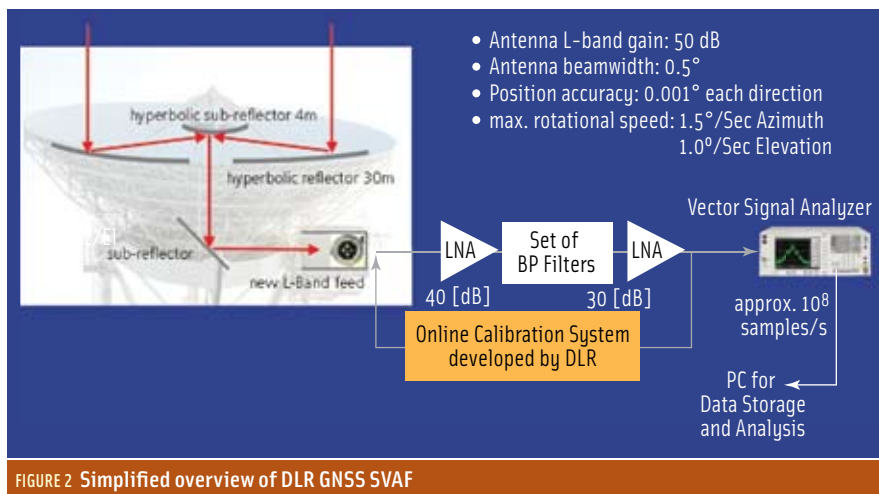FIGURE 1 **Architecture of Stanford GNSS Monitor Station**

L-band feed
Cavity filter
LNA 45dB
50' cable

Az/El

- On demand operation
- 1.8m steerable dish antenna
  - High gain
  - Directional
- Flexible data collection system

Nova for Windows Satellite Tracking Software

Agilent Vector Signal Analyzer

FIGURE 2 **Simplified overview of DLR GNSS SVAF**

hyperbolic sub-reflector 4m

hyperbolic reflector 30m

sub-reflector

new L-Band feed

- Antenna L-band gain: 50 dB
- Antenna beamwidth: 0.5°
- Position accuracy: 0.001° each direction
- max. rotational speed: 1.5°/Sec Azimuth
  1.0°/Sec Elevation

LNA 40 [dB]
Set of BP Filters
LNA 30 [dB]

Online Calibration System developed by DLR

Vector Signal Analyzer

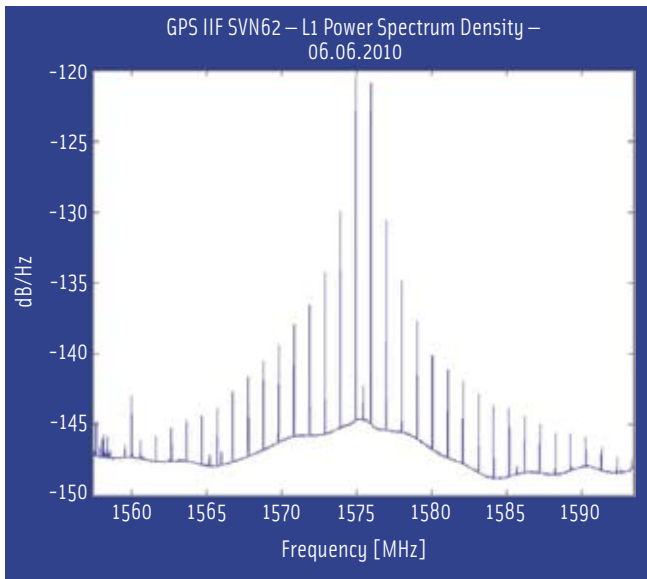approx. 10^8 samples/s

PC for Data Storage and Analysis

FIGURE 3 **L1 power spectrum density plot during initial broadcast tests with satellite transmitting '010101…' sequence. Data captured with 1.8-meter dish from SGMS.**
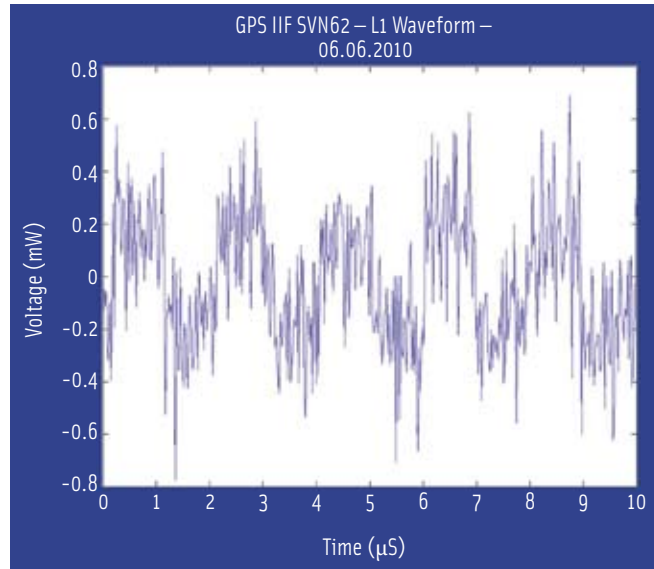

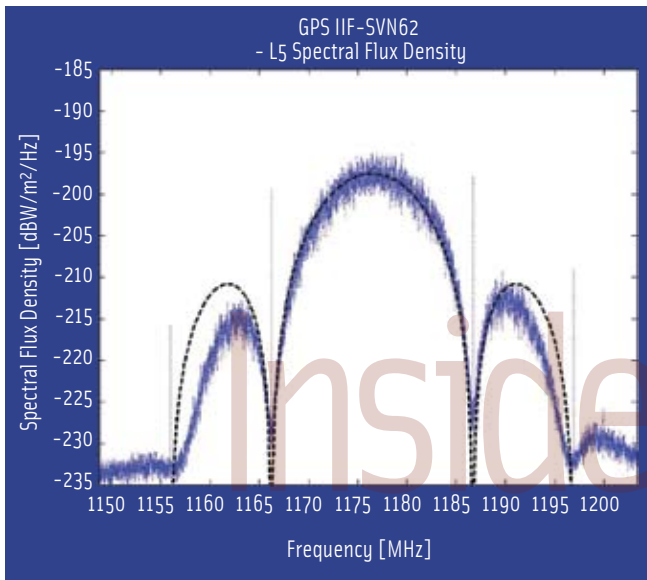FIGURE 4 **Satellite transmits '010101…' sequence. The signal was captured with 1.8-meter dish from SGMS**

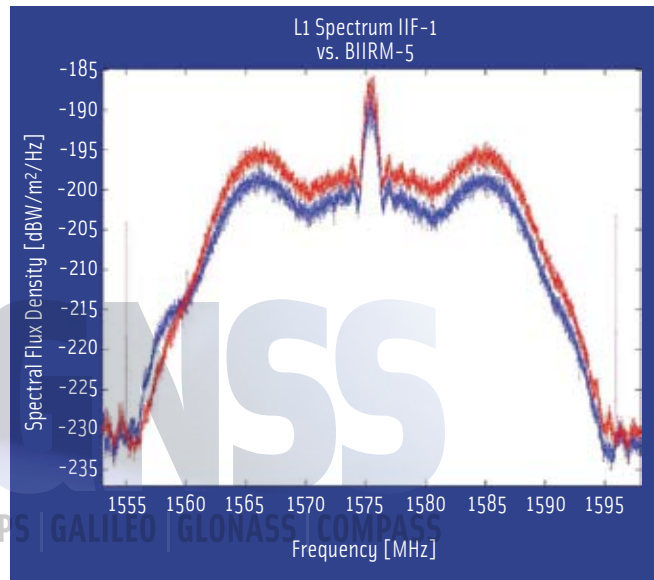FIGURE 5 **The very first received L5 Signal of SVN62 with overlaid theoretical spectrum**

FIGURE 6 **L1 Spectrum of IIF-1 (red) and BIIR-M5 (blue) recorded at 80° elevation angle**

M (BIIRM) generation. For that reason we chose a IIR-M satellite that also performed a comparable high-elevation pass over the facility shortly after the SVN62 track.

A complete high-elevation pass of BIIRM-5 (GPS SVN57/PRN29) was recorded on June 30. In **Figure 6** the spectral shapes of the L1 signal — recorded at the same elevation angle — of both satellites are overlaid and compared to each other.

Figure 6 shows that both spec-trums are very clean and have a very symmetric shape. IIF-1 (red) emits a signal with slightly increased power compared to the BIIRM satellite (blue). This can also be detected with a standard GNSS receiver by a slightly increased carrier-to-noise density (C/N$_0$) value.

In **Figure 7**, C/N$_0$ versus the satellites' pseudoranges for the L1 signal is plotted based on data from the International GNSS Service (IGS) network site "wsrt" (Westerbork, the Netherlands). We can clearly see the increased L1 power of

PRN25 assuming the receiver has the same C/N$_0$ for the same power output and range of two different satellites.

If we have a look at the L2 spectrum as shown in **Figure 8**, we see a notable asymmetry of IIF compared to the overlaid theoretical L2 signal shape (black). Comparing this to the BIIRM spectrum and the theoretical shape, we recognize a nearly reversed left to right asymmetry between IIF and BIIRM. It seems that for the L2 signal path of the IIF satellites a front-end filter of significantly differ-
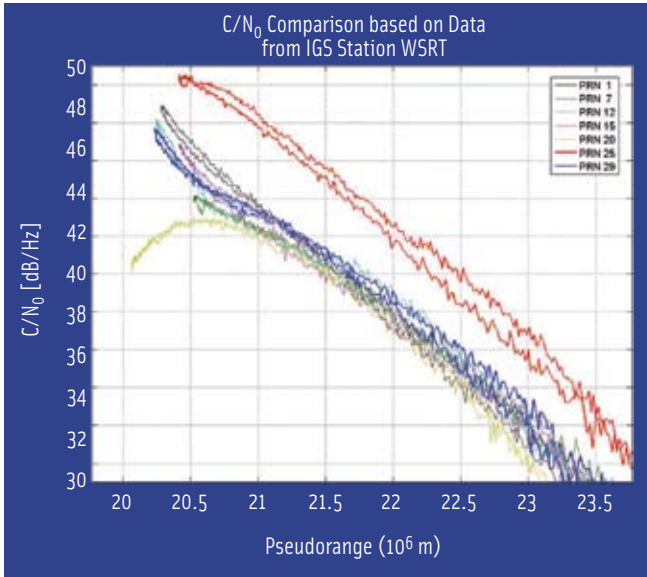
FIGURE 7 C/N₀ vs. Pseudorange comparison of several GPS satellites. IIF (PRN25) red and BIIRM-5 (PRN29) blue. Plot is based on the data captured on Day 170 (Jun 19).
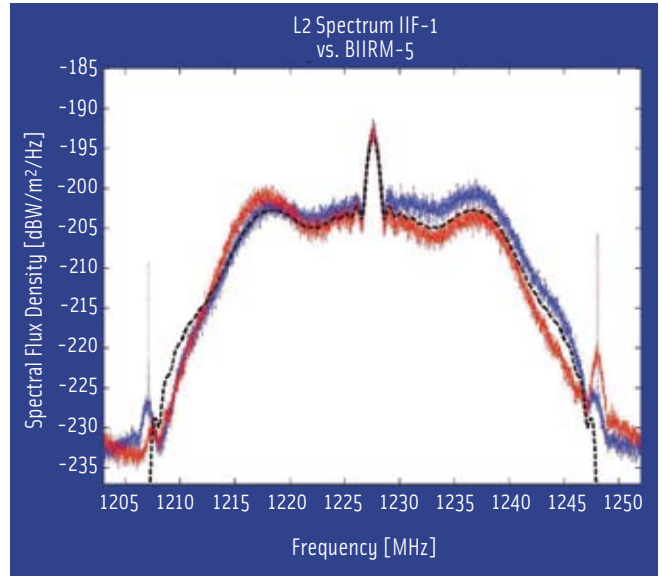

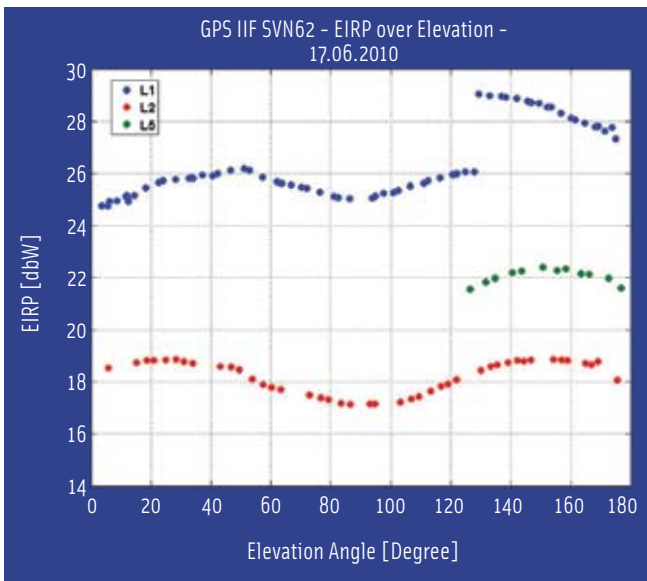FIGURE 8 L2 Spectrum of IIF-1 (red) and BIIR-M5 (blue) recorded at 80° elevation angle

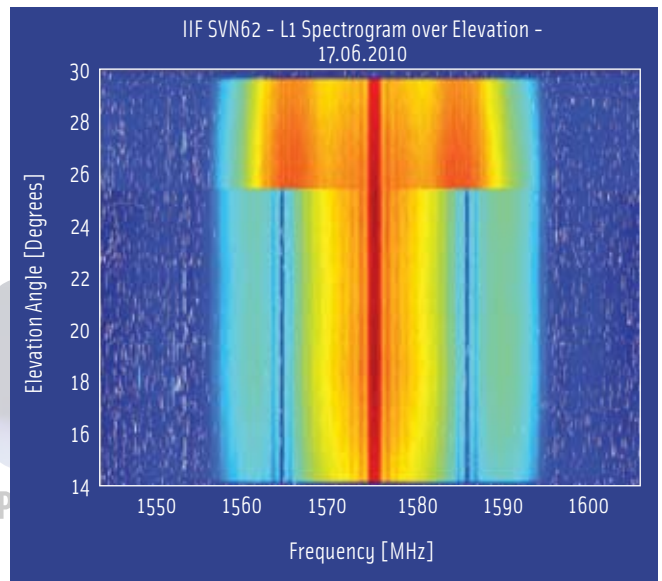FIGURE 9 EIRP-over-elevation of SVN62 during June 17

FIGURE 10 Spectrogram of IIF-1 L1 signal received on June 17, 2010

ent characterization compared to the BIIRM is utilized.

Power of Received Signals

The SVAF is fully calibrated and therefore allows accurate absolute measurements of GNSS signals power levels. So, the facility can be used to analyze the radiated power of IIF-1 navigation signals.

Figure 9 shows the effective isotropic radiated power (EIRP) of different composite signals of the satellite transmitted at L1, L2, and also L5 plotted over the corresponding elevation angle of the space vehicle. The EIRP value is calculated on the received signal power by considering the calibrated amplification of the measurement system (including the gain of the 30-meter dish) and the frequency-dependent free-space-loss of the signal that is significantly attenuated as it travels from the satellite down to earth.

One can clearly recognize that during the June 17 pass at first the L5 sig-

nal (green) was switched on at around a 60-degree elevation angle during the descending of the satellite and shortly thereafter the L1 M-code signal, which leads to an three-decibel increase of the L1 signal band power.

The corresponding L1 spectrogram plot (**Figure 10**) of this track — generated by plotting all recorded L1 spectral snapshots versus the satellites elevation angle — also shows the switchover to the additional M-code signal with increased signal bandwidth.
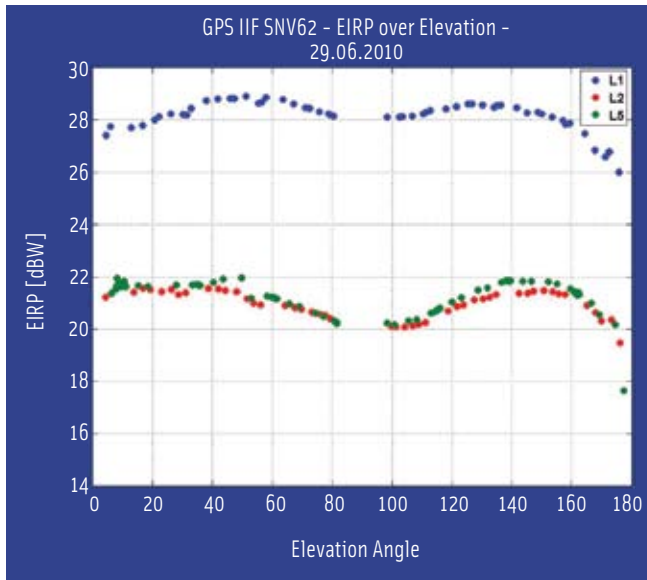
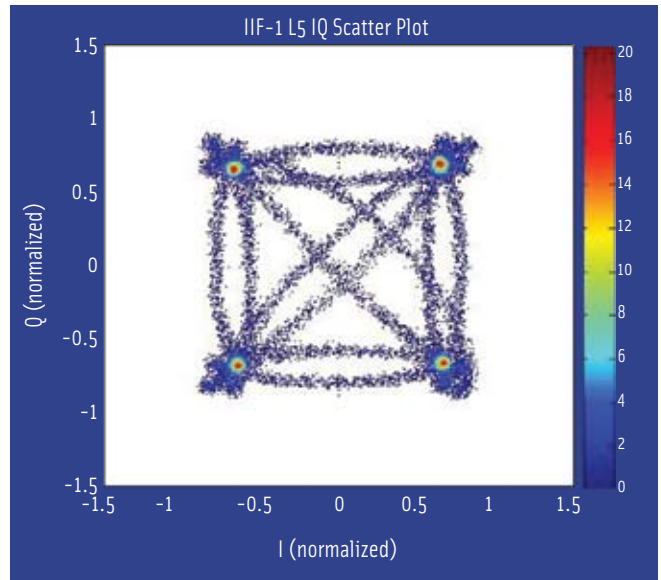FIGURE 11 **EIRP-over-elevation of SVN62 during June 29**

