"We are endowed with reason and can understand cause and effect, survey the course of things and make the necessary preparations."

-- Cicero, "On Obligation" (44 B.C.)
CICERO

GPS/Galileo Radio Occultation Program that takes this remote atmospheric sounding technology operational. Initial constellation is 24 spacecraft, with customer designs up to 100 continuously operating GNSS RO sensors.

Status
Started in late 2004, grew out of the COSMIC follow-on studies

Conclusions of the on-orbit data processing and studies are:

Higher resolution of soundings (more s/c and more radio sources)
Higher S/N (antenna gain and receiver front end sensitivity)
Reduce data latency, especially for space weather

First 2 launches late in 2010 and early 2011 (12 S/C per launch)

Mission PDR next month
Science, Sensor, Data Processing, System Costing

Spacecraft PDR December 2007
Spacecraft Specific

Radio Occultation…what is it?
What is a GPS Occultation? The very accurate and precise measurement of the rising and setting GPS signals, and measuring the path delays and perturbations caused by the refraction through the varying densities of the atmosphere and ionosphere.
Mariner IV Occultation at Mars: Earliest Results

Science, 10 Sep 65

Ionospheric Model Fit

Atmospheric Model Fit

Entry Phase Residual

Kliore et al., 1965
First on orbit GPS Occultations, matching in situ measurements

Though, not getting down near the surface of the Earth

Santa Cruz Islands
5 April 1995

credit UCAR/NSF
Next, a series of other Demonstrations and technology improvements: Navigation, electronics, antennas and tracking loops.

- **CHAMP**
- **TerraSAR-X**
  - Germany
- **SAC-C**
  - Argentina
- **ROCSAT-3/COSMIC (6)**
  - Taiwan/US
- **TACSAT-2, US**
- **Tandem-X**
  - Germany
Location of COSMIC Spacecraft 11 August 2007
(Launched in April, 2006)
• IGOR performance on TerraSAR-X is comparable with BlackJack type receivers on missions as CHAMP and GRACE

• Derived 3D position (NAV solution < 10m RMS)

• Undifferenced ionosphere-free pseudorange and carrier phase combinations yield ~70 cm and ~7 mm residuals, resp.

• Derived Rapid Science Orbits fit to SLR measurements within 2 to 5 cm

• Stable tracking of up to 12 satellites for POD with good SNR; no loss of lock during SSL manoeuvres; no susceptibility to X-Band radar operations!

• Clock steering well within specification

• Effect of cross-talk between individual RF antenna ports exists also for the IGOR on TSX (first observed for the BlackJack on CHAMP)

• There are indications for a likely RF interference of IGOR with the onboard MOSAIC GPS receiver on TSX when IGOR is powered up

• TSX v1.0 and v1.1 S/W show still deficiencies (memory leak, P2 phase)
~50% of occultations penetrate to under 1 km for COSMIC with 6 to 12 times the number of occultations.

~50% of occultations penetrate to under 2.5 km for CHAMP.

CICERO will be ~3dB more sensitive, with an order of magnitude more soundings as compared to COSMIC.

credit UCAR
Data acquired and derivative products are similar to data from the weather balloons.

Temperature, Pressure, Density, moisture content.

But unlike most weather balloons, the data is better distributed, and includes ocean/sun interface interaction, besides being more precise and accurate.
Current IGOR™ derived data, flying on COSMIC, TACSAT-2 & TerraSAR-X:
  Real Time position ~ 3 meters
  Post Process position ~ 10cm
  Derived Occultation temperature profile accuracies ~ 0.02->0.05 degrees K
    An order of Magnitude better than weather balloon temperature profile
  Space Weather, Ionospheric disturbance measurements
  Density & moisture content derived data as well as
  All based on accurate time measurements
  no instrument bias

2004 until 2008, most efforts were sensor development specific NRE & ASIC design
2006 until 2009, efforts in spacecraft design, infrastructure and production run set up

Technology improvements of CICERO since the COSMIC launch
  add L5 to the L1 / L2 frequencies
  add Galileo correlators
  add 2 bit sampling
  add RF front-end hybrid ASICs and improved LNA’s
  add Rad-hard processor
  add near ultra stable oscillator ( ~ 3 orders of magnitude better)
  add 3 axis stabilized platform
  add Real Time Operating System & Memory Protection
Designing CICERO, the Numerator Approach

**Numerator Style of designing**

- Maximizing Science and Data return, mission optimization
- No inherent system design margins, or constraints, no accounting limitations
- Technology Conscious, prefer new, if efficiencies are justified and attainable
  - Technology progression, “heritage between the ears”
  - Quantity opportunity, NRE < #*Recurring for such things as FPGA vs. ASICs
- Numerator items & components: Instruments, payloads, fundamental improvements, consolidation of functions to approach ‘system on a chip’
Enabling Technology
Lower cost power real estate mass
Higher accuracy precision
More fun

GNSS Front-end through correlators

Hybrid ASIC under development

RF Input Filters

L5 Channel
L2 Channel
L1 Channel
RT Channel
Optional Channel

Synchronized LO Generation

Integer-N Synthesizer

2-bit Sampler

GPS and Galileo Correlators

96 Channels

Stable Oscillator
PowerPC™ 440 ‘System on a Chip’, manufactured on Honeywell’s 150nm Radhard process 400MIPS 400MFLOPS
Minimum 20 spacecraft for initial constellation
Operational Altitude: 700 to 800 km
Inclination: 70 to 75 degrees
Three Axis Controlled, Nadir following mission mode
Attitude Knowledge: < +/- 1 degree
Attitude Control: < +/- 2 degrees
Power consumption: < 50W OAP
Propulsion capability: ~400 m/s
Launch mass each: ~ 30 kg
Data latencies:
  Weather: < 100 minutes
  Space weather: < 5 minutes
  Climate: no requirement
Data volume: < 10 MBytes/orbit
Hurricane Ernesto
Aug 2006

NCAR initiated two trial forecasts while Ernesto was a weak tropical depression, four days before it became a hurricane.
4-Day Ernesto Forecasts

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecasts

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecasts

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Satellite Photo

30 hrs

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
Satellite Photo  

NOAA forecast w/GPS RO  

NOAA forecast w/o GPS  

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Satellite Photo

66 hrs

NOAA forecast w/GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

102 hrs

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecasts

Satellite Photo

NOAA forecast w/GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecasts

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS
4-Day Ernesto Forecast

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
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Satellite Photo

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NOAA forecast w/GPS RO

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Satellite Photo

NOAA forecast w/GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Satellite Photo

102 hrs

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

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NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Satellite Photo

78 hrs

NOAA forecast w/GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
4-Day Ernesto Forecast

Satellite Photo

90 hrs

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)
102 hrs

4-Day Ernesto Forecast

Satellite Photo

NOAA forecast w/ GPS RO

NOAA forecast w/o GPS

Ying-Hwa Kuo (NCAR)