CRICKET Campaign: Setup and Execution
LWA Memo Report

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Introduction

This report describes the Coordinated Radio Interferometry and COSMIC Experiment in Tomography (CRICKET) campaign held during September 15-17, 2007. The campaign had the goal of demonstrating three-dimensional ionospheric specification using high sensitivity measurements of local ionospheric gradients made by the Very Large Array (VLA) radio telescope near Socorro, New Mexico and measurements of the regional ionospheric structure made during overflights of Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites. The experimental concept was to bring together the various measurements of the local and global ionosphere into a coherent picture using ionospheric tomography to produce a three-dimensional picture of the ionosphere over the Southwestern United States and to tie this into the global picture of the ionosphere provided by the COSMIC satellites. This memorandum report describes the experimental setup, summarizes the results, and discusses problems encountered during the measurements. The lessons learned in coordinating a set of satellite observations with the VLA (and, in the future, with the Long Wavelength Array: LWA) are summarized. Additionally recommendations are made regarding the set up and performance of future campaigns.

Campaign Description

<u>Introduction:</u> The COSMIC Radio Interferometry Combined Experiment in Tomography (CRICKET) campaign was a joint experiment combining the capabilities of the Very Large Array radio telescope with the *Constellation Observing System for Meteorology, Ionosphere, and Climate* (COSMIC) satellite constellation to demonstrate and perform volumetric ionospheric tomography over the Southwestern United States. The experiment was to be performed during three ~1.5-hour-long observing windows or Epochs in which the VLA was operated at 74 MHz in the A, or largest, configuration where the maximum antenna separation is ~35 km. When the VLA is operating at 74 MHz, it is most sensitive to variations in the Earth's ionosphere with 1° of phase difference between antennas corresponding to a change of approximately 0.0015 TECU (total electron content units: 10^{12} electrons cm^{-2}). The key aspect of these experiments was to compare and combine ionospheric measurements made using the VLA to those made by COSMIC and by ground-based GPS receivers. This allowed us to cross-validate and cross-compare the measurements made by the different instruments and measurement techniques.

COSMIC Program Overview: The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC, also known as FORMOSAT-3 or CF3 in this work) is a six-satellite constellation (CF3-1,…,6) launched on April 15, 2006 to perform measurements of tropospheric weather and to study the Earth's ionosphere. The CF3 program was executed jointly by the United States of America and Taiwan (Republic of China, ROC). Each satellite contains three instruments for the measuring ionosphere: a GPS Occultation Experiment (GOX) built by Broad Reach Engineering for the University Corporation for Atmospheric Research (UCAR), a TIP or Tiny Ionospheric Photometer, and a Tri-Band Beacon (TBB) both built by NRL. The GOX is a high-precision GPS receiver which measures the slant total electron content (TEC) between the CF3 satellite and satellites in the GPS constellation. The TIP is a far-ultraviolet photometer designed to measure density gradients in the night-time ionosphere. The TBB is a coherently emitting radio beacon operating at UHF, VHF, and L-band frequencies. The three instruments when used together represent a powerful measurement suite for characterizing the Earth's F-region ionosphere. The CF3 data are down-linked and archived at the TACC (Taiwan Analysis Center for COSMIC) and the satellites are commanded from the MMC (Multi-Mission Center) in Taiwan. The CF3 data are also archived at the UCAR in Boulder, CO. Additional details of the CF3 program and the early science return are summarized in *Anthes et al.* [2008]. The CF3 program was funded by the Taiwanese National Space Office (NSPO), the US National Science Foundation, and the US Office of Naval Research. Figure 1 shows a diagram of a CF3 satellite indicating the instruments.

Tiny Ionospheric Photometer

The TIP instrument for the CF3 satellites has to provide accurate and precise measurements of the electron density gradients in the ionosphere and complement GOX TEC measurements, which are of very high precision. The instrument used a design based on measurement of the O I 135.6-nm emission produced by radiative recombination of O^+ ions and electrons, a natural decay process of the ionosphere. In order to perform tomographic inversion of the TIP and GOX data simultaneously, the data sets should have comparable signal-to-noise ratios. However, this is difficult to achieve for a compact optical instrument as the airglow signals are can be very weak and the small size of the instrument limits the collecting area of the telescope. The design selected was a compact narrow-band ultraviolet photometer. Additional details of the instrument and its design can be found in *Kalmanson et al.* [2004]; we summarize the relevant design features here.

The TIP instrument is a narrow-band photometer that measures the 135.6-nm emission over the passband of 132.5 nm to ~160 nm. The instrument is divided into two sections: the interface electronics box and the photometer head, as shown in Figure 2. The interface electronics provides an interface to the space vehicle and is the control system for the TIP instrument. The photometer subsystem consists of an off-axis parabolic telescope feeding a sub-miniature Hamamatsu photomultiplier tube (R7511) with a cesium iodide photocathode. The photometer includes a filter-wheel assembly with additional filters and a shutter to block the light path so that the on-orbit radiation background seen by the photomultiplier tube can be measured. The passband of the system is controlled by the filter and photocathode combination.