FIGURE 12 **L5 I/Q Scatter Plot**

Figure 11 shows the EIRP values for the three different IIF signals recorded during a high elevation pass on June 29. We recognize that about three decibels more power is introduced to the additional L2 M-code signal compared to the measurements from June 17. This additional signal component can also be clearly identified within the L2 spectrum that is shown in Figure 8.

Signal Modulation Quality

For an initial assessment of L5 modulation quality the scatter plot of the I and Q components is plotted in **Figure 12**. Compared to the L5 demo signal of GPS IIR-M SVN49 that only transmitted a dataless Q-component signal, the operational IIF L5 signal consists of both I and Q components.

The four possible states are clearly visible in the constellation diagram. Nearly all transitions show a very symmetric orientation between two I-Q states. But we also see one distorted transition, from I-Q state [1 -1] to [-1 1], that shows an unusual behavior. This asymmetric transition points to a non-linear distortion effect maybe created at the amplification or I-Q modulation stage of the satellite transmitter chain. Further detailed analysis on the observed effect is ongoing.

In **Figure 13** the corresponding eye-diagram for the IIF L5 I and Q signal is plotted. The eye-diagram is also a very useful tool for qualitative analysis of signal quality for digital communication systems. It provides an at-a-glance evaluation of the modulation quality and gives a quick insight into signal imperfections and distortions like the I-Q scatter plot.

The digital sampled signals of the I and Q channels are repetitively plotted for this representation. We clearly see typical amounts of distortions, signal overshots, and minimal jitter at the zero crossing point, which can be caused by the band limitations of the front end filters and amplifiers used in the SVN62 navigation payload.

A more detailed analysis on IIF-1 signal distortions and deformations can be found in the article "Aviation Grade: New GPS Signals — Chips Off the Block IIF," beginning on page 36 in this issue of *Inside GNSS*.

IIF Code Analysis

With the 30-meter high gain antenna at Weilheim, we can look in detail at the transmitted L5 code chips. The signals of the satellites are raised high above the noise floor and allow precise code analysis after Doppler wipe-off.

In **Figure 14** we compare the first 10 microseconds of the received L5 SVN62 I and Q signal with the two ideal theoretical codes for PRN25 L5 I and Q channels. The codes were obtained with a L5 code generator implemented in a mathematical software package. The analysis was also performed for several full code periods and shows that the code structure of both signal components is in full compliance with the "theoretical" codes described in the official L5 signal interface specification document, IS-GPS-705.

The code structure of both L5 signal components is in full compliance with the "theoretical" codes described in the official L5 signal interface specification document, IS-GPS-705.

