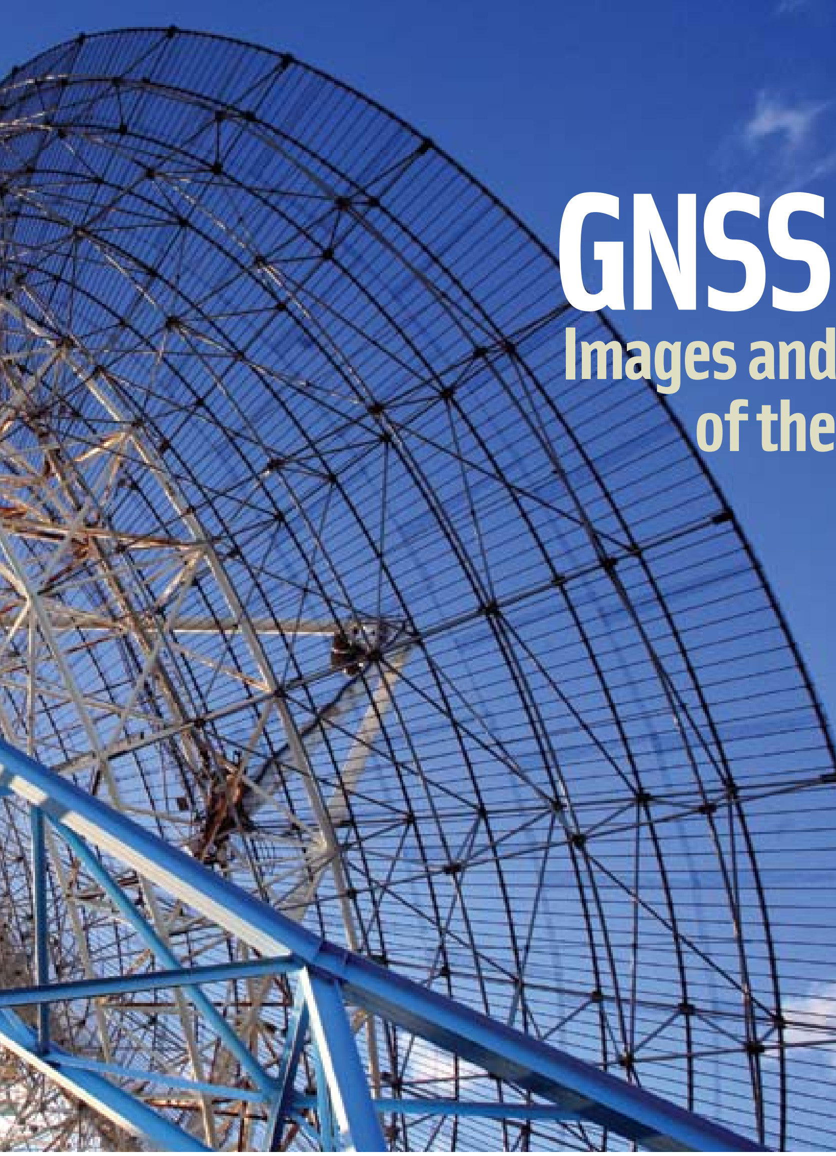

GNSS Album

Images and Spectral Signatures of the New GNSS Signals

A lot of radio signals are traveling around out there in the ether these days — and an increasing number of them are carrying modernized GNSS navigation messages. Although invisible to the human eye and ear, these signals emanate distinctive spectral signatures of crucial importance to GNSS users and product designers: bandwidth, waveform, message code structure, spreading modulation, data rate, and so on. This article by an international team of radio and electronic engineers employs a variety of RF monitoring technologies to capture, portray, and characterize the new signals in space from GPS, GLONASS, Galileo, and Beidou.

The SRI Stanford "Big Dish"

SHERMAN LO, ALAN CHEN, PER ENGE & GRACE GAO
STANFORD

DENNIS AKOS
UNIVERSITY OF COLORADO

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CNES

Until now, civilian global satellite navigation systems (GNSS) receivers have had essentially only one signal, the GPS L1 C/A-code, reliably available for navigation. However, in the coming years, many more operational GNSS signals, systems, and frequencies will become available to civilian users.

Some of these signals represent new navigation systems, while others are modernizations of existing GNSSes. Although we cannot predict how these signals will be used when they become more prevalent, the current GNSS environment allows us to take a glimpse into the potentials and challenges of that future.

The new signals provide a wealth of possibilities for improving performance, such as accuracy and availability. Different signals and possibilities, however, also pose technical challenges. Research centers and universities around the world are working on ways to use and take advantage of this new GNSS resource. In order to do that, observations of the signal in space are necessary to develop an understanding of the real RF spectral dynamics.

The difficulty with such observations is that the power of spread spectrum RF transmissions, which comprise the GNSS signals, is well below the noise floor. Although correlation can be used to bring the signal out of the noise, the codes from some of the new signals are not yet publicly available. This article presents data and measurements performed by two organizations, Stanford University and CNES (Centre National d'Études Spatiales), which are independently studying the new signals.

Stanford University and CNES have had an active role in the development of systems such as SBAS (WAAS, EGNOS) and other GNSS for aviation. Stanford University pioneered research in GPS, pseudolite attitude determination, and differential GPS navigation for airborne and space users. CNES developed a family of spaceborne GNSS receivers, and had a key role in the GALILEO signal design.

Brief History of GNSS

For the last 20 years, the term GNSS has nearly been synonymous with the U.S. NAVSTAR Global Positioning System. During this period, GPS broadcast its code division multiple access (CDMA) signals at two frequencies, L1 (1575.42 MHz) and L2 (1227.6 MHz). While authorized military users found the encrypted P(Y)-code available on both frequencies, civilians could only access the L1 C/A-code signal.

Of course, GPS was not the only GNSS available. Russia's GLONASS system was also fully operational during part of this period. GLONASS uses frequency division multiple access (FDMA) to separate broadcasts of its CDMA signals. Its first-generation system also used two center frequencies: GLONASS L1 and L2 at 1602 MHz and 1246 MHz, respectively.

Until December 2003, GLONASS also only had one civil signal (at L1) although both frequencies contain the military P-code. However, for most of the past 10 years, GLONASS utility remained low as its constellation generally lacked an adequate number of satellites for reliable, general applications. **Figure 1** shows the spectrum of this first generation of GPS and GLONASS. Due to the limited GLONASS constellation, civilian users of GNSS were essentially limited to GPS L1 for navigation.

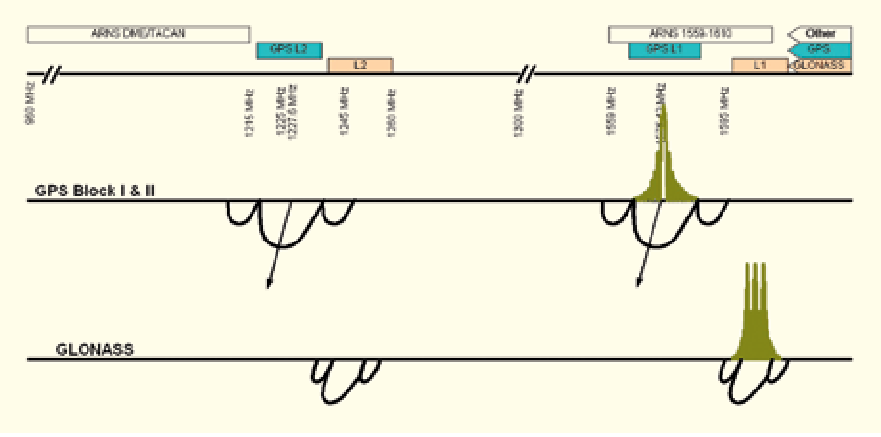

FIGURE 1 GNSS Signals, 1978–2003

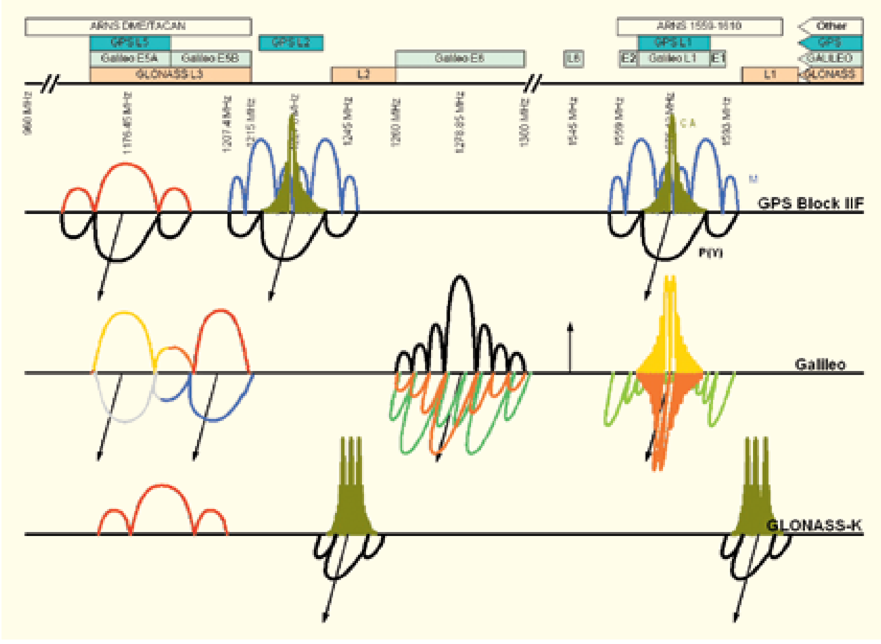

FIGURE 2 Current and Planned GNSS Signals

A New Era

By the turn of the millennium, however, the significance and value of satellite navigation was becoming recognized by a larger and larger audience. New ideas and entrants to the satellite navigation arose. Most significantly, the concept of a third GNSS was being born in Europe. This system, named Galileo in 1999, would have up to 10 different navigation signals in three frequency bands.

At the same time, GPS was well on it way towards modernizing its signals. Civilian L2 (L2C) and L5 (1176.45 MHz) signals were developed, providing similar capabilities as the Galileo signals, and a new military signal (M-code) was added on L1 and L2.

Both new Galileo and GPS signals leveraged 20-plus years of experience with the first-generation GNSSes to create these new signals. As a result, the new signals include such features as higher chipping rates, error correction on data, pilot (dataless) channels, longer codes, and secondary codes (such as Neuman-Hoffman codes).

These signals and their features enable GNSS to be used in more places and with better performance than the first generation of GNSS. Just as important, most of the signals will be available for open use.

The Russian government also moved to replenish and modernized GLONASS. This includes both new satellites and new signals. The new GLONASS-M adds a civilian L2 signal, and GLONASS-K will also add a signal, termed the GLONASS L3, located between 1164 and 1215 MHz.

Once services are implemented, the GNSS signal spectrum will become much more diverse, as seen in **Figure 2**.

(top) The monitoring earth station at Leeheim, Germany; (bottom left) CNES Tracking Antenna (from right to left: Lionel Ries, Joel Dantepal, Thomas Grelier);(bottom right) Stanford GNSS Monitor Station (from right: Dennis Akos, Alan Chen, Sherman Lo)

GNSS Augmentation

The last decade has also seen the development and implementation of regional satellite navigation and augmentation concepts. The most prevalent are satellite-based augmentation systems (SBAS) for civilian GNSSes. SBAS uses geostationary satellites to broadcast pseudorange corrections, integrity messages, and ranging information to GNSS users via an open L1 signal similar to the GPS C/A-code.

The U.S. SBAS, known as the Wide Area Augmentation System (WAAS), became operational July 10, 2003, although it had already been transmitting for many years. This was the first of many to be developed.

Other SBASs are being tested or being designed. Both the European Geostationary Navigation Overlay Service (EGNOS) and the Japanese Multi-Functional Satellite Augmentation System (MSAS) are currently under going tests. EGNOS began its initial operational phase in July 2005. The Indian SBAS, GPS and GEO Augmented Navigation (GAGAN), is also under development.

The next generation of SBAS will also have a wideband civilian signal. For WAAS, this signal is on GPS L5 while for EGNOS, the signal will be on either Galileo E5A or E5B. Tests of the L5 signal are currently underway in the United States.

In 2000, China fielded the first of three Beidou geostationary satellites. These satellites provide augmentation to GNSS and transmit in the band 2483.5-2500 MHz. China is also developing a future GNSS system in L band, termed COMPASS.

A Landmark Year

The year 2006 represents a major milestone for satellite navigation, as many of the ideas of the second generation of GNSS become reality. This year represents the first on-air transmission of the Galileo navigation signal. Already, the Galileo E1-L1-E2, E5, and E6 signals have been transmitted from its first satellite the GALILEO In-Orbit Verification Element A (GIOVE-A).

For GPS, 2006 will mark the first full year of operational GPS L2C broadcasts and the testing of WAAS L5. For GLONASS, this is the second year of operation with GLONASS-M. Recent GLONASS policy statements indicate an intention to accelerate the process towards restoring a full operational capability (FOC) in its constellation by 2009.

So, nearly all the civilian signals in Figure 2 can be seen on at least one satellite transmission allowing us to have a peek into the future of satellite navigation.

Equipment

Stanford University has developed an on-demand capability for observing GNSS signals using the Stanford GNSS Monitor Station (SGMS). The SGMS has a 1.8-meter steerable parabolic dish antenna with an L-band feed and is pictured in the accompanying photo.

When higher gain signals are desired, researchers can use a 150-foot (45.7 meters) parabolic reflector dish antenna (the "Stanford Dish" pictured on the opening page of this article). Located on the Stanford University Radio Science field, the antenna is operated by SRI International. Data is collected from either antenna using a vector signal analyzer.