The field of view is circular with a diameter of 3.8°; this was driven by the size of the photocathodes available for the photomultiplier tube, by the focal length of the telescope mirror, and by the desired scale sizes we wished to observe. This field of view provides a best-case spatial resolution at the F-region peak (~350 km) of ~11 km when the satellites were in their initial orbit at ~515 km altitude and ~30 km when the satellites are at their nominal orbit altitude of ~800 km. This spatial resolution is smeared out along the orbit track by an additional 8.3 km due to the satellite's orbital motion and the nominal 1.18 second integration time for the TIP measurements. Using measured values for the quantum efficiency, the filter transmittance, and the known values for the reflectance and area of the telescope mirror, the TIP sensitivity was estimated to be ~400 ct s^{-1} $Rayleigh^{-1}$. The internal structure of the photometer head is shown in Figure 2. The on-orbit performance of the TIP instruments is presented in *Budzien et al.* [2009] and *Dymond et al.* [2009].

GPS Occultation Experiment (GOX)

The primary payload of each COSMIC satellite is a GPS radio-occultation receiver developed by NASA's Jet Propulsion Laboratory (JPL). By measuring the phase delay of radio waves from GPS satellites as they are occulted by the Earth's atmosphere (Fig. 3), accurate and precise vertical profiles of the bending angles of radio wave trajectories are obtained in the ionosphere, stratosphere and troposphere. From the bending angles, profiles of atmospheric refractivity are obtained. The procedures used to obtain stratospheric and tropospheric bending angle and refractivity profiles from the raw phase and amplitude data for the COSMIC mission are described by *Kuo et al.* [2004].

The radio occultation (RO) method for obtaining atmospheric soundings is summarized by *Kursinski et al.* [1997] and in a special issue of *Terrestrial, Atmospheric and Oceanic Sciences* [TAO, 2000]. The TAO volume also describes the RO method; application of RO to weather, climate and ionospheric research; and the COSMIC mission. For ionospheric studies, the index of refraction, N, is a function of electron density (n_e in number of electrons per cubic meter) and frequency of the GPS carrier (f in Hz):

$$N = -4.03 \times 10^{7} \frac{n_e}{f^2} . \tag{1}$$

The RO technique and its history, which starts with the exploration of Mars in the 1960s and later was applied to other planets, are described by *Yunck et al.* [2000].

The GOX instrument aboard COSMIC performs dual-frequency measurements of the slant TEC through the ionosphere between a CF3 satellite and a satellite in the GPS constellation. These slant TEC measurements are routinely inverted using an Abel inversion algorithm and are available for download from the COSMIC Data Acquisition and Analysis Center (CDAAC) web site [*CDAAC*, 2008]. A preliminary study demonstrating the accuracy and providing validation of the electron density profiles can be found in *Lei et al.* [2007]. During the CRICKET campaign, the GOX profiles were downloaded from the CDAAC website. Additionally, the slant TECs were also downloaded and inverted at the Naval Research Laboratory to ensure consistency of the analysis.

Tri-Band Beacon and Receivers

The Tri-Band Beacon is a coherently emitting three-frequency radio beacon operating at 150 (UHF), 400 (VHF), and 1066 (L-Band) MHz. The TBB was built by the Plasma Physics Division at the Naval Research Laboratory. The beacon emission is observed using a set of ground-based receivers and antennas. As mentioned in equation ~~2~~ (1) above, the ionospheric index of refraction is a function of both frequency and electron density. Thus, measurements of the relative phases of the three frequencies can be used to infer the slant TEC between the receiver and the transmitting beacon to very high precision. The TBB can be either operated in 3-frequency mode or in 2-frequency mode depending on space vehicle power concerns and upon operational constraints. During the CRICKET campaign described in more detail below, the TBB was operated using only the UHF and VHF bands to conserve power on the satellite. The TBB signal was observed using a set of four ground-based receiving stations each consisting of a patch antenna, receiver, and laptop computer (Figure 3), which were located near the center of the VLA (at the Long Wavelength Demonstration Array, LWDA, site) and at VLA antennas near the ends of the VLA arms.

<u>Very Large Array:</u> The VLA radio telescope is located near Socorro, NM. The array consists of 27 antennas dispersed in a “Y”-shaped configuration with arms that extend ~20 km the largest A-configuration. Each antenna consists of a 25-m radio paraboloid with an altitude-azimuth mount; a 74-MHz receiver is located at the prime focus. The RF measurements from each antenna are transmitted back to the control center via fiber-optic cables. The 74-MHz dipoles and receivers were added to the VLA as a cooperative project between the NRL and NRAO in the 1990s~~.~~ [*Kassim et al.*, 2007]. The VLA configuration indicating the locations of the TBB receivers is shown in Figure 4.

