TriG: Next Generation Scalable Spaceborne GNSS Receiver

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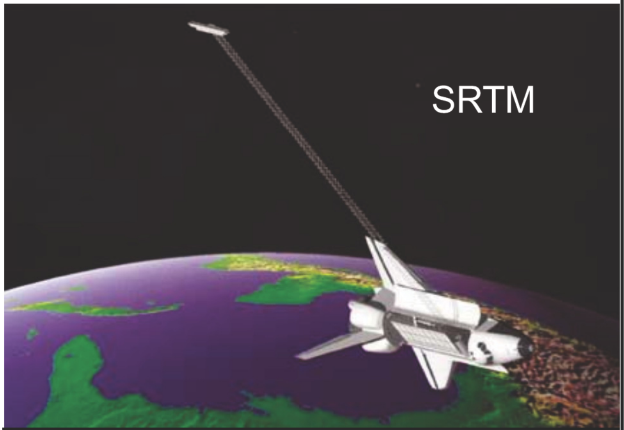
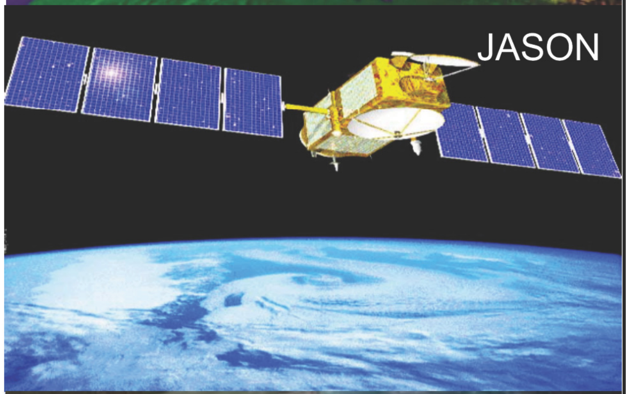
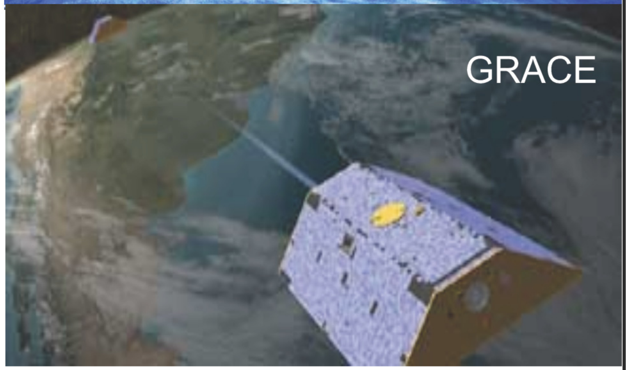
TriG GNSS Receiver Development

- Global Navigation Satellite Systems (GNSS) provide Positioning, Navigation, and Timing fundamental to nearly all NASA Earth Remote Sensing missions.
- The refraction and reflection of GNSS signals enable remote sensing of the ionosphere, atmosphere and Earth's surface with robust and cost effective technology.
- NASA's BlackJack and TurboRogue GPS receivers have demonstrated these capabilities on numerous missions (SRTM, CHAMP, SAC-C, GRACE, ICESat, JASON, OSTM, COSMIC, etc).
- NASA's GNSS space-borne receivers need to be upgraded due to rapidly evolving GNSS signals and advancing science requirements.



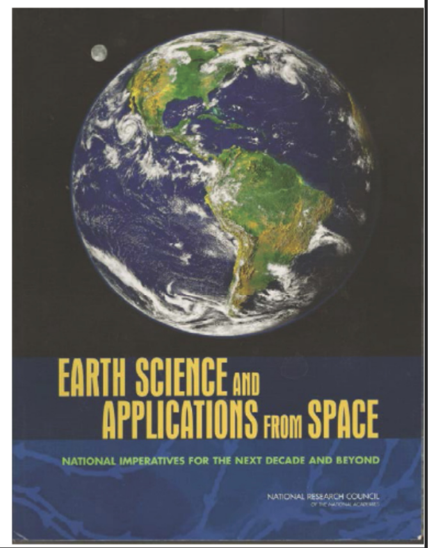




2007 NASA Decadal Survey Recommendations

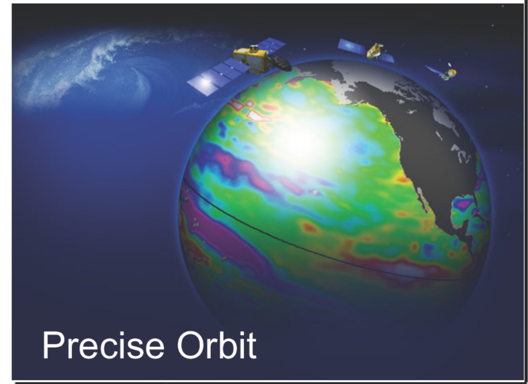
- 2007 NASA Decadal Survey Recommends:
  - *NASA should implement a set of 15 missions phased over the next decade. All of the appropriate low Earth orbit (LEO) missions should include a Global Positioning System (GPS) receiver to augment operational measurements of temperature and water vapor.*
  - *In view of the importance of the occultation measurement and the accurate positioning of the satellite for other sensor measurements, GPS receivers should be a standard part of both NASA and NPOESS low-Earth-orbit payloads.*

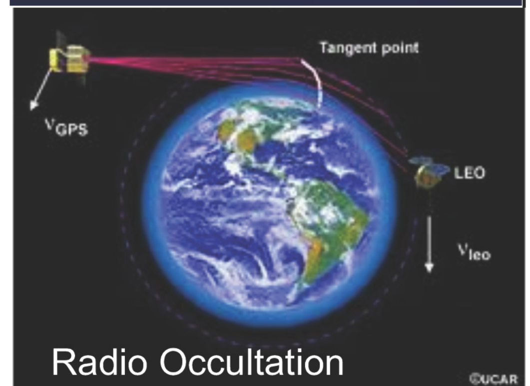
- The receivers envisioned in the Survey are described as:
  - *The payloads would be advanced RO receivers that could receive GPS, GLONASS, and Galileo radio signals.*



TriG GNSS Receiver

- Next Generation GNSS Science Instrument
  - Precise Orbit Determination (POD)
  - GNSS Radio Occultation (RO)
    - Neutral Atmosphere, Ionosphere, and Scintillation
  - GNSS Reflections
- Developed in collaboration with Broad Reach Engineering (BRE)
- Upcoming missions:
  - COSMIC-2, ICESat-2, DSAC, and other NASA/NOAA missions
- Key missions needs:
  - Track more GNSS signals…
  - Higher SNR (particularly for RO and reflection)
  - Higher reliability to meet mission critical needs
  - Greater flexibility to accommodate requirements


Precise Orbit



Radio Occultation


Surface Reflection

TriG GNSS Receiver for COSMIC-2

COSMIC-2 Mission Objective:

- Providing operational global GNSSRO-based Earth observations (including refractivity, temperature, moisture, and electron content and density profiles of the troposphere, stratosphere, and ionosphere)

Partnership: NOAA/USAF (SSAEM)/NSPO (Taiwan)

Orbit: 500km equatorial (24°); 800km polar

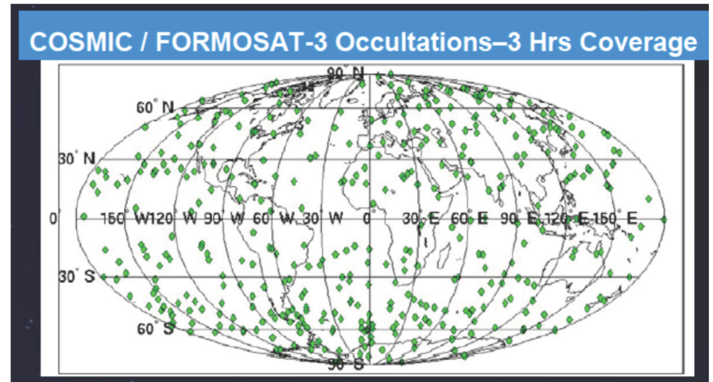
Number of S/C: 12

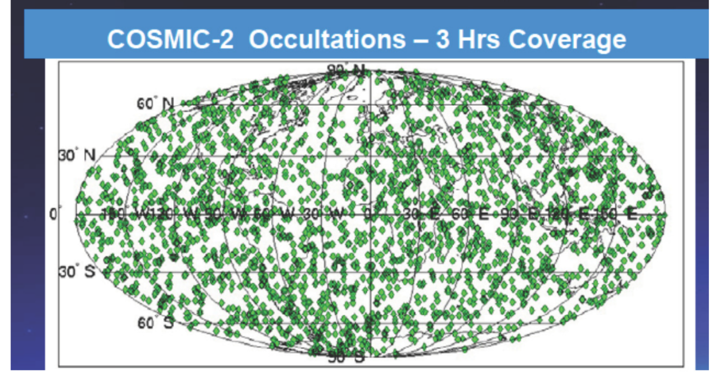
Launch: 6 S/C on 2015; 6 S/C on 2017

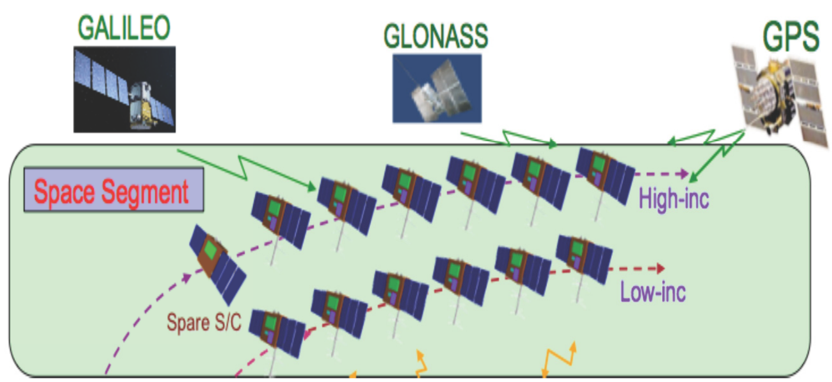
Mission Life: 5 years

Key GNSS Receiver Requirements:

- GPS/Glonass FDMA (Threshold) / Galileo (Objective)
- Neutral Atmospheric Soundings / day / payload:
  - 1125 (Threshold) / 1600 (Objective)
- Ionospheric Soundings & Arc / day / payload:
  - 1125 (Threshold) / 2250 (Objective)
- Ionosphere Scintillation

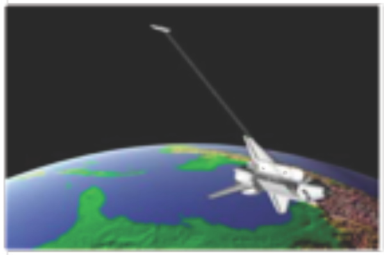




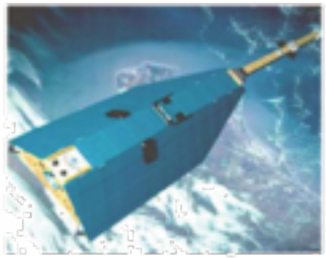


TriG GNSS Receiver Heritage

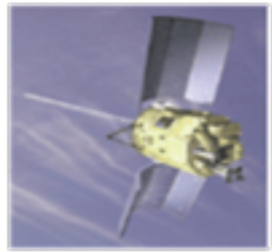
JPL/NASA BlackJack GPS Receivers: > 115 Flight Years of Successful Space Operation
The most precise GPS receivers flown in space – enabling new science and navigation capabilities



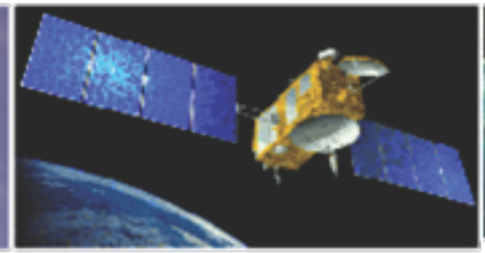
45-cm accuracy
SRTM
Feb 2000



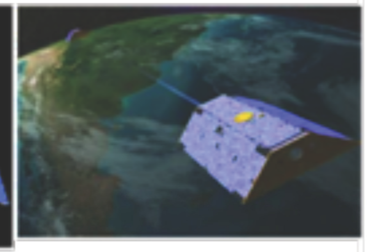
4-cm accuracy
CHAMP
Jul 2000



4-cm accuracy
Sub-meter real-time demo
SAC-C
Nov 2000

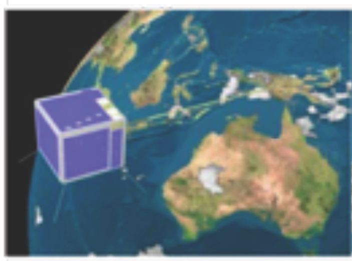


1-cm accuracy
JASON-1
Dec 2001

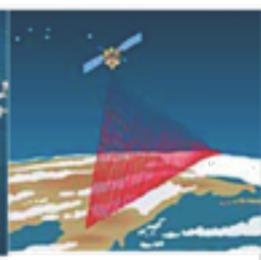


1-cm accuracy
GRACE
Mar 2002

Dec 2002
FedSat

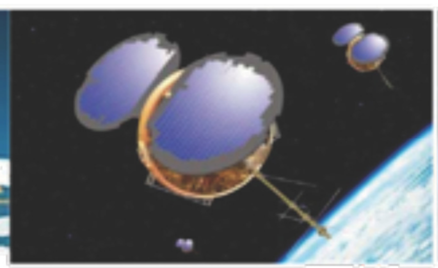


Dec 2002
ICEsat

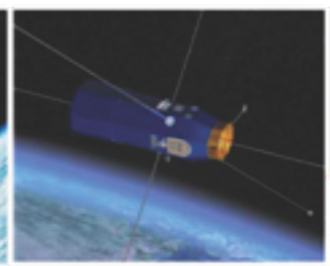


5-cm accuracy

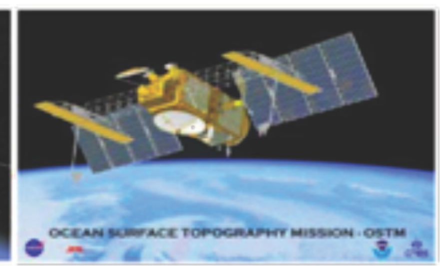
Apr 2006
COSMIC



Apr 2008
C/NOFS



Jun 2008
OSTM



Yoaz Bar-Sever

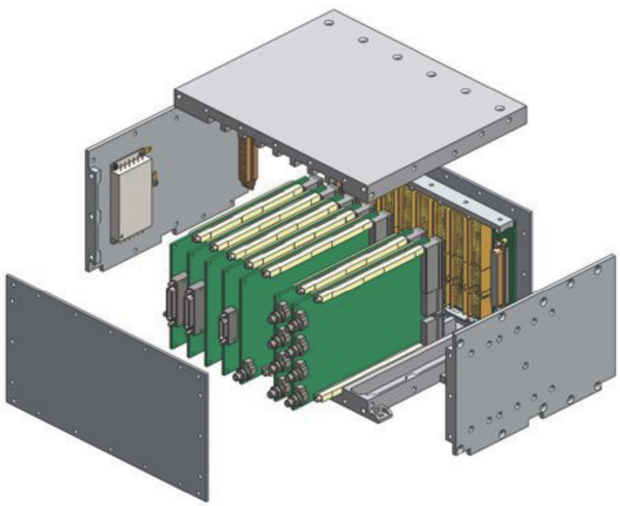
Key Features

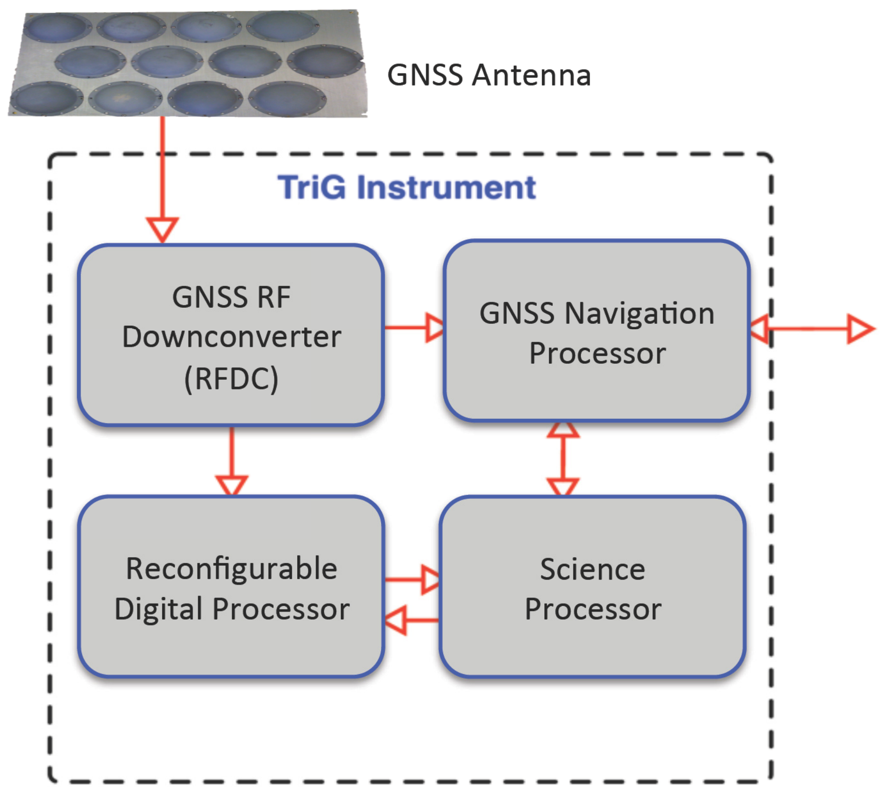
- Scalable 3U Architecture
- Receives GNSS signals (GPS, Galileo, GLONASS, Compass,…) + DORIS
- Multiple digitally steered high-gain beams.
- Linux based Science processor allow easy modification of onboard processing by non-receiver experts
- Large reconfigurable signal processing resources
- Advanced signal processing including open-loop tracking, Blue Shift processing, etc.
- Allow either internal or external frequency reference.
- Highly reliable design with TID > 40krad
- Autonomous Operations

TriG Hardware Architecture

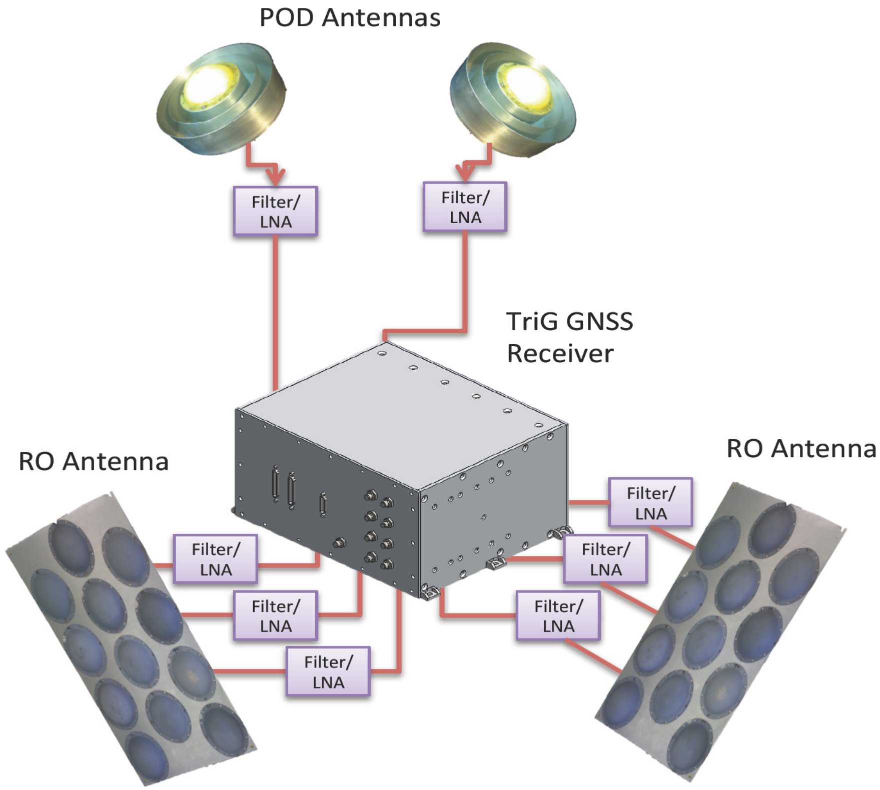
TriG receiver electronics are based on the 3U architecture comprised of 4 main components:

- RF Downconverter (RFDC)
  - Four RF channels per antenna input
- GNSS Navigation Processor
- Science Processor
- Reconfigurable Digital Processor

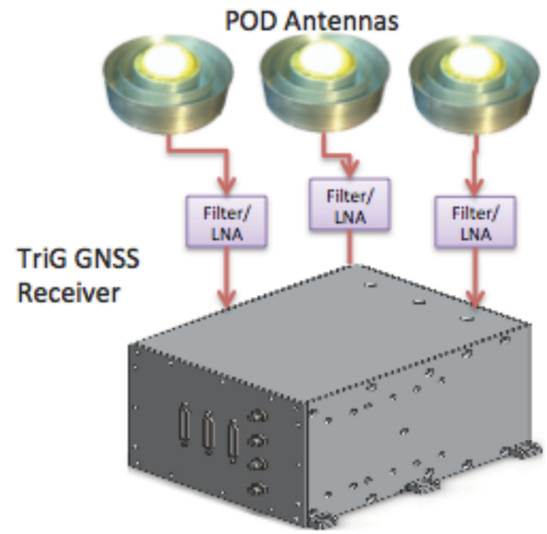




3U Scalable Architecture



8 antenna inputs, dual processor configuration for COSMIC-2 GNSS RO Mission

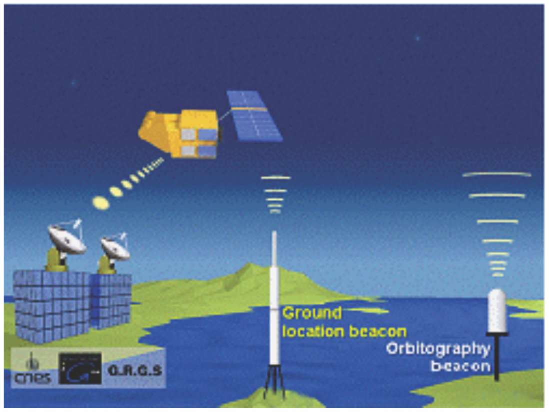


3 antenna inputs, single processor candidate configuration for the DESDynI Mission

Scalable 3U architecture enabling optimization to meet specific mission requirements

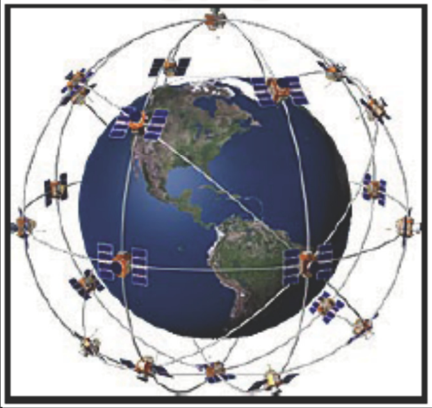
Receive All GNSS Signals

- Wide bandwidth RF Downconverter capable of receiving all GNSS signals:
  - GPS, Galileo, GLONASS, Compass
  - Other navigation signals (QZSS, DORIS, etc)
- TriG will track both legacy and new GPS signals
  - Provide uninterrupted multi-frequency GPS tracking service through 2020 retirement of semi-codeless
- Tracking more GNSS signals will improve both POD and the quality and quantity of the measurements from RO and surface reflection observations.

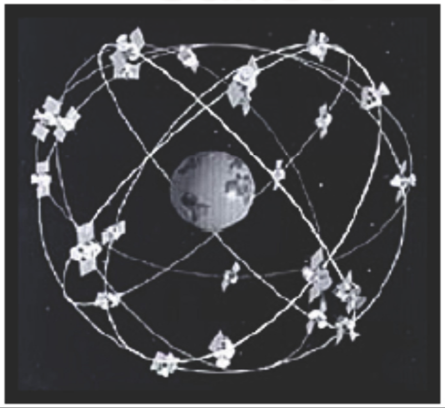


DORIS Transmitting Station

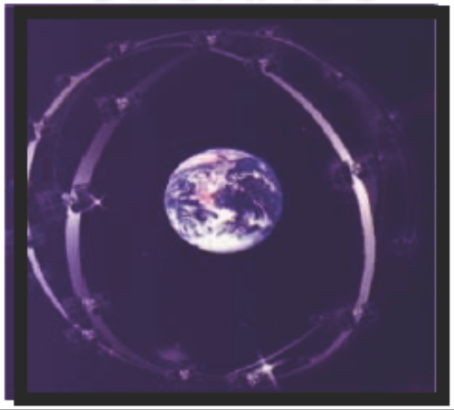
GPS



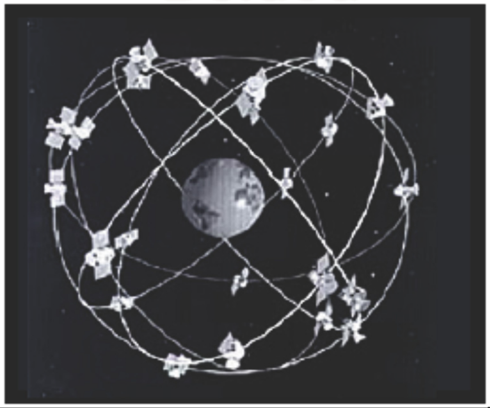
Galileo



GLONASS

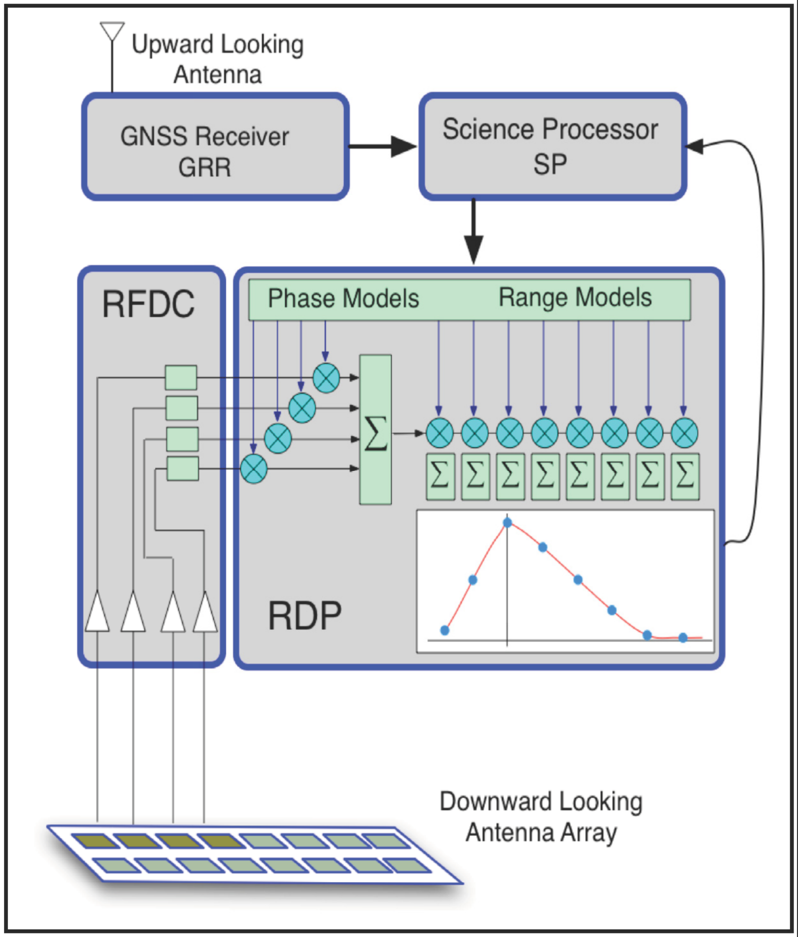


Compass



Multiple Digital Beam Steering

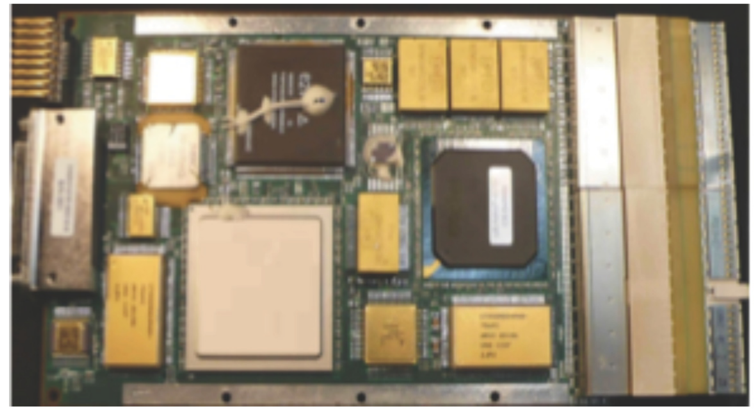
- TriG accommodates up to 16 antenna inputs with four frequency channels each
- Digitally combined to produce multiple beams with high-gain for all receive frequencies
- Improves both low and high altitude occultation performance as well as the ability to acquire synoptic surface reflections data over a wide swath of ocean or solid earth
- Reduces multipath and RFI susceptibility by providing reduced gain toward the sources of multipath and RFI



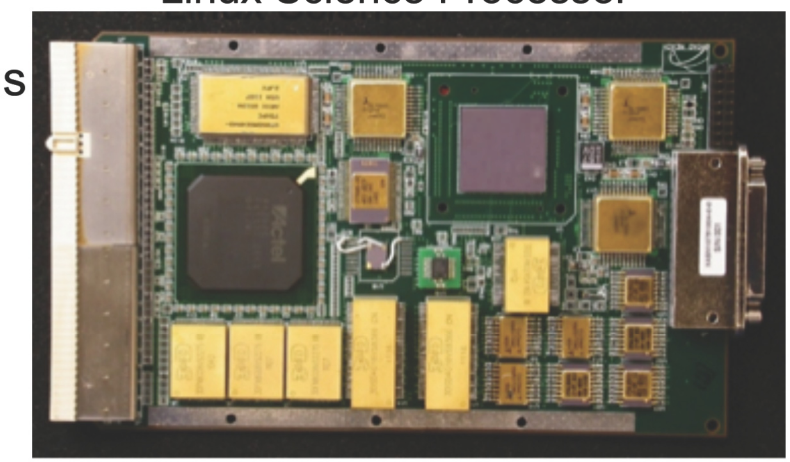
Dual Processor Architecture

- Dual processors with more than 6 times the throughput of the BlackJack GPS receiver
- Navigation Processor based on the BlackJack design that has successfully flown on more than than 16 flight missions
- New Science Processor based on Linux operating system
  - Allows signal processing algorithms to be developed on standard Desktop Linux systems
  - Eliminates the need for receiver experts to implement advanced experiments
- Navigation processor with one RFDC constitutes a low power and mass TriG configuration for precise positioning

Navigation Processor



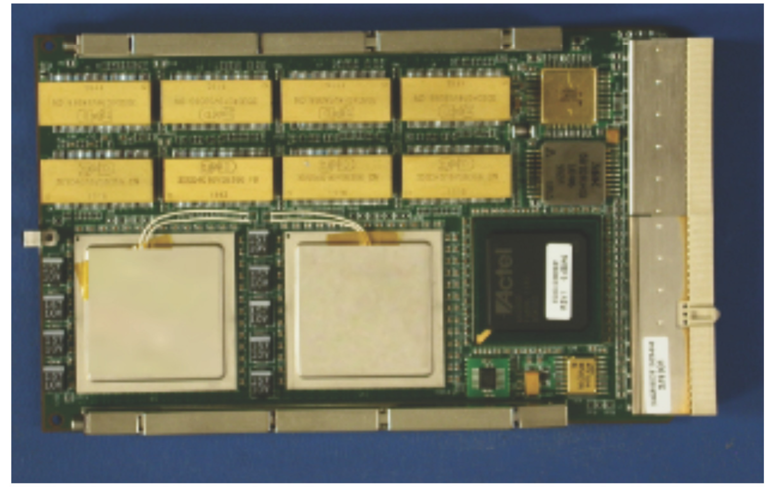
Linux Science Processor



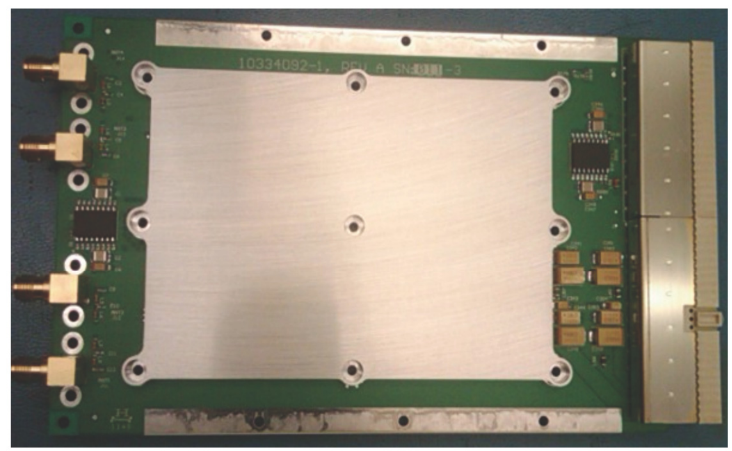
Flexible Architecture with Large Reconfigurable Resources

- Software and signal processing firmware are fully reconfigurable post-launch.
- Large reconfigurable signal processing logic resources with up to 300 reconfigurable satellite signal processing channels.
- Programmable LO in the RFDC allows each RF channel to down-convert signals from any GNSS frequency within the front-end bandwidth
- Individual RF channels are enabled as needed to control power consumption

Reconfigurable Digital Processor

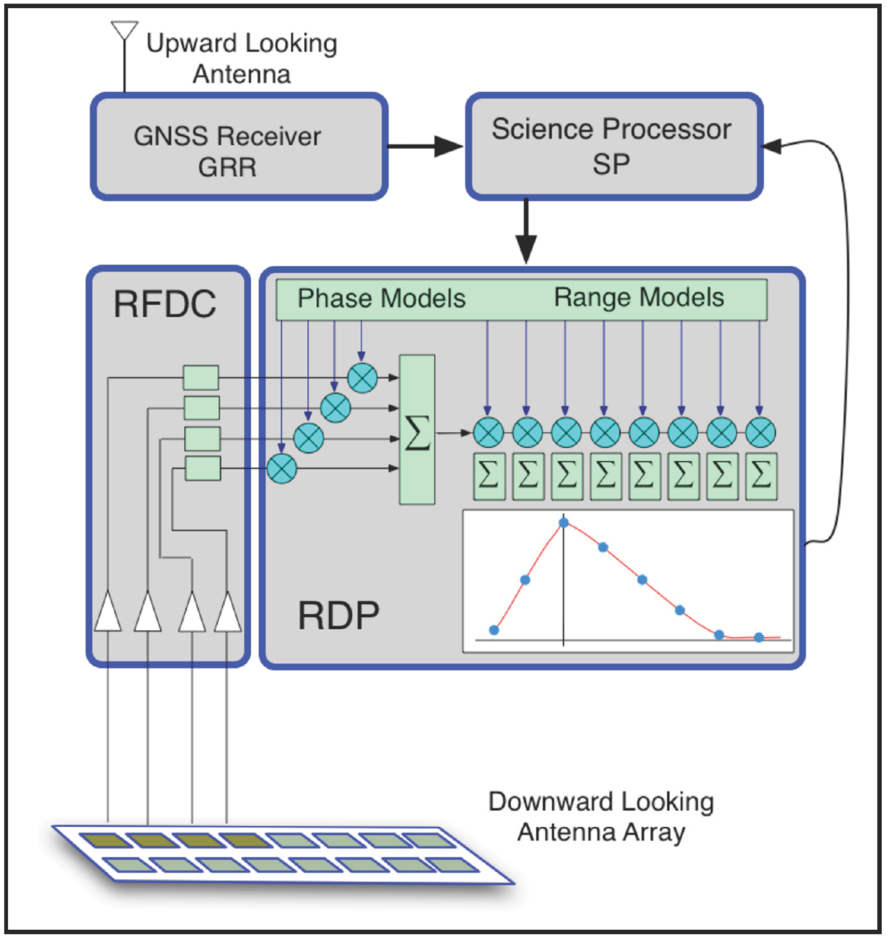


Wideband RF Downconverter



Advanced Signal Processing

- *Multi-Lag Processing*:
  - Allows use of a spread of range and Doppler models so that rising signals can be reliably captured for atmospheric occultation.
- *Time Delayed Processing*:
  - Large buffer memory for sample data storage allows occultation data to be processed after receiving more accurate models of SC geometry and oscillator behavior from the Navigation processor.
- Open Loop Tracking
  - Generate data from signals below the threshold for closing tracking loops



Frequency Reference

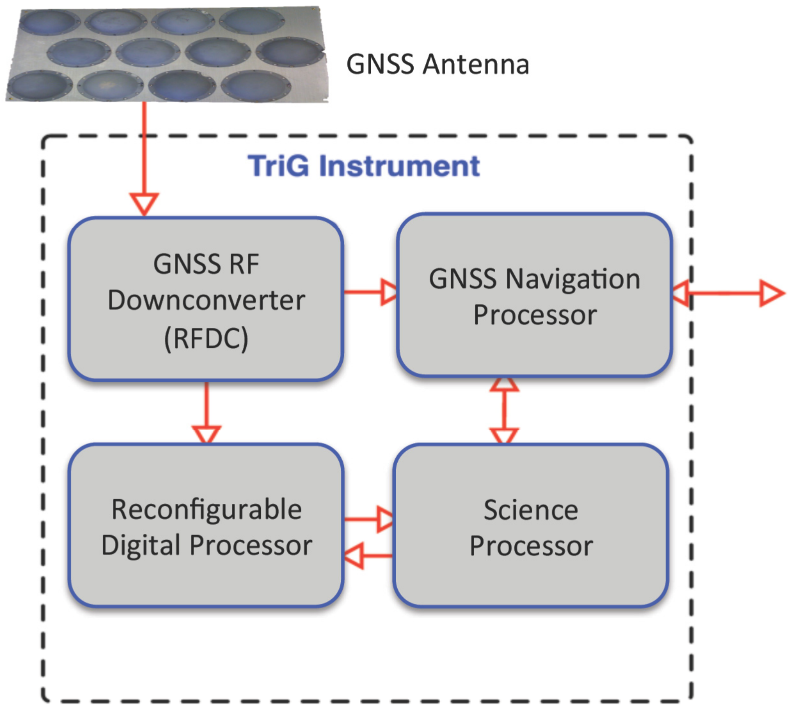
- Internal Ovenized Crystal Oscillator (OCXO)
  - < 3E-12 (1 sec) for 1 sec clock differencing
  - < 6E-11 (0.01 sec) for 100 Hz clock differencing
- Allow external USO inputs for
  - Zero difference allows for better precision at highest altitudes and traceability to International Standard of Unit (SI) for Climate Benchmark.
  - High precision inter-satellite ranging missions (e.g. GRACE-FO)

High-Rel Features

- TriG offers higher reliability design to meet mission critical needs
  - Use high-rel parts with TID of > 40 krad
  - Single Event Latchup (SEL) threshold of > 60MeV
  - Implemented Single Event Upset (SEU) mitigation
    - Memory Error Detection and Correction (EDAC)
    - FPGA configuration memory scrubbing
    - Triple Module Redundancy (TMR) voting scheme on EEPROM
    - Selective TMR could be implemented in the signal processing FPGA if necessary pending on mission requirements

