

## Community Initiative for Continuing Earth Radio Occultation CICERO

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### ABSTRACT

*The CICERO Project* will deploy a constellation of 100 small (~30kg) 3-axis stabilized remote sensing satellites that produce atmospheric temperature, pressure and moisture profiles and ionospheric electron density profiles worldwide, along with a host of derived products. This remote sensing satellite system will supply high fidelity real-time weather and climate data to the meteorology industry. This dataset is essentially a ‘finite element dataset’ of the entire Earth’s atmospheric and ionospheric conditions. This international mission establishes a model of private space development for the public good that changes the way we collect and disseminate Earth observational data. *The CICERO Project* inaugurates this model with an evolved third generation technique for weather and climate sensing known as Global Navigation Satellite System (GNSS) Radio Occultation, or GNSS-RO. This method not only enables large improvements in weather and storm path predictions, but is becoming the definitive standard in vertical temperature profile retrievals for climate research and calibrating other terrestrial and space based sensors. Previous Radio Occultation missions have used the GPS satellites as signal sources. CICERO will use both GPS and Galileo and potentially other high stability radio sources. GNSS-RO instruments are bias and drift free and are tied directly to absolute SI time standards.

### 1. BACKGROUND

#### *The cosmic mission and its users*

The CICERO Program is designed as the operational follow-on to the COSMIC/Formosat-3 mission. The COSMIC GPS-RO payloads are on orbit and are delivering the highest precision global atmospheric soundings ever produced. These GPS-RO receivers were launched on the six Formosat-3 Taiwanese spacecraft in April of 2006. The data is processed by the University Corporation of Atmospheric Research in Boulder Colorado. This data is currently being assimilated into the forecast and climate models at NOAA, UKMET, Taiwan, and various other weather centers in the countries listed in table-1.

This list represents nearly 500 separate users, ranging from individual atmospheric scientists and national and international weather forecasting centers.

Argentina	Australia	Austria
Brazil	Bulgaria	Canada
Chile	China	Czech
Denmark	Dubai	Egypt
Finland	France	Germany
India	Indonesia	Ireland
Italy	Japan	Korea
New Zealand	Nigeria	Norway
Peru	Phillipines	Portugal
Russia	South Africa	Spain
Switzerland	Taiwan	The Netherlands
Thailand	United Kingdom	United States
Vietnam		

Table 1: Countries using COSMIC GPS-RO Data Products, June 2007

Early results showing the impact of the data from the COSMIC mission have been published, showing that this data is highly valuable in many ways. For some of the results, see:

“The COSMIC/FORMOSAT-3 Mission: Early Results” that was submitted to the Bulletin of American Meteorological Society, dated 5 April 2007

CICERO will continue the Earth’s GNSS Radio Occultation campaign with 3dB improvement in Signal/Noise and with the additional capabilities for L5 and E1/E5a frequencies, making it Galileo compatible when the Galileo system is commissioned.

**Radio Occultation History**

Planetary radio occultation is the method of transmitting a calibrated radio source through an atmosphere, and measuring the path delays which in turn derives the refracted bending angles, and atmospheric densities. Pressure/density/temperature and moisture content is derived as well. Radio occultations applied to planetary atmospheres planets were first performed by the NASA Mariner IV mission in 1965 during the Mars Flyby and again with Mariner V’s October 1967 flyby of Venus. Data from the Mars occultation is shown in Figure 1.

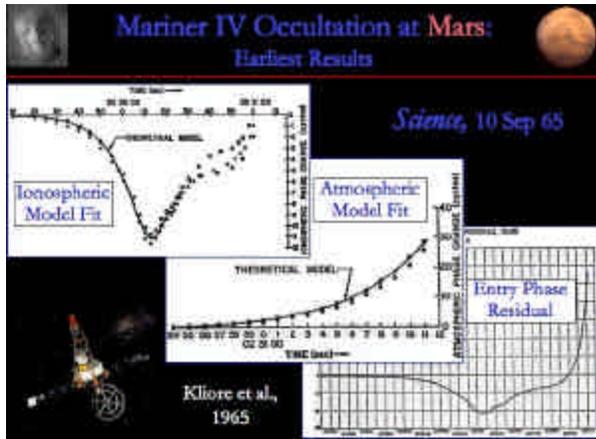


Figure 1: Interplanetary Occultations from the 1960’s (Credit T.Yunck, Occultation Science; OPAC-1 Graz, Austria, Sept 2002)

Earth based radio occultation applications are primarily conducted using the GPS system as a radio transmission source with highly accurate multi-frequency GPS receivers in low earth orbit. The first demonstration of this technique was funded by a National Science Foundation grant with collaboration from University Corporation for Atmospheric Research, and with instruments designed and built by the Jet Propulsion Laboratory. This flight mission was called GPS-MET

and was flown in 1995. Figure 2 below is a chart from one of the first processed GPS radio occultations from this mission.

As shown, the data derived from the GPS occultation matches the Radiosonde as well as corresponding models. This GNSS-RO type of data have since aided in the atmospheric model’s improvement. The data derived from this technique has since been shown to be accurate to ~0.02 to ~0.05 degrees Kelvin. This is at least twice as accurate as needed for long term climate data. This data is valid at altitude, which has not been routinely available for climate research in the past.

Other missions flown to date using GNSS-RO are CHAMP, SAC-C, GRACE, METOPS, COSMIC, TACSAT-2 and the recently launched TerraSAR-X. Missions in development that are baselining GNSS-RO payloads are Tandem-X, Kompsat-5, Megha-Tropiques, and EQUARS.

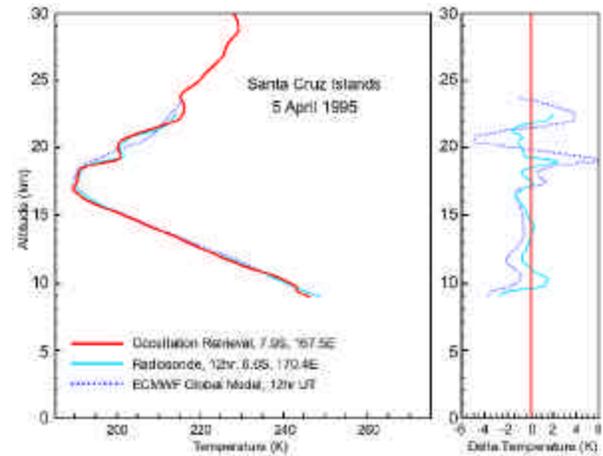


Figure 2: First processed GPS-RO from GPS-MET depicting agreement to in-situ and then current atmospheric models (courtesy B. Kuo, UCAR)

The COSMIC mission is a collaboration between the National Space Program Office in Taiwan (NSPO) and the University Corporation for Atmospheric Research (UCAR) in the US. The majority of the funding has been provided by Taiwan with US funding from the National Science Foundation, NASA, Office of Naval Research and NOAA. The spacecraft is based on the Orbital Sciences MicroStar™ bus, with final assembly, integration and test performed in Taiwan.

The primary instrument on this spacecraft is the Integrated GPS Occultation Receiver (IGOR). This instrument also controls two other payloads, namely the Tiny Ionospheric Photometer (TIP) and the Tri-Band Beacon, both from the Naval Research Lab. A picture

of the launch configuration being tested on a vibration table in Hsin Chu Taiwan is shown in Figure 3. Note the four-patch GPS antenna array for the radio occultation measurements. These antennas are 10.5 by 45 cm and have a mass of about 500 grams. Also note the standard single patch antennas that are used for Precision Orbit Determination and some Ionospheric Soundings (about 12 cm by 12 cm).

For mission updates and the science behind this mission, please see the COSMIC User's web sites and links from the University Corporation for Atmospheric Research at the following address:

[www.cosmic.ucar.edu](http://www.cosmic.ucar.edu)



Figure 3: Stacked COSMIC/Formosat-3 spacecraft (NSPO, UCAR)

The TacSAT-2 mission was a 'mission of opportunity' for additional radio occultations. The radio occultation community has been actively looking for rides of opportunity to get more real time atmospheric soundings and had convinced AFRL to help with the integration and test of this receiver into TacSat-2. This instrument was originally going to be launched prior to COSMIC, and was going to act as an on-orbit validation receiver. It however launched a year after COSMIC. IGOR is currently used as the mission's primary GPS navigation source with real time accuracies in the 3 meter rms range, and post processed accuracies around 10 cm. The spacecraft routinely flies in a solar inertial mode, making it not yet a viable

platform for regular radio occultations. Efforts are ongoing to schedule this spacecraft to fly mostly in a nadir following configuration during routine operations, which would allow more Radio Occultation measurements to take place.

Also, just launched in June of this year, is the German TerraSAR-X mission, with a picture of the spacecraft below in figure 4. TerraSAR-X also carries an IGOR payload, for both precision orbit determination and as a Radio Occultation Payload. As this is a much larger spacecraft, the antennas are not readily seen, and a close up of the installed occultation antenna is in the inset picture.

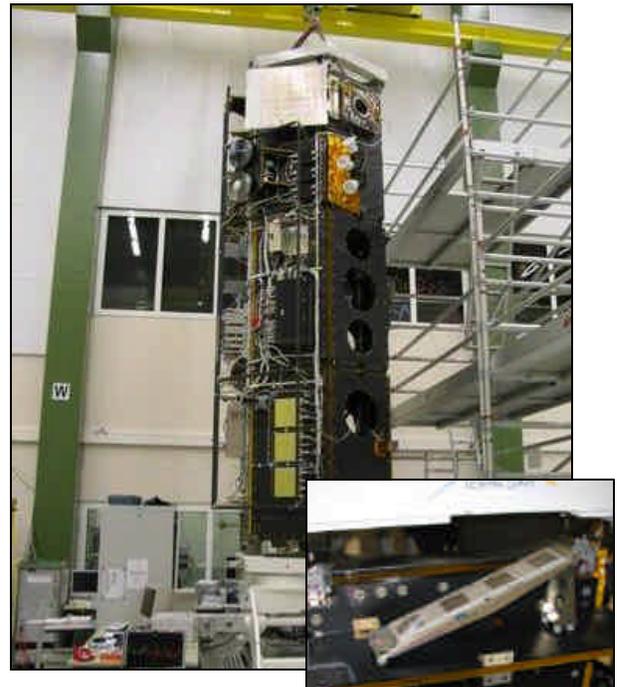


Figure 4: TerraSar-X Spacecraft. Radio Occultation Antenna (1 of 2) shown in inset. (photographs courtesy Astrium)

### The Radio Occultation technique

The basic physics behind a radio occultation relies on the refraction of radio waves as they penetrate through differing densities of fluids, the same as light is bent as it enters obliquely into water. The refraction or bending is proportional to the integrated densities along the path of the ray. In figure 5 we see that the signal is being ‘bent’ as it enters into the Earth’s Ionosphere, stratosphere and down through the troposphere, and as the LEO spacecraft, which carries the sensor, continues to rise in relation to the GPS satellite, the ‘tangent’ of the refracted signal rises until a direct, unaffected signal is obtained, essentially calibrating each sounding to the high accuracy of the GPS time.



Figure 5: Geometry of GPS or GNSS RO

One of the benefits of this method is that the fundamental measurement is time, a time which is directly related to the atomic clocks keeping the SI time for the world. This means that these classes of instrument are technology independent and only dependent on how precise your measurements are. That is, this type of measurement provides bias free historically independent data, perfect for long term climate studies.

Figures 6 and 7 show some statistical results from COSMIC and CHAMP on how deep into the atmosphere and how well this technique works. The CHAMP mission, launched in July of 2000, and has an earlier version of the JPL BlackJack receiver with a slightly lower gain antenna pattern over limb sounding volume. The blue line shows the percent of soundings vs. altitude, showing that COSMIC routinely achieves soundings below the clouds, with 50% of soundings to the lower 500 meters of the surface. The CHAMP soundings 50% mark is at approximately to 2500 meters. The COSMIC data returning these lower atmospheric conditions represents a large improvement in enabling the forecasters to stretch further into the future with weather forecasts and particularly steering currents of hurricanes.

### COSMIC

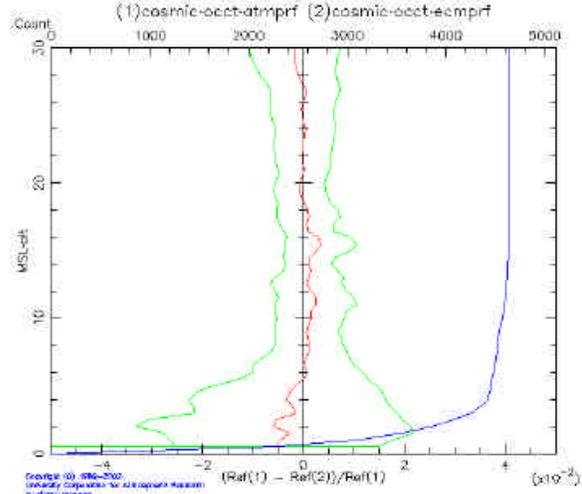


Figure 6: COSMIC atmospheric sounding depths (blue line – number of measurements at altitude) (UCAR, CDAAC)

### CHAMP

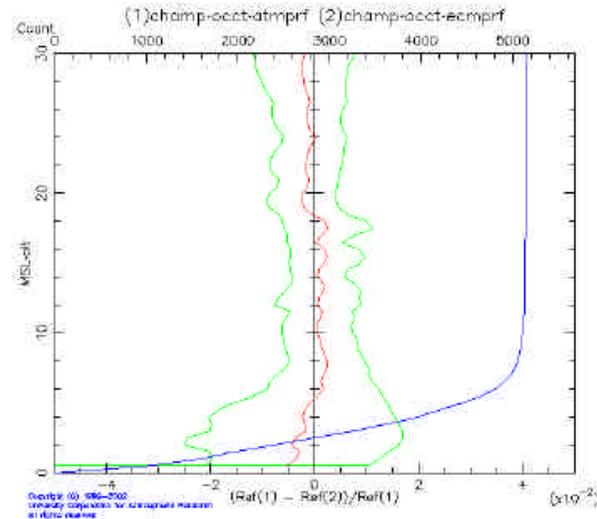


Figure 7: CHAMP Atmospheric sounding depths (GFZ/UCAR/CDAAC)

By using GPS, Galileo, and potentially other ultra stable radio sources such as GLONASS or Beidou, a properly equipped GNSS Radio Occultation received is a ready instrumented laboratory in space to utilize this technique. The actual measurement consists of detection of tiny variations and differences of phase in the carrier signals of multiple frequencies as the signals are received ‘through’ the atmosphere. Figure 8 further illustrates the concept.

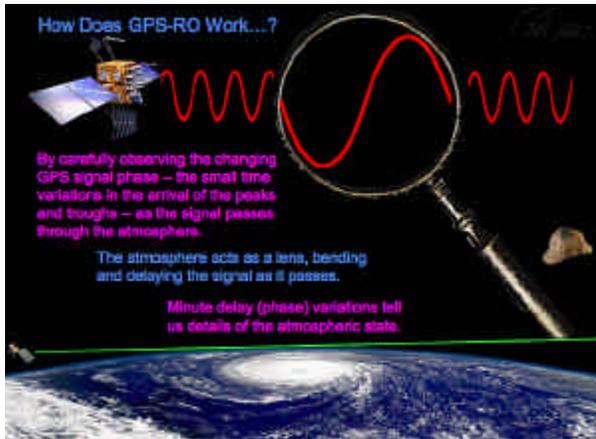


Figure 8: GPS phase difference measurements (courtesy GeoOptics, LLC)

By using GNSS as the radio source we are able to use this enormous existing infrastructure for ‘free’ with a direct fundamental connection to the international time standard. This means that the instruments that use this technique do not have instrument bias nor aging degradations, making this data perfect for long term climate trending as well as near term weather forecasting. The data can also be a fundamental reference that other types of instruments can use as a calibration source.

**COSMIC Radio Occultations**

The COSMIC mission was launched in April 2006, and is currently delivering operational data from each of the six spacecraft. The constellation’s orbits are still being modified for optimum spatial data distribution of the resulting measurements. The data distribution being acquired over 3 hours for COSMIC is depicted in figure 10 when the final constellation orbits are achieved.

Four of the satellites are in their operational orbits, with 2 more still migrating their orbital planes with respect to the other 4, see figure 10.

It is important to note that weather centers around the globe run their forecasting models every 3 hours, so the data latency and quality checks and calibrations if any have to be ready prior to the forecasting updates. For space weather, the data is more urgently desired with latency of 5 minutes or less.

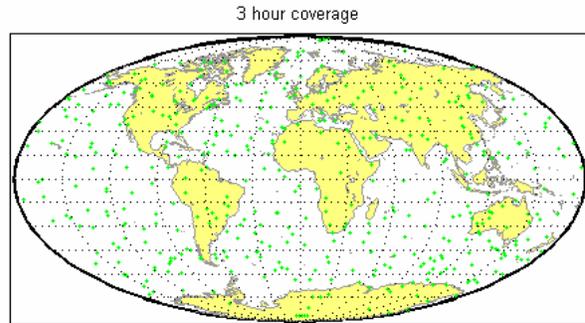


Figure 9: Representative data distribution collected over 3 hours for COSMIC’s 6 satellites. (courtesy Igor Lazbin, BRE)

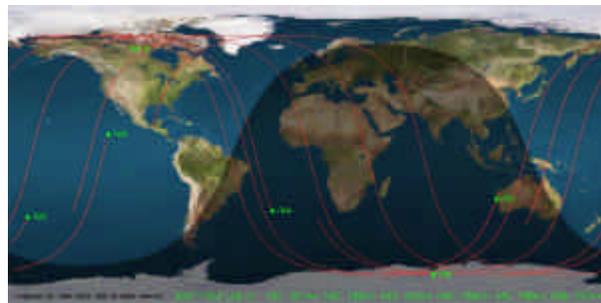


Figure 10: COSMIC spacecraft distribution as of June 2007. (see <http://www.cosmic.ucar.edu/> for latest locations)

For comparison, the below figure 11 depicts the data atmospheric soundings that will be available over 3 hours with the CICERO initial constellation.

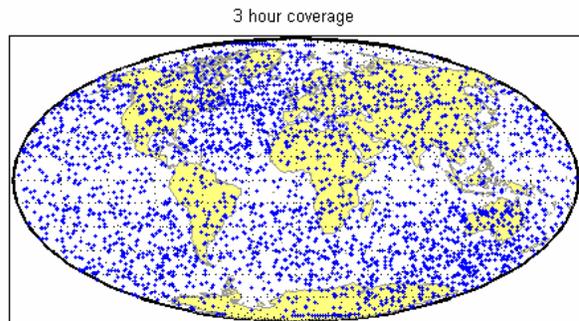


Figure 11: Representative data distribution collected over 3 hours for CICERO’s first 20 satellites. (courtesy Igor Lazbin, BRE)

***The impact and value of GNSS-RO data***

GNSS-RO data represents an almost unprecedented improvement in data quality for weather forecasting and climate research. The data is globally homogeneously dispersed, accurate across sensors and time, and precise. The data extends both the weather modelers forecast horizon and forecast accuracy, in addition to having the necessary and previously unavailable precision to definitively measure climate variability.

Below are just some examples of how GNSS radio occultation data has improved results in real-world weather service modeling and forecasting. In figure 13 we see that the current weather model completely missed Hurricane Ernesto, but the same weather model when the GNSS-RO data was assimilated predicted its existence as verified if compared with the GOES imagery.

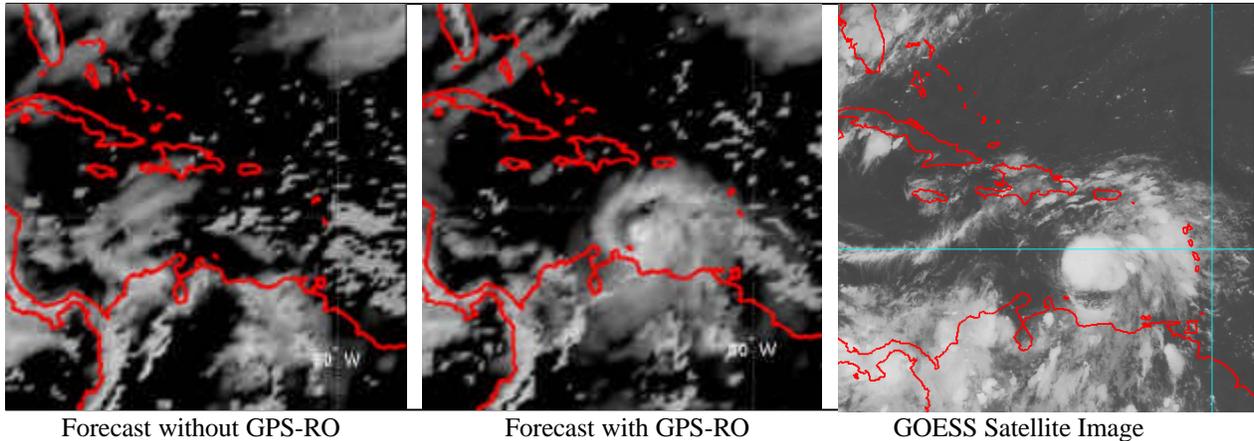


Figure 12 - Hurricane Ernesto’s development modeled with GPS-RO, from a 66 hour forecast (Chen et al.) (courtesy of UCAR, The COSMIC/FORMOSAT-3 Mission: Early Results, April 2007)

## 2. THE CICERO MISSION

### The CICERO Instrument

The primary instrument for CICERO is a tailored version of the next generation 'Pyxis' receiver made by Broad Reach Engineering. This receiver expands on the JPL BlackJack™ GPS radio occultation technologies, and the IGOR implementation thereof, in several ways. The Pyxis receiver adds the following features that will be expanded on below and in figure 14:

- Replacement of existing dual frequency RF front end with tri-frequency RF Hybrid IC
- Addition of L2C processing
- Addition of L5 frequency to the L1 & L2 baseline
- 2 bit sampling vs. 1 bit in IGOR
- Higher throughput, fully rad-hard BRE 440 processor
- Addition of a user application programmers interface
- High precision oscillator
- Design based on 100% radiation hard/tolerant parts

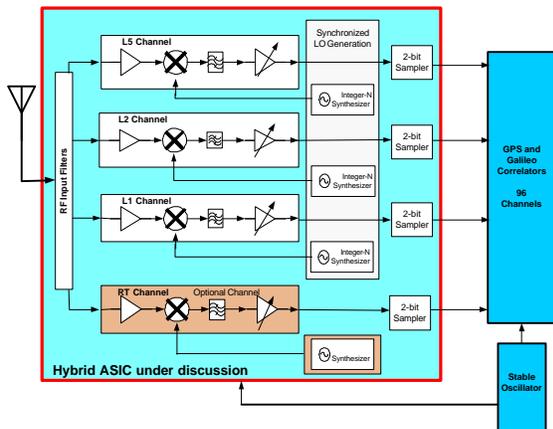
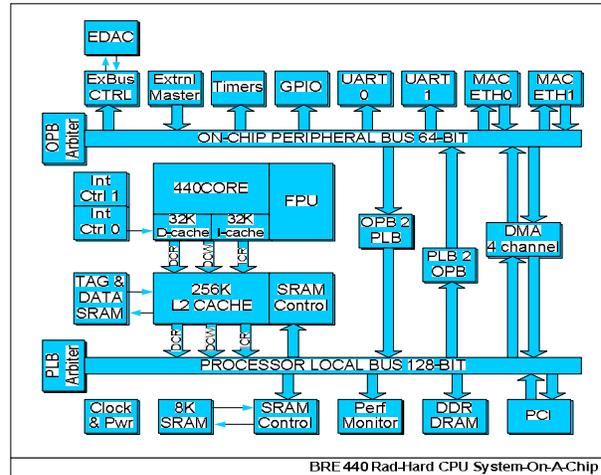


Figure 13: Functional diagram of RF Hybrid IC under development

This tri-frequency GNSS ASIC currently under development is enabling the coherent reception of the L1 L2 and L5 frequencies with high precisions. This in turn supports not only high precision orbits, but also supports the next higher level of atmospheric condition derivations by the weather and climate centers. The L1 and L5 frequencies of GPS overlap the same RF allocation for Galileo, enabling this one RF front end design to capture both constellations for the navigation solutions and RO atmospheric soundings.

The two bit sampling vs. the current on-orbit one-bit sampling enables more resolution as well, and represents about 0.5 dB worth of Signal/Noise improvement.

The new radiation hardened processor, Figure 15, will enable the high level of processing necessary for the navigation and scientific data. This processor will have the capability of 400MIPS and 400MFLOPS and its benefit over the older 603e flying now is the data throughput, DMA controllers, and a full L2 cache on chip. This new processor is being manufactured on the Honeywell's 150nm line with availability next summer.



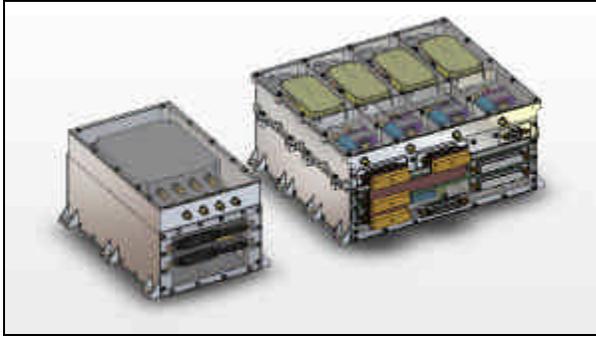


Figure 15: Size comparison of Pyxis (left) and IGOR (right).

### ***The CICERO Constellation***

The CICERO constellation consists of a total of 100 spacecraft, ~evenly spaced around the globe at an altitude of approximately 750km and an inclination of 72 degrees. The first phase of the constellation deployment starts with the October 2010 launch, with the first 10 CICERO spacecraft and a second 10 soon after. The constellation should be operational in the middle of 2011. This constellation will provide low latency data right away, at a spatial and temporal resolution far greater than previous missions.

Further spacecraft will be launched in sets of 10 per launch to build the final constellation of 100 spacecraft by 2015. To achieve this and to maintain the constellation thereafter, 20 new spacecraft will be launched and commissioned each year.

The CICERO constellation will provide a much greater number of occultation measurements, at a much denser global spacing, and much reduced latencies. Global weather centers will be able utilize the data for all near term forecasting, including space weather monitoring and alerts.

Due to a novel downlink method, the CICERO spacecraft will be able to transmit their data to the ground with very low delays, making it possible to update the global state of the atmosphere models at intervals measured in minutes, rather than hours.

### ***The CICERO Sensorcraft***

The CICERO space-borne platform is designed specifically for the CICERO mission. It is designed with a focus towards low cost and rapid manufacture. The necessity of having 100 vehicles on orbit, and having to replenish the constellation at a rate of 20 spacecraft per year, calls for a development and manufacturing approach more akin to commercial product development, rather than a ‘space systems’ approach.

A lot of the design decisions are direct results of this mentality. A great deal of effort has gone into reducing the number of parts, subsystems, boxes, boards, cables, etc... to reduce the time and cost of assembly, integration, and test.

Having said all this, this mission lends itself very well to this approach. There is only one payload, a GNSS receiver. The receiver is also the spacecraft avionics. The receiver software also hosts the spacecraft functions. The payload (with some additional software) also provides position to better than 3m and attitude determination to better than 1 degree.

For the CICERO mission– the spacecraft is the sensor, and the sensor is the spacecraft.

Functionally, the CICERO spacecraft is designed to improve upon the lessons learned from previous GNSS-RO spacecraft (CHAMP, SAC-C, COSMIC). Generally speaking, the improvements are in a number of areas as follows:

- Improved Signal to noise
- Reduced Multipath
- Increased Phase Center stability
- Increased Pointing knowledge & control
- Oscillator stability
- Data latency
- Number of atmospheric soundings
- costs
- schedule
- miniaturization

The CICERO small satellite is a three-axis-stabilized vehicle, equipped with a propulsion system, advanced telecom system, the GNSS receiver (described earlier), solar arrays, battery, torque rods, reaction wheels, antennas, and quartz gyro package.

Each vehicle has a dry mass of less than 30kg and 5kg of hydrazine propellant. The system is a single string design highly integrated in its electronics, and modular in its subsystems, in order to facilitate fast integration and just in-time manufacture and delivery of components.

The system is sized to provide at least 50W orbit average power over all beta angles, using a set of GaAs triple junction solar cells.

The avionics of the entire system are tightly integrated with the payload electronics and telecom system. This higher level of integration results in a much reduces system mass, power consumption, manufacturing cost, and final integration and test effort. The

communications link is provided through use of geostationary relay satellites, allowing a large number of CICERO craft to be in ‘ground contact’ at any given time, with data delivery latencies measured in seconds or minutes, rather than hours.

The payload antennas are derivatives of the COSMIC and Tacsat-2 RO instrument antennas – with some improvements made specifically for CICERO.

Attitude determination is achieved using GNSS phase measurements (already available as ‘science data’) via a set of 4 GNSS POD antennas. Attitude determination is aided by a magnetometer for coarse determination. The algorithms implemented for CICERO in combination with the advanced GNSS receiver functions yield a worst case attitude knowledge error of less than 1 degree – more than sufficient for the mission at hand. Attitude control is achieved using 3 miniature reaction wheels and three torque rods. A 3-axis quartz gyro package is added to provide rate information during propulsion maneuvers. Attitude control errors are less than 3 degrees – also sufficiently small for the proposed mission.

The propulsion system consist of a single tank, hydrazine based, monopropellant system with 4 thrusters and approximately 5kg of propellant. The prop system is used for orbit insertion and maintenance. The basic dimensions and artist view of the spacecraft are depicted in Figure 17, 18 and 19.

The spacecraft’s system engineering I/O chart is shown on page 11.

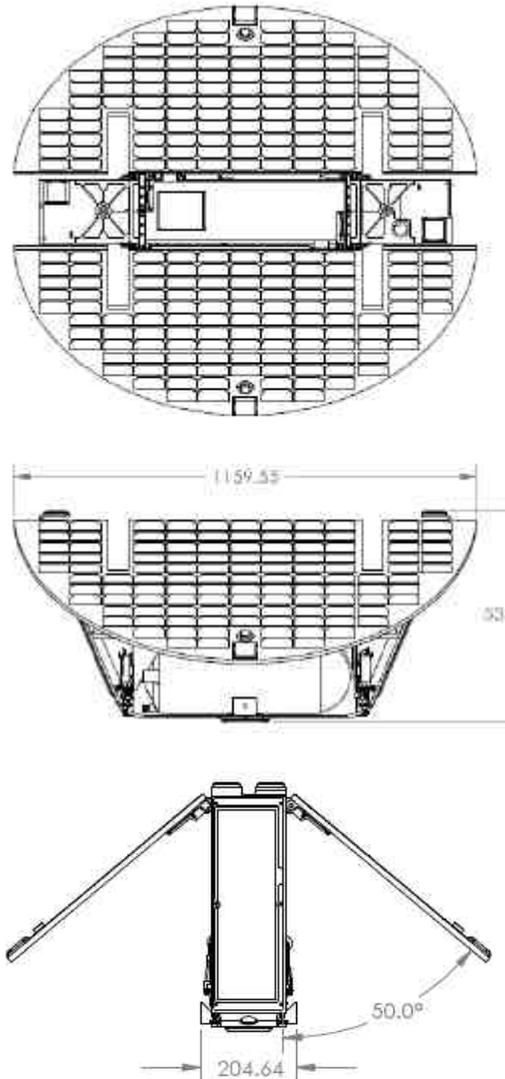


Figure 16: CICERO Sensorcraft (Dimensions in mm)

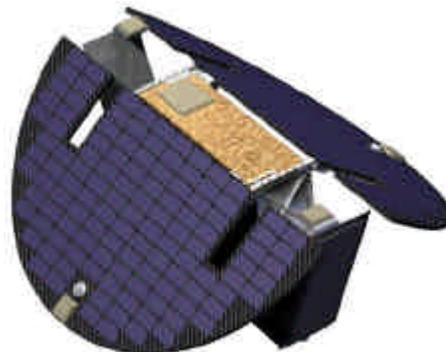


Figure 17: CICERO Sensorcraft rendering deployed configuration

### **Design Approach**

As the CICERO mission is a commercial venture, the system design was driven heavily by the total data cost, or cost to deliver the data per year, keeping in mind that the mission itself may be extended indefinitely in some form or another.

As a baseline, a study was performed to determine system design which minimizes the cost per delivered occultation data, assuming an initial 20 sensor constellation for launch in 2011.

It is important to repeat the fact that the cost considerations are made for the entire system to deliver the data to the user. This means that cost trades include the data backhaul, mission operations, launch, design costs, replacement costs, and manufacturing costs – not just the cost to design a single spacecraft.

Examples of decisions made follow:

- For a much more stable platform as compared to COSMIC the vehicle is a three axis stabilized satellite containing reaction wheels and torque rods.
- To lower the latency of data, and increase the value of the data to the users, the system is designed to send the acquired data through geostationary assets to enable ‘immediate’ delivery of the science data if desired.
- For cost and schedule savings some up-front engineering efforts are larger but result in a direct reduction in recurring cost and deployment time.

Conceptually, this approach can be illustrated with the following three development equations:

#### **System Study equation #1**

Life Cycle Costs (LCC) = F(  
Non-Recurring-Engineering,  
# of S/C \*(Recurring S/C costs),  
Communications Costs,  
Operations Costs,  
parts, subcontracts, obsolescence, ...  
Launch Costs)

#### **System Study Equation #2**

Maximum Performance (MP) = Spacecraft stability  
# of Spacecraft,  
# of Radio Occultation transmitter sources,  
latency of the data delivery,  
stability of the clock sources,  
S/N of GNSS receiver)

#### **Systems Study Equation #3**

Time to Market (TTM) = Obtain operational status prior to COSMIC either being de-commissioned or

otherwise beyond its operational lifetime. This is assumed to be late 2010 to late 2011.

Through this design process, and the understanding that we have the ability to buy down the recurring costs with non-recurring engineering, it was possible to consider new component and piece part development, and not only consider heritage or existing parts and designs.

We set up three ‘differential equations’ in order to define our trade space.

We conceptually set ‘dMP’ and ‘dLCC’ and ‘dTMM’ = 0 to find out where our maximum performance and minimum costs points, as well as some knowledge of the ‘stability’ of those points. For instance a low stability point would be relying exclusively on a technology that has not been attempted before. This does not mean that one can not derive the next product of a series, or the next smaller feature size of an ASIC foundry. Although one can argue about all the real and perceived risk, costs, weighting functions and such on this forever, we came up with the current design that we believe is the lowest risk, lowest costs, and highest performance system within the allotted time to market.

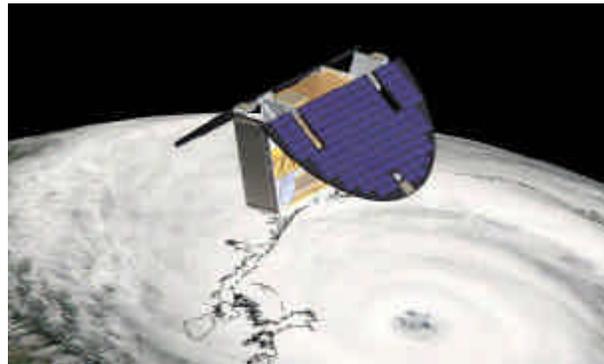
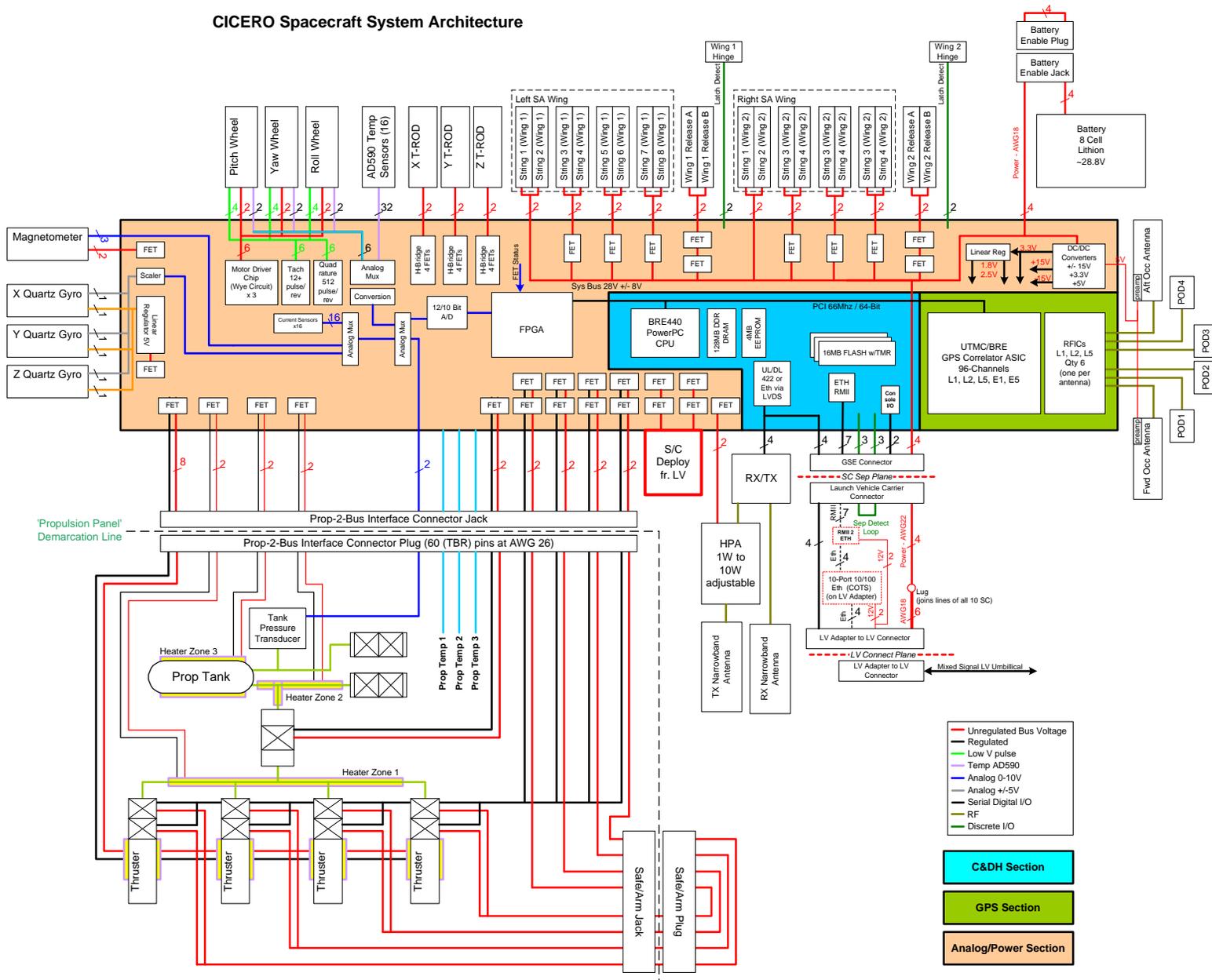


Figure 18: Rendering of the CICERO sensor craft.

#### **Baseline Specifications:**

Minimum 20 spacecraft for initial constellation  
Operational Altitude: 700 to 800 km  
Inclination: 70 to 75 degrees  
Attitude Knowledge: < +/- 1 degree, 3 sigma  
Attitude Control: < +/- 2 degrees, 3 sigma  
Power consumption: 40W OAP  
Data latencies:  
Weather: < 100 minutes  
Space weather: < 5 minutes  
Climate: no requirement  
Data volume/craft: > 10 MBytes/orbit

# CICERO Spacecraft System Architecture



### 3. CICERO BUSINESS PLAN

The CICERO mission is fundamentally a commercial venture that sells GNSS Radio Occultation data and derived data products to governments, industry, and academia world wide.

The CICERO business plan is set up as a revised ‘private public partnership’ in that capital markets are providing the funding for the development of this mission, with an intention of spreading the costs and benefits amongst all the user communities, with large agencies such as NOAA being anchor clients.

The first ‘C’ in CICERO stands for “Community”, and we have tapped into the weather forecasting and climate communities to help sponsor this mission, both in data analysis and infrastructure development. A direct precedent of a working business model where remote sensing data is sold is the high resolution imagery markets serviced by DigitalGlobe and GeoEye and their governmental agency clients. Other examples are the increased use by government agencies of space based telecommunications systems.

In addition to investor based financing, Broad Reach Engineering has been investing over the last 10 years, in the underlying technologies to make these types of missions possible. Broad Reach Engineering has licensed JPL’s Blackjack technology which has allowed the development and deployment of the IGOR receiver on COSMIC, thus paving the way for CICERO. Broad Reach has spent their internal research funding on the development of higher performance processor and a more capable and tightly integrated GNSS RF front end. We are continuing to fund these technologies through various product improvement plans, adding features and capabilities to support the weather data, navigation solutions and attitude determination users.

Broad Reach and the CICERO mission customer, GeoOptics’ business plan, relies on the realization that the value of the data is being established with the COSMIC mission. Reasons for that are plenty, but for further reading, please see the COSMIC web site at [www.cosmic.ucar.edu](http://www.cosmic.ucar.edu) as well as the “The COSMIC/FORMOSAT-3 Mission: Early Results” that was submitted to the Bulletin of American Meteorological Society, dated 5 April 2007.

The generic business sustainability equation, equation 1 below, should be second nature, but in engineering pursuits, is sometimes ignored. This is unfortunate.

$$\int_0^t \text{cost} \, dt = \int_0^t \text{price} \, dt = \int_0^t \text{value} \, dt$$

Equation 1: Business Sustainability

That is, the sum over time of your costs has to be less than the price of your goods and services, which in turn has to be less than your customer’s real and perceived value for them to make their purchases. The time aspect of this is very important, in that the time includes short term necessities such as payroll, and long term competitive pressures that should keep product development costs as a part of re-investments and continual product improvements. This is all happening under the tensions of the market and tensions of owners and investors desiring a return.

Now, there are lots of business school orchestrations of this and other equations, but mostly in narrowing the focus of the generic investor. Either in terms of pure “Return of Investments” (ROI) or in EBITDA, Earnings Before Interest Taxes Depreciation and Amortization. The ROI is generally the business investment until the business sold, and what was the amount of return over what time frame. The EBITDA if positive, is mostly that the business has achieved some kind of sustainability in that it is covering its operational costs, and that there is left over monies to start paying down the investments and paying taxes.

Although some ideas seem to be very viable on first impressions, and that investments are being made, the overall rationalization of the investments and effective ROI expectations may be misplaced. Only the development and realization of the technology, with effective adoption of the technology, and selling of the technology will prove that the investment was worth it. This is a necessity, but is not sufficient. The value to the customer must also be greater than the costs. Examples of good technology implementation with inadequate value (in relation to the market *at the time of implementation*) are the Globalstar, Iridium and Orbcomm constellations. Their business is currently a success primarily because they were able to write off the initial investments of the spacecraft and launch costs, and revamped their business in covering their costs of operating their ‘free’ constellations. Billions were lost so that millions can be made.

In CICERO’s case, the costs of constellation development vs. price vs. value is playing out to be self sustainable. For background, the COSMIC constellation containing 6 spacecraft launched in April 2006, was a \$100M investment through the first year of operation. The data is proving to be unprecedented in terms of temperature accuracy (to 0.02K), which is five times more accurate than what is required for detailed climate record and climate studies.

The COSMIC data when assimilated into current models is the only known method that is able to

forecast the development of a tropical depression into tropical storms and hurricanes, see figure 13. The example of the Ernesto Hurricane during the 2006 season, forecast the Hurricane four days in advance, and predicted its location within 50 km. NASA's own requirements for the year 2030 is to be able to predict hurricanes 3 days in advance with accuracies better than 150km. COSMIC is currently collecting more atmospheric soundings, and at an order of magnitude more precise than all the weather balloons every day.

The initial CICERO program will contain the 20 GPS + Galileo capable spacecraft vs. COSMIC's 6 spacecraft that is GPS only, so CICERO will have an order of magnitude more soundings with improved accuracies and precision due to the improved sampling techniques and algorithms.

When complete, the 100 craft constellation will increase this by another order of magnitude. Table below is normalized to the effective three hour data collection, due to the weather center's routine updating their forecast every 3 hours.

3 Hour Data Acquisition	COSMIC 6 S/C	CICERO 20 S/C	CICERO 100 S/C
# of Atmospheric Soundings GPS Only	~ 300	~ 1,000	~ 5,000
GPS + Galileo	~ 300	~ 2,000	~ 10,000

#### 4. CONCLUSION

In addressing a 'mission that matters', CICERO paves new ways of doing business in the space business and provides a dataset that brings with it knowledge and understanding for all of us on this planet. In its implementation and orchestration, CICERO, is technically feasible, due to the continually improvements of the underlying technology and is financially viable due to its low costs.

The implementation presented also pushes the commonly accepted envelope of system design, borrows techniques across engineering and science disciplines, and finally promises to deliver unprecedented results outside of the typical channels of arguably slow and inefficient government procurement cycles.

The CICERO mission is a clear example of a problem that is well addressed using small spacecraft, or sensor

craft. It is an example of a mission that makes sense because it provides a data set that is more accurate, more timely, cheaper, and more complete than any other method known to obtain world wide high precision results.

#### References

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