L5 – The New GPS Signal

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BIOGRAPHIES

Stefan Erker received his diploma degree in Communication Technology at the Technical University of Kaiserslautern, Germany in 2007. In the same year 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 Thölert received his diploma degree in Electrical Engineering with fields of expertise in high-frequency engineering and communications at the University of Magdeburg in 2002. 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). In 2006 he changed to the Department of Navigation at German Aerospace Centre (DLR), Institute of Communications and Navigation. Now he is working within the topics of calibration, civil security and automation of technical processes.

Johann Furthner received his diploma degree in Physics with fields of expertise of laser physics at the University of Regensburg in 1990. In 1994 he finalized his Ph.D. work in laser physics at the University of Regensburg. Since 1995 he is scientific staff at the Institute of High Frequency, since 2000 of the Institute of Communication and Navigation, both at German Aerospace Centre (DLR). In 2008 he stayed half year at ESA/ESTEC in the Galileo Project Team as Navigation Performance Engineer. Johann Furthner is working since 1995 on the development of navigation systems in a number of areas (systems simulation, timing aspects, GNSS analysis, signal verification, calibration processes).

Michael Meurer received the diploma in Electrical Engineering and the Ph.D. degree from the University of Kaiserslautern, Germany. After graduation, he joined the Research Group for Radio Communications at the Technical University of Kaiserslautern, Germany, as a senior key researcher, where he was involved in various international and national projects in the field of communications and navigation both as project coordinator and as technical contributor. Since 2005 he has been an Associate Professor (PD) at the same university. Additionally, Dr. Meurer joined the German Aerospace Centre (DLR), Institute of Communications and Navigation in 2006. Since June 2008 he is the director of the Department of Navigation.

ABSTRACT

The constant development in the field of global satellite navigation systems opened the door for a new type of safety critical applications. To meet the challenging requirements which include precision of the positioning solutions as well as robustness of the service new technologies have to be implemented in developing and modernized satellite navigation systems. In early spring this year a next important step in GPS modernization took place. With GPS IIR-20(M) a new satellite was added to the actual constellation which carries an L5 demo payload. This satellite transmitted the first GPS L5 signals from a Medium Earth Orbit in space after its launch. Since L5 is claiming to be a GPS “Safety of Life” signal which intends to increase precision and robustness of the navigation solution due to mitigation of ionospheric refraction errors and an enhanced signal design which includes a higher signal strength and advanced code structure compared to the existing GPS civil signal. Starting in September 2005 the DLR Institute of Communications and Navigation established an independent monitoring station for the analysis of GNSS signals. The core of this facility is a 30 meter deep space antenna located at DLR Groundstation at Weilheim, Germany. The use of this antenna which is characterized by its high gain and small beamwidth and the absolute calibration of the whole measurement setup including also the 30m antenna allow very precise and absolute calibrated measurements on a single navigation satellite. The paper gives a brief overview of DLRs GNSS verification facility. This includes a description of the measurement setup and the performed calibrations on all components. Afterwards a detailed analysis of the transmitted L5 signal is presented. Signal imperfections like spectral asymmetries or distortions are discussed and evaluated using different signal representations like spectra, constellation diagrams, sample analysis and correlation functions.

INTRODUCTION

In the course of the GPS modernization the US decided in August 2002 in coordination with the International Telecommunication Union Radio communication Sector (ITU-R) the transmission of a new civil signal on a third frequency known as L5. This new signal will be part of the new IIRF modernized filing, which includes the military (M) code signal on L1 and L2 frequencies and a new civil signal on L2. The filing in 2002 requires transmission of the signals from a MEO at least in summer 2009. To fulfill this task a Block IIR-M satellite was selected to finally bring a L5 demo payload into the earth orbit. Beside this mission the main objective of this spacecraft is to encourage the existing constellation with an additional IIR-M payload. A simplified L5 payload was designed to meet the requirements of the frequency filing and avoid any possible compromises to the main objective of the satellite. Even though a first meaningful civil use of this new L5 signal will possible in maybe two or even three years, when a sufficient number of IIF satellites have been brought successful into orbit. The first measurements of the transmitted L5 signal will help to analyse the signal quality of this payload in detail and allow further investigation on interference aspects which will come along with this new signal located in the Aeronautical Radio Navigation Services (ARNS) band, that is also populated by the Galileo E5a signal and ground navaids like DME and TACAN at this frequency. Since L5 is claiming to be a GPS “Safety of Life” signal which intends to increase precision and robustness of the navigation solution due to mitigation of ionospheric refraction errors by the use of multi frequency L5 receivers it is necessary to observe the performance of the enhanced signal design which includes a higher signal strength and advanced code structure compared to the existing GPS civil signal. These aspects are intended for pushing the signal especially for situations where high precision is needed under demanding conditions.