Observations

During each E~~e~~poch, either the ionospheric conditions (according to the time of day) or the operating mode for the VLA varied. Data were acquired by the VLA using either “self calibration” (self-cal) or “field calibration” (field-cal) techniques to characterize the ionosphere over the VLA [*Cotton et al.*, 2004; *Kassim et al.*, 1993; *Kassim et al.*, 2007]. Gathering data during different times of day would allow the study of the ionosphere when different physical processes dominate ionospheric dynamics. There were three Epochs (observation intervals) defined for study:

1. Epoch 1 was a nighttime observation to allow all three COSMIC instruments on the CF-4 satellite to be used and the VLA was used in self-cal mode, its most sensitive ionospheric mode.
2. Epoch 2 was a mid-day observation with the VLA in self-cal mode, but the TIP on the CF3-4 satellite could not be used due to strong contamination of its signal by scattered sunlight.
3. During Epoch 3, the VLA was operated in field-cal mode. In this mode the VLA is less sensitive to the ionosphere but its field of view at 350 km (the canonical ionospheric pierce point) is much wider, ~11.6° or ~100 km in the A-configuration viewing the zenith. Epoch 3 occurred during the middle of the night, so all three of the COSMIC instruments on the CF-4 satellite were to be used.

Data were successfully gathered using TIP, GOX, and VLA during Epochs 1 and 3 but the VLA was not operated during Epoch 2 due to due to a change in schedule. Data from the TBB were gathered during Epoch 1 but due to a slip in schedule, the VLA antennas blocked the lines of sight from the TBB receivers to the CF3-4 satellite rendering the data useless. During Epoch 3, the TBB was unavailable to conserve vehicle power for other commitments.

Epoch 1: The VLA observed at 73.8 MHz in the A-configuration, with 20 antennas in operation, on 15 September 2007. As the absolute phase of the radio source is not a known quantity, the VLA measurements are performed relative to an arbitrarily chosen reference antenna. The relative phase measurements are phase-stable to ~1° corresponding to ~0.0015 TECU at 73.8 MHz. The VLA measured the ionospherically induced phase relative to an antenna near the center of the array (W4) with a 3-minute cadence from 08:00-09:20 UT. The VLA operated in self-calibration mode in which the ionosphere was "back illuminated" by bright radio source 3C134, at RA 05h 04m 4.20s and DEC 38° 06m 11.0s (J2000). In self-calibration mode, a bright unresolved radio source is observed by all antennas [*Kassim et al.,* 2007]. As the source is effectively at infinite distance, the lines of sight from individual antennas probe the ionosphere with spatial sampling determined by the projected separations of antennas in the direction of the source. These lines are separated by a maximum of 35 km when the VLA is in the A-configuration. The CF3-4 satellite passed to the East of the VLA over western Oklahoma, central Texas, and the Gulf of Mexico, as shown in Figure 5 (a).

Epoch 3: The VLA observed at 73.8 MHz in the A-configuration, with 20 antennas in operation, on 17 September 2007 from 07:56 – 10:14 UT. During this Epoch, the VLA operated in the field-calibration mode in which the ionosphere was "back illuminated" by a set of weaker unresolved radio sources than were used in self-calibration mode, with the field of view centered at RA 22h 25m 34.70s and DEC 19° 19m 22.90s (J2000). In field-calibration mode, unresolved radio sources are observed and their refractive motion or displacement from known astrometric positions are used to determine the ionospheric phase screen (or relative TEC variation across the field of view) [*Kassim et al.,* 2007]. As the radio sources are effectively at infinite distance, the lines of sight from individual sources probe the ionosphere with spatial sampling determined by the projected field of view of an antenna onto the ionosphere. The size of the field of view of an antenna is given by the Rayleigh criterion for the antenna and wavelength, which for the VLA operating at 74 MHz is approximately 12°; the field-calibration coverage is ~70 km when projected toward the zenith for an ionosphere at 350 km. The CF3-4 satellite passed to the West of the VLA over Washington state, central California, and the Gulf of California, as shown in Figure 5 (b).

VLA-Specific Requirements

EMI Testing: As the beacon receivers and antennas were to be operated in conjunction with the VLA antennas, they were to be powered and operated from the VLA antennas. This introduced electromagnetic interference (EMI) requirements that the receivers and their associated laptop computers had to meet. While the detailed EMI specifications are not presented here, the receivers were found to be EMI compliant while the laptop computers were not. This meant that the receiver/laptops could not be operated during times that were not allocated to CRICKET measurements, so that there was no interference with measurements made by other scientists. This also meant that the receiver/laptops needed to be turned on at the start of the CRICKET observations and shut off at the end. Thus, three teams were required to operate the receiver/laptops during the campaign.

Wildlife Protection: The VLA shares land with various cattle ranchers. And there are large wild animals, such as elk and pronghorn antelope, sometimes present. These animals have been known to rub on any structures present in order to assuage itching caused by ticks, fleas, flies, and other vermin. Thus, the TBB patch antennas, which are rather fragile compared to steers and elk, needed to be fenced in for protection. The fencing consisted of steel fence posts driven into the ground around the antennas. The steel fence posts also had additional guy-lines attached to stakes for additional strength and stability. These posts were draped with barbed wire, as shown in Figure 6. These fences were removed after the CRICKET operations.

Campaign Execution

Coordination with COSMIC Program: Coordination with the COSMIC satellite operators in the TACC in Taiwan was carried out via e-mail. There is a 13-hour time difference between the Eastern US and Taiwan, or 11 hours between New Mexico and Taiwan. These large time differences complicated campaign planning as telephone communication was difficult to arrange. The planned VLA dates and Epochs were e-mailed to the TIP experiment representative at TACC and the satellite planning was carried out. An additional complication for the CRICKET campaign was the simultaneous ionospheric spread-F campaign being carried out over the Pacific Ocean. The TBB was only operated for 20 minutes per orbit due to satellite power constraints. This meant that, unlike the TIP and GOX, TBB operations had to be scheduled through the TACC.

VLA Coordination: VLA coordination was accomplished via e-mail for loading the target lists and getting observing time. Two of the CRICKET planners were also on-site at the VLA which made communication easy.

Team Disposition and Coordination: There were two two-person teams available for support of the campaign. Two-person teams are a safety requirement of the VLA site. There were three receivers to operate. This made things difficult during Epoch 1 when one team had to drive across the VLA to turn on one of the receivers. Inter-team communication was accomplished using the VLA walkie-talkie system. (Cell phone usage is strictly prohibited at the VLA due to EMI concerns.)

Lessons Learned

VLA Size: As shown in Figure 7, the VLA in the A-configuration is approximately the diameter of the Washington, DC beltway and the waveguide roads along the arms of the array are, for the most part, fairly rough dirt roads. This means that a trip from the end of one arm of the array to the other takes about 1 hour, because the distances are roughly 20 miles while the average comfortable speed attainable is about 20 mph. If cross-site travel is required, this guideline must be kept in mind.

Take away: The VLA is HUGE and the terrain is rugged. Be prepared. Also, be prepared to be awed by the majesty of this monster; it really is a testament to human ingenuity.

Satellite Program Coordination: Coordination with satellite programs is a tricky business. As the COSMIC program routinely cycled power on the TBB to conserve vehicle power, careful planning was necessary. The campaign was further complicated by the COSMIC program running a concurrent ionospheric campaign over the Pacific. Since the TBB was limited to 20 minutes of operation per orbit, this meant that satellites being used in the Pacific campaign could not be used for the CRICKET campaign, and vice versa. Additionally, the CRICKET epochs slipped in time, due to VLA operational constraints, so that the plans made to use CF3-1, which would have transited to the west of the VLA, could not be used. The TBB patch antennas were deployed to the westward of the VLA antennas to avoid sky-blockage when using CF3-1. When the CRICKET epochs slipped, satellite CF3-4 had to be used instead. CF3-4 transited to the East of the VLA during Epoch 1, which resulted in sky-blockage during part of the transits. During Epoch 3, the CF3-4 satellite transited to the west of the VLA but the NSPO CF3-4 mission planners would not support the CRICKET campaign and used CF3-4 to support the Pacific campaign instead. Further planning complications occurred due to the 13-hour time difference between Washington, DC and Taipei, ROC. Plans had to be made by e-mail with limited voice communication. Additionally, even though two instrument principal investigators from the COSMIC mission were involved in the CRICKET campaign, there was no knowledge passed to them from the NSPO COSMIC program office of the Pacific campaign until plans for the CRICKET campaign had already been made and VLA time allocated.

<u>Take away</u>: Plan as far as possible in advance. Keep all lines of communication open. Be flexible. Be lucky.

VLA Planning & Coordination: The VLA staff was extremely helpful and supportive. CRICKET planning was complicated by two facts: the receiver/laptops produced EMI, which limited the time they could be operated; the CRICKET observations were scheduled "dynamically" along with several other observations that also depended upon outside constraints (weather, for example). The final observing times were negotiated and allocated only a day or two before Epoch 1 started.

<u>Take away:</u> Working at VLA helped because a face could be put to a voice.

EMI Issues: As discussed above, the receivers were found to be EMI compliant while the laptop computers were not. This meant that the receiver/laptops could not be operated during times that were not allocated to CRICKET measurements, to avoid interference with observations made by other scientists. This also meant that the receiver/laptops could be turned on only at the start of the CRICKET observations and had to be shut off at the end of the observations. Thus, three teams were required to operate the receiver/laptops during the campaign. Unfortunately, only two teams were available. One team turned on the receiver/laptop at the end of the East Arm and then rushed across the VLA using the waveguide roads to the site at the end of the North Arm. As the VLA is very large and the roads are rough, the team arrived at the North Arm after the COSMIC satellite had passed, and so no data were collected from the North Arm. EMI tests indicated that, in all likelihood, with appropriate shielding the receivers could be operated continuously.

<u>Take away:</u> EMI can seriously complicate coordinated observations with the VLA. Anytime you are planning on having sensors in close proximity to the antennas, you need to plan for EMI testing and plan to accommodate any EMI-driven requirements. Had the program planning and

EMI testing started earlier, it would have been possible to have shielded the receivers to make them EMI compliant.