GNSS measurements have been done in the Toulouse Space Center (CST) of CNES, in the Transmission Technique and Signal Processing Department. Measurements at CNES station are taken with a system receiving and processing GNSS satellites signals, developed in collaboration with the European Space Agency (ESA). This system (see photo with CNES personnel) is composed of a tracking system (a 2.4-meter dish, pictured), a broadband digitizer (bit-grabber), and a high capacity recorder (datalogger). The system allows for post-processing of signals. The CNES bit-grabber and Leeheim dishes were used together to collect data over a one-week period in early April 2006

The monitoring earth station at Leeheim, operated by the Bundesnetzagentur, supported a data collection effort to study GNSS signals. The station has two steerable parabolic reflector antennas with diameters of 12 (Antenna 1) and 7 meters (Antenna 4) and shown in the accompanying photo.

In addition to measuring GPS, GLONASS, and GALILEO signals, this location can also monitor one of the Chinese Beidou satellites. The CNES bit-grabber and Leeheim dishes were used together to collect data over a one-week period last summer.

Motivation

Examining the transmitted signal aids in understanding how to best utilize the signal. Even if the signal can be simulated under laboratory conditions, sooner or later we must measure and assess the actual transmitted signal in the field.

One early objective is assessing nominal signal performance. The ability to understand error modes and perform rapid diagnosis of signal anomalies requires an understanding of the directly observed signal operating normally. This has particular importance for navigation signals used for safety-of-life applications such as aviation.

A second objective is to understand the interference environment that the signal will have to operate in. A final motivating factor is that measuring the signals in space helps us to understand the actual transmitted GNSS bandwidth. This aids receiver designers to make the best compromise between maximum processed bandwidth and interference mitigation.

The abundance and diversity of signals will mean that hardware receivers cannot economically be designed to use all possible signals. Eventually, they must make a choice of what seems to be the optimal mix of signals for particular applications in the marketplace. Ultimately, signal diversity favors software GNSS receiver designs, which could easily be adapted to process new signals with a new software version.

Galileo Observations

Probably the highest profile development in 2005-2006 was the inauguration of a new GNSS, Galileo, with the launch and operation of GIOVE-A. The space vehicle, sent into orbit on December 28, 2005, transmitted its first signals on January 12.

The GIOVE-A will broadcast navigation signals on three frequencies L1 (E1-L1-E2), E5 A/B, and E6. The Galileo L1 signal (E1-L1-E2) is an interplex between L1 OS data, L1 OS pilot and L1 PRS centered at 1575.42 MHz and ranges from 1559 to 1593 MHz. It includes Open Service (OS) and a Public Regulated Service (PRS) signals. The GIOVE-A OS uses a BOC(1,1) modulation. GALILEO L1 OS and GPS III L1C currently plan on using either a BOC(1,1) or an optimized BOC(1,1) modulation named MBOC. For further details on MBOC, see the article in Working Papers in this issue of *Inside GNSS*.

The PRS is a BOC(15,2.5) modulation introduced by CNES, in accordance with terms of the 2004 US-EU agreement on GPS and Galileo. The binary offset carrier or BOC(n,m) moves the main lobe of the transmitted signal roughly n MHz above and below the center frequency. The main and side lobes are approximately $2*m$ and m MHz wide, respectively.

By moving the signal power off the center frequency, the BOC design results in low interference with existing GPS signals. Furthermore, it has the potential to provide better code tracking, multipath rejection, and other benefits.

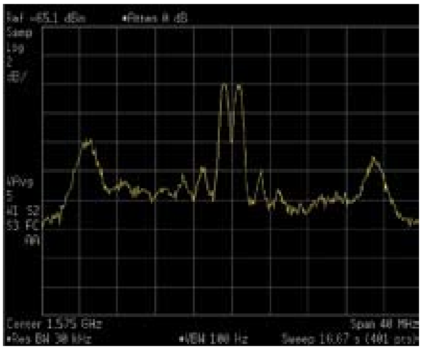

FIGURE 3 A First Look: GIOVE-A E1-L1-E2 signal collected using the SGMSs

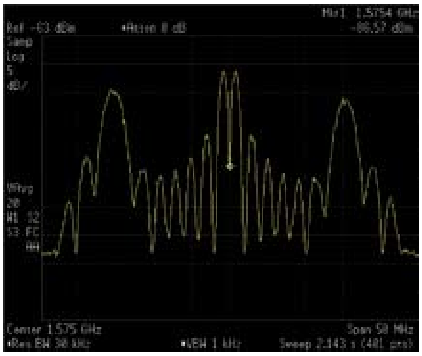

FIGURE 4 GIOVE-A E1-L1-E2 signal collected using the Stanford Dish

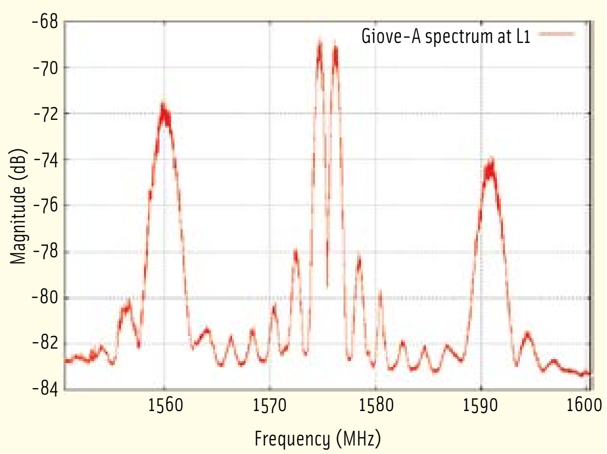

FIGURE 5 GIOVE-A spectrum from CNES bit-grabber connected to CNES dish

Figure 3 shows wideband L1 measurements made by the SGMS shortly after GIOVE-A began its broadcast. Both the BOC(1,1) and BOC(15,2.5) can be clearly made out. **Figure 4** shows the spectrum measured using the Stanford Dish. CNES measurements are seen in **Figure 5** and **Figure 6**.

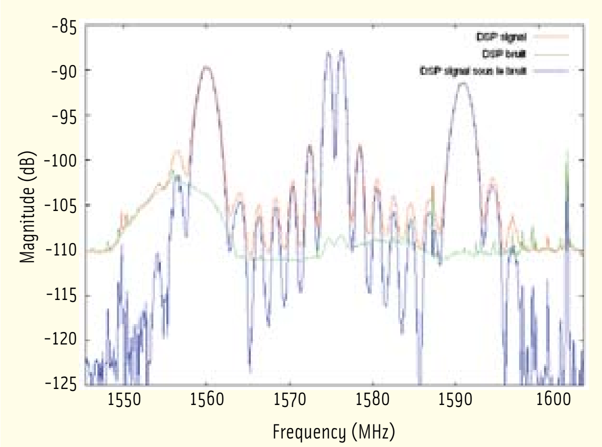

FIGURE 6 GIOVE-A E1-L1-E2 spectrum with CNES bitgrabber connected to Leeheim dish