MEASUREMENT FACILITY AND SETUP

Starting in September 2005 the Institute of Communications and Navigation of the German Aerospace Center (DLR) established an independent monitoring station for the analysis of GNSS signals. The core of this facility is a 30 meter deep space antenna located at DLR groundstation at Weilheim, Germany (Figure 1) and was originally built up in early seventies for the first US/German interplanetary satellite mission HELIOS-A/B.

Figure 1 DLR Groundstation Weilheim, Germany

For the new challenge the antenna has 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 were installed at the antenna during the preparation for the GIOVE B IOT campaign in spring 2008. In this time also intensive work on the system calibration was performed using well known signals from radio stars and EGNOS satellites for antenna gain determination and suitable calibration methods for the receiving system. This calibration leads to a remaining cumulated absolute measurement uncertainty significantly less than 1dB. The use of this antenna which is characterized by its high gain and small beam width and the absolute calibration of the whole measurement setup including also the 30m antenna allow very precise and absolute measurements on a single navigation satellite.

The antenna is based on a shaped Cassegrain system with elevation over azimuth mount and is characterized by a gain value of around 50dB in the L-band and a beam width around 0.5°. The absolute position accuracy of this antenna is 0.001° in each direction.

Figure 2: The 30m High Gain Antenna at Weilheim

The measurement system adapted to the 30 meter antenna includes two Low Noise Amplifiers with a total gain of almost 70dB. Several directional couplers are used for the injection of pilot and calibration signals. So it is possible to calibrate the receiving system during operation near real-time. The setup also has several signal outputs for external equipment like bit grabbers or navigation receivers. Another main item of the receiving system are several band pass filters dedicated to the individual GNSS navigation bands This helps to reduce out-of-band interference which could saturate the amplifiers or the used measurement equipment. The signals are recorded using a vector signal analyzer. Figure 2 shows a simplified schematic of the facility setup including the high gain antenna, feed and measurement equipment.

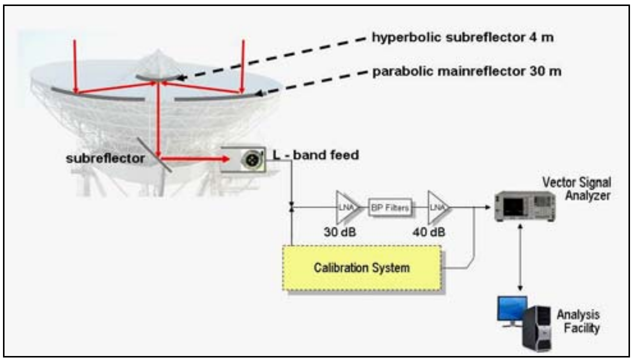

Figure 3: Facility Setup Overview

Due to the distance of the antenna location from the Institute at Oberpfaffenhofen (around 40km) it is necessary to perform all measurements and calibrations procedures during a measurement campaign via remote control. A software tool is able to control any component of the setup. In addition this software performs a complete autonomous operation of the whole system by a pre-definable sequence over any period of time. More detailed information about the facility and measurement setup can be found at [3].

SYSTEM CALIBRATION

The measurement setup in Weilheim is used for Signals-in-Space quality assessment and performance characterisation of navigation satellites. Influences caused by the used measurement setup need to be characterized accurately and removed within the post processing of the measurement data. To achieve a combined absolute measurement uncertainty significantly less than 1.0 dB it is essential to calibrate every part of the used system very precisely. This includes beside all RF components of the receiving system also the high gain antenna itself.

For the characterisation of the high gain antenna two values are assessed. The first one is the antenna pointing accuracy. This error contributes with a reduced maximum power value caused by the miss pointing of the antenna pattern. So the pointing offset is measured for azimuth and elevation using the geostationary satellite Artemis. The measurements show a systematic elevation offset of 0.02° and an azimuth offset of 0.03°. This offset is corrected in the antenna control. The second value is the antenna gain. For accurate measurement of the antenna gain natural sources like radio stars or artificial sources like geostationary satellites are well suited. For a characterization over the complete used frequency range the radiostar Cassiopeia A is used. Cassiopeia A is one of the strongest wideband radio emitters on the northern hemnisphere. The star is circumpolar and therefore usable for calibrations at every time of the year. With the help of the well-known flux density of the celestial radio sources Cassiopeia A the G/T can be measured, which is the relation between the gain of the antenna and the noise temperature of the receiving system. After a precise determination of this noise temperature the antenna gain can be calculated. More information about the antenna calibrations can be found at [3].

For the receiving system calibration several techniques are used. The State-of-the-Art method is the use of a network analyzer. This analyzer can be calibrated remotely and connected to the receiving system by a group of dedicated switches. These precise measurements of gain and phase are performed periodical and show a maximal deviation over all measurements of around 0.2 dB. A frequency and power stabilized signal generator is used in combination with two power meters for an online system gain determination during signal measurements. This method is used for detection of gain variations of the low noise amplifiers and passive elements of the receiving system. It is also possible to detect if one of the amplifiers is saturated and working outside specified limits.

THE L5 SIGNAL

During the definition of the GPS modernization process many civil user groups demanded two new civil GPS signals. With the L2C on the block IIRM satellites one of this new civil signal is already implemented. An operational L5 payload will be integrated on the Block IIF satellites, which should have the first launch in 2010.

With the new L5 signal GPS will feature a completely new civil signal which will transmitted on a frequency of 1176,45 MHz within a 24 MHz bandwidth. L5 is intended to be a “safety-of-life” signal for aircraft navigation but will be of course useable for all civil users. This makes L5 to a valuable third civil GPS signal beside the C/A and L2C signal.

The structure of the future operational GPS L5 signal will offer a two carrier components signal. Both components – In-phase (I) and quadrature-phase (Q) will have the same signal power level. 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 will carry different but nearly orthogonal and time synchronized PRN Codes. The Q channel of the L5 signal will be a data-less channel, transmitting only a pilot signal modulated with the specific satellite PRN, which is useful for a long coherent integration time. On the I channel the navigation message is modulated with 100-symbol per seconds. In addition the L5 signal uses a Neuman-Hoffman synchronization code. The usage of two different PRN Codes helps to prevent possible tracking biases. The two channels are only dependent on the same carrier phase, which is typically provided by the atomic frequency standards of the SV. The L5 signal uses a chipping rate of 10.23MHz and which is 10 times the rate of the C/A and L2C codes. With this chipping rate the signal has 20.46 MHz null-to-null bandwidth which is exactly the same as the legacy P(Y) code signal. Thus the signal features satisfy the requirements for a new Safety-of-Life signal with increased bandwidth, higher signal accuracy und robustness under rough conditions. The code period of the L5 signal is 10230 chips. One millisecond of code is generated by the modulo-2 sum of the output of two shift registers (XA and XB) with a length of 8190 and 8191 chips. For the I5 and Q5 channel the same XA sequence is used. The XB sequence is different for both signal components.

The L5 I Channel NAV Data is very similar to the L2 C channel and includes Space Vehicle ephemerides, system time and clock behavior data, status messages and time information.

L5 MEASUREMENT RESULTS

The transmitted L5 signal of SVN49 is only a dataless demo signal and containing only a quadrature component. The L5 signal generation is hardwired to L5 Q PRN 63 and is not intend for operational use. For L1 and L2 the satellite is currently assigned with PRN1. After the successful launch of the Block IIR-20(M) satellite DLR performed continuous tracking of the satellite waiting for the L5 signal to be switched on. The high elevation passes every night - most of them with an elevation angle over 80 degree - allow long observation time for each SVN49 transit. To ensure a correct tracking of the satellite with the high-gain antenna the latest two-line elements were used from U.S. Air Force Space Command. The very first L5 signal transmission over Europe could be recorded at the pass on April 10. Compared to later measurements, the power of the L5 payload signal was measured with a very low power level on this first pass. This observation points to a very common “power fade in” procedure during the commissioning of a new satellite payload. A controlled and slow heating of the payload elements avoids possible damage caused by the out-gassing of the power amplifiers, for example.

