GORS - A GNSS Occultation, Reflectometry and Scatterometry Space Receiver

A. Helm, O. Montenbruck, J. Ashjaee, S. Yudanov, G. Beyerle, R. Stosius, and M. Rothacher

1 GeoForschungsZentrum Potsdam (GFZ), Germany
2 German Aerospace Center (DLR), Germany
3 JAVAD GNSS (JAVAD), Russia

BIOGRAPHY

Achim Helm is a project scientist at GFZ. He is responsible for the project management of the GORS receiver development. Since 2002 he is working in the field of GPS reflectometry and receiver technology. Formerly he was engaged in radar altimetry data processing.

Oliver Montenbruck is head of the GNSS Technology and Navigation Group at DLR’s German Space Operations Center (GSOC). His current field of work comprises the development of on-board navigation systems, spaceborne GPS applications, and satellite formation flying.

Javad Ashjaee founded Ashtech in 1986 and led it to impressive technical and financial success till 1995. After being the President and CEO of Javad Positioning Systems – founded in 1996 – since 2005 he is the leader of Javad GNSS.

Sergei Judanov is working as senior software developer at JAVAD GNSS. His current field of work comprises the development of on-board navigation systems and receiver firmware.

Georg Beyerle is a senior scientist at GFZ. His research interests include GNSS-based remote sensing and GNSS receiver technology.

Ralf Stosius is a project scientist at GFZ and since 2006 concerned with a feasibility study on using spaceborne GNSS-R altimetry for Tsunami detection and warning. Formerly he was engaged in geostatistics of radar altimetry data over the Antarctic ice sheet at the University of Trier.

Markus Rothacher is Professor for Satellite Geodesy and Earth Studies at Technical University Berlin. Since 2005 he directs the department of geodesy & remote sensing at GFZ.

ABSTRACT

Within the German Indonesian tsunami early warning system (GITEWS) project, the GeoForschungsZentrum Potsdam (GFZ) has set up a team consisting of GFZ, the German Aerospace Center (DLR) and JAVAD GNSS to adapt and extend their new generation GNSS receivers for advanced space applications. The occultation, reflectometry and scatterometry GORS space receiver prototype consists of a commercial off-the-shelf JAVAD GNSS GeNeSiS-112 72 channel receiver board with raw data and position solution output. The GORS receiver can process all presently available GNSS radio signals, including the latest GPS L2C, GPS L5, GLONASS C/A L2, and GALILEO GIOVE-A signals. Specific adaptations address the improvement of the cold start time-to-first-fix, the selection of optimal tracking loop parameters and channel slaving for monitoring of reflected signals. Besides pseudorange, phase and signal-to-noise measurements, the modified receiver allows output of in-phase and quadrature-phase accumulations at 5msec intervals (200Hz). As major step forward compared to current space receivers, the new receiver supports tracking of the civil L2C signal of the GPS constellation. This will enable loss-less dual-frequency tracking of occultation events down to very low altitudes. Channel slaving can be performed for GPS L1 C/A and L2C in parallel. Hence, carrier phase observations of coherent reflected signals are possible with two frequencies. By combining both observations and therefore enlarging the measuring wavelength, coherent carrier phase observations of reflected signals are expected to be recovered even at higher sea roughness conditions. This paper presents first results of a ground-based reflectometry experiment and first tests with a signal simulator. The experiment was conducted on July 16–20, 2007 at the moun-
occultation measurements are considered to be of great interest as one component for a future enhanced tsunami and Earth observation system. The general idea is that multi-frequency receivers, as add-on payload to independently planned Earth observation missions, could establish densely spaced grids of sea surface heights (see Fig. 2) with decimeter precision fairly rapidly [1, 2]. Several space-based experiments [3, 4, 5, 6] demonstrated the feasibility of reflectometric measurements using GPS signals. In future a dedicated constellation of 10 to 20 small affordable LEO satellites is planned which can monitor the ocean with the required high resolution in space and time in order to detect a tsunami. The required performance of such a space-based monitoring system demands most advanced GNSS receivers with improved algorithms for the various possible applications and quasi real time data processing capabilities to satisfy as a minimum the needs of a future space-based tsunami early warning system. The small market segment and high specialization of dedicated space-borne GNSS receivers, e.g., the successful Black-Jack receiver or Advanced GPS/GLONASS ASIC (AGGA) based receivers, as well as the associated test and qualification effort inevitably results in high unit cost ranging from roughly 100K Euro to 1M Euro. Hence, the price of such a receiver rapidly reaches the budget of a typical small satellite science mission. Small scientific satellite missions often do not require the utmost reliability and rigorous space qualification. Various companies and research institutes have therefore made efforts to come up with low cost solutions based on the use of terrestrial commercial off-the-shelf (COTS) components. The feasibility of this approach is nicely illustrated by the GPS Orion receiver design of MITEL, which forms the basis of several independent one frequency GPS receivers like, e.g. the Space GPS Receiver SGR-20/10 on UK-DMC [6] or the Phoenix GPS receiver, selected for the Proba-2, Flying Laptop, TET, ARGO, and X-Sat missions [7]. Promising investigations [8, 9] show that this approach can be extended to existing dual-frequency COTS receivers. Aside from enhanced ionospheric corrections, a dual-frequency system can overcome the limitations that sea roughness imposes on carrier phase coherence which is a major issue in reflectometry [10].