Code CL1-B: 4092 bits, 4 ms, Gold code
Polynomial 1 = X13+X10+X9+X7+X5+X4+1
Initial State: [1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial 2 = X13+X12+X8+X7+X6+X5+1
Initial State: [1 1 0 1 1 1 0 0 0 0 0 1 1]
Code CL1-C: (primary code) x (secondary code) = 204600 bits, 200ms
Primary Code: 8184 bits, 8 ms, Gold code
Polynomial 1 = X13+X10+X9+X7+X5+X4+1
Initial State: [1 1 0 0 1 1 0 0 0 0 0 1 1]
Polynomial 2 = X13+X4+X3+X+1
Initial State: [1 1 1 1 1 1 1 1 1 1 1 1 1]
Secondary Code: [1 0 1 1 0 1 1 0 0 1 0 0 0 1 1 1 0 0 0 0 0 0 0 0 1 0]

FIGURE 7 Generator Codes for GIOVE-A L1 BOC(1,1) Signals

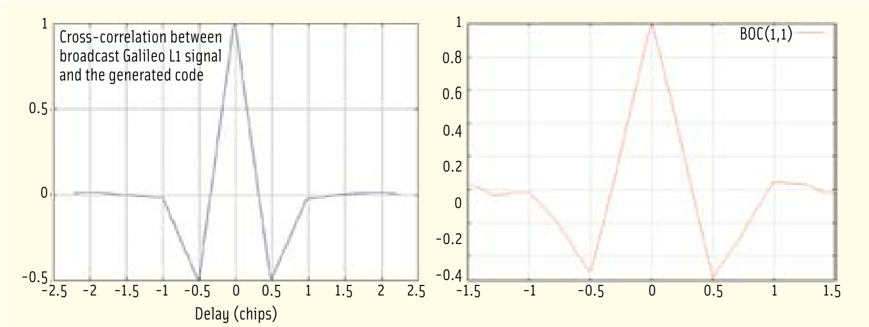

FIGURE 8 Normalized correlation function of GIOVE A BOC(1,1) modulation at L1 (Stanford (Left), CNES (Right)

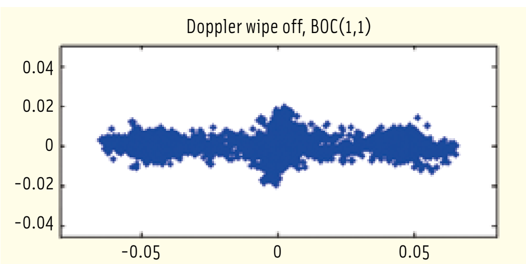

FIGURE 9 Inphase Quadrature Plot of Narrowband L1 (BOC(1,1) only) from Stanford Dish Measurements

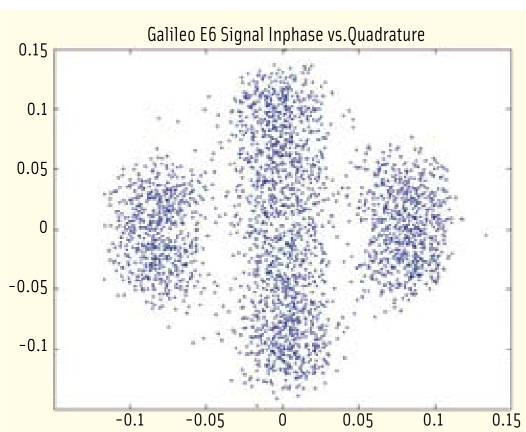

FIGURE 10 Inphase Quadrature Plot of Wideband L1 from Stanford Dish Measurements

Narrowband (~4 MHz) observations about L1 can isolate the GIOVE-A BOC(1,1) signal. Narrowband measurements made using the SGMS helped produce estimates of the Galileo OS code. The methodology that was used to make the code and code generator estimation can be found on the Stanford University GPS website <http://waas.stanford.edu/GalileoCode/index.html>.

The BOC(1,1) transmission was found to be a combination of two codes. The code generator function factors into two 13th-order polynomials. One code is 8,184 chips long (pilot channel) and the other is 4,092 chips long. The result is shown in **Figure 7**. The result was verified using the Stanford Dish.

CNES also verified these results. Stanford used the derived codes to correlate with data collected at the dish. The correlation results using one of those codes is shown in **Figure 8**. The result is typical of a BOC(1,1) signal and matches with the correlation function generated by CNES from its own signal measurement, also shown in the figure.

Observation of the Inphase-Quadrature (I-Q) plot (**Figure 9**) generated using Stanford Dish data shows that there are three states to the BOC(1,1) signal. This indicates that the BOC(1,1) signal is a combination of two separate codes, which is consistent with our observations as well as statements in the Galileo signal definition that indicate a data and data-free component on this signal.

Taking wideband L1 measurements allows us to examine the PRS BOC(15,2.5). From the wideband L1 I-Q plot, shown in **Figure 10**, we can see a constellation of points that is almost in quadrature to the OS code. These points represent two signals: the PRS code and a balancing code to preserve constant envelope.

The balancing signal shifts the overall constellation so that it is not completely in quadrature with the OS code even though the PRS is in quadrature with the OS. This results in a circular signal constellation and ensures constant envelope. Being in quadrature to the OS signal minimizes interference. A look at spectral measurements of GIOVE-A L1 by Stanford, CNES, and others shows that the upper main lobe of BOC(15,2.5)

Giove-A broadcast codes			Type	Length	Period	Generated by	With data?
L1 BOC (1,1) codes	L1-B		Truncated Gold code	4092	4msec	Two 13-stage LSRs	Yes
	L1-C	Primary	Truncated Gold code	8184	8msec	Two 13-stage LSRs	No
		Secondary		25	200msec (With Primary)		
E6 BPSK codes	E6-B		Truncated Gold code	5115	1msec	Two 13-stage LSRs	Yes
	E6-C	Primary	Truncated Gold code	10230	2msec	Two 14-stage LSRs	No
		Secondary		50	100msec (With Primary)		

TABLE 1. Summary of Assessment of the GIOVE-A L1, E6 Code

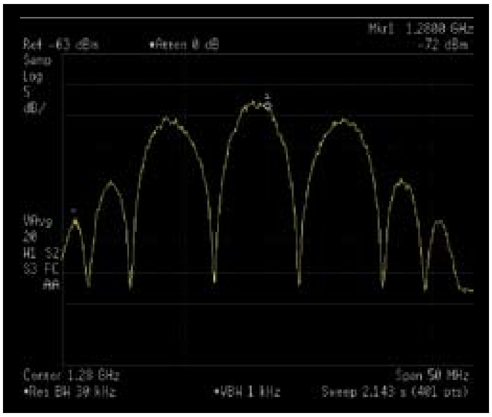

FIGURE 11 GIOVE-A E6 Measured by the Stanford Dish

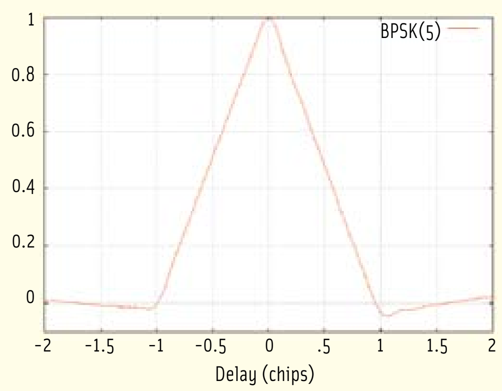

FIGURE 12 Normalized correlation function of GIOVE-A BPSK(5) signal at E6, from CNES dish measurement