Figure 4 shows the SVN49 L5 spectrum calibrated as Spectral Flux Density over the corresponding frequency range. We see the typical shape of a binary phase-shift-keyed signal. The overlaying theoretical spectral mask (red) allows a first qualitative rating of the spectral shape.

The signal is significantly band limited by the used front end filters of the L5 payload ensuring the required spectral separation from the operational GPS L2 frequency. We note a slight asymmetry of the spectral shape. The peak level of the two side lobes differ around 2.5 dB in this spectral snapshot. Those spectral asymmetries typically result from frequency selectivity in the RF transmitter chains of the satellite payloads including the amplifiers and antennas.

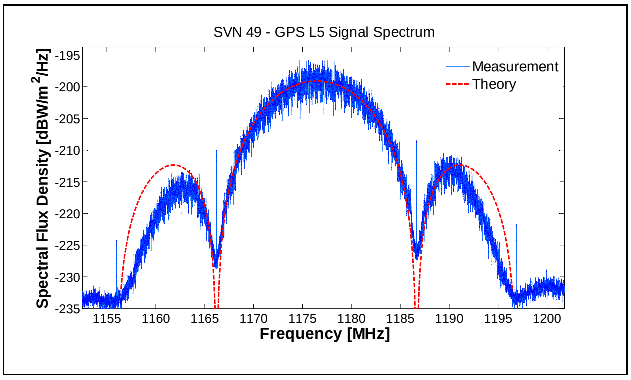

Figure 4 The SVN 49 L5 Spectrum

Figure 5 shows the spectrogram plot which is generated by plotting all recorded L5 spectra of one satellite pass versus the observation time. We can see a very strong elevation dependency of the signal power. The two side lobes are only visible for higher elevations.

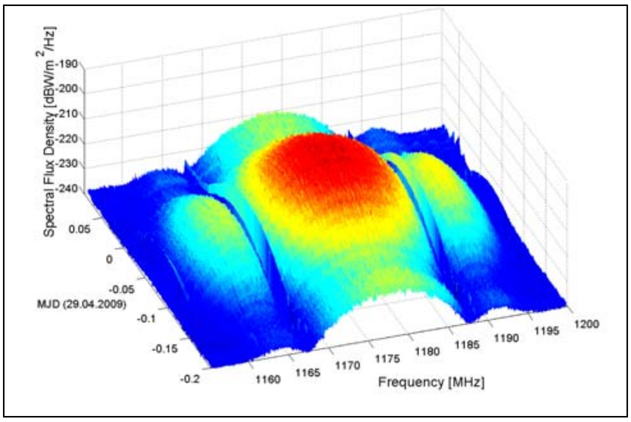

Figure 5 L5 Spectrogram recorded over a whole satellite pass

To have a closer look on this issue we use the calibrated setup of the GNSS verification and analysis facility for accurate absolute measurements on GNSS signal power levels of SVN49 as received on the ground (see Figure 7). The Figure shows the power levels of signals transmitted in the L1, L2 and L5 frequency band in terms of the received power per square meter versus the elevation angle of the satellite. We see that the received power flux of L5 shows a strong elevation dependency. The variation is around 18dB between low and high elevation which is not normal for a standard GPS signal. The variation for L1 and L2 are as expected around 3dB between low and high elevation. In this Figure the combined power of L1´s and L2´s I and Q Channels are plotted. So the L1 and L2 curve includes the power of C/A-, P(Y) and M-Code.

The unusual behavior of the L5 signal can be explained if we have a look into the antenna coupler network of SVN49. We can see that the L5 payload is connected to the auxiliary port J2. Most part of the signal power of J2 is directed by the input coupler to the helical antennas of SVN´s outer antenna ring. This outer ring is normally used to reduce the high elevation power by radiation a sharp pattern with reduced power and boost the power for low elevations by providing in-phase power in addition to the broad pattern of the inner ring which transmits most of the L1 and L2 power from J1. The L5 power curve of SVN49 shows very good the behavior of the sharp outer ring antenna pattern.

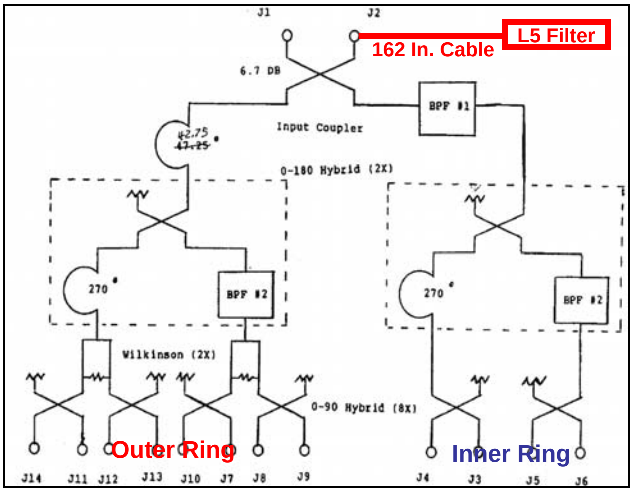

Figure 6 Satellite Antenna Coupler Network (GPS WING)

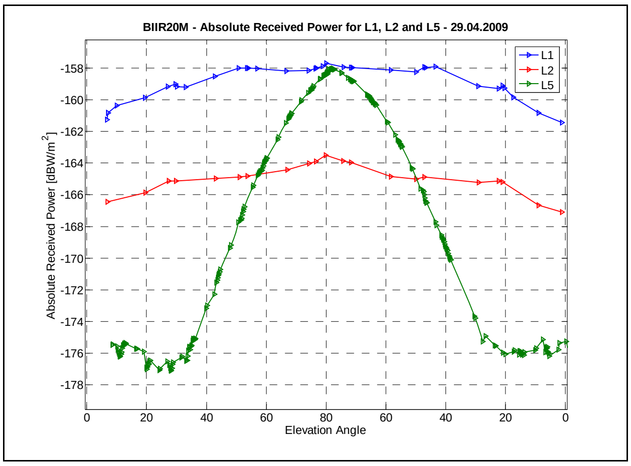

Figure 7 SVN 49 Absolute Received Power Levels for L1, L2 and L5

For further analysis of spectral asymmetries the L5 signal power variations over a complete satellite pass are plotted. In Figure 9 the absolute received power flux for different signal frequency bandwidth parts of the signal are plotted. We compare the power of 4 different slices each of 10.23 MHz bandwidth. The first two (blue & red) cover the upper and lower L5 main lobe. The last two cover the L5 sidelobes as seen in Figure 8.

It can be seen that the elevation dependent power variations are visible for all different frequency parts of the L5 spectrum. The black markers show the absolute received power flux over elevation for a signal bandwidth of 20.46 MHz. The two dashed lines show the power for the lower and upper L5 side lobe. The red and blue line represents the power for the lower half and upper half of the nominal L5 bandwidth. The figure reveals spectral asymmetry for both components of the L5 signal with a maximum value at high elevations.