Receiver Signal Tracking

During SVN62's initial in-orbit test phase, which is expected to last around 90 days, the satellite remains
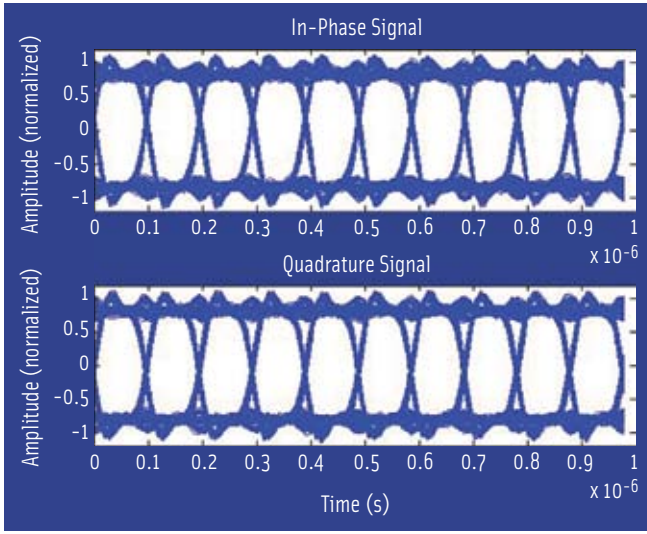
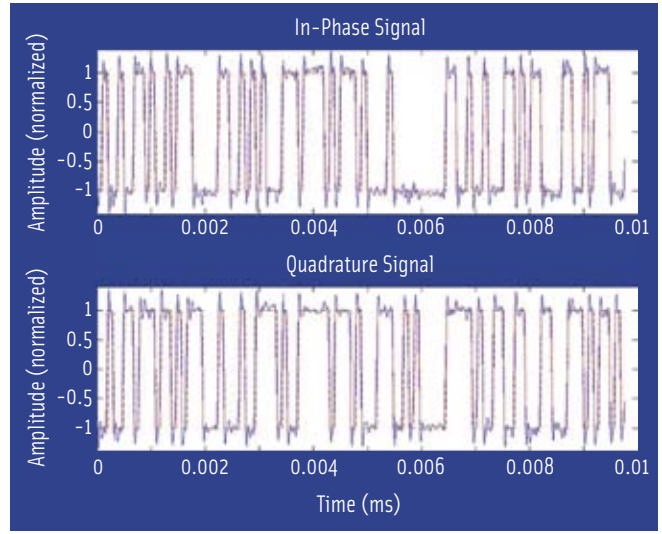FIGURE 13 Eye–diagram for L5 PRN25 I and Q signal component

FIGURE 14 Comparison of measured L5 I and Q code chips (blue) with theoretical code sequence (red)

set "unhealthy" so that common GPS receivers generally will not track the space vehicle. Nevertheless, certain receivers can be configured to ignore the health flag and track the satellite with its designated pseudorandom noise code.

Figure 15 shows the tracking results using our software receiver. We have used this software receiver to acquire and track many GNSS satellites, such as the GIOVE satellites and the Compass M-1, reported in previous *Inside GNSS* articles. The tracking loops, including the phase lock loop and the delay lock loop, both converge. The success of acquisition and tracking verifies that the SVN62 broadcast PRN code is the same one as defined in the GPS ICD.

Another reason why we would like to show Figure 15 is that it captures an interesting transition moment. The satellite had an intermittent testing period when the satellite was only transmitting
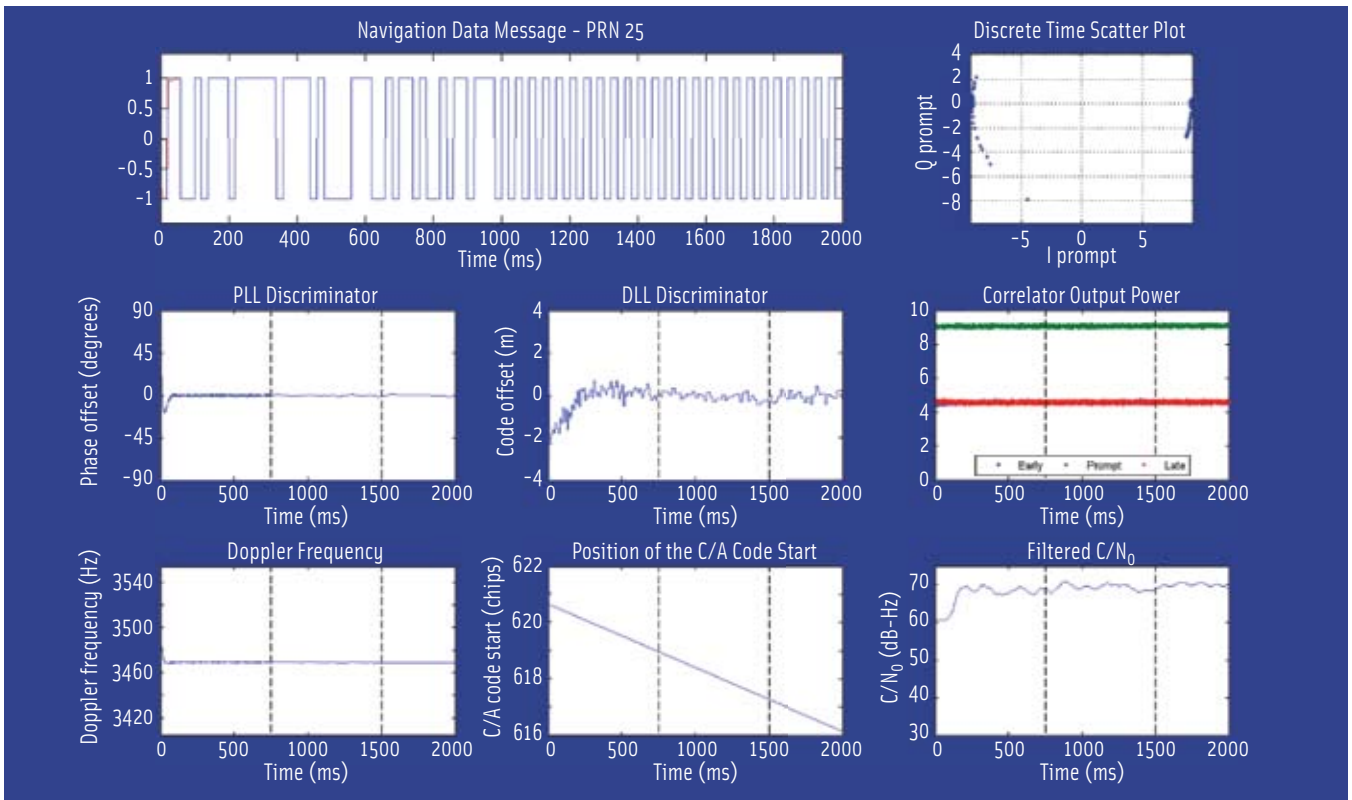

FIGURE 15 Tracking results of GPS IIF SVN62 PRN 25, L1, during intermittent testing period

"010101…" rather than the Neumann-Hoffman code or navigation bits. The upper left subplot shows the transition to the intermittent testing period.

Conclusion

This first analysis of SVN62 shows that the IIF L5 signal, with respect to the analysis presented in this article, is nearly in line with the specifications described at the IS-GPS-705 document. We were able to track all three signals of SVN62 — which is still set unhealthy — using different commercial receivers as well as an implemented software receiver.

The carrier-to-noise ratio of SVN62's L1 signal slightly outperforms all other existing GPS satellites. A notable amount of distortion is visible at the L5 I/Q scatter plot that will be analyzed further. Detailed measurements and analyses of SVN62 have to be conducted after the satellite has run through extensive in-orbit tests and is set healthy.

Authors

Stefan Erker received his diploma degree in communication technology at the Technical University of Kaiserslautern, Germany. In 2007 he joined the Institute of Communications and Navigation of the German Aerospace Center (DLR) at Oberpfaffenhofen. He mainly works on the topics of GNSS verification and corresponding signal analysis.

Steffen Thoelert received his diploma degree in electrical engineering with fields of expertise in high-frequency engineering and communications at the University of Magdeburg, Germany. The next four years he worked on the development of passive radar systems at the Microwaves and Radar Institute at the German Aerospace Centre (DLR) and in 2006 changed to the DLR's Department of Navigation, Institute of Communications and Navigation. Now he is working within the topics of GNSS verification and system calibration.

Michael Meurer, Ph.D., is the head of the Department of Navigation of the German Aerospace Center (DLR), Institute for Communications and Navigation, and the coordinating director of the DLR Center of Excellence for Satellite Navigation. He received the diploma and Ph.D. degrees in electrical engineering from the University of Kaiserslautern, Germany. Since 2005 he has been an associate professor (PD) at the same university. His current research interests include GNSS signals, GNSS receivers, interference mitigation, and navigation for safety-critical applications.

Note: *The biographies for the Stanford University co-authors can be found at the end of the following article on page 45.* IG