E6-B code: 5115 bits, 1ms, Gold code
Polynomial 1: X13+X12+X11+X1+1
Initial state: [0 1 0 1 0 1 1 1 0 0 0 0 0]
Polynomial 2: X13+X10+X8+X5+1
Initial state: [1 1 1 1 1 1 1 1 1 1 1 1 1]
E6-C code: (primary code) x (secondary code) = 511500 bits, 100ms
Primary code: 10230 bits, 2ms, Gold code
Polynomial 1: X14 +X8+X7+X4+X3+X2+1
Initial state: [0 1 1 0 1 0 0 0 0 1 1 1 0 1]
Polynomial 2: X14+X11+X6+X1+1
Initial state: [1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Secondary code: 50 bits
[0 1 0 1 1 1 1 1 1 0 0 1 0 1 1 1 0 1 0 1 1 0 0 0 0 1 0 0 1 0 1 0 0 0 0 1 1 1 0
1 1 0 0 1 1 0 0 0 1 0];

FIGURE 13 Generator Codes for GIOVE-A E6 BPSK(5) Signals

had less power than the lower main lobe during the recent observations.

The GALILEO E6 signal is an interplex between E6 CS data, E6 CS pilot, and E6 PRS, is centered at 1278.75 MHz, and is roughly 40 MHz wide. Both Commercial Service (CS) and PRS signals will be transmitted there, reportedly with a binary phase shift key (BPSK) modulation for the CS signal and a BOC(10,5) modulation for the PRS.

The E6 signals from GIOVE-A is shown in **Figure 11** verify these statements. There are three 10 MHz wide lobes with the center lobe only 1-2 dB above the other two lobes. This corresponds well to the spectrum of the anticipated signal — a roughly 5 megachips per second (Mcps) BPSK signal in the inphase and a BOC(10,5) signal in quadrature.

As seen in **Figure 12**, data from CNES shows that the correlation function of BPSK(5) has the classical triangle form. Using the same methodology as in the L1 signal, Stanford determined the code and code generator for the E6 signals modulated using BPSK(5). These results are presented in **Figure 13**.

The determination of code and code generator allowed for acquisition and tracking of GIOVE-A E6 B/C with slight modifications to our GPS software receiver. Both Stanford and CNES teams estimated the data and data free E6 codes to have 5,115 and 10,230 chips, respectively. A summary of the assessment of the GIOVE-A code is given in **Table 1**.

Galileo E5 is centered at 1191.8 MHz and is roughly 90 MHz wide. A signal using BOC-like modulation, termed AltBOC(15,10), is expected to be retransmitted soon here. This modulation, introduced by CNES, will result in two main lobes approximately 20 MHz wide centered at 1176.45 (E5A) and 1207.14 MHz (E5B). Either lobe can be used independently.

The wideband signals enable higher accuracy measurements of the code and better multipath performance. The inclusion of a data-free channel allows longer signal averaging that results in signal acquisition at lower signal-to-noise (SNR) levels. No measurements of this signal were made by CNES or Stanford, but others parties have observed E5 ALTBOC during the satellite evaluation phase.

GPS & Augmentations

After more than 20 years of operation, GPS also introduced its first major signal addition with the first Block II-RM (Block II-R Modernized) that became operational in December 2005. This satellite, NAVSTAR 57, broadcasts L2 civilian (L2C) and modernized military (M-code) signals in addition to the current

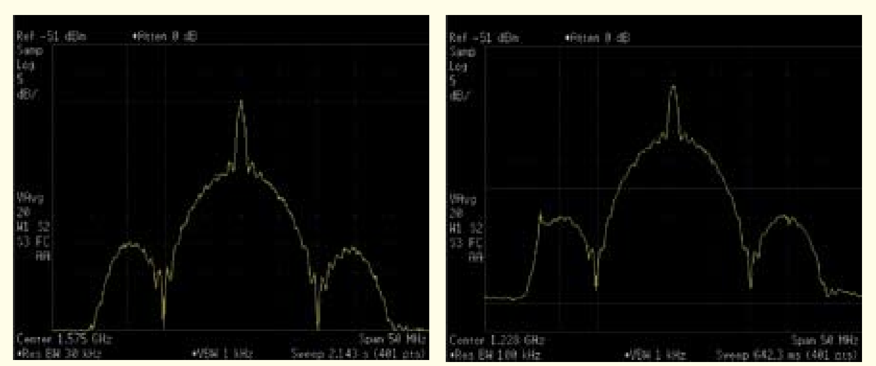

FIGURE 14 NAVSTAR 57 L1 and L2 Spectrum from Stanford Dish

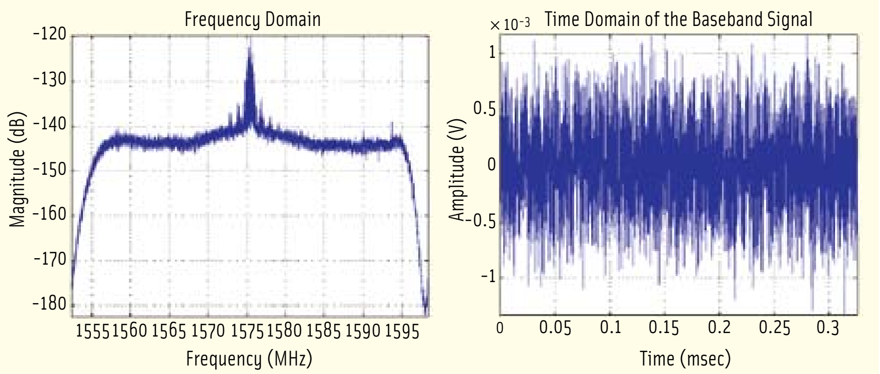

FIGURE 15 L1 Spectrum and Time Domain of NAVSTAR 57 (GPS IIR-M) from SGMS

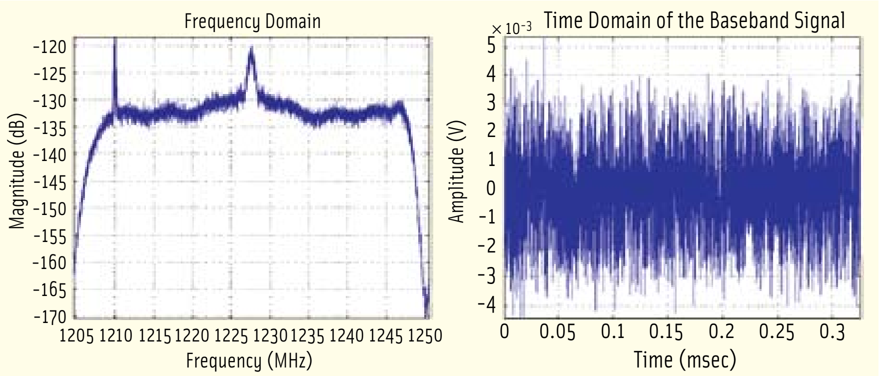

FIGURE 16 L2 Spectrum and Time Domain of NAVSTAR 57 (GPS IIR-M) from SGMS

C/A and P(Y) codes. The GPS L1 and L2 signal of GPS IIR-M and GPS II-F also uses interplex modulations (plus time multiplexing for L2C). This spectrum can be seen in **Figure 14**. The M-code, a BOC(10,5) signal, is transmitted on both L1 and L2.