For use in reflectometry, scatterometry and radio-occultation measurements as well as high-precision navigation applications, specific adaptations of the receiver firmware are desirable, which require a close interaction between scientists and the receiver manufacturer. Within the GITEWS project, the GeoForschungsZentrum Potsdam (GFZ) has set up a team consisting of GFZ, the German Aerospace Center (DLR) and JAVAD GNSS (JAVAD) to adapt and extend their new generation GNSS receivers for advanced space applications. Specific adaptations address the improvement of the cold start time-to-first-fix, the selection of optimal tracking loop parameters and channel slaving for monitoring of reflected signals.
Fig. 2 Predicted reflection point coverage over the Indian Ocean. Simulation of GPS (red) and GLONASS (yellow) reflections with respect to a receiver assumed to be on a LEO in a CHAMP-like orbit scenario (blue ground tracks).

Fig. 3 The JAVAD GeNeSiS-112 receiver board has a physical dimension of 112x100x14mm and a weight of 110g.

GORS RECEIVER

The GORS receiver prototype consists of a JAVAD GeNeSiS-112 72-channel GNSS OEM receiver board (Fig. 3) with raw data and position solution output. The receiver can process all presently available today GNSS radio signals, including the latest GPS L2C, GPS L5, GLONASS C/A L2, and GALILEO GIOVE-A signals. The receiver board is specified for an operating temperature of -40°C to +75°C and typical power consumption is 2.7 W. The board has a physical dimension of 112x100x14 mm and a weight of 110 g.

A specially adapted receiver firmware allows output of in-phase (I) and quad-phase (Q) accumulations at 5msec intervals (200 Hz) for GPS L1 C/A, L2, and the new GPS civil L2C signals (Figs. 4a–4b). Actually, slaving of correlator channels is realized for GPS L1 C/A and GPS L2C signals (Figs. 4c–4d). Thus, for the first time civil dual-frequency phase measurements of reflected GPS signals are possible. Currently, only one reflection event can be observed simultaneously.

FIRST TERRESTRIAL TESTS

The first test with a GeNeSiS-112 receiver board was conducted February 22, 2007 at Moscow. Measurements are performed with a dual-frequency chokering antenna which is fixed on top of Triumph Pallace building at 55.80°N/37.52°E. Fig. 4a and 4b show the recorded 200Hz I and Q correlation sums of L1C/A and L2C signals of PRN 31, presented as correlation power (calculated by \( \sqrt{I^2 + Q^2} \)) versus time and I versus Q plot, respectively. As expected, the recorded L2C signal power can be observed at 33% of L1C/A signal power. In order to prove the functionality of channel slaving, different delays are applied to the slaved correlator channels, ranging from a correlator delay offset equivalent to -1.5 C/A code chips to +1.5 C/A code chips offset (Fig. 4c). Hence, the typical correlation triangle of GPS L1C/A and L2C signal could be mapped successfully (Fig. 4d).

A second test was conducted with a GeNeSiS-112 receiver board on April 24, 2007 at Potsdam. Measurements are performed with the MarAnt+ antenna which was fixed on top of a former water tower at 52.38°N/13.06°E with nearly unobstructed view to the horizont. The antenna was directed to about 340° azimuth and tilted by 90° toward the horizon in order to optimize signal reception at very low elevation angles. The receiver successfully tracked GPS L1C/A, L2C and L2 signals of PRN 12 which descended from 1° down to 0° elevation until the signals faded away. I and Q correlation sums are recorded for all GPS L1C/A, L2C and L2 signals with a data rate of 200Hz. Fig. 5 shows the calculated correlation power of L1C/A (Fig. 5a), L2C (Fig. 5b) and L2 (Fig. 5c). A much higher signal-to-noise ratio (SNR) can be observed in the recorded L2C signal compared to the L2 signal. This can be explained due to the
fact that L2C can be directly tracked and L2 is tracked by semicodeless tracking. All signal amplitudes show a certain correlation in time. Thus, the influence of the Earth troposphere can be clearly sensed within all three I and Q data recordings. This demonstrates the already achieved tracking performance of the receiver at low observation angles for radio-occultation applications.