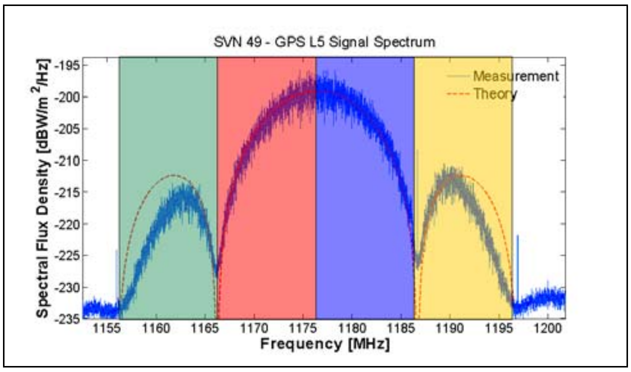

Figure 8 Compared frequency bands of the L5 signal

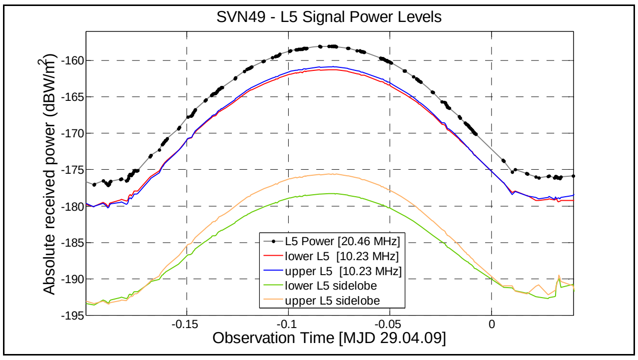

Figure 9 L5 Power Signal Power Levels

A detailed overview on the power difference between the two component pairs is presented in Figure 10. These points to an increased asymmetry for the side lobes with a maximum value of around 2.6 dB at maximum satellite elevation. The power asymmetry between upper and lower L5 signal part (12 MHz each) is less than 0.5 dB for highest elevation value. This frequency depend influence may be caused by the use of a legacy Block IIR-M satellite antenna on SVN49, which is to the authors' knowledge not optimized for the L5 frequency and may work outside its design limits.

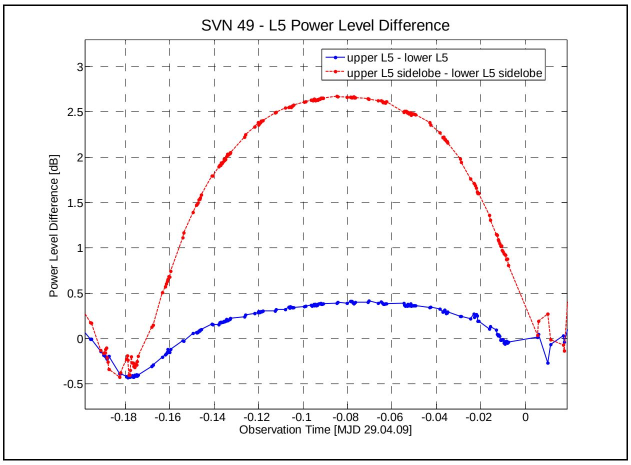

Figure 10 L5 Power Level Difference Plot

Figure 11 is a temporal snapshot of the L5 signal after removing the Doppler frequency shift caused by the satellite orbital motion for the I and Q channel. The length of this record is 10 milliseconds. In compliance with [1] we can see that L5 is a bi-level signal with a chip rate of 10.23 Mcps on the Q component.

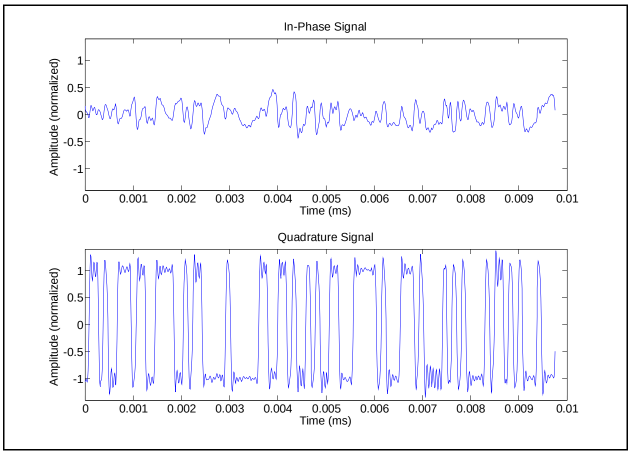

Figure 11 I and Q component time sample plot

If we have a close look on just one L5 (Q) code chip we are able to check the chip rate of the signal. The measured time between the rising and falling edge of the chip is around 97 ns which leads to the well known frequency of 10.23 MHz.

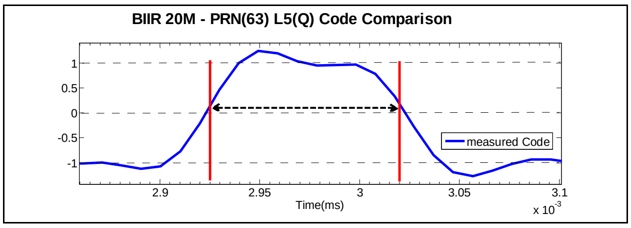

Figure 12 Detailed view of one L5 (Q) code chip

Plotting the normalized histogram of the L5 signal (Figure 13) we see a deformation of the Q component after Doppler removal. The L5 signal transmitted by the test payload only contains a dataless Q component, but shows a non-negligible contribution on the I channel. This distortion may result from nonlinear and frequency-dependent amplification of the Q based signal which leads to crosstalk between the I and Q channels.

