# A GNSS receiver for small-sats enabling precision POD, Radio Occultations and Reflections

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## ABSTRACT

A low cost, low power, and low mass GNSS receiver (called Cion) has been developed and is currently flying on the CICERO cubesats. The receiver was designed in less than a year by JPL for Tyvak and GeoOptics for use in the GeoOptics CICERO constellation and leverages 25 years of JPL GNSS reciever design experience. Cion uses a commercial off-the-shelf (COTS) computer along with existing space qualified RF down-converters, software, and firmware to produce atmospheric Radio Occultation (RO) data. By combining a FPGA with dual core ARM processor and an embedded system controller, the Xilinx Zynq processor is an enabling technology that provides a customizable digital signal processing platform integrated into the computer (System on a chip) and enables off-the-shelf hardware to become the main engine behind this software defined radio. Using Linux for the on-board computer allows for fast development times and liberal use of existing open source software libraries. The parts of the receiver that require real-time implementation are performed in the Field Programmable Gate Array (FPGA), which can also be reprogrammed in flight. While the Zynq is not rad hard, the silicon on insulator (SOI) technology is rad tolerant 'by accident', allowing for its use in many space-based applications. Early results show that the Cion is working as designed, has demonstrated the first known GLONASS occultations, and obtains high quality atmospheric profiles with excellent lower troposphere penetration (near Earth's surface).

Keywords: CICERO, GNSS, Radio Occultation, Cubesat, TriG, POD

## 1. INTRODUCTION

Billions of dollars' worth of transmitters orbit the earth every day. Launched from countries that have invested heavily in global navigation satellite systems (GNSS), these transmitters provide free signals that can be used by inexpensive earth orbiting receivers to determine precision satellite position & time, atmospheric conditions (via Radio Occultations), and Space Weather (via Total Electron Content (TEC) and scintillation). Through surface reflections, these transmitters can also provide data on sea surface roughness, soil moister, snow, ice, and even topography. While the receiver embedded in your phone uses a similar technology to quickly guide you to the latest 4.5 star, $$ restaurant, the ability to perform on-orbit science observations capable of discerning phase offset delays of a few picoseconds between two dual frequency transmitters, while processing the Doppler shifts and signals buried in the noise, is a whole different level of measurements. JPL has been designing precision receivers for ground use and the harsh space environment for over 35 years. For example, missions such as Jason, SRTM, GRACE and others have shown incremental improvements in positioning to the point where sub centimeter, post processed precision orbit determination is now common place. GNSS Radio Occultations began with GPS Met, CHAMP, and SAC C, and have proven to improve weather forecasting at a relatively low cost though missions such as COSMIC, GRACE, and others. Additionally, CYGNSS provides GNSS reflections of the ocean which can be used for tropical cyclone forecasting and possibly even soil moisture. The JPL designed, NASA funded TriG reciever is now flying on GRACE FO and is planned to be use on DSAC, COSMIC 2A (6), SWOT, NiSAR and Sentinel 6. This 'gold standard' is appropriate for flagship missions operating in harsh conditions with a five-year life-cycle, but is not a good fit for low cost, small sat missions.

Recently, under a reimbursable task with Tyvak and GeoOptics, JPL designed the Cion, a low cost and low power software defined radio receiver based on an 'off the shelf' computer- the PicoZed. This implementation approach was largely enabled by the availability of a combination of FPGA's, system controllers, and processors on a single chip (Zynq). The Zynq allowed for a custom interface between the high speed digital signal processing on the FPGA and an off-the-shelf embedded solution, whereas the previous state of the art needed a custom computer board that requires years to design, program, and implement. This transformation is also driven by the need for low cost and highly capable GNSS receiver payloads for the fleet of Cubesats being planned over the next few years. GNSS receivers for spaceflight often require custom designs for a number of reasons. These include:

1. Harsh environmental conditions such as: 16 temperature cycles per day as the orbits transition from day to night, the vacuum of space, and solar radiation. While total ionizing dose (TID) is the most widely known form of radiation, destructive latch up, bit flips, and transient voltages must also be considered. For low earth orbits, these effects are often ignored, but it is prudent to consider them even in the most benign environments.
2. Most of the time, GNSS receivers are used for position and timing, but other applications, including space weather, radio occultations (RO), and surface reflections (SR) can require customization in hardware, software, and digital signal processing. This can also require many separate RF inputs and techniques such as 'open loop tracking' (for RO) and Delay Doppler Maps (for SR).
3. Satellite Interfaces are often custom, driven off of 28 VDC, and can have communication, commanding, data packetization and other very specific requirements
4. Unique Mission designs such as:
   a. determining position and time from ***above*** the GNSS constellations in geosynchronous orbit.
   b. formation flying constellations
   c. continuous cycling to save on power

This paper will discuss the design approach for the Cion GNSS receiver, outline some key features, and show recent results from the first Cion in space.

## 2. CION INSTRUMENT DESIGN

The Cion Software and Firmware is largely based on previous GPS and GNSS reciever development at JPL with some aspects of the design going back over 30 years. This consists of a GPS antenna, RF Front end (Band pass filter and Low Noise Amplifier), RF downconverter, RF sampler, precision sample clock, digital signal processing (DSP) and software, running on an off the shelf embedded system with a real time operating system. In order to enable the quick turnaround required to build a cubesat RO instrument, a Novatel OEM 628 is used for POD and driving the tracking loops for this application, but future instantiations of this design will phase it out and implement that functionality internally (Figure 1). Additionally, as a software defined radio, other RF signal processing is accommodated by simply adding new downconverters and ADC's also planned for future designs. This section breaks down the key components of the design of the Cion for CICERO.

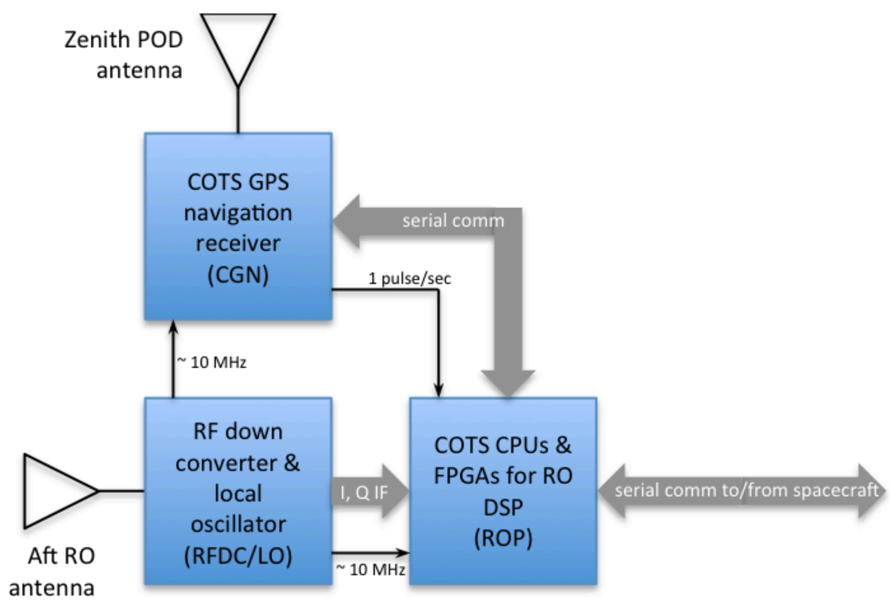


**Figure 1:** The basic Cion Architecture

### 2.1 Hardware

The Cion design was adapted by Tyvak to fit within a 6U cubesat and consists of an off-the-shelf Picozed embedded computer with a Xylinx Zynq 7030 as the CPU and FPGA. While the PicoZed is not typically intended for use in space, it was a good fit for this commercially led mission. Because other space processor cards use the Zynq and the ability to switch over to another platform is straight forward. This self-contained embedded computer runs the software and firmware described below and enables a rapid development time. The Host board supplies power for the PicoZed, interfaces with the flight computer, provides a high precision clock and clock distribution, and down-converts the GNSS signals (TriG heritage) before sending them to the Zynq for sampling, processing, accumulations, and correlation. A photo of the flight unit is shown in Figure 2.

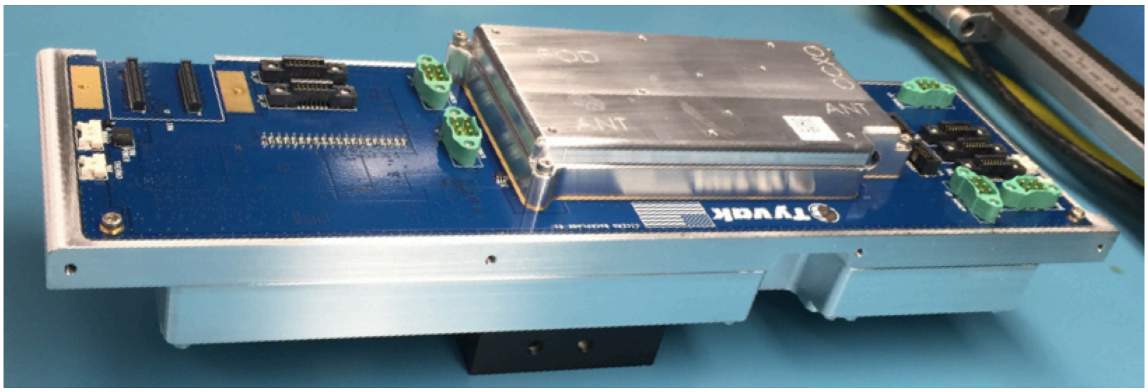

**Figure 2:** Tyvak Built Cion for CICERO

### 2.2 OS and Software

The brain of the Cion is the PicoZed, and at the heart of the PicoZed is the Zynq SoC. Along with the Zynq SoC the PicoZed contains all of the necessary peripherals for proper operation of the Zynq, including DDR3 memory, eMMC NAND flash, Ethernet PHY, and clocks. The Zynq SoC contains FPGA fabric with a high-speed connection to both 1GHz ARM Cortex-A7 processor cores as well as many on-board peripherals such as a gigabit Ethernet MAC and I2C, SD, UART, and SPI controllers.

The PicoZed has support for booting from both SD card and the on-board eMMC NAND flash memory. When development was completed, the eMMC was programmed with a golden image that would allow us to boot up if the sd card ever became corrupted.

We chose to use Yocto as our development environment. Yocto is a set of tools that allowed us to create our own, perfectly tuned, Linux distribution. It allowed us to easily build our custom software as well as any open-source tools that we need. It builds not only the Linux kernel, but the entire root file system.

The Zynq running Linux is the perfect host for an SDR system. Software defined radio takes much of the processing that was traditionally done in the analog domain and moves it to the digital domain. Having access to such a high speed processor and reconfigurable FPGA logic, allows us the flexibility of processing almost all of the GNSS signal on-board the Zynq. The Zynq is able to 1-bit sample the baseband signal from the RF downconverters. After that it is completely in the digital domain and our combination of firmware and software can process it to perform state-of-the-art radio occultation measurements.

Our software running under Linux on the Zynq performs several functions, including command and telemetry handling, programming of the RF downconverters, model generation for the FPGA DSP, streaming, scaling and packetizing the output from the FPGA DSP, and periodic logfile generation. The software architecture is such that many of these functions operate independently from the rest and communicate over sockets and files. The ability to make use of standard Linux system calls and the open-source glibc, libstdc++, and boost, granted a great ease of development, testing and verification.

The software developed for CION is easily portable to other ARM based systems. In fact, it has already been ported and is running well on another Zynq board called the CHREC Space Processor (CSP). The CSP is also based on the Zynq SoC, but targeted towards space operations. It could be used in a variety of missions in LEO and beyond. The software architecture that we developed can be expanded to incorporate other samplers including high speed multi-bit ADCs. The use of the Yocto development environment makes porting to other boards as simple as creating a new machine configuration file.

The process of porting the previous generation of the receiver software to Cion was greatly expedited by the fact that the TriG science processor and the Cion both use the Linux operating system. Minor updates had to be made in order to ensure that the software was compatible with the ARM processor utilized by the Zynq as well as with the digital signal processing on the Zynq's FPGA. Specifically, these included modifying and/or adding kernel drivers and software libraries. Otherwise, the similar directory structures meant that the overall software organization and architecture were preserved.

A major difference for Cion is that it utilized the COTS Novatel GPS receiver whereas the previous generation of the software was built to provide internal navigation solutions. Additional software was implemented as part of the new software architecture and GPS receiver interface in order to handle and service the serial data coming from the Novatel. In addition to fixing software bugs from the previous version of the receiver software, we were also able to make enhancements by leveraging off of prior experience working with the past system. Debugging scripts were developed using Python and Matlab for rapid troubleshooting during the initial stages of the porting process. Since these scripts directly used the software output data logs, they can also easily evolve into data analysis tools for the Cion receiver. Lastly, CMake was introduced for the compilation process for the Cion receiver software. The cross-platform compiler supports applications that depend on multiple libraries and greatly simplifies the building and testing process of the Cion software.

### 2.3 Zynq FPGA and Digital Signal Processing

The instrument uses a Zynq 7030 SoC device that contains a dual-core ARM processor paired with a reprogrammable FPGA in a single chip. Existing technology for JPL RO receivers was heavily leveraged for this design.

The FPGA uses a PLL locked to a 10MHz input reference clock to generate a 30MHz sampling clock. This clock is used to generate 1-bit samples of the input GPS I/Q antenna data. The existing receiver channel design tracks GNSS signals in the incoming data, referenced against carrier and code models as specified by FSW. The antenna data is mixed from IF to baseband, then correlated against the appropriate GNSS signal PRN code. Currently-supported GNSS signals include GPS L1CA, GPS L1P, GPS L2P, GPS L2C, GPS L5, Glonass L1CA, and Glonass L2CA. The time-tagged results of the correlation(s) are streamed to a storage FIFO. The FIFO is connected to a DMA interface that allows the FSW to access the data at a later time.

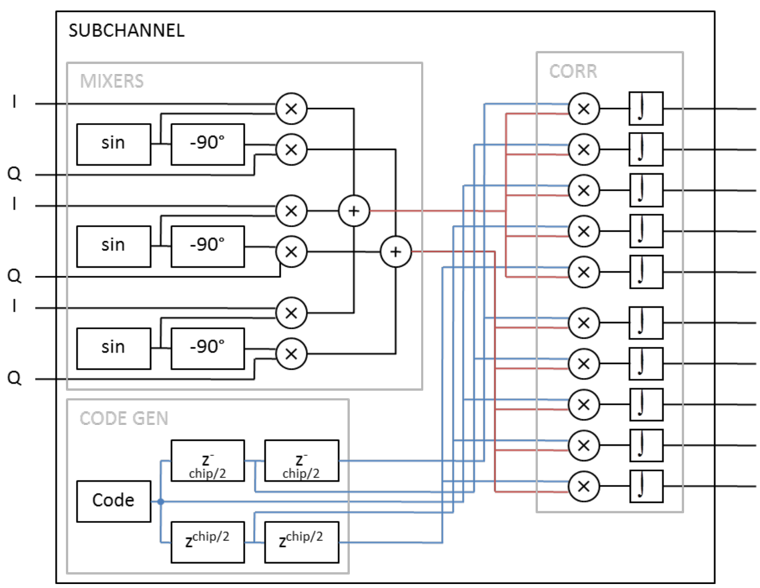


**Figure 3:** Single channel of the GNSS DSP logic.

Each DSP signal chain contains three mixers, each attached to separate antenna inputs (configurable by software) for potential beam forming (Figure 3). The sampled GNSS data is nominally mixed to baseband. The resulting baseband signal is correlated against five almost identical codes, with a one-half chip spacing in between each code. The correlation is performed over a software-defined number of samples, then packetized in preparation of being read out by software. The FPGA currently supports 21 independent signal chains which are grouped in sets of 3. Each channel (set of 3) is configured by software to track a single satellite (nominally L1CA, L1P, L2P or L1CA, L2CM, L2CL).

By leveraging many of the Xilinx FPGA cores and associated software drivers, existing GNSS DSP FPGA code was easily adapted to the Zynq platform. The control and data interfaces to the between the processor and the FPGA DSP logic were altered to use AXI4 and AXI4-Stream protocols. AXI4 interconnects support memory-mapped communication between the processor and the configuration registers of the various functional modules in the FPGA. Data flows—such as the raw data input and the processed data product outputs—are propagated throughout the design using the AXI4-Stream protocol. The Xilinx-provided DMA interface facilitates high speed data exchanges between the FPGA and the processor.

### 2.4 Open Loop Radio Occultation Software

GNSS signals are greatly attenuated as they are occulted by Earth's neutral atmosphere [1]. Previous implementations of radio occultation (RO) instruments employ traditional phase-lock loop processing; i.e. closed-loop, for ray-height altitudes above ~10 km and invoke an open loop (OL) signal processing mode for the region from 10 km to the surface where signal to noise ratio (SNR) becomes too weak to process using traditional phase tracking methods. Closed loop (CL) processing relies on maintaining a model signal from recent measurements and feeding back corrections, OL processing "guesses" the model signal based on orbits of transmitter and receiver, clock drifts and shifts in Doppler caused by the atmosphere [2]. On Cion, there is no closed-loop phase processing as on previous JPL RO missions, in spite of sufficient SNR at high ray heights. The entire occultation altitude range from approximately 100km to the surface is processed with an OL model. Maintaining OL processing over the full occultation altitude range simplifies the on-board processing and subsequent ground processing of the high-rate phase data by avoiding CL-OL transition boundaries where alignment of phase models and time tags must be maintained. Still, significant OL model errors in frequency and range will result in RO profiles with large biases, cycle slips.

To mitigate the effects of model error causing loss of signal, the Cion instrument uses parallel digital signal processing (DSP) channels to collect the 100 Hz phase results for the two frequencies of interest from each satellite in occultation. A real-time, 2nd order geometric range model is computed using GNSS broadcast ephemeris and instrument navigation solution. For regions below 30 km ray height, a real-time model of the atmospheric contribution to the range model, as a function of altitude and latitude, is added to the geometric model. This forms the total OL model which drives the DSP logic to correctly process phase and range. Test data shows the OL model used on Cion to have less than 20 Hz of frequency error and 60 meters of range error over 100 km to -120 km slant line-of-sight (SLA). OL model errors will contribute to SNR loss and can require much more cycle slip editing on the ground. Closed loop track can be less noisy at higher altitudes where the SNR is higher and signal dynamics are better behaved. But for Cion and the upcoming COSMIC-2 mission, closed-loop processing of RO data is removed in favor of less complex processing. Figure 4 shows the RO Doppler – the model for a COSMIC-1 RO profile. Note the first ~60 secs of the profile are closed loop processed, and Doppler error is zero. Figure 5 shows Cion RO Doppler – model for a recent RO profile. Note that there is some Doppler error, of up to 5Hz, in the first 35 seconds. This is the altitude range where closed loop tracking is employed in previous JPL instruments. Also, the Doppler scatter is larger due to the 100 Hz sampling vs 50 Hz for COSMIC-1. The Doppler error results in some loss of SNR but the effect here (100Hz data) is small, about 1.5% signal loss with 10 Hz model error.

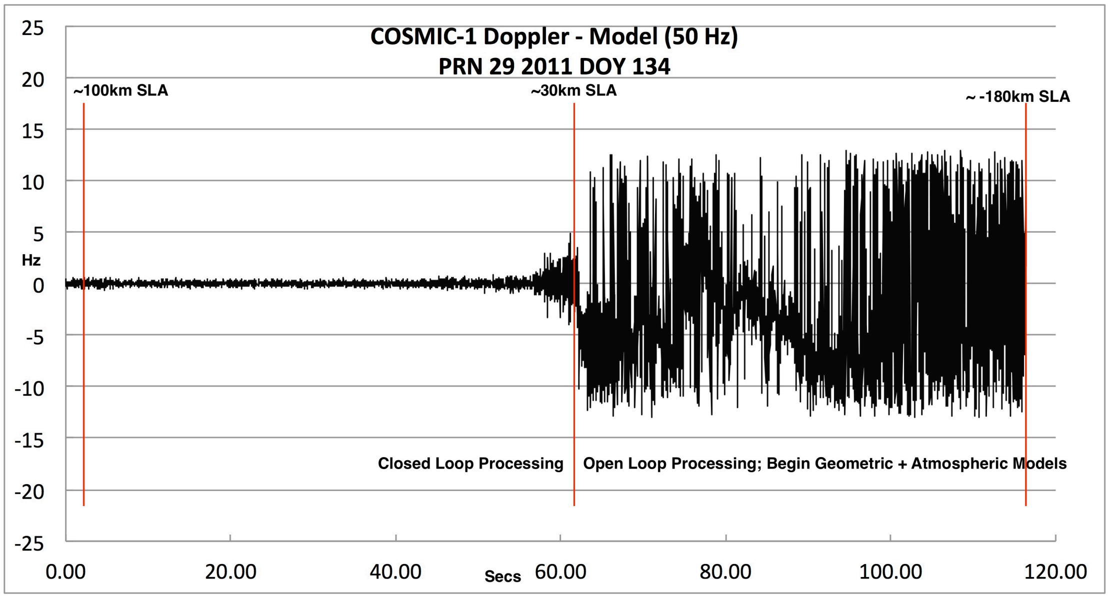


**Figure 4:** Residual Doppler using COSMIC 1 RO processing

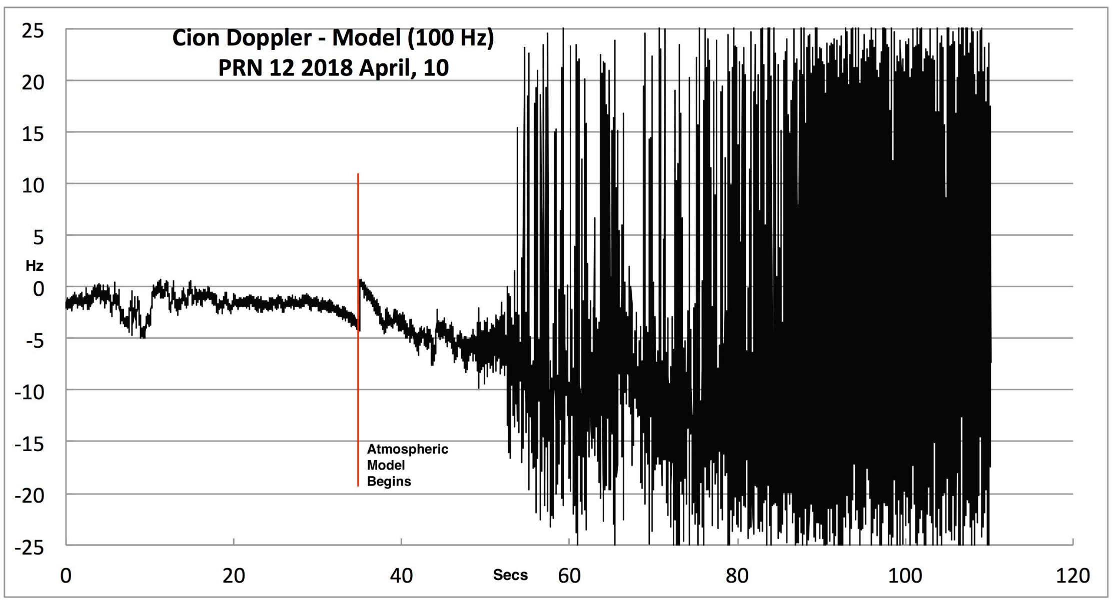


**Figure 5:** Residual Doppler using Cion RO processing

### 2.5 Cion Clock Strategy

High-rate RO phase-rate measurements contain errors from multiple sources. Contributions from system noise are significant. Error in our knowledge of the transmit and receiver clock rates can be a dominant error in certain instances. The GNSS satellite transmit clocks can be estimated from ground tracking data. The receiver clock must also be estimated. For CICERO, the Cion clocks are estimated from post-processed Precise Orbit Determination (POD) solutions at a 1-second rate. The sub-second clock rates are interpolated to RO measurement intervals using fits to 1-second POD estimates.