**SIGNAL SIMULATOR TEST RESULTS**

As part of the ongoing adaptation and space qualification of the GeNeSiS-112 receiver, initial tests in a GPS signal simulator test bed have been conducted to assess the tracking and navigation capabilities under high signal dynamics (Fig. 6). The tests were performed with a Spirent GSS7700 signal simulator capable of simulating dual-frequency (L1, L2) GPS signals for up to 12 visible satellites. For compatibility with earlier tests of spaceborne GPS receivers \[9\] an established scenario for a polar satellite at 515 km altitude was used throughout all tests, which is representative of the TerraSAR-X satellite. Ionospheric path delays were modelled through a Lear model with a constant vertical total electron content of 10 TECU.

The distribution of tracked satellites on the celestial sphere (Fig. 7) illustrates that the GeNeSiS receiver properly acquires and tracks all simulated satellites above the adopted elevation mask of $5^\circ$. Likewise, the histogram of tracked satellites shows a smooth distribution up to the simulated maximum of 12 satellites. Following the start-up phase at least six satellites are permanently available for navigation and 10-11 satellites are simultaneously tracked on average (Figs. 8–9). The achievable measurement qual-
Fig. 5 Correlation power of PRN 12 GPS L1C/A (a), L2C (b) and L2 (c) signals, calculated from I and Q recordings at elevation angles below 1° on April 24, 2007 at 52.38°N/13.06°E.

Fig. 6 GeNeSis-112 receiver with external low noise amplifier in the signal simulator test bed

Fig. 7 Skyplot of tracked satellites in the orbital frame.

Fig. 8 Histogram of tracked satellites in the orbital frame.

The initial signal simulator tests demonstrate the capability of the GeNeSiS receiver to provide proper GPS measurements for orbit determination and scientific applications under the signal dynamics of a user satellite in low Earth orbit. Further tests will be conducted to optimally tune the tracking-loop bandwidth in a trade-off between low noise measurements and robust tracking.
Fig. 9 Number of tracked satellites over a 12h arc.

Fig. 10 Double-difference analysis of GPS raw measurements in the signal simulator test.

Fig. 11 PRN 22–25 double-difference measurement errors for L1 C/A code (top) and carrier phase (bottom).

Fig. 12 PRN 22–25 double-difference measurement errors for L1 P code (top) and carrier phase (bottom).

Fig. 13 Fahrenberg location with unobstructed view to Lake Kochel and Lake Walchen.

EXPERIMENTAL SETUP AND DATA ACQUISITION

The experiment was conducted on 16-20 July, 2007, 50 km south of Munich, Germany, in the Bavarian alpine upland at the mountain top of Fahrenberg (11.32°E, 47.61°N, 1625m above sea level) with unobstructed view to Lake Kochel and Lake Walchen. The lakes are situated 1026m and 824m below the receiver position, respectively (Fig. 13). A single conventional GPS patch antenna (JAVAD MarAnt+ antenna, size: 142 x 142 x 53mm, weight: 492g) was used and tilted by 45° from zenith direction (Fig. 14) to allow direct and reflected GPS signal reception in parallel. The active low profile right-hand circular-polarized (RHCP) patch antenna operates in the L1 and L2 frequency bands and the integrated low noise amplifier (LNA) has a gain power of 32 dB.

Depending on the predicted reflection event, the tilted antenna was oriented 24° azimuth toward Lake Kochel and 165° azimuth toward Lake Walchen, respectively. An external program communicates via the serial port with the GORS receiver and controls the measurement. Depending on the visible GPS signals and a user defined elevation and
Azimuth mask, a reflection event of one GPS satellite is triggered, defined by its pseudo random noise (PRN) number. The receiver records I and Q data of the target GPS satellite with a data rate of 200 Hz. The measurement stops in case the receiver loses track of the direct signal. During a reflection event the master channel continues to track the direct signal. A second, so-called slave correlator channel is set to the same GPS signal. With respect to the master channel the slave channel is steered with an additional delay in code space. Thus, the slave correlator channel is set to the estimated delay of the reflected signal. The estimated delay \( \delta \) is calculated using the observed elevation angle \( \epsilon \) of the target GPS satellite, the estimated height \( h \) of the target reflector and the speed of light \( c \) according to

\[
\delta = \frac{(2h \sin \epsilon)}{c}.
\]

Within the observation period both lakes show mirror-like surface conditions. A meteorological sensor and a tide gauge were installed at the shore of Lake Walchen to monitor the surface and wind conditions. Observed wave heights at Lake Walchen are limited to 2 cm.

**DATA ANALYSIS AND DISCUSSION**

Fig. 15 and Fig. 16 show the results of coherent GPS L1 C/A carrier phase observations of PRN 16 reflection event originated at Lake Kochel on July 19, 2007. At 6° elevation the fraction of reflected signal power recorded by the RHCP antenna with a peak power of 60% of the direct signal is very high. Strong interferometric fluctuations can be seen in the signal amplitude (Fig. 15). The signal amplitude is calculated from the recorded I and Q data. I and Q are obtained by the slave correlator which is steered at an additional delay of 0.73 code chips (Fig. 16, top left panel). Hence, the remaining correlation power of the direct signal is still sensed in I. Fig. 16, bottom left panel, shows I and Q data after applying a running average filter of 0.055 sec width and subtracting the mean power in order to filter noise and suppress the influence of the direct signal. Plotting the filtered data I versus Q, the evolving phase difference between direct and reflected signal can be recognized by the circular rotating movement of the I/Q vector, indicating a coherent reflection (Fig. 16, right panel). In a subsequent processing stage, which is currently under development, a relative height profile of the lake surface can be calculated using the known receiver and satellite geometry.

At Lake Walchen reflection events occur mainly at much higher elevation angles compared to Lake Kochel. Thus, the power of the reflected signal is expected to be much lower. Fig. 17 and Fig. 18 show the results of coherent GPS L1 C/A carrier phase observations of PRN 17 reflection event on July 18, 2007. At 25° elevation the RHCP antenna registers the reflected signal with 12% peak amplitude compared to the direct signal. Although the signal-to-noise ratio (SNR) has decreased in comparison to the previously shown PRN 16 observations from Lake Kochel, the typical interferometric pattern of a reflection event can clearly be observed. Beforehand, a running average filter with a width of 0.105 sec has been applied to the data (Fig. 17). The slave correlator was set to an additional delay of 2.33 code chips. Thus, no remaining correlation power of the direct signal can be sensed in I (Fig. 18, top left panel). Fig. 18, bottom left panel, shows I and Q data after applying a running average filter of 0.105 sec width in order to filter noise. The evolving phase difference between direct and reflected signal can be sensed by the circular rotating movement of I/Q vectors, indicating a coherent reflection (Fig. 18, right panel).

The GPS satellite with PRN 17 not only disseminates the L1 C/A signal but the new civil L2C signal, too. Fig. 19 and Fig. 20 show data of coherent GPS L2C carrier phase observations of PRN 17 reflection event on July 18, 2007 which have been recorded in parallel to the previously shown L1 C/A measurements. Although the SNR has further decreased to a value of 2.5% average amplitude compared to the direct signal, the typical interferometric pattern of a reflection event can still be detected (Fig. 19). Beforehand, a running average filter had to be applied on the data and the filter width has to be increased. Equal to the L1 C/A carrier phase measurements, the slave correlator was set to an additional delay of 2.33 code chips, but the filter width of the running average filter has to be increased to 0.205 sec (Fig. 20, left panel). Although dealing with very weak signals in case of the L2C carrier phase measurements, the evolving phase difference between direct and reflected signal can be recognized by the circular rotating movement of the I/Q vector (Fig. 20, right panel).

Figs. 21–21 show a 2 sec long data segment extracted...
from a GPS L1 C/A (blue) and L2C (magenta) I,Q data recording of PRN 17 reflection event originated at Lake Walchen on July 18, 2007. In Fig. 21 the filtered I and Q correlation sums of the slave correlator are plotted for the L1 C/A signal (blue) and L2C (magenta). Fig. 22, left panel, shows the evolving phase which is calculated from L1 C/A I,Q data (blue) and L2C I,Q data (magenta), respectively. The phase represents the phase difference between direct and reflected signal. From the unwrapped phase the difference in path length between direct and reflected L1 C/A (blue) and L2C (magenta) signal can be calculated for both carrier frequencies (Fig. 22, right panel). From the changing path length difference the altimetric height of the reflector can be derived in a subsequent processing step.