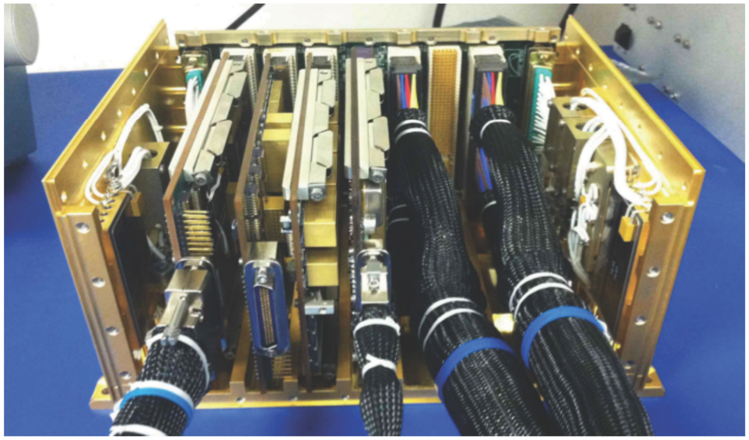
Fully Autonomous Operation

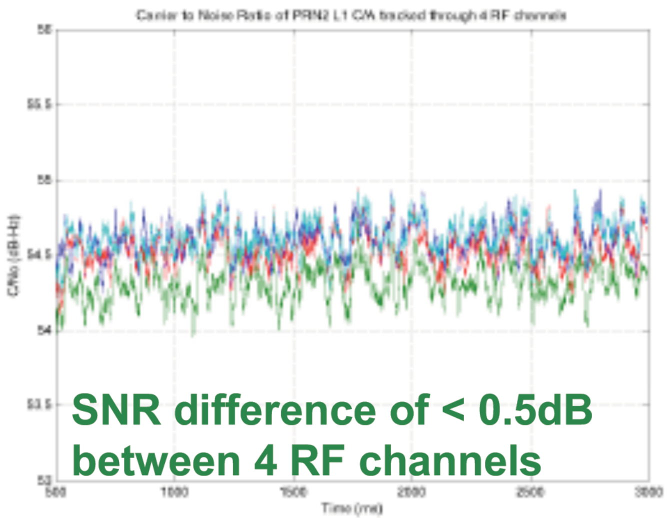
- GNSS Realtime Nav Processor
  - Acquires and tracks GNSS signals
  - Sets Real Time Clock
  - Generates Position, Velocity, and Time (Option for 10-cm-level realtime solution)
  - Outputs time-tagged phase/range/snr
  - Tightly coupled with science processor
- Science Processor
  - Schedules Iono/Atmo Occ Profiles and reflection measurements
  - Extracts 1 ms phase/range/amp
  - Formats observables



Recent Development Status

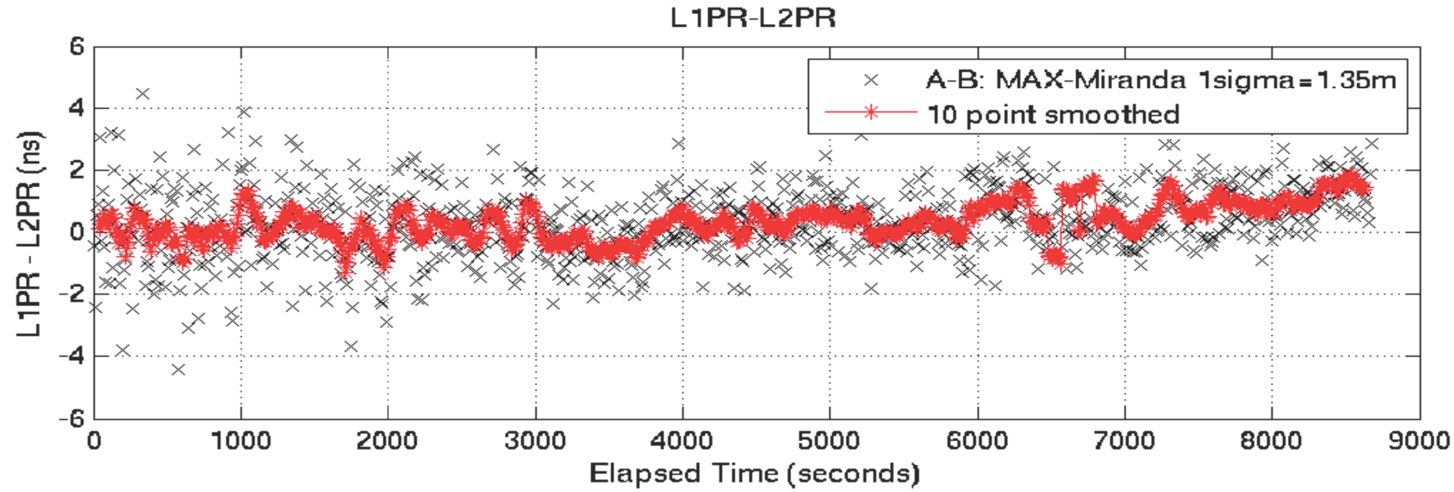
- TriG Engineering Model (EM) has been built and testing is currently underway at Broad Reach Engineering and at JPL
- Porting of BlackJack GPS software to run on the Navigation Processor is nearly complete
- Preliminary performance of the wide-band RFDC has been verified against a BlackJack GPS receiver
  - The SNR across all RF channels is comparable to the performance of the high-performance BlackJack/IGOR receiver front-ends.

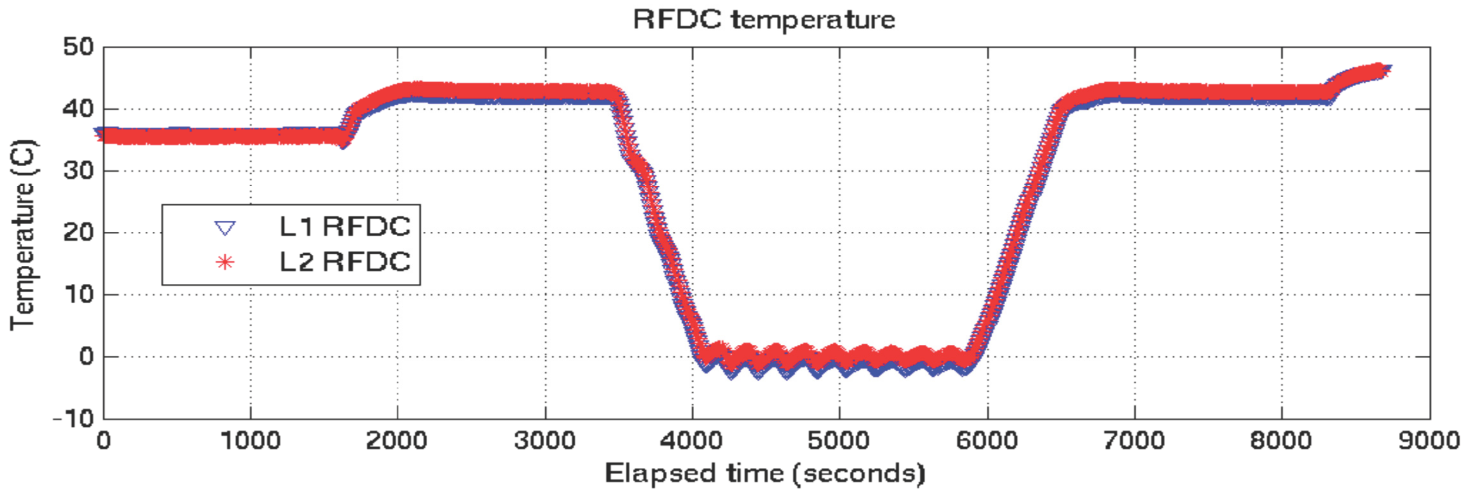




TriG RFDC L1-L2 Group Delay Variation

(key parameters for absolute TEC and TEC variation)

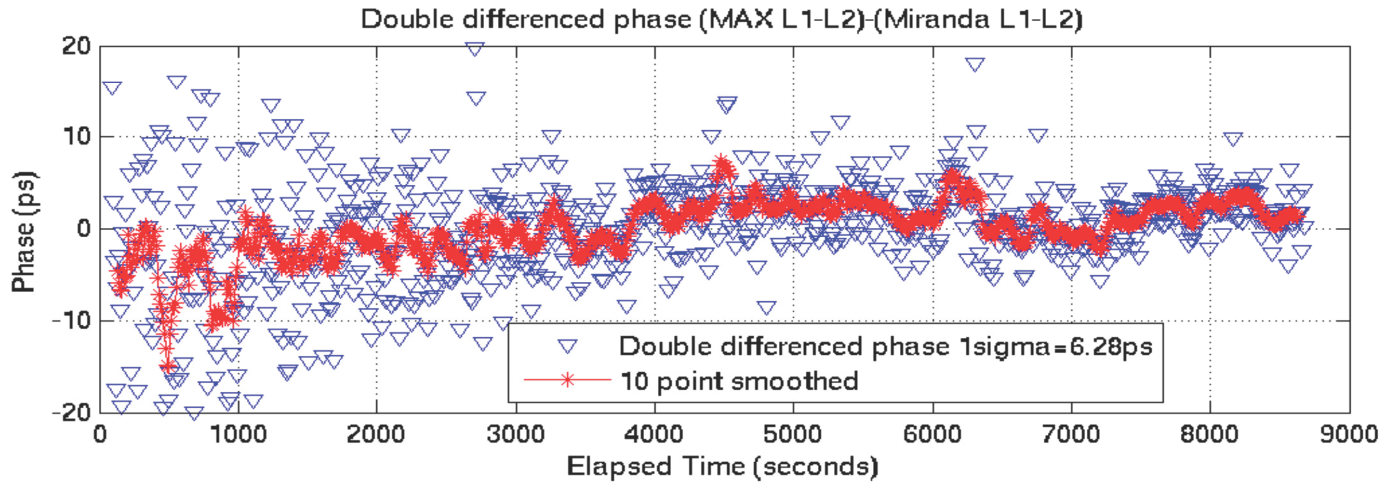


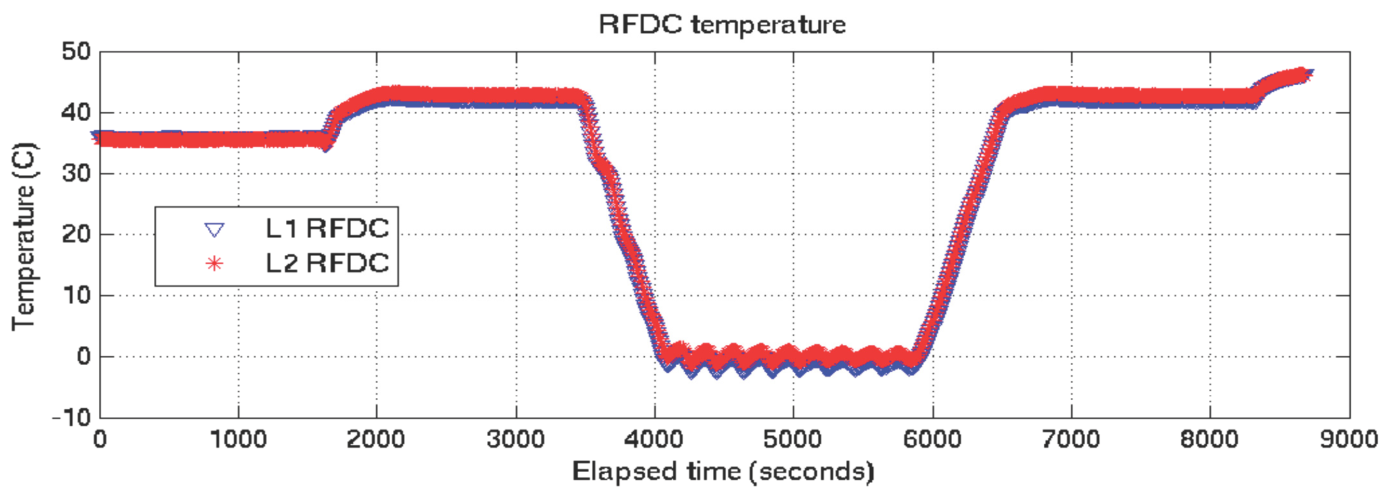


- Less than 2 ns over temperature range from 0 to +40C.

TriG RFDC Double Differenced L1-L2 Phase

(key parameters for absolute TEC and TEC variation)





- < than 10 ps over temperature range from 0 to +40C.

Key Milestones

▪ Verify GPS Tracking Performance	April 2012
▪ Integrate GLONASS Tracking Capability	Sept 2012
▪ Verify RO Tracking Performance	Nov 2012

Mass, Power, Dimensions

Configuration	Power (W)	Mass (kg)	Dimension LxWxH (cm)
Single Antenna/Single Processor	16 to 20	4	20 x 16 x 12
Four Antenna/Single Processor	18 to 25	4	20 x 16 x 12
Four Antenna/Dual Processor	30 to 50	5	20 x 20 x 12
Eight Antenna/Dual Processor	40 to 60	6	20 x 23 x 12

- TriG GNSS receiver is scalable and the mass, power, and dimensions varies with configuration.
- Antenna assembly is not included in the mass and dimensions estimates.

Summary

- TriG is the next generation of NASA scalable space GNSS Science Receiver
- Will track all GNSS and additional radiometric signals (GPS, GLONASS, Galileo, Compass, and DORIS)
- Scalable 3U architecture and fully software and firmware reconfigurable, enabling optimization to meet specific mission requirements.
- TriG GNSS EM is currently undergoing testing and expected to complete full performance testing later this year.

Acknowledgements

- This task was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (Earth Systematic Mission Program Office – ESMPO).

- The authors would like to thank Ted Stecheson, Jacob Gorelik, and Tim Rogstad for their work on porting software to the TriG Navigation and Science processors; and Jehhal Liu for his work on the signal processing FPGA.

- Special thanks to Broad Reach Engineering for improvements they made to the BlackJack design with their IGOR occultation instrument.