Figure 15 shows the spectrum and time domain sequence from a 200-millisecond record of 36 MHz bandwidth surrounding the 1575.42 MHz L1 carrier frequency captured using the SGMS. In spectrum plots, the first few lobes of the L1 C/A code and primary lobe of the L1 P(Y)-code spectrum are clearly visible.

Neither Stanford nor CNES have observed M-code transmission though other parties reported observing it during the satellite evaluation phase. As expected, no major RF interference (RFI) components are visible in either frequency or time domain representations.

Figure 16 shows the spectrum and time domain sequence from a 200 msecond record of 36 MHz bandwidth about the 1227.6 MHz L2 carrier frequency taken by the SGMS. **Figure 17** shows the L2 spectrum as measured with Leeheim Antenna 4. In the spectrum plots, the first few lobes of the L2C code and primary lobe of the L2 P(Y) code spectrum are clearly visible. Again, no M-code signature appears.

A significant RFI component is clearly visible in the frequency but not in the time domain representation. This is likely a result of local radar activity because GPS L2, as with GLONASS L2 and GALILEO E6, falls into a band that is also authorized for radiolocation (i.e., radar), in addition to satellite navigation. The L2 frequency is not designated an aeronautical radionavigation (ARNS) band, a more restricted designation that, while not interference free, is carefully limited to aviation use.

The first L5-capable GPS Block IIF satellite is now scheduled for no sooner than March 2008. However, we do not have to wait until then to see an L5 navigation broadcast. WAAS is currently testing its L5 transmission, which is similar in signal structure to the GPS L5 signal. The primary difference is that GPS L5 will also have a data free (pilot) signal.

Two new WAAS geostationary satellites capable of L5 transmission are currently in orbit. These two satellites, PanAmSat Galaxy 15 and Telesat Anik F1R, are both radiovisible from Stanford. Comparison of the L1 transmissions from these indicates that received signal strength is greater than that of previous WAAS satellites (by about 4.5 dB). **Figure 18** shows the clearest picture of the L1 and L5 spectrum of the Galaxy 15 satellite. These plots are generated using the Stanford Dish.

Figure 19 shows a 200-millisecond record of 36 MHz bandwidth around the 1176.45 MHz L5 carrier frequency from data captured by the SGMS. The primary lobe of the 10.23 MHz L5 PRN code spectrum is apparent. Multiple significant RFI components are also visible in both the frequency and time domain representations. These are pulsed interferences from the inband distance measuring equipments (DMEs) in the surrounding area. L5 is in a designated ARNS band, including use by DME.

Figure 20 shows expanded time domain plots confirming this conclusion.

Data collections at Stanford show the presence of a number of different DMEs, identifiable by their underlying frequencies, with varying signal strength. In Figure 20, two different DMEs can be identified, the strongest lying within 3.5 MHz of the L5 center frequency.

The currently planned GNSS L5 signals (GPS L5 and GALILEO E5A/B) are wideband (20 MHz main lobe) and will experience pulsed interference as a result of these inband DME transmissions. Consequently, L5 (E5A/B) GNSS receivers will have to use pulse blanking to cost effectively minimize the effect of the DMEs.

GLONASS

GLONASS has been replenishing and upgrading its constellation steadily during the last four years. Spacecraft in orbit now include two operational, modernized GLONASS-M satellites (GLONASS 701 and 712) launched in December 2003 and 2004, respectively. Two additional GLONASS-M space vehicles (SVs) launched December 25, 2005, have been moved into slots in orbital plane 3, but have not yet begun broadcasting.

Although GLONASS-M satellites still broadcast on the two original frequencies — one centered at 1602 MHz and the other 1246 MHz, some changes have been made. First, GLONASS–M SVs also transmit a civil L2 signal. Second, GLONASS operators are improving the system's signal generation and reducing its interference with other systems.

Figure 21 shows measurements of the GLONASS 701 L1 and L2 spectrum taken at the Stanford Dish. We can clearly see the civilian L2 transmissions in the figure as a narrowband signal at roughly 5 dB below the signal strength of the L1 signal. **Figure 22** shows measurements of the GLONASS 712 spectrum taken at Leeheim.

The changing of the GLONASS spectrum can be seen on both diagrams, especially when compared to the spectrum of the prior generation GLONASS satellite (GLONASS 798) shown in **Figure 23**. Filtering has been

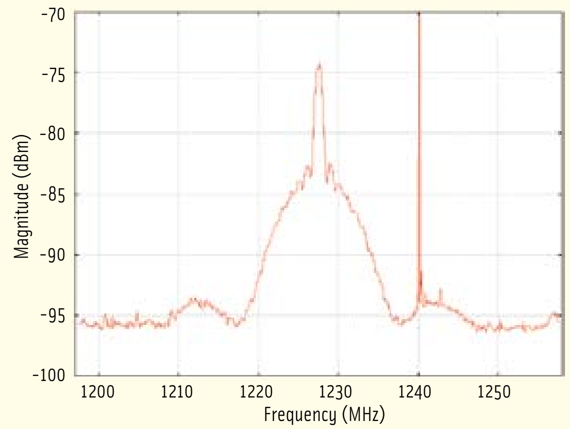

FIGURE 17 L2 Spectrum from NAVSTAR 57 (GPS IIR-M) measured at Leeheim

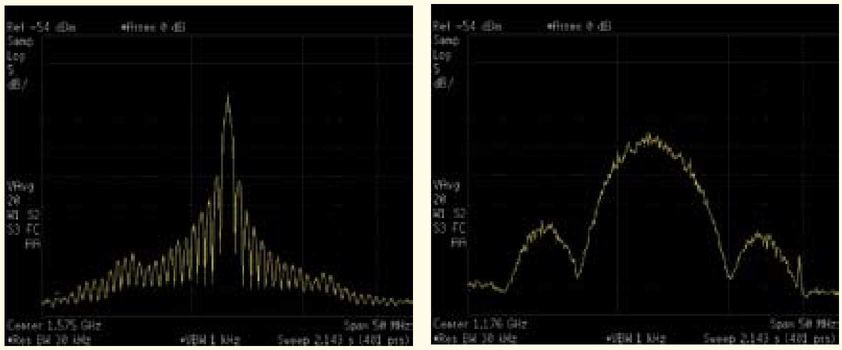

FIGURE 18 WAAS Galaxy 15 L1 and L5 Spectrum from Stanford Dish

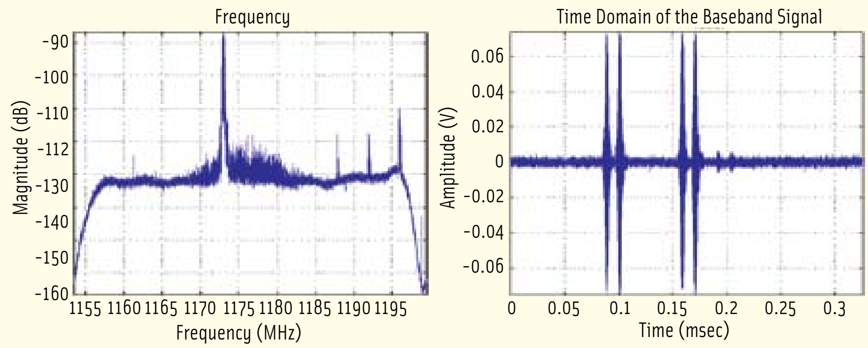

FIGURE 19 L5 Spectrum and Time Domain of Galaxy 15 from SGMS

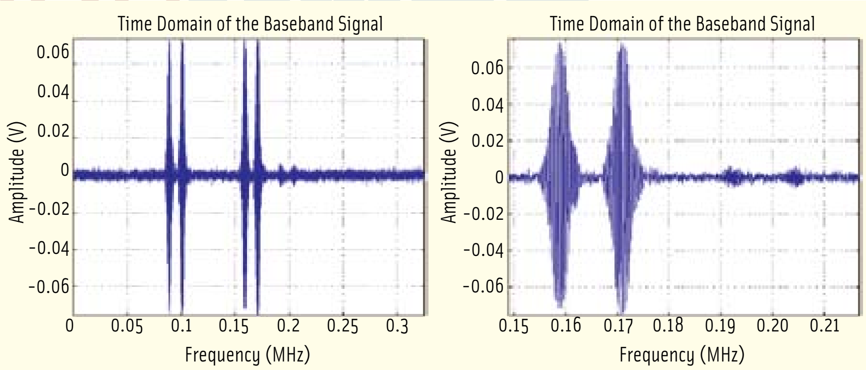

FIGURE 20 Zoomed L5 Time Domain from SGMS

added to reduce emissions in the radioastronomy band (1610.3-1613.8 MHz). This was requested by IUCAF (the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science) in 1993. The GLONASS signal power emitted in the remainder of the radioastronomy band is still under study by CNES.

Another development is GLONASS-M's elimination of the null spikes that were present on the old GLONASS satellite spectrum, which was achieved by changing the modulator.

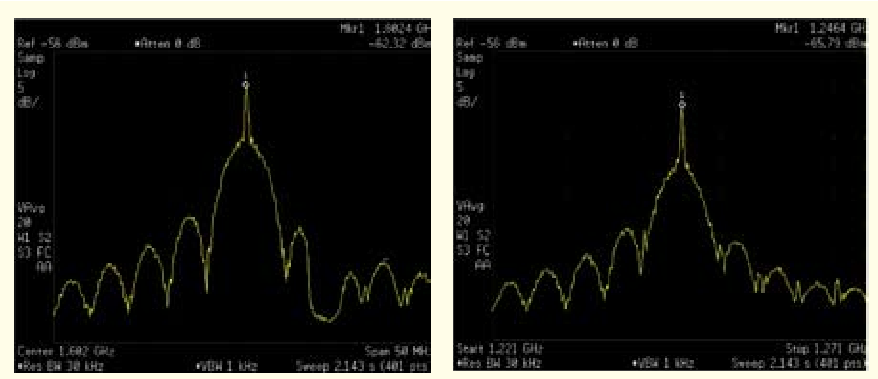

FIGURE 21 COSMOS 2404 (GLONASS 701) L1 and L2 Spectrum

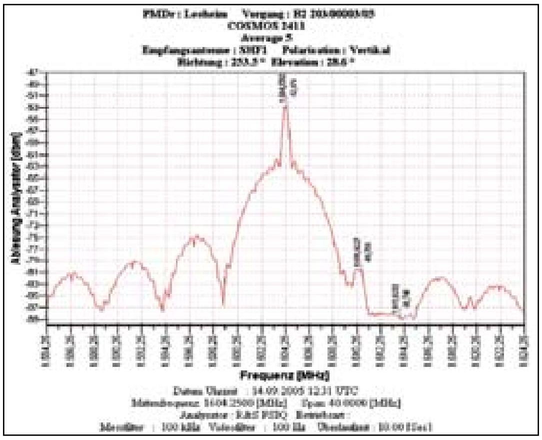

FIGURE 22 GLONASS 712 signal measured with Leeheim spectrum analyser

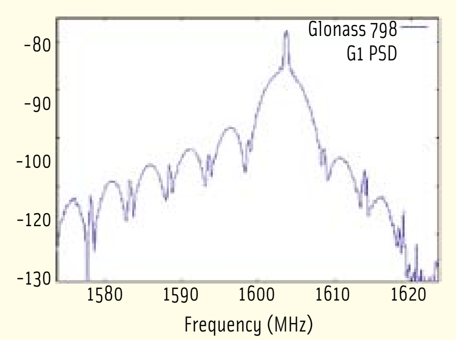

FIGURE 23 L1 Glonass 798 spectrum measured with CNES bitgrabber connected to Leeheim dish (Cut off frequency is at 1618 MHz)

Beidou

Beidou is a Chinese regional navigation system comprised of three geostationary satellites located at 140°, 110.5°, and 80° E. The Beidou satellite coverage footprints can be seen in **Figure 24**. The system is based on the Geostar and Locstar concepts. (For further discussion of the Beidou system design, see the articles by Shaofeng Bian et al and David Keyser, listed in the Additional Resources section at the end of this article.)

The Beidou 1B, at 80° E, is observable from Leeheim station at and elevation of 3.4 degrees. CNES researchers made measurements at Beidou's center frequency (2491.75 MHz) using Antenna 4. Two kinds of measurements were performed: measurements with a spectrum analyser, and measurements below the noise floor (MuR). Details of these measurements are given in in the article by Thomas Grelier et al listed in Additional Resources.

Figure 25 displays the overall Beidou spectrum across a 20 MHz bandwidth (±10 MHz around the center frequency). The blue line represents the Beidou spectrum averaged from 50,000 samples; the green line is the noise spectrum averaged from 50,000 samples with the antenna pointed away from the satellite (2.5° in azimuth direction) to get background noise; the red line is the spectrum resulting from the dif-

FIGURE 24 Beidou Satellite Footprint

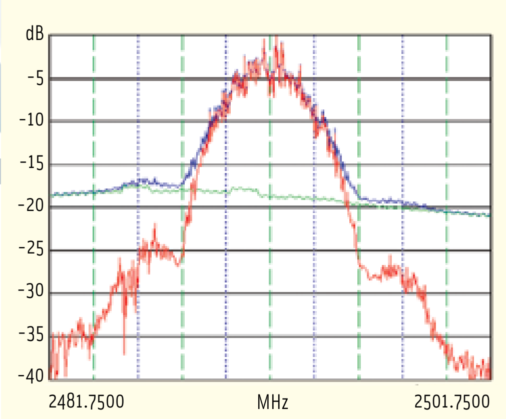

FIGURE 25 Beidou 1B measured spectrum at 2491.75 MHz

ference of both. **Figure 26** and **Figure 27**, respectively, show the lower and upper sidelobes as well as the noise level below and above the sidelobes.

The spectrum plots indicate the bandwidth of the main lobe to be slightly larger than 8 MHz or a chip rate of roughly 4 Mcps. If we assume a reference frequency of 1.023 MHz, this would imply a chipping rate of 4.092 Mcps. The first secondary lobes are filtered as they are only 2 MHz wide and have an amplitude 20 dB smaller than that of the main lobe.

Figure 28 presents an observation of the Beidou signal over a frequency span of 500 kHz around the center frequency. In order to compensate for the signal power variations, the spectra were averaged on the basis of several sweeps, which also decreased the noise floor.

The measurement allows us to observe the frequency line spacing, which was estimated to 16.03 kHz. Given an assumed 4.092 MHz chipping rate, a code sequence of 255 chips would yield a code repetition rate of 16.047 kHz, which seems consistent with the observed frequency lines. These assumptions still have to be confirmed.

Figure 29 is a time domain plot over 100 ms and reveals a little more about the code. The signal power shape over the time suggests a fixed signal cycle of roughly 31.5 ms, decomposed into two parts of roughly 23 and 8.5 ms. This period of almost 32 ms could represent 512 repetitions of code.

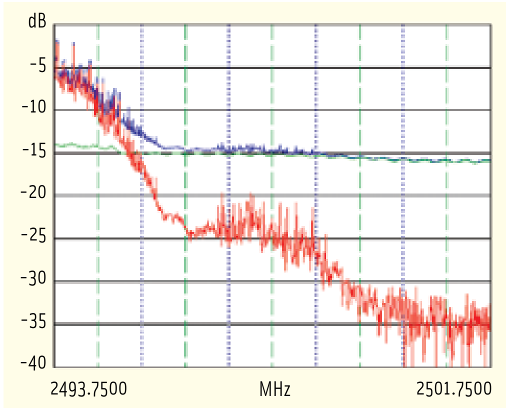

FIGURE 27 Upper first sidelobe of Beidou spectrum

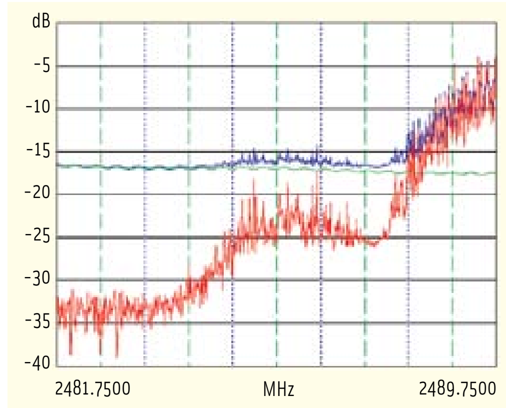

FIGURE 26 Lower first sidelobe of Beidou spectrum

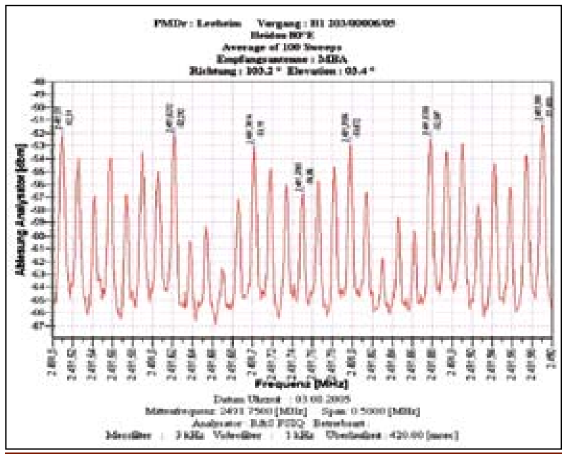
FIGURE 28 Beidou spectrum lines

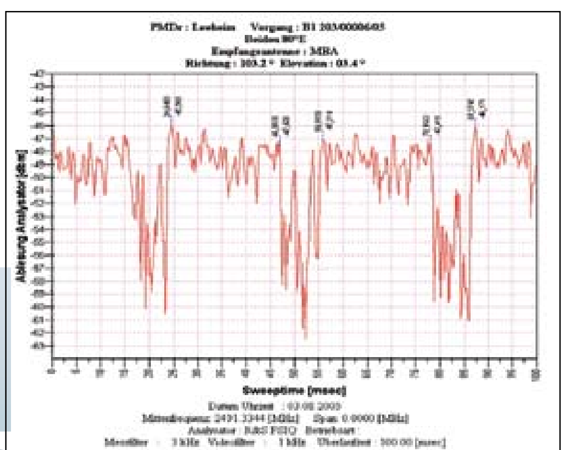
FIGURE 29 100-ms time representation of Beidou signal

Conclusion

GNSS is going through a transformative age that will result in more and better signals becoming available to civilian users. These changes will offer significant benefits and enable new applications.

Although we will soon have many more GNSS signals to choose from, economics will dictate that most consumer receivers use a subset of available signals. Hence, a receiver designer must choose with prudence. Perhaps only one, two, or three frequencies will be used, depending on the application.

The design of these new signals incorporate a variety of features. As such, some features are more suitable to a given application than others. Hence, we no longer have to make one signal fit all our applications. Rather we can choose the best signal for each use.

Furthermore, the frequency diversity offered by multiple GNSS signals also provides interference mitigation. This will make future GNSS receivers more robust. In using these new signals, receiver designers need to pay attention to the particular interference environment of the signal. For example, E5 and L5 users will need to mitigate pulse interference from DME. However, the challenges faced are small compared to potential benefits.

Few would have thought of all the uses and applications of original GPS signal when the system first came on line. The next generation of GNSS, too, will offer many possibilities beyond what we can imagine today.

Manufacturers

Stanford University researchers use an 89600 vector signal analyzer, from Agilent Technologies**, Palo Alto, California**, USA, to collect signals received at either the SGMS or Stanford "Big Dish" antennas. An Agilent E4404B Spectrum Analyzer is used for collecting spectrum images. CNES uses two versions of the bitgrabber from **SMP**, Toulouse, France. The first version is a single channel broadband digitizer (0.5 – 2.2 GHz) sampling at 250 MHz on up to 10 bits. The new version now allows simultaneously processing of two or four GNSS bands and serves well for research on AltBOC E5, for instance. The ESA/CNES datalogger used to store the samples from the digitizer was developed by **M3Systems**, Lavernose, France. The CNES 2.4-meter dish has been delivered by **Datatools**, Strasbourg, France.

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Lionel Ries is a navigation engineer in the Transmission Techniques and Signal Processing Department at CNES since June 2000. He is responsible of research activities on GNSS2 signals, including BOC modulations and modernized GPS signals (L2C & L5). He is currently responsible for several pre-developments of GPS/GALILEO receivers. He graduated from the Ecole Polytechnique de Bruxelles, at Brussels Free University (Belgium), and then specialized in space telecommunications systems at Supaero in Toulouse. IG