Miscellaneous Problems: One problem that was encountered was that the TBB receiver located at the LWA site did not gather any data during Epoch 1. This receiver could be operated continuously because it was far enough from any of the LWA antennas that there was no EMI interference. However, during the evening prior to Epoch 1, it was decided that a dual-frequency GPS receiver would be co-located at the LWA site with the TBB receiver. The GPS receiver also required a computer for data acquisition. As no other computer was available, it was decided to operate both the GPS receiver and the TBB receiver with the same laptop. Both P. Bernhardt from NRL and the LANL group who provided the GPS receiver were consulted and neither thought there would be a problem. The GPS receiver software was then installed on the same laptop that ran the TBB receiver. The two software packages worked together with GPS data being gathered and beacon data being received and archived from other satellites with radio beacons, such as the OSCAR satellites. Several OSCAR passes were acquired and archived while the GPS data were gathered. But no campaign data were acquired. A post-campaign analysis showed that everything worked well until [local, 0600 UT?] midnight, when the GPS software executed a reset. This reset disabled both the GPS software and the beacon/receiver software, and as a result no data from either source were gathered during the Epoch 1. As mentioned elsewhere, the TBB was not operated during Epoch 3.

<u>Take away</u>: When possible, test the configuration for at least a day or two in advance of the campaign measurements.

Miscellaneous Observations: One concern for campaign planning was whether there was sufficient space within the fences around the bases of the VLA antennas to accommodate the TBB receivers and laptops. The answer is “Yes”.

Summary

Running a successful satellite campaign in conjunction with the VLA is not an easy prospect. Careful planning and coordination is an absolute necessity. Communication with the satellite operators and the VLA is crucial to the success of the campaign. Campaigners must also be aware that the VLA is a fairly rough environment that drives requirements on staffing, equipment safety, EMI/EMC, and personal safety.

Acknowledgements

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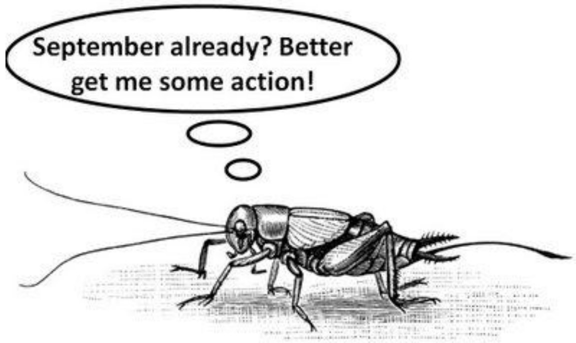

CRICKET planning…

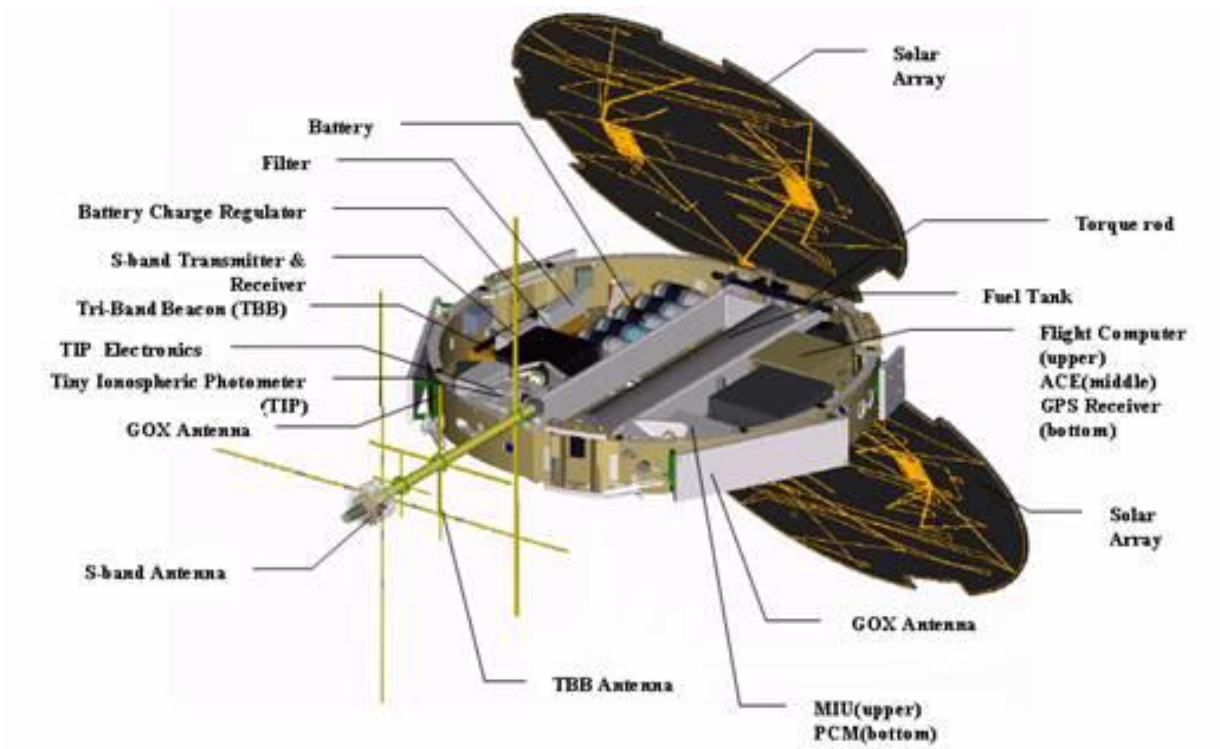

Figure 1: *Illustration of a COSMIC Satellite.* The construction and internal components of one of the COSMIC satellites is shown. (http://space.cv.nctu.edu.tw/research/COSMIC_Gravity/main.files/image002.jpg)

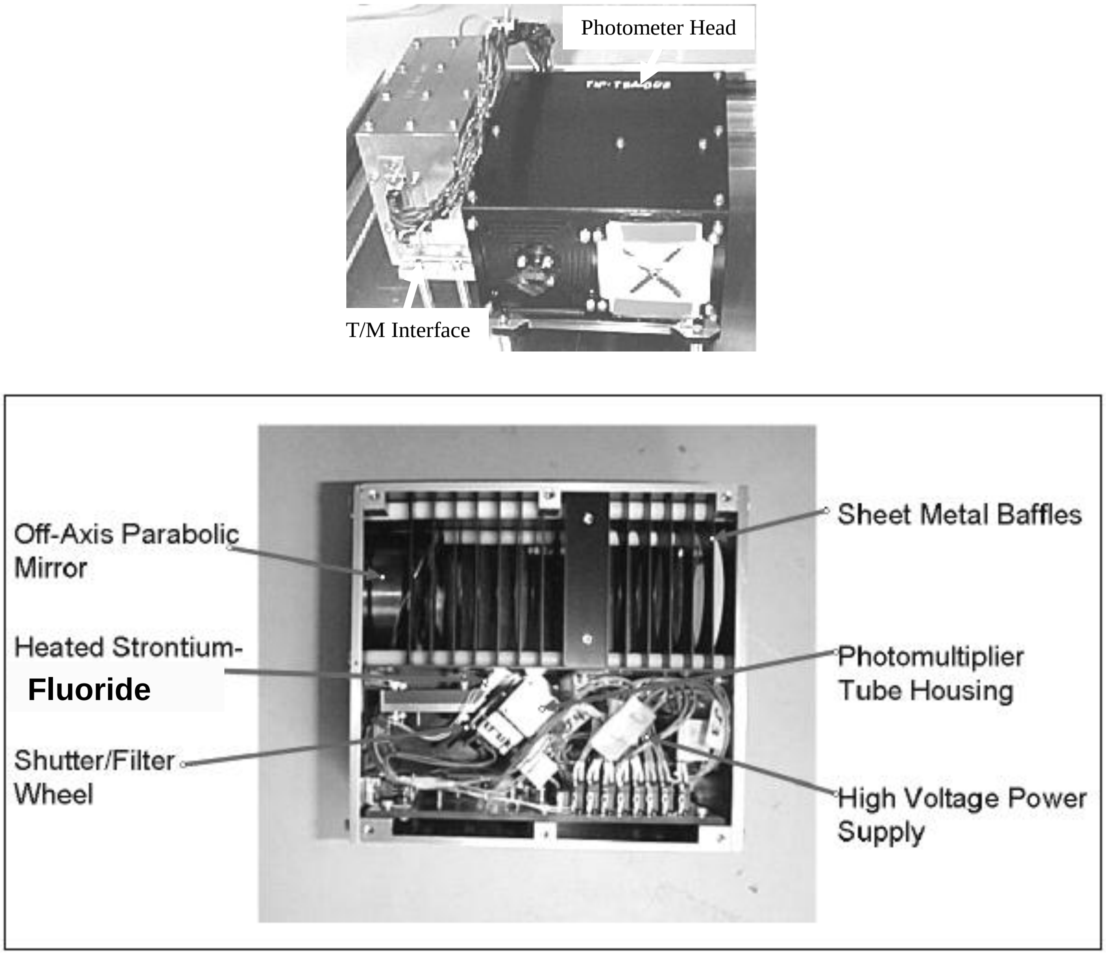

Figure 2: *Tiny Ionospheric Photometer.* The top panel shows the two components of the Tiny Ionospheric Photometer (TIP). The bottom panel shows the internal structure of the photometer head.

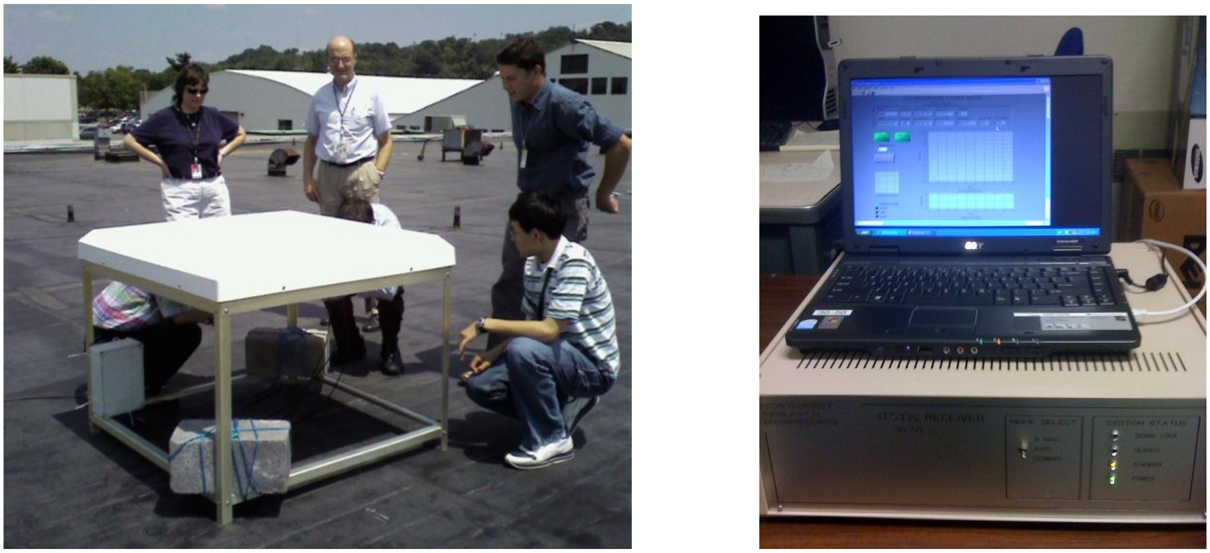

Figure 3: *TBB Patch Antenna and Receiver*. A patch antenna (left panel) used to observe the TBB signal is shown with its base support. The antenna is approximately 1-meter square. The assembly was broken-down for shipping and re-assembled at the VLA. The TBB receiver and accompanying laptop computer are shown in the right panel. The system requires 110 VAC and requires connection to the antenna via three coaxial cables (one for each frequency).

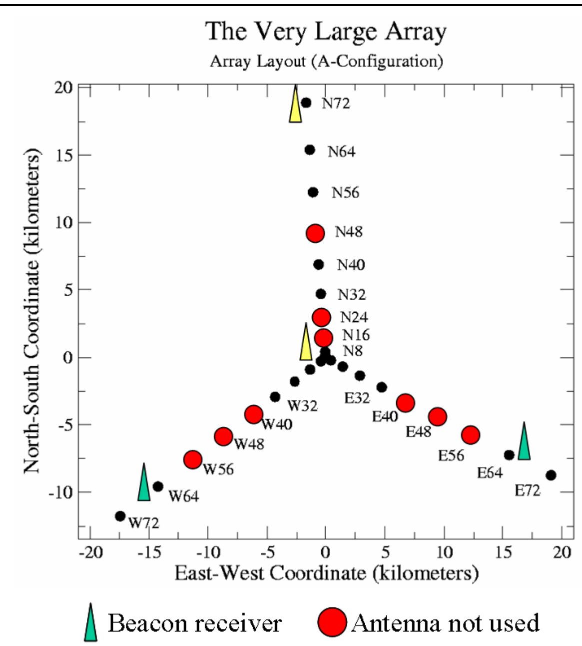

Figure 4: *CRICKET VLA Configuration.* This is the layout of the VLA during the CRICKET observations showing the positions of the beacon receivers. The VLA antennas indicated by red dots were not on-line for observations.

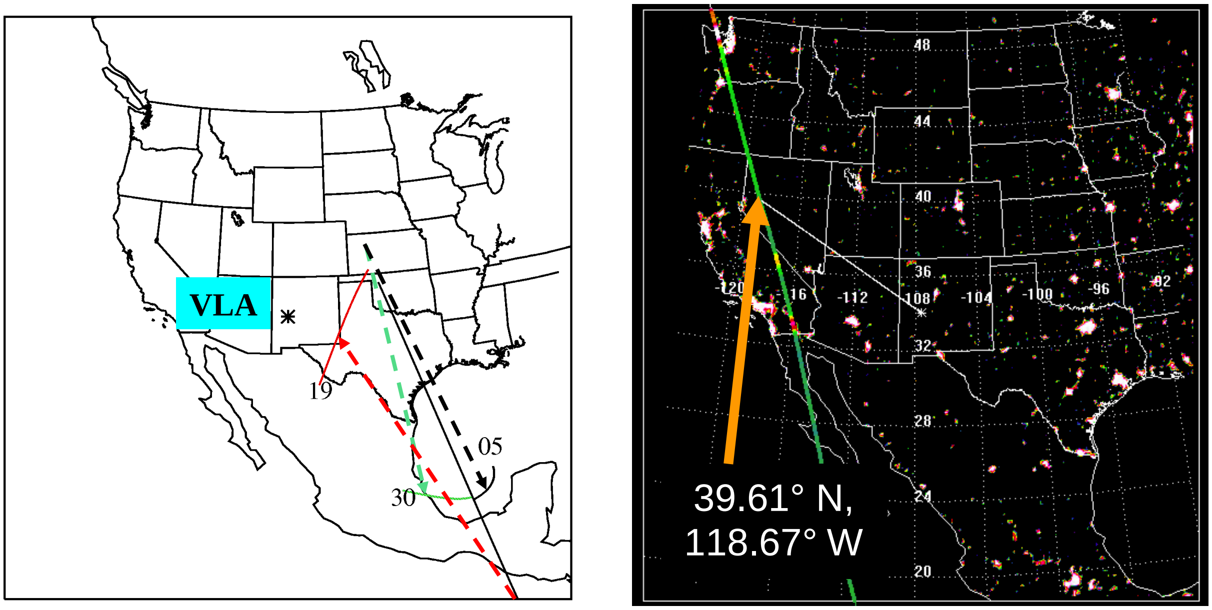

Figure 5: *COSMIC and VLA Observations During Epoch 1 and 3.* (a) The panel on the left shows the COSMIC orbit (solid line) and the three GOX occultations (indicated by PRN numbers of the GPS satellites observed: 05, 19, and 30) and the lines-of-sight (LOS) from the CF3-4 satellite to the minimum tangent ray height of the LOS. (b) The panel on the right shows the CF4-3 orbit color encoded to indicate the TIP count rate (white is high and green is low), which is proportional to the square of the vertical TEC. The VLA LOS is show by the white line (extending from near longitude 108 W to the CF3-4 orbit). The point of closest approach of the VLA LOS and the CF3-4 orbit is indicated by the arrow.

Figure 6: *Fencing for the TBB Antenna.* The panel at the left shows the installation of the fence posts at one of the VLA antennas. The picture at the right shows the fencing nearly complete with the barbed wire installed. For additional stability against large animals, the corner posts had barbed wire guy lines attached.

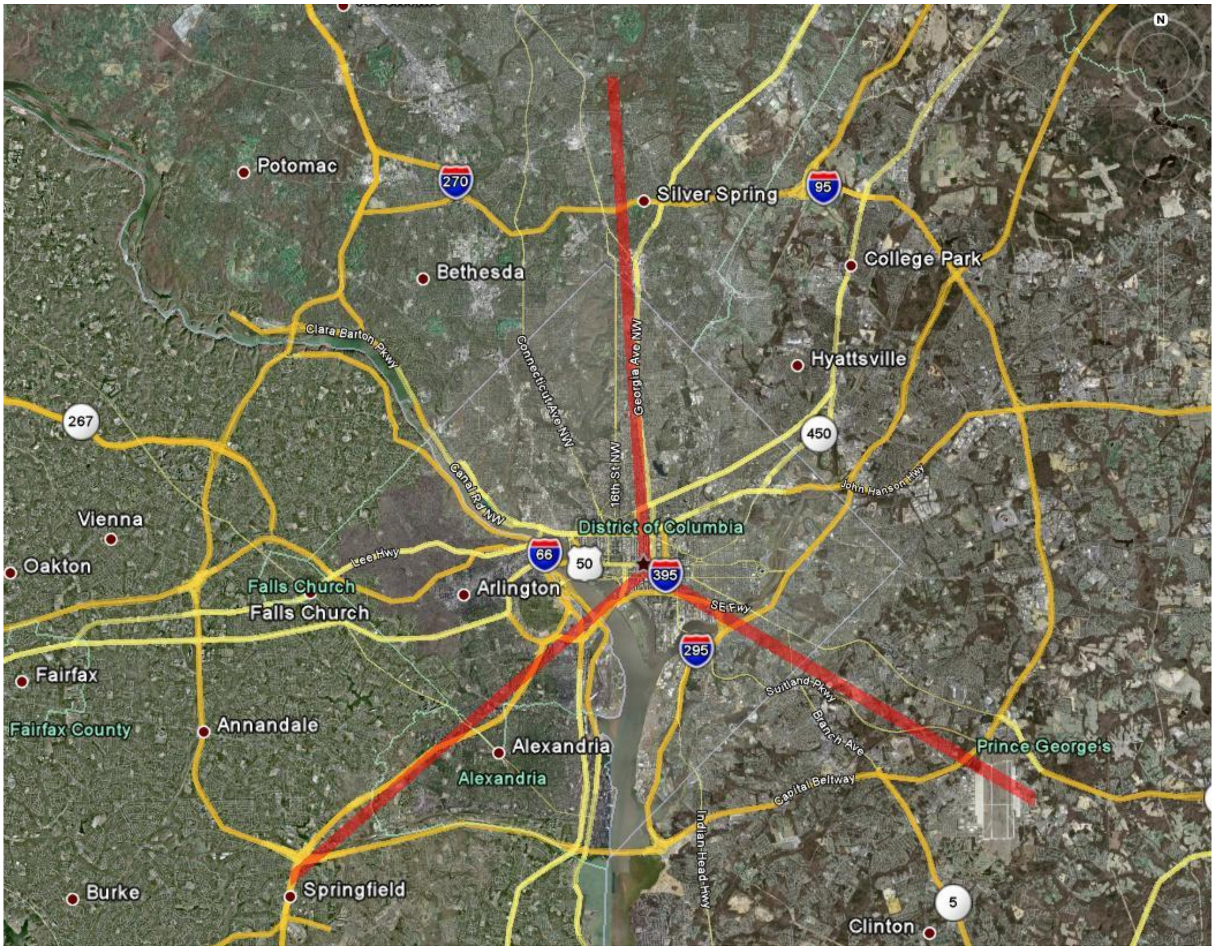

Figure 7: *VLA Overlaid on Washington, DC.* The VLA in its A-configuration is shown projected onto the Washington, DC metro area centered on the Washington Monument. The red lines indicate the VLA arms and are ~20 km [or 13 mi] long.