# Qualification of a Commercial Dual-Frequency GPS Receiver for the e-POP Platform onboard the Canadian CASSIOPE Spacecraft

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## INTRODUCTION

CASSIOPE, the CAScade demonstrator Smallsat and IOnospheric Polar Explorer, is a Canadian satellite scheduled for launch in 2007. It is a hybrid mission designed for a wide range of tasks including space-based communication, high capacity information delivery, and observations of the Earth's atmospheric environment. A dedicated suite of eight scientific instruments, called e-PoP, will investigate space storms in the upper atmosphere and provide GPS-based navigation information. In view of budgetary restrictions, the design of e-PoP is based on the use of commercial-off-the-shelf (COTS) GPS receiver technology and NovAtel's OEM4-G2L dual-frequency receivers have been selected as the candidate hardware for this project. A total of five receivers on the satellite will be used for high precision navigation, attitude determination, and radio occultation measurements. These receivers will be cleared by the Canadian government for operation outside the common altitude and velocity limitations, but will not otherwise be significantly modified or adapted for the space application.

Experience in the use of commercial components for spaceborne GPS receivers has earlier been collected on other missions, but is so far restricted to low-grade single-frequency receivers and a limited range of correlator chipsets. e-PoP in contrast, aims at the use of a fully commercial, geodetic grade dual-frequency receiver with no heritage in space applications. An extensive series of tests has therefore been conducted to assess the suitability of the envisaged approach. These include GPS signal simulator tests to validate the signal acquisition and tracking performance, as well as environmental tests to demonstrate the survivability of the receiver hardware under space conditions.

## THE e-POP MISSION

The Enhanced Polar Outflow Probe (e-POP) is a satellite mission to investigate atmospheric and plasma flow processes in the polar ionosphere. Its primary science objective is to study the detailed quantitative relationship between the solar electromagnetic (EUV) energy input, the photo-ionization of the polar region of the atmosphere, and the acceleration and outflow of the polar wind plasma and accompanying neutrals to the magnetosphere. The data to be returned will help to unravel the micro-scale characteristics of plasma acceleration and outflow and its effect on radio propagation.

The e-POP satellite mission is funded by the Canadian Space Agency and the Natural Sciences and Engineering Research Council of Canada. Development work is being managed through the Department of Physics at the University of Calgary with a team of instrument principal investigators and researchers at 10 Canadian universities as well as government agencies in Canada, the United States, and Japan. Several private sector companies are involved in constructing mission hardware and the spacecraft bus.

The e-POP platform includes a suite of eight scientific instruments including plasma imagers, radio wave receivers, magnetometers, and cameras. Canadian research teams will provide six of these instruments, one will come from Japan and the other one from the United States. Among these instruments is the GPS Attitude and Positioning Experiment (GAP).

The e-POP mission, originally intended to involve a separate satellite, has been combined with another mission: CASCADE. CASCADE will demonstrate a potential new communications service that will allow very large amounts of information to be delivered to anywhere in the world. If successful, the demonstration will pave the way for a commercial “digital package delivery service” to users ranging from oil and gas exploration companies to medical facilities in isolated communities.

The combined platforms will be hosted on the three-axis stabilized CASSIOPE small satellite.

CASSIOPE is envisaged to have a hexagonal shape with dimensions of roughly 1.5 m x 1.5 m x 1 m with a mass of approximately 375 kg. The nominal orbit characateristics are given in Table 1.

| | |
|---|---|
| Semi-major axis | 7280 km |
| Eccentricity | 0.08 |
| Apogee | 1500 km |
| Perigee | 325 km |
| Inclination | 80° |

Table 1. CASSIOPE nominal orbit parameters.

Overall responsbility for the CASSIOPE spacecraft rests with MacDonald, Dettwiler and Associates, Richmond, British Columbia, Canada. The spacecraft bus is being designed and constructed by Bristol Aerospace Ltd., Winnipeg, Manitoba, Canada.

## RECEIVER SELECTION

The GAP instrument for e-POP is designed to be a multi-function instrument, providing both engineering and scientific data. Not only will it determine the position and velocity of the spacecraft in real time, it will also determine its attitude in real time and provide a clock signal to the rest of the spacecraft. And, through post-processing downloaded pseudorange and carrier-phase data, high-fidelity spacecraft trajectory and attitude will be determined. In addition to these kinematic and clock parameters, GAP will also be used for measurements on setting or occulted GPS satellites to determine profiles of ionospheric electron density. The GAP instrument is being designed and constructed in collaboration with Bristol Aerospace.