With the use of a high gain antenna it is possible to 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 wipeoff. In Figure 14 we compare the first 10 milliseconds of the received L5 Q signal with the ideal theoretical code for the PRN63 L5 Q channel. The code was obtained with an implemented Matlab L5 code generator.

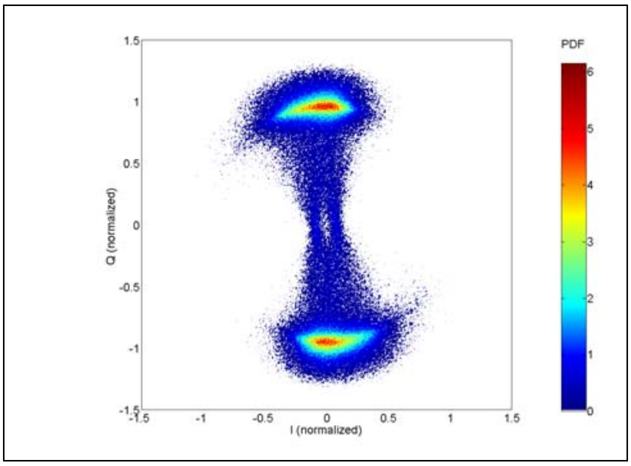

Figure 13 IQ Power Density Function Plot

The analysis was also performed for several full code periods and shows that the demo payload´s Q5 code structure is in full compliance with the "theoretical" code described in the official signal interface document [1]. In our comparison we see that the measured L5 Q signals shows typical overshoots after each code bit transition caused by the band limitation of the real L5 signal. Figure 15 shows the code compliance for the correlation of the received L5 (Q) signal of SVN49 with the theoretical PRN63 Code.

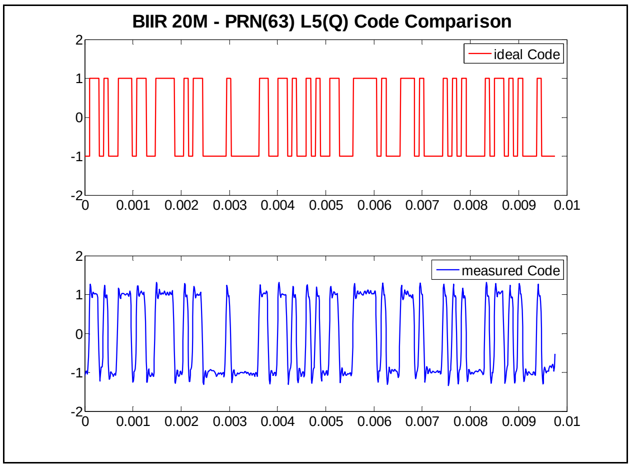

Figure 14 L5 Q Channel Code Analysis for PRN 63

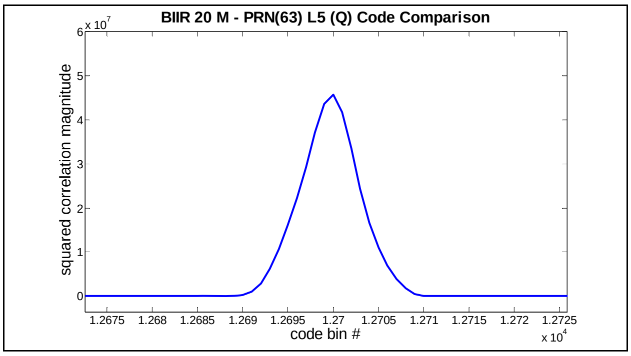

Figure 15 Correlation for L5 PRN(63) (Q) Code

CONCLUSION

This paper shows first measurement results and analyses of the new SVN49 L5 signal. Although this signal is only a transmitted by a demonstration payload which fulfills ITU requirements to bring the L5 signal into use. The measurements of the first MEO L5 signal show the enhanced L5 signal structure which will allow more accurate and reliable positioning in the future, when the L5 signal is deployed.

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