In order to overcome the limitation of only one steerable slave correlator, the following waveform measuring mode was implemented in order to scan the waveform of the reflected signal. As in the previously described measurements the slave correlator is steered according to the current predicted delay of the reflected signal. Additionally, the predicted delay is varied with time in small steps in a manner that an interval of +/- one code chip is covered. A waveform scan was conducted on July 19, 2007 which recorded a PRN 17 reflection event originated at Lake Walchen. The waveform recording measurement started at an elevation of 5° and continued until an elevation of 27° was reached. Plotting the resulting signal amplitude of each super-imposed single correlator measurement versus code delay for GPS L1 C/A and L2C, between 0.5 and +1.0 code chips delay the typical triangular waveform of the direct signal can be observed. The direct signal of GPS L2C has a peak amplitude of 50% in relation to the direct GPS L1 C/A peak amplitude. Although covered in the super-imposed single measurements, at delay offsets between 1.5 and 2.0 code chips, some of the reflected signal amplitudes are much higher than the noise level for both signals L1 C/A and L2C, respectively. Reflected GPS L1 C/A signals with amplitudes of up to 40% of the direct signal amplitudes can be observed. The reflected GPS L2C signal amplitudes reach up to 20% of the L1 C/A signal...
amplitude. Thus, the implemented waveform scan mode demonstrates the feasibility of measuring reflected waveforms with the GORS receiver prototype for applications in GPS scatterometry.

SUMMARY AND OUTLOOK

In the frame of the GITEWS project first promising results toward a multi-frequency GORS receiver could be achieved. As major step forward compared to current space receivers, the new receiver supports tracking of the civil L2C signal of the GPS constellation. This will enable loss-less dual-frequency tracking of occultation events down to very low altitudes. Channel slaving can be performed for GPS L1 C/A and L2C in parallel. Hence, carrier phase observations of coherent reflected signals are possible with two frequencies. By combining both observations and therefore enlarging the measuring wavelengths, coherent carrier phase observations of reflected signals are expected to be recovered even at higher sea roughness conditions. The COTS based GORS prototype successfully acquired and tracked GPS signals under simulated LEO space conditions. The receiver firmware was modified to record I and Q data with 200 Hz data rate for GPS L1 C/A, L2, and L2C. At the Fahrenberg location carrier phase observations of coherent signals, reflected from a mirror-like lake surface, could be recorded successfully for both GPS L1 C/A and L2C signals with a single, tilted RHCP patch antenna. The demonstrated waveform scan mode shows the feasibility of measuring reflected waveforms with the GORS receiver for applications in GPS scatterometry. In the next step the number of independent steerable correlator channels has to be increased. This allows recording of more than one reflection event in parallel which is an important factor for monitoring applications and tsunami detection [12]. Furthermore, the waveform can be measured by 16 or even more slave channels synchronously which also allows to stack these measurements in order to increment the SNR of the resulting reflected waveform. Additional signal simulator tests are scheduled and thermal vacuum and total
Fig. 19 Raw (blue) and filtered (black) amplitude fluctuations of coherent GPS L2C carrier phase observations of PRN 17 reflection event on July 18, 2007 at 25° elevation.

Fig. 20 Raw (blue) and filtered (magenta) 200 Hz I and Q data recorded by the slave correlator which is steered at an additional delay of 2.33 code chips and rotation of I,Q vector.

ionization tests are projected with the GORS prototype.

ACKNOWLEDGEMENT

The support of Spirent Communications in the preparation and performance of the signal simulator tests is gratefully acknowledged. The authors greatly acknowledge the cooperation and engineering support from JAVAD GNSS. This is GITeWS publication No. 19. The GITeWS project is carried out through a large group of scientists and engineers from GFZ and its partners from DLR, Alfred-Wegener-Institute for Polar and Marine Research (AWI), GKSS Research Centre, Leibniz-Institute for Marine Sciences (IFM-GEOMAR), United Nations University (UNU), Federal Institute for Geosciences and Natural Resources (BGR), German Agency for Technical Cooperation (GTZ), as well as from Indonesian and other international partners. Funding is provided by the German Federal Ministry for Education and Research (BMBF), Grant 03TSU01.

REFERENCES


Fig. 21 Filtered 200 Hz I and Q data of coherent GPS L1C/A (top panel, blue) and L2C (bottom panel, magenta), respectively.

Fig. 22 Raw and filtered 200 Hz I and Q data recorded by the slave correlator which is steered at an additional delay of 2.33 code chips