Besides reducing the data volume during RO by up to a factor of 2 compared to using a high-rate clock differencing satellite, this technique can produce more precise profiles. Because the receiver clock is more stable over short time intervals (<1 sec) than the GNSS satellite oscillators, we avoid substituting the poor short-term GNSS clock performance. Note that Cion clock steering is turned off during occultations to avoid introduction of short-term clock instability. In addition, we avoid significant error from the clock-difference satellite's low-gain zenith antenna measurements taken over short (~0.01 second) integrations. Instead, we fit the zenith antenna measurements over typically 2 seconds, and use all satellites tracked to estimate the Cion clock.

Using parameters representative of antenna gains, receiver and GNSS clock Allan Deviations, etc, for a CICERO satellite, we can calculate the estimated bending angle error using high-rate clock differencing versus the new clock-interpolation method. This example is for a 0.5 second fit at an altitude of about 30 km, and only includes errors due to the single-frequency CA code measurement. Depending on how much smoothing is used, additional noise will be contributed by the ionosphere.

Under these conditions the estimated bending angle error is 0.81 micro radians using high-rate differencing and 0.33 micro radians using an interpolated 1-second POD clock estimates. This is a significant improvement, based on the stable onboard oscillator and high-gain RO antenna. The improvement will not be as great for occultations which are not along the RO antenna boresight, and which are at lower ray heights and so are subject to significant atmospheric defocusing.

### 2.6 Prelaunch Radiometric Performance

Once Tyvak completed the reciever build, a 'zero baseline test' was done between the RO receiver and the Novatel OEM628 receiver by feeding the same antenna signal into both receivers. Since clocks are common, single differenced phase (between the two receivers) should be relatively flat. The L1-L2 residual is very well behaved for the RO receive path. The Novatel L1-L2 does wander around by a few millimeters (Figure 6). Outdoor tests at the instrument and satellite level were also performed prior to launch and simulator testing helped ensure a successful commissioning.

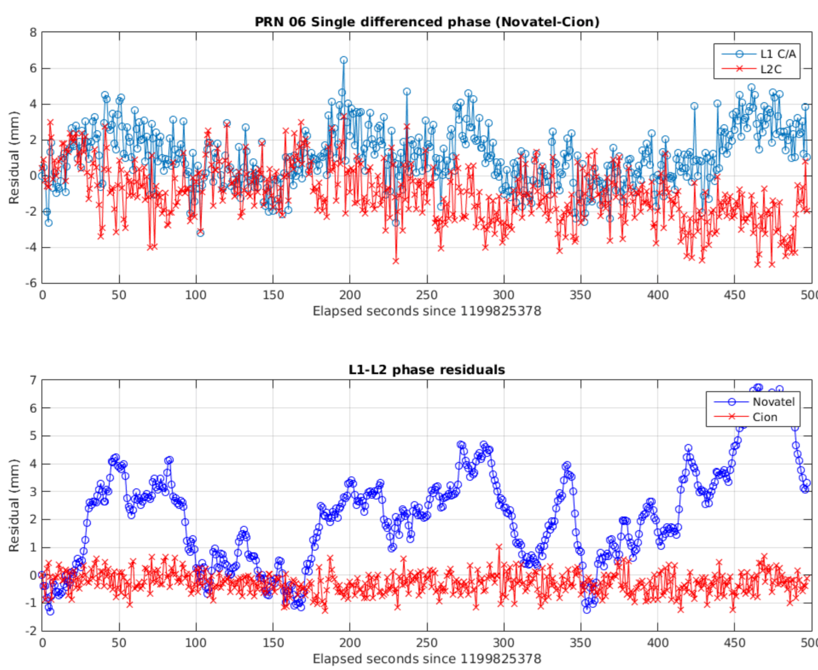


**Figure 6:** L1-L2 phase residuals from ground testing show that the Cion L1-L2 noise is about 2mm.

## 3. RESULTS

### Precise orbit determination

To extract atmospheric information from the occultation tracking data, precise orbits and clock offset information are required for the LEO and the GNSS satellites. We use GPS orbit and clock offset products from the JPL FLINN process [3,4], and we obtain GLONASS orbits and clock offsets from the GDGPS system [5,6]. To compute the LEO orbit and clock offset time series, we use GPS tracking data from the Novatel receiver. The tracking data is combined with FLINN GPS orbits, clock offsets, and earth orientation parameters and used as input to the GipsyX [7,8] software which does the precise determination of the LEO orbit and clock offsets.

### Extracting atmospheric profiles from the occultation data:

We convert the Cion open loop tracking data taken during an occultation into atmospheric parameter profiles at the tangent point (where the light path comes closest to the Earth) using the GOAS software [9] as follows:

The Cion receiver tracks GNSS satellites as their L1 and L2 signals pass through the atmosphere. It records the phase models used in the tracking, and the tracking correlation sums. On the ground, these are combined with the 50 bit per second navigation data bitstream collected by the GDGPS system, to produce the tracked L1 and L2 carrier phase. To isolate the atmospheric effect on the phase, Cicero orbits and clock offsets from the CICERO Precise Orbit Determination, and GNSS orbits and clock offsets and earth orientation parameters from the Flinn or GDGPS system, are used to subtract geometric range and clock effects from the phase, and produce the L1 and L2 "excess atmospheric phase". Then the excess atmospheric phase and spacecraft orbit information can be combined to compute the atmospheric bending angles experienced by the L1 and L2 signals. (The method of canonical transform is used below 20 km to remove diffraction and atmospheric multipath effects.)

The bending angles at the L1 and L2 frequencies can be combined to remove ionospheric bending and hence isolate the neutral atmospheric bending angle. An Abel inversion on the neutral bending angle is then performed to produce the atmospheric refractivity profile at the occultation tangent point. Atmospheric refractivity is a function of temperature, pressure, and water vapor pressure. Combining the refractivity with the condition of hydrostatic equilibrium, we can compute the temperature and pressure profiles below some altitude by initializing the hydrostatic integration with auxiliary temperature data from the NCEP weather analysis [10] at that altitude (usually ~ 30-40 km). At low altitudes where water vapor pressure becomes significant, we solve for pressure and water vapor pressure assuming temperature from NCEP weather analysis.

### Cicero atmospheric products

Examples of refractivity and temperature profiles for a CICERO-GPS satellite occultation are shown in Figure 7. The occultation shown is at the edges of the CICERO antenna gain (Figure 8), where SNR are lowest. Despite the relatively low SNR in this particular case, the occultation shows excellent penetration into the lower atmosphere, ending at 1 km. The refractivity and temperature profiles derived from the NCEP analysis are also shown for comparison. The NCEP analysis has much lower resolution than the occultation data, but the NCEP analysis and occultation profiles agree very well.

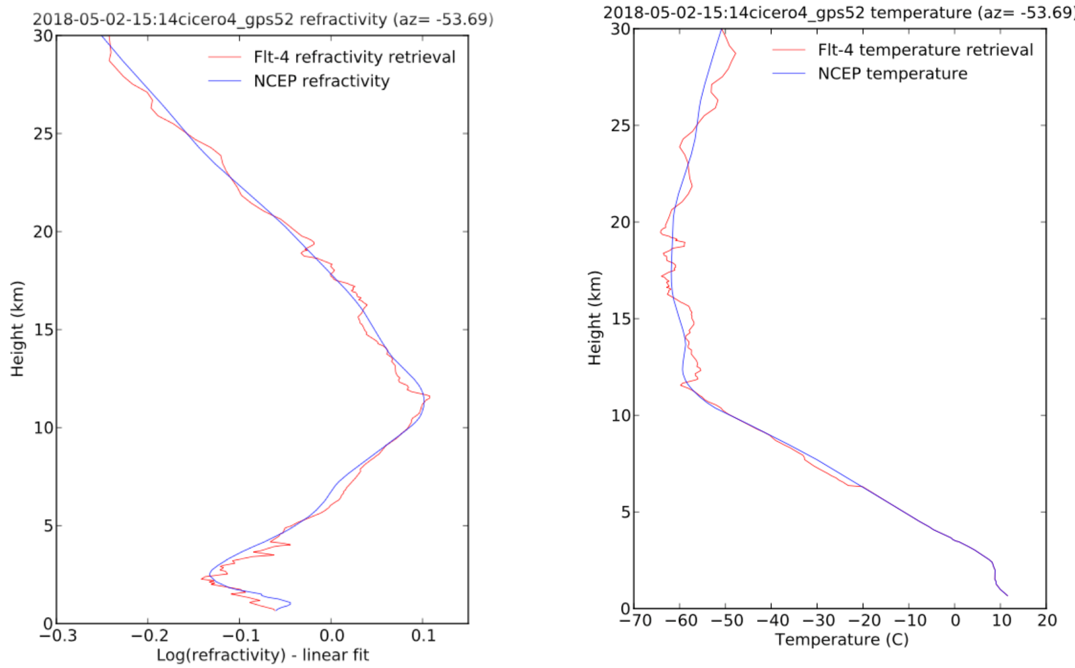


**Figure 7:** GPS RO Refractivity and Temperature profiles for Satellite 52 on May 2nd, 2018

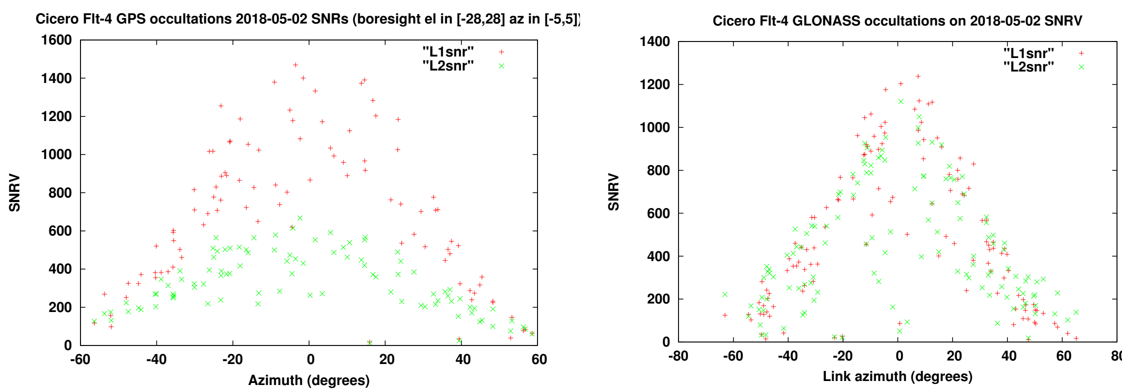


**Figure 8**: SNR's as a function of Azimuth show how the signal drops off when outside of the antenna boresight

The GOAS software we used to process the GPS radio occultations is not yet completed for GLONASS. We are developing an updated version of GOAS, and used parts of that new system to process the GLONASS occultations.

Figure 9 shows an example of atmospheric profiles from a CICERO-GLONASS satellite occultation. Once again the occultation profile shows excellent agreement with NCEP. The profile doesn't go quite as low in the atmosphere as the GPS occultation. This is probably due to the fact that we used a new but incomplete occultation data processing system in order to process the GLONASS occultations (and specifically the parts of the new system for the lower atmosphere, such as canonical transform, are still incomplete). We expect the GLONASS profiles to penetrate as low as the GPS profiles in the atmosphere when the new processing system is complete.

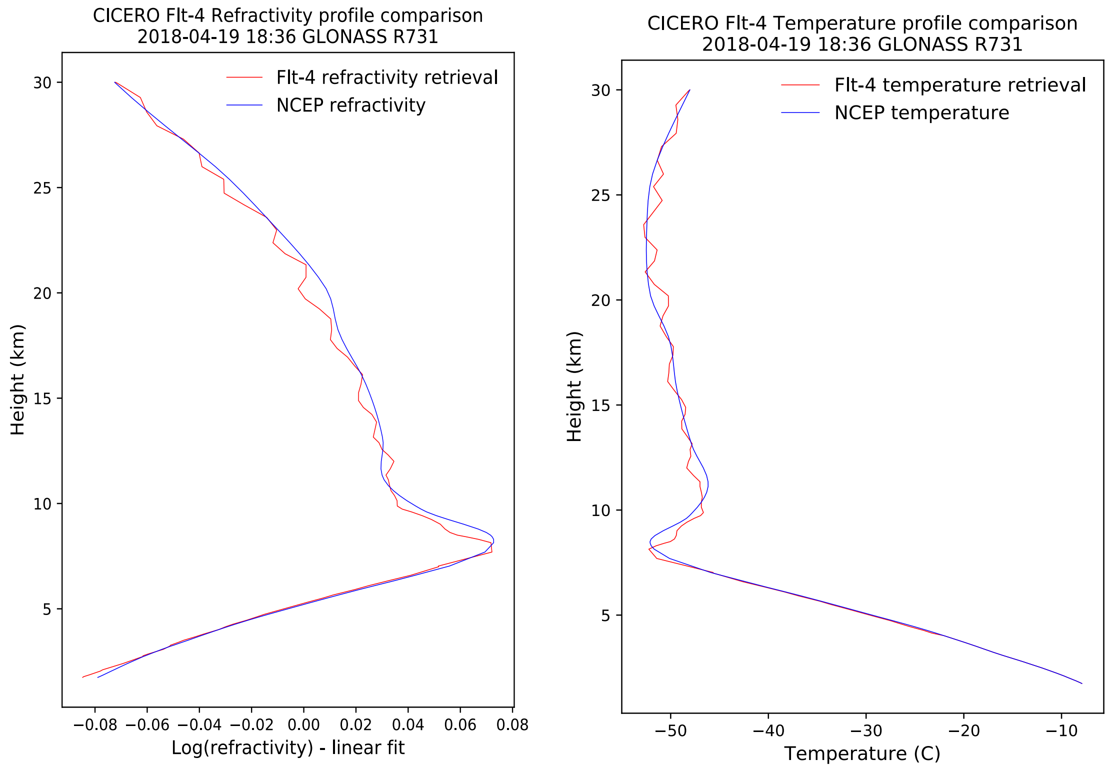


**Figure 9**: First known Glonass Radio Occultations from Space.

## 4. CONCLUSION

The space industry is changing rapidly and as launches become less expensive, greater risk taking is enabling lower power, high performance payloads to make observations similar to larger platform missions. Additionally, NASA partnerships and technology transfers to industry are important to both entities and the Cion is a good example of how this can happen. It is expected that CICERO will continue to launch cubesats with the Cion on board and that future NASA and NOAA missions will be able to use modifications of this design as a basis for a low cost payload for missions requiring a reconfigurable software defined radio. Commercial and Space Flight embedded systems with customizable FPGA's that are easy to program and connect to customizable front ends have also enabled the next generation of instruments with applications for GNSS and future signals of opportunity with only modest software and hardware modifications.

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