For convenience, the kinematic and clock functions are referred to as GAP-A and the occultation function as GAP-O.

The GAP instrument consists of five GPS receiver cards, a controller, an antenna switching module, and five antennas with associated preamplifiers. The four antennas to be used for GAP-A will be mounted on the zenith-facing side of the spacecraft and one antenna for GAP-O on the anti-velocity side.

The GPS receiver cards to be used are NovAtel OEM4-G2L dual-frequency units (see Figure 1) [1]. The OEM4-G2L is a small, high-performance, self-contained receiver with a rich heritage of novel receiver design. The NovAtel OEM series of receivers have been used in a wide variety of demanding applications including machine control, deformation monitoring, and airborne applications. Four of the receivers will be fed by zenith-facing microstrip patch antennas; the fifth by a NovAtel “pinwheel” antenna.

The five GPS receiver cards will be housed in a stacked aluminum enclosure together with an antenna switching card which will permit switching the occultation antenna between two of the receiver cards. An additional enclosure will house a power supply card and an interface card. The interface card interfaces the e-POP data handling unit with the receiver cards. It is based on a Bristol Aerospace controller architecture with spaceflight heritage and with an added field programmable gate array.

Early in the mission design, it was decided to base the GAP instrument on a COTS dual-frequency receiver rather than a space qualified one. The decision was based primarily on economics. Of course, this raises the issue of whether a receiver intended for terrestrial applications could withstand the rigours of spaceflight. A series of tests were carried out to help determine the viability of using a COTS GPS receiver for a satellite mission.

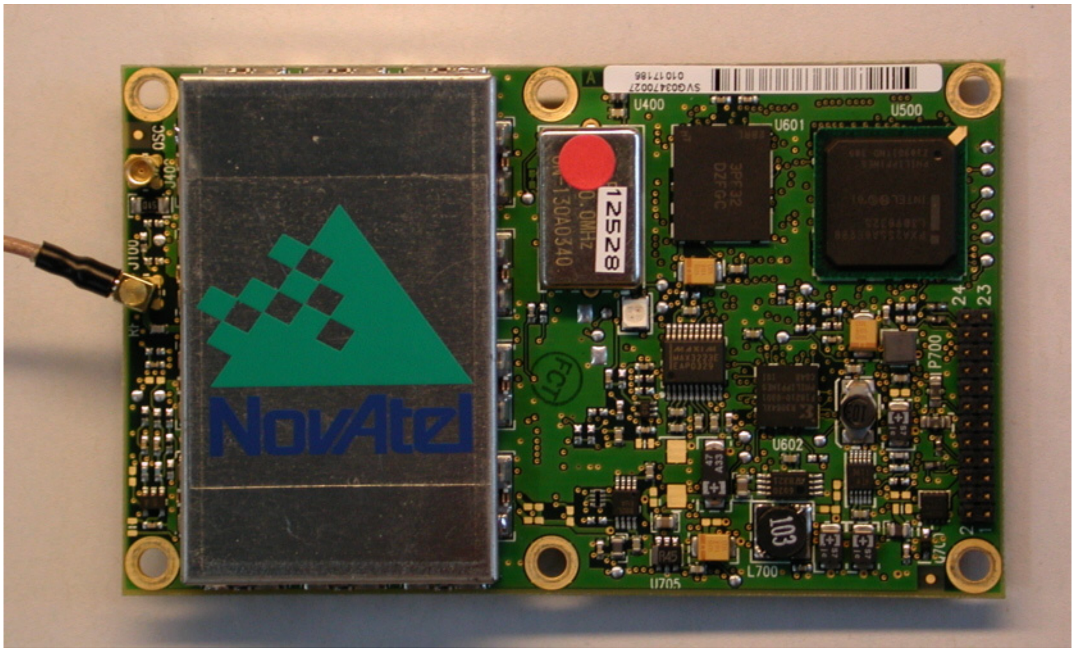

Fig. 1. The NovAtel OEM4-G2L dual-frequency GPS receiver

## TRACKING TESTS

As a first test, the capability of the receiver to properly acquire and track GPS signals under the increased signal dynamics of an orbiting spacecraft was verified. At an orbital speed of roughly 7.5 km/s, Doppler shifts of up to 40 kHz may be encountered that far exceed the design specification for a terrestrial or aerospace GPS receiver. Likewise, the receiver must be able to cope with much higher line-of-sight acceleration that amount to roughly 1 G for a receiver in low Earth orbit (LEO) but might even be much larger when tracking a boosted launch vehicle. The high-signal dynamics is of particular concern due the fact that geodetic receivers should employ tight tracking loop bandwidths in order to minimize the tracking noise. This might result in steady state tracking errors and, in extreme cases, a loss-of-lock whenever the receiver is subject to increased acceleration or jerk.

We tested a NovAtel OEM4-G2 receiver [2], a similar receiver to the OEM4-G2L but with different input/output capabilities and a higher power drain. Being designed for terrestrial and airborne applications, the OEM-4-G2 receiver does not provide dedicated commands or operations modes for GPS LEO tracking. Despite this apparent limitation, it turned out that the receiver is, nevertheless, well able to acquire and operate under such non-nominal signal conditions.

To assess the tracking performance of a spaceborne GPS receiver, artificial GPS signals are generated which closely match the signals received by a LEO spacecraft. The raw measurements and the navigation solution obtained by the receiver may then be compared against the simulated values. Other than ground based testing with a roof antenna, the use of a signal simulator provides a realistic signal dynamics including high Doppler shifts and line-of-sight accelerations.

All tests were conducted at the ESA/ESTEC Radio Navigation Laboratory in Noordwijk, The Netherlands. A Spirent STR4760 signal simulator supplying 12 channels of L1 (C/A-code+Pseudo-Y) and L2 (Pseudo-Y) was used.

The simulation was configured for a spacecraft orbiting the Earth in a near polar-orbit of 450 km altitude, 87° inclination, and an eccentricity of 0.005, rather than the expected CASSIOPE orbit. The epoch, which coincides which the ascending crossing of the equator, was chosen as 6 November 2001, 0:00 GPS Time, i.e. the beginning of day 2 of GPS week 1139. Consistent with this epoch the GPS constellation is modeled based on the actual GPS almanac for week 1138. Typically, all relevant test data can be collected in a simulation run of two hours.

The signal level of the GPS signal simulator was set to +14 dB (referred to the GPS-specified guaranteed signal strength of –130 dBm for L1C/A, -133 dBm for L1P(Y) and – 136 dBm for L2P(Y)). This results in C/A-code carrier-to-noise ratios (C/N0) of about 38- 48 dB-Hz and P2 code C/N0 values of about 31-43 dB-Hz roughly matching those obtained with standard ground-based antennas.

The key results of these tests are as follows:

1. Other than expected prior to the test, no special aiding was required to assist an initial acquisition. Without any user intervention, a first satellite was usually acquired within a minute after booting the receiver and a 3D navigation solution was achieved in 2-12 min. Subject to the availability of an almanac, the remaining of GPS satellites were typically acquired within a minute after the first position fix.

2. In view of a tight control of the reference oscillator frequency, all measurement epochs can be considered to refer to GPS time without any further correction. Peak clock offsets are well below 100 ns, which is negligible even at orbital velocities of about 7.5 km/s.

3. The carrier-phase smoothing of pseudorange measurements employed inside the OEM4-G2 receiver does not exploit the full potential of dual frequency measurements and is sensitive to code-carrier divergence. In view of notable ionospheric path delay variations (~10 mm/s) the smoother time constant should not exceed a value of 10 s in a LEO application. The default smoothing interval of 100 s recommended for terrestrial usage results in unacceptable code measurement errors.

4. At a representative C/N0 ratio of 45 dB-Hz, a noise level of 0.3 m, 0.8 mm, and 1.5 cm/s was obtained for unsmoothed pseudorange, carrier phase and Doppler measurements on the L1 frequency. Almost identical accuracies (0.3 m, 1 mm/s, and 1.5 cm/s) were obtained for L2 tracking at the corresponding carrier-to-noise ratio of 39 dB-Hz under Anti- Spoofing (i.e., P-code encryption).

5. The L1 and L2 code measurements exhibit a latency of 1.0 µs and 3.1 µs (assuming proper synchronization of all signals in the STR4760 signal simulator).

6. The carrier-phase noise level and the absence of acceleration errors indicates the use of a wide band (ca. 15-20 Hz) 3rd order phase-locked loop for carrier tracking. The receiver should thus tolerate even much higher signal dynamics than encountered onboard a LEO satellite.

7. A moderate correlation exists between the L1 and L2 phase measurements, which slightly reduces the noise level of the ionosphere-free linear combination compared to the value expected for uncorrelated measurements.

8. The Doppler measurements exhibit systematic variations of about 5 cm/s that clearly exceed the short term measurement noise. Also, the measurements appear to be ahead of their time tag by 5 ms. Based on the observed noise level and the lack of an acceleration dependence it is suspected that the Doppler data are actually obtained by 2nd order finite differences of the carrier phase measurements. The extreme correlation of D2 and D1 Doppler measurements furthermore shows that both data types are not independent but derived from a single, common source.

9. The navigation solution is notably corrupted by the application of tropospheric range corrections irrespective of the receiver’s altitude. For a circular low Earth orbit, this results in an average radial offset (–13 m) of the computed position and a much higher scatter than expected from the native measurement accuracy. The velocity solution for the LEO orbit exhibits a radial error of about –5 cm/s, which is most likely due to a systematic timing error of the Doppler measurements (ca. 5 ms).

Overall, the tests demonstrate that high-precision dual-frequency tracking of low Earth orbiting satellites using an OEM4-G2 receiver (or, by implication, an OEM4-G2L) is feasible even with unmodified, standard firmware. Operation of the receiver at the higher than normal signal dynamics is made possible by a safe cold start capability and robust tracking loop settings. Even though the receiver achieved a 3D navigation status without any user intervention in all tests, additional commands for setting the approximate receiver velocity or for position-velocity aiding based on orbital elements would, however, be highly desirable to improve the time-to-first-fix. A complete report on the tracking tests has been completed [3]. Tests of the capability of the OEM4-G2 receiver to support formation flying have also recently been completed [4].

## RADIATION TESTING

In the series of signal simulator tests described above, the receiver appeared to be capable of supporting the increased signal dynamics of an orbiting satellite. However, it remained unclear whether the employed Minos-4 correlator and the Intel PXA250 microprocessor (which is manufactured in a 0.18µ process [3]), would tolerate the radiation environment typically encountered in a low Earth orbit.

To address this question, a total ionizing dose (TID) radiation test has been performed at the Fraunhofer Institute for Technological Trend Analysis (FhG/INT) using a Cobalt-60 gamma ray source. Similar tests with DLR's COTS-based GPS Orion and Phoenix receivers have demonstrated a representative total dose tolerance of 15 krad but demonstrated an increased rate of cycle slips and a systematic frequency offset of the reference oscillator in proportion to the applied total dose [6].

Due the pronounced cost of the OEM4-G2L, it was decided to avoid a destructive test and limit the applied total dose to a value of 10 krad. This would allow subsequent use of the receiver in other tests.

In accord with the concept proposed in [6], the total dose test of the OEM4-G2L GPS receiver was performed in a zero-baseline configuration, in which the test receiver and a reference receiver were jointly connected to a roof-top antenna. In this way the impact of ionizing radiation on the tracking performance could be studied along with physical parameter changes (current increase) monitored in traditional radiation tests.

The overall test setup is illustrated in Fig. 2. Equipment to the right of the dashed red line was placed inside the locked test chamber throughout the test. Only the receiver main board was directly exposed to gamma radiation, while the interface board and support electronics were placed behind a concrete/lead wall with a separation of 2-3 m from the source. The reference receiver available for the test was an OEM4-G2 receiver, operating a slightly different software release than the test receiver. Despite the subtle hard- and software differences, both receivers exhibit a sufficiently high level of communality to allow their joint use in a zero-baseline test. The separation between the Gammamat TK1000 Co60 source and the test receiver was adjusted to a value of 28.2 cm to achieve the desired dose rate of 1 rad/s. This setting accounts for the predicted source activity on the test day and would be different on other dates or after replacement of the cobalt pill. Since the distance of the (point-) source and the receiver exceeded the semi-diagonal length of the OEM4-G2L board (58.3 mm) by more than a factor of three, a beam homogeneity of better than 90% was assured in accord with common test specifications ([7], [8]).

Two radiation tests have been conducted on different receivers.

### Radiation Test 1

For the first test, the receiver was irradiated from 8:00:00 GPS time for a total of 10000 s (roughly 3 hours) thus giving an accumulated total ionizing dose of 10 krad. No malfunction occurred during this period and the receiver remained fully functional throughout the test and immediately thereafter. A more detailed discussion of physical parameter changes and tracking quality is given in the subsequent section.

#### *Current Consumption*

The OEM4-G2L receiver has a specified power consumption of 1.8W, which corresponds to a 550 mA supply current at the 3.3 V operating voltage. If the low noise amplifier of the antenna is fed by an external power source, this current is further reduced by 35-50 mA thus yielding a typical value of 500 mA. However, the actual consumption exhibits pronounced short-term and long-term variations. Over time-scales of a few seconds, a typical jitter of 20 mA (peak-to-peak) was observed, which was ultimately compensated by a 3 s integration interval in the current measurements during the radiation test.

Over extended intervals, fluctuations were observed which are apparently related to the overall number of tracked satellites and the related change in processor activity. For example, current consumptions down to 420 mA were encountered in an earlier test with only five satellites in view. As a best estimate, the power consumption can be assumed to change by roughly 3.3% with each additional satellite handled by the receiver.

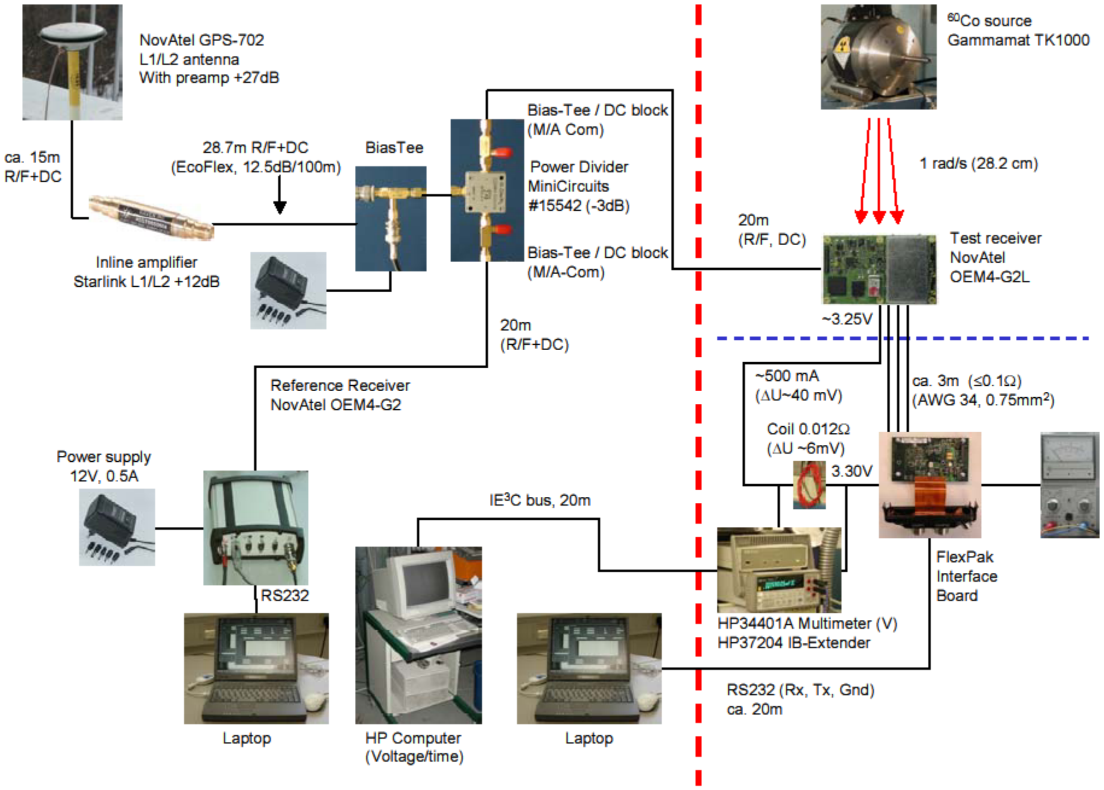

Fig. 2. Test setup for OEM4-G2L total ionizing dose test

The current consumption measured before, during and after the irradiation are illustrated in Fig. 3. For ease of interpretation (and due to the lack of calibrated measurements) only relative changes with respect to the start time are given. Furthermore, sudden changes in the power consumption caused by the changing satellite visibility have been compensated by adding or subtracting integer multiples of 3.3%. The resulting graph shows a near negligible change in the power consumption for the initial 4000 s (4 krad total dose) and a near constant increase by up to 6% near the end of the test (10 krad total dose). While a small degradation of the receiver electronics is evident, the receiver did not break down during and continued to operate properly throughout the test.

*Oscillator Drift*

Based on experience with the GPS Orion and Phoenix receivers [6], a radiation induced variation of the reference oscillator frequency was considered a potential concern in the OEM4-G2L tests.

In standalone operations, the OEM4-G2L receiver employs an internal 20 MHz voltage controlled, temperature-compensated crystal oscillator (VCTCXO) as its reference frequency [9]. A clock filter estimates the instantaneous clock bias and clock bias rate from the navigation solution and steers the oscillator such as to drive both values to zero. By default a 0.03 Hz bandwidth is employed in the clock steering process [10]. Since any changes in the reference frequency caused by environmental effects are directly compensated by the clock steering process, the actual oscillator frequency remains essentially constant during normal operations unless the (unknown) control dead-bands are violated.

As a consequence, radiation induced frequency variations could not be measured directly but had to be inferred from the output of the control loop. To this end use has been made of the CLOKSTEERING data log of the OEM4-G2L receiver, which was recorded at 10 s interval throughout the test. It provides the value of the “pulsewidth”, which is continuously adjusted by the clock steering process in an attempt to drive the receiver clock offset and drift terms to zero [10].

The variation of the pulse width parameter before, during and after the irradiation was noted. While a change in the gradient of the pulse width curve is evident right at the start and end of the gamma-ray exposure, the pulse width values remain well within the range encountered in normal operations. This is nicely illustrated by the respective values of the OEM4-G2 test receiver, which was operated outside the radiation at a likewise near constant room temperature.

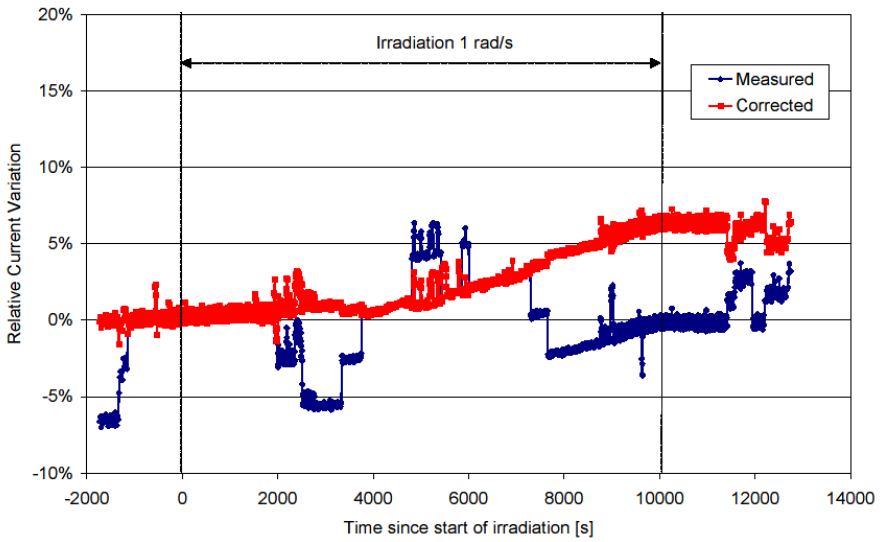

Fig. 3. OEM4-G2L current consumption. Actual measurements are indicated by blue diamonds. The red curve has been adjusted for the varying number of processed GPS satellites by adding or subtracting multiples of 3.3%.

### *Tracking Accuracy*

The position and velocity solution generated by the OEM4-G2L receiver did not exhibit any outliers that would indicate an instability of the tracking process as a result of the radiation exposure. Since bad measurements might not enter the navigation solution due to the application of a data screening process inside the receiver, it was decided to further assess the raw tracking data quality. To this end, the measurements were differenced against the reference receiver and further among a pair of GPS satellites (PRN 6 and 21) with continued visibility during the entire data arc. The zero-baseline double differences provide a direct indication of the measurements noise and can readily be used to identify cycle slips in the carrier tracking process. In accord with earlier recommendations for spaceborne applications [3], carrier phase smoothing of the code measurements has been deactivated (or minimized) by the “CSMOOTH 2 5” command.

Double differences for all measurements types (C/A and P2 code, L1 and L2 carrier phase and Doppler) were examined. Representative L1 carrier phases are shown in Figs. 4. For clarity, the initial values of the carrier phase ambiguity have been removed. Evidently, no traces of radiation induced tracking errors may be recognized. In particular, no cycle slips have been encountered even at low elevation angles with an inherently worse carrier-to-noise ratio. This observation corresponds well with the lack of a pronounced oscillator frequency shift and suggests a much better of performance of the Filtro VCTCXO oscillator compared to the TCXOs employed in the Orion and Phoenix receivers.

Unfortunately, a couple of days after the radiation test, the receiver failed to operate. On powering on the receiver, the onboard status indicator LED did not light and the current consumption was only about 330 mA compared to the normal current of at least 420 mA. A post-mortem analysis of the receiver board by NovAtel found a permanently-pulled-down reset line on the microprocessor indicating that the microprocessor had failed, possibly due to electrostatic discharge (ESD) but radiation damage could not be ruled out. The microprocessor was replaced and the receiver then operated within specifications except that the 5 V supply for the antenna low-noise amplifier was now 5.16 V instead of a maximum value of 5.1 V. It was speculated that perhaps a voltage regulator on the board also suffered damage.

A preliminary report on the first radiation test has been completed [11].

## Radiation Test 2

In light of the inconclusiveness of the first radiation test as to whether the receiver failed due to ESD damage or radiation-induced damage, a second radiation test was carried out on two more OEM4-G2L receivers.

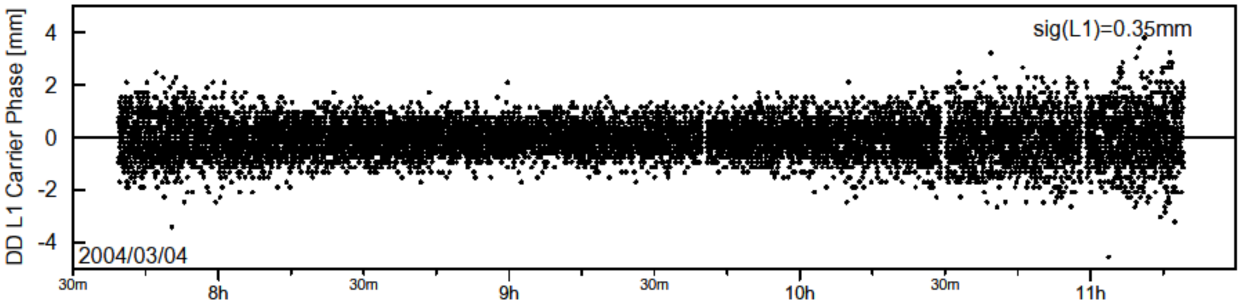

Fig. 4. Double differences of L1 carrier-phase measurements for the PRN 6-21 satellite pair. Short data gaps are caused by serial communication dropouts in the reference receiver data log.

For the second test, receiver power was cycled off and back on during the test. The first receiver was rebooted after one hour (at 3.6 krad) as well as after two hours (at 7.2 krad). In accord with the previous test, a small increase in the average current as a response to the accumulated dose was observed during the second hour of the test. No other signs of degraded performance were apparent. However, despite the flawless operation up to this time, the receiver failed to reboot after the second power cycling. The current consumption amounted to only 60-70% of the nominal value, no communciation could be established, and the LED on the receiver board remained dark.

In view of this unexpected and surprising result, we decided to deviate from our original test plan and conduct the test of the second receiver with more frequent (once per krad) interrupts. This procedure is less suited for analysis of the tracking behaviour and power increase but allows a better bounding of the range of critical total doses. This time the receiver survived the reboots up to a TID of 5 krad but failed after 6 krad.

After a week or so, the first receiver tested (radiated to 8 krad TID) was still dead but the second receiver (radiated to 6 krad TID) came back to life. A plan to bake the first receiver to see if self-annealing might bring the receiver back to life was considered, however as a result of discussions with colleagues at Bristol Aerospace on possible causes of the receiver's failure, it was decided to by-pass the low-voltage monitor on the board (a TCM811 integrated circuit). This device is used to monitor the input power to the board and hold the microprocessor in a reset condition until the voltage reaches about 3.08 V. Most such monitoring devices contain a band gap reference which is susceptible to radiation.

The TCM811 was removed from the dead receiver board and replaced with a manual reset circuit. After powering on the receiver and manually switching the receiver out of the reset condition, it operated normally. Clearly, the TCM811 had failed during radiation testing. For use on the e-POP mission, the low-voltage monitor integrated circuits on the OEM4-G2L boards will be removed and reset logic provided on the GAP interface card.

Overall, and despite the low-voltage monitor failure, the radiation tests demonstrated a surprisingly high robustness of the OEM4-G2L GPS receiver against ionizing radiation despite the use of advanced (and potentially sensitive) electronic components. However, it should be kept in mind that single event effects have not been assessed within the TID test. While appropriate unit level tests may be difficult to perform, a latch-up protection should certainly be considered in the design of the receiver interface electronics, to avoid the risk of irreparable receiver damages.

## THERMAL VACUUM TEST

The thermal characteristics of the OEM4-G2L receiver board operating under vacuum were unknown. Therefore a thermal vaccum (TVAC) test was conducted to help define the thermal model of the GAP receivers that would be used for the overall thermal model of the GAP instrument. The results of the test would also be used to determine what thermal mitigation schemes, such as thermal staking, might be necessary.

An OEM4-G2L receiver board was subjected to a TVAC test using facilities at Bristol Aerospace. The receiver was tested from –35°C (-40°C unpowered) to +50°C in a small vacuum chamber under a vacuum of about $10^{-5}$ torr. The board was outfitted with about 13 thermistors that were monitored during the test. Before the test, the receiver's Minos-4 ASIC was removed and resoldered with thermal compound added between the ASIC and the board since it was suspected that it might be a significant heat generator. Facilities did not exist to remove and replace the ball grid array PXA250 microprocessor so that it, too, could be thermally staked. During the test, the board was powered, its voltage and current monitored, and connected to an external antenna. Raw pseudorange and carrier-phase data were collected at a 1Hz data rate . The test went well. As confirmed by post-processing the collected data, the receiver performed normally throughout the test. The only anomaly was a communication failure between the data recording computer and the receiver towards the end of the test when the chamber was at 50°C. After about 20 minutes of operation at this temperature, the computer stopped logging data. This appeared to be a computer software / serial-port problem as a reboot of the computer rectified the problem.

The temperature of the hotest component on the board was only about 22°C different from the temperature of the thermal control plate. During the test, power consumption of the board was near nominal. It consumed about 200 mW more power at the extreme high temperature of the test.

## CONCLUSIONS

The tests conducted so far provide good evidence for a proper functioning of the OEM4-G2L receiver in a low Earth orbit satellite and opens up new prospects for future low-cost science missions. Once qualified, the use of a geodetic grade COTS receiver offers a factor of ten or more cost saving compared to presently available dual-frequency GPS receivers for space applications. Among others, use of an OEM4-G2L receiver has already been suggested for the next Sunsat mission of Stellenbosch University

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] *OEM4-G2L Data Sheet*, NovAtel, <http://www.novatel.ca/Documents/Papers/oem4g2.pdf>, 2003.

[2] *OEM4-G2 Data Sheet*, NovAtel, <http://www.novatel.ca/Documents/Papers/oem4g2l.pdf>, 2004.

[3] O. Montenbruck, *Performance Assessment of the NovAtel OEM4-G2 Receiver for LEO Satellite Tracking*; DLR-GSOC TN 03-05, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, 2003.

[4] R. Kroes and O. Montenbruck, “Spacecraft Formation Flying: Relative Positioning Using Dual-Frequency Carrier Phase,” *GPS World*, Vol. 15, No. 7, pp. 37-42, July 2004.

[5] Intel PXA250 Applications Processor with Intel XScale Technology, Intel Product Brief #298621, <http://www.intel.com/design/pca/prodbref/pxa250.pdf>, 2002.

[6] M. Markgraf and O. Montenbruck, *Total Ionizing Dose Testing of the Orion and Phoenix GPS Receivers*, DLRGSOC TN 04-01, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, 2004.

[7] ESA/SSC, *Total Dose Steady-State Irradiation Test Method*, ESA/SCC BASIC Specification No. 22900 Issue/Rev. 4, April 1995.

[8] M. Dentan, “Overview of the ATLAS Policy on Radiation Tolerant Electronics*,” Proceedings of the 6th Workshop on Electronics for LHC Experiments*, Cracow, Poland, 11-15 September 2000, CERN-2001-005/CERN-LHCC-2001-034.

[9] *OEM4 Family of Receivers User Manual - Vol. 1 Installation and Operation*, OM-20000046, Rev. 12, 2003/07/31, NovAtel Inc., Alberta, Canada, 2003.

[10] *OEM4 Family of Receivers User Manual - Vol. 2 Command and Log Reference*, OM-20000047, Rev. 12, 2003/07/31, NovAtel Inc., Alberta, Canada, 2003.

[11] M. Markgraf and O. Montenbruck, *Total Ionizing Dose Testing of the NovAtel OEM4-G2L GPS Receiver*, DLRGSOC TN 04-04, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, 2004.