DEVELOPMENT AND INITIAL OPERATIONS OF THE RAX-2 CUBESAT

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ABSTRACT

RAX-2 is a 3U CubeSat that is studying the formation of plasma irregularities in the ionosphere. The primary payload is a UHF radar receiver which is used in conjunction with ground-based incoherent scatter radar stations to characterize the irregularities. RAX is the first CubeSat funded by the United States National Science Foundation's Small Satellite Program for Space Weather Research. The satellite, launched October 28, 2011, continues the scientific mission started by the RAX-1 CubeSat. This paper discusses the mission and the initial operations of the satellite. After successful checkout, RAX-2 began scientific operations on November 22, 2011. With the exception of an SD card anomaly, the spacecraft has performed well on orbit. 19 radar experiments have been performed, and RAX-2 measurements of radar scatter from the ionospheric irregularities have already provided unprecedented detail for characterization and improved understanding of the formation of the irregularities.

1 MISSION OVERVIEW

The second Radio Aurora Explorer satellite, RAX-2, is a triple CubeSat that launched October 28, 2011. RAX-2 is continuing the mission started by RAX-1, which launched November 19, 2010, but ceased operations after two months due to a solar panel failure [1] [2]. RAX is the first mission funded by the United States National Science Foundation's Small Satellite Program for Space Weather Research [3]. The mission is a joint effort between SRI International, located in Menlo Park, California, USA, and the University of Michigan, located in Ann Arbor, Michigan, USA.

The purpose of the RAX mission is to study plasma irregularities in the ionosphere. Plasma instabilities generate magnetic field-aligned irregularities (FAI) that are known to disrupt communication and navigation signals between Earth and orbiting spacecraft. To study the FAI, RAX utilizes an on-board ultra-high frequency (UHF) radar receiver in conjunction with a ground-based incoherent scatter radar (ISR) station [4] [5]. This is a bi-static configuration, where the transmitter is the ground-based, megawatt-class ISR station, and the receiver is onboard RAX. The ISR station transmits pulses into the ionosphere, which scatter off the FAI into space. RAX measures the scattered signals as it passes overhead. A schematic of the radar measurements is shown in Figure 1. The primary ISR for the RAX mission is the Poker Flat Incoherent Scatter Radar (PFISR), located in Poker Flat, Alaska, USA. Experiments have also been conducted with the Resolute Bay Incoherent Scatter Radar (RISR), located in Resolute, Canada, and the RAX radar receiver is compatible with four additional ISR stations (ESR, Millstone, Arecibo, MUIR [5]). The goal of the mission is to improve the understanding of FAI and enable the development of short-term forecast models. RAX-2 measurements have already provided unprecedented detail for characterization of the ionospheric irregularities; this is discussed further in Section 4.

The scientific payload (radar receiver) was developed by SRI, and the satellite bus was developed primarily by students in the Michigan Exploration Laboratory (MXL) at the University of Michigan. Spacecraft integration and testing was carried out by MXL. The primary satellite operations center is located at the University of Michigan; the science operations are coordinated by SRI International. This paper presents an overview of the RAX-2 satellite as well as a summary of satellite operations and performance from the time of launch through the April, 2012, at the time of this writing. In Section 2, we describe the satellite subsystems and transition from RAX-1. In Section 3, we discuss launch and operations, and in Section 4, we discuss the scientific measurements. We conclude with a summary in Section 5.

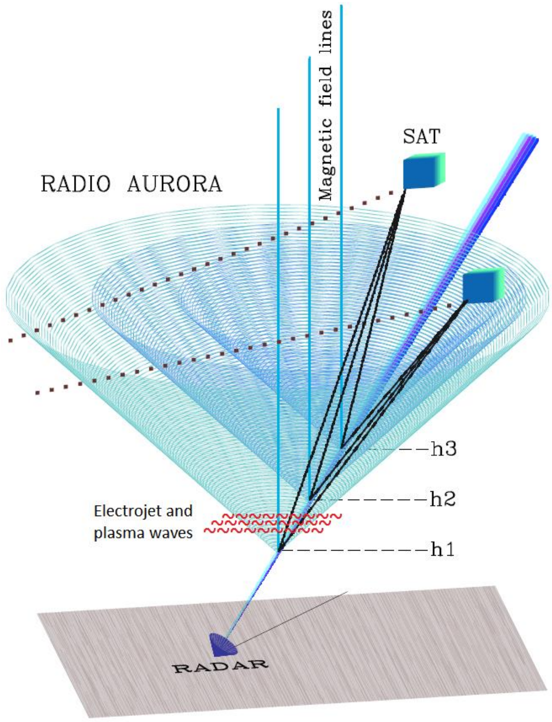

Figure 1. Drawing of the radar measurement geometry [4] [5]. The ground-based incoherent scatter radar station transmits pulses into the ionosphere, which scatter from the magnetic field-aligned plasma irregularities. The scattered signals are measured by the satellite-based radar receiver passing overhead. In the figure, the cones represent scattering from irregularities at three different altitudes. The cubes represent two passes of RAX-2.

2 SPACECRAFT SUBSYSTEMS AND INTEGRATION

RAX-2 is a continuation of the mission started by RAX-1. RAX-1 launched in November 2010, and after successful initial operations, which included one processed radar experiment [5], the mission ceased after approximately two months due to a solar panel failure [2]. An investigation of the cause of the failure took place in early 2011, and it was found that the primary cause of the failure was partial shadowing from the turnstile antenna, seen in Figure 2. Shadows cast on individual solar cells or parts of cells series can cause reverse biasing of the cell which can result in destructive shorts. This failure can be prevented by including reverse bias protection diodes in parallel with each individual solar cell, which was not done on RAX-1. Details of the RAX solar panel investigation and re-design will be presented in a journal paper that is currently in development.

With the exception of the solar panels, the designs of RAX-1 and RAX-2 are very similar. The satellite subsystems are discussed in [1], and are summarized below in Table 1. Flight results from RAX-1 are provided in [2], and additional details on the satellite design will be presented in a future publication [6]. Details of the attitude determination subsystem are given in [7], and design papers dedicated to the other subsystems are also in development.

Table 1. Description of RAX-2 subsystems.

Subsystem	**Description**
Flight central processing unit (FCPU)	A MXL-developed subsystem utilizing a Texas Instruments MSP430 microprocessor, Delkin 2 GB SD card, and watchdog timer for fault protection.
Electrical power system (EPS)	MXL-developed, provides power regulated at 3.3V and 5V, as well as 7.4 V from the battery. The battery is a 7.4V, 4.4 A-hr Li-Ion. There are four body-mounted solar panels each with 7 Emcore BTJM solar cells producing 7.2W peak power at 25ºC.
Attitude determination	MXL-developed subsystem that includes magnetometers, photodiodes, and a three-axis rate gyroscope [7]. Raw sensor data is downloaded for calibration and attitude estimation. Demonstrated accuracies of 2°-3º 1-σ [8].
Attitude control	Passive magnetic with a 3.2 A-m^2 permanent magnet and 2 g of HyMu80.
Position and time	MXL-developed subsystem utilizing a Novatel OEMV-1 GPS receiver and a real-time clock.
Communication	Primary radio: Astronautical Development Lithium-1 (UHF, GMSK, 9600 bps) Secondary: Microhard MHX2400 (S-Band, up to 83 kbps)
Radar receiver	Developed by SRI International, 426-510 MHz, 230 g, 2.6 W [5]
Payload interface module (PIM)	Receives data at 1 MHz from the radar receiver, stores it on a flash-based memory, providing access to both the IDPU and FCPU. Utilizes a FPGA and 2 GB of flash RAM.
Instrument data processing unit (IDPU)	Processes the radar data. Utilizes a Colibri PXA270 module and 2 GB SD card.

Integration of the RAX-2 flight unit took place in late July and early August, 2011, using many spare components from a backup RAX-1 flight unit. The satellite was delivered to Cal Poly University for PPOD integration and subsequent integration into the launch vehicle in September, 2011. A picture of the RAX-2 satellite is shown in Figure 2.

3 LAUNCH AND OPERATIONS

RAX-2 launched on October 28, 2011, through the NASA CubeSat Launch Initiative. The launch vehicle was a Delta II and the primary payload was the NASA NPOES Preparatory Project (NPP) satellite. Five other CubeSats were included in the ELaNa 3 launch: DICE-1 and -2, MCubed, AubieSat-1, and the Hiscock Radiation Belt Explorer (formerly named Explorer-1 Prime). The CubeSats were deployed into a 102° inclination, 400 x 820 km elliptical orbit.

In this section, we describe the operations since launch. In Subsection 3.1, we summarize the major events from launch through April, 2012. In Subsection 3.2, we describe an SD card anomaly that occurred in January. And in Subsection 3.3, we describe nominal operations for the RAX-2 mission.

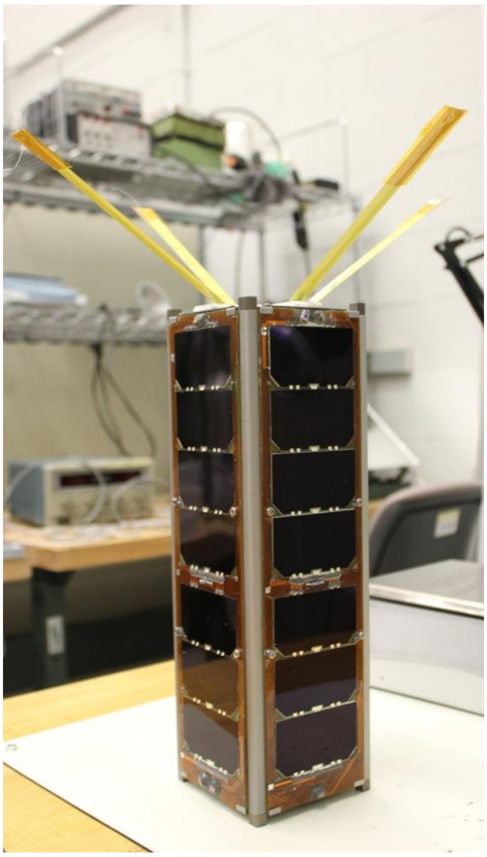

Figure 2. The RAX-2 flight unit.

3.1 Summary of Events

The launch was successful, and RAX-2 beacons were heard within hours after launch. The cumulative number of beacons received over the first week of the mission is shown in Figure 3. RAX-2 partners with the amateur radio community to increase data returns from the spacecraft. A ground station client is publicly available which decodes the telemetry for display to the user and also uploads the telemetry to the RAX database.

Reliable commanding was demonstrated and spacecraft checkout began in early November. One hertz telemetry was collected and showed that the spacecraft subsystems were performing as expected. The total power collected and the battery voltage during this time are shown in Figure 4 and Figure 5, respectively. The data shows that the solar panels are healthy and performing as expected. The total power collected is less than the full potential of the panels because minimal spacecraft subsystems are turned on during this time. The collected telemetry, along with the spacecraft response to commands tested in the checkout procedures, demonstrated that the UHF radio, FCPU, watchdog timer, EPS, solar panels, and attitude determination subsystems were all functioning properly. Samples of one hertz telemetry continued to be collected at least once per week for analysis of subsystem performance, and showed the satellite remained healthy.

The functionality of the payload receiver, PIM, and IDPU were all demonstrated on-orbit in mid-November. The first RAX-2 radar experiment, an end-to-end test of scientific capabilities, took place November 22, 2011. The range-time-intensity (RTI) plot from this experiment is shown in Figure 6. The RTI plot is the result of on-board processing of the raw radar measurements. This plot shows the intensity of the radar measurements along with time between transmission and receipt of the signals versus time into the experiment. In this plot, no radar scatter was detected from FAI. This was expected given the calm space weather conditions at the time of the experiment.

With spacecraft checkout complete, we transitioned into nominal operations, described in Subsection 3.3, and the frequency of radar experiments gradually ramped until we reached one experiment per day in January. Daily experiments were performed through January 16, when nominal operations were paused due to an SD card failure. This is discussed in Subsection 3.2. Experiments resumed approximately one month later; the next experiment took place February 20, 2012. Daily experiments resumed on March 6. RAX-2 had its first detection of radar echo on March 8, 2012. This was the 17th RAX-2 radar experiment. At this time, experiments were paused again to download raw measurements to supplement the processed data. No experiments were performed between March 8 and April 25, 2012, because space weather activity remained calm. Instead, the primary focus was downloading raw radar data from the March 8 experiment. On April 25, 2012, the Kp index reached 6, indicating relatively high geomagnetic activity. The next experiment was performed at this time, and again, RAX-2 measured radar scatter from FAI. These experiments are discussed further in Section 4.

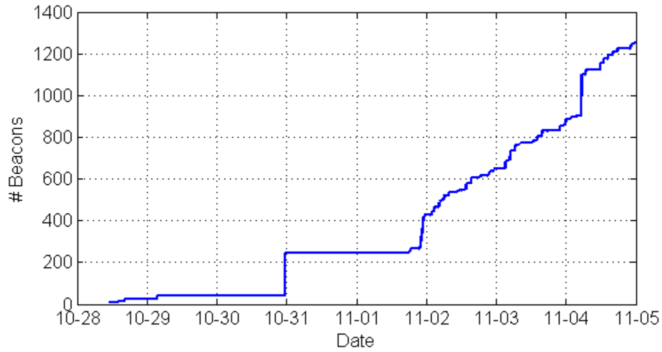

Figure 3. Cumulative number of beacons received over the first week of the mission. The steps in the data, such as at 10-31 and 11-2, are due to batch uploads to the database. Nominally, amateur radio operators use the publically available RAX ground-station client, and the beacons are automatically uploaded to the RAX database. Early in the mission, as the system was being deployed, there were some batch uploads rather than real-time uploads.

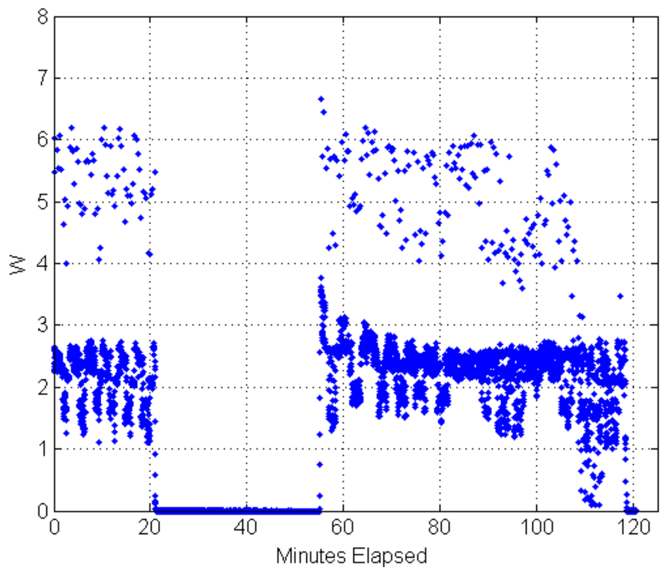

Figure 4. Sum of power collected from all four solar panels versus time, where time is minutes elapsed since 04 November 18:29:45 UTC. The portions with zero power collected are in eclipse. The data points with the higher power relative to the majority of data are when a beacon is transmitted. The power collection shown in this data is less than the full potential of the panels as minimal subsystems are turned on during this test.

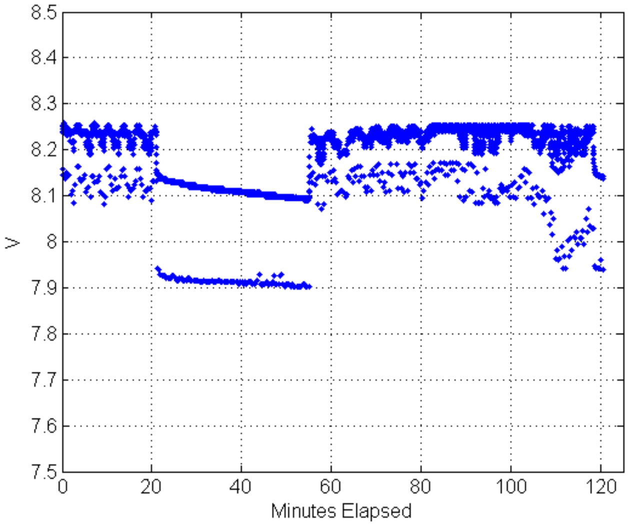

Figure 5. Battery voltage versus time for the same time period shown in Figure 4. As in Figure 4, the voltage points that are lower than the majority are when the radio is transmitting a beacon.

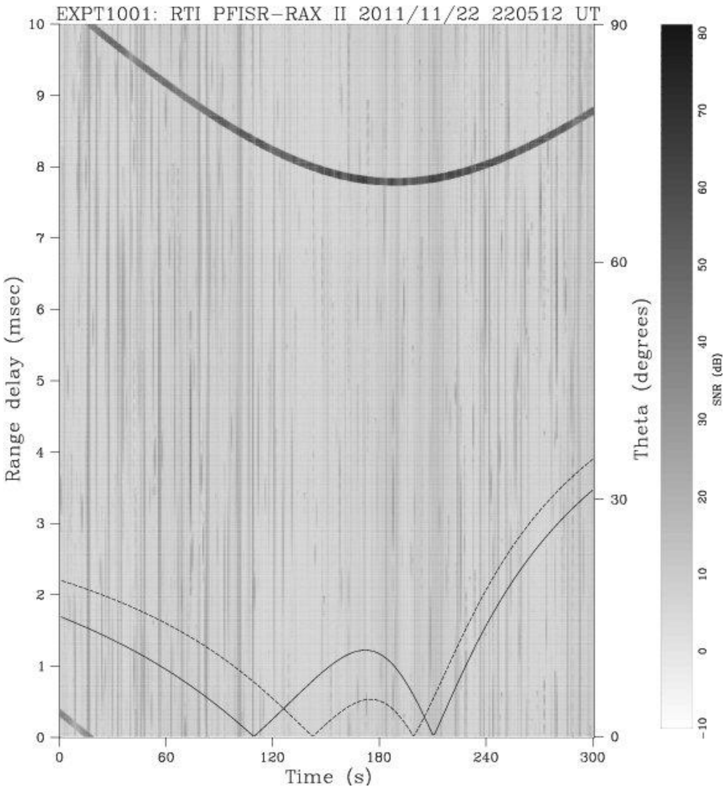

Figure 6. The range-time-intensity (RTI) plot from the first RAX-2 radar experiment, which was performed with the Poker Flat Incoherent Scatter Radar Station (PFISR) on November 22, 22:05:12 UTC. The y-axis is the delay time between transmission and receipt of the radar pulses. The x-axis is time into the experiment; each experiment lasts 5 minutes as the spacecraft passes over the radar station. The thin solid and dashed lines show the aspect angles of scattering for the altitudes of 100 and 300 km, respectively. The right y-axis is used for the aspect angles. The shading is the signal-to-noise ratio. The saturated signal with a range delay between 7 and 10 ms is the direct radar signal from PFISR. No radar scatter was detected during this experiment, which was expected given the space weather conditions at the time. The vertical streaks in the plot are noise.

3.2 SD Card Anomaly and Recovery

On January 16, the SD card used by the FCPU stopped functioning properly. This SD card serves a number of functions that are critical for RAX-2 operations: it is used to store commands that are time-tagged for later execution, to store sensor data from across the spacecraft (including beacons) and GPS data, and all data downloaded is first moved to the card. The symptoms of the failure included an increase in current draw (approximately 7 mA), non-sensible error status, and the inability to read to or write from the card. Neither rebooting the spacecraft nor power cycling the SD card helped to restore normal behavior.

We sent custom sequences of commands to the card in an attempt to diagnose the failure. From this testing, we verified that the card had not become write-protected or password-protected, and attempts to reformat the card failed. We found that we could communicate with the SD card, but could not initialize the card, read, or write data. At the time of this writing, we are not actively debugging the failure, but instead have implemented a workaround to continue satellite operations without using the SD card.

To re-enable the ability to schedule commands and downlink data, we bypass the SD card by uplinking and executing custom code. There is 2 kB of reconfigurable code space on the FCPU's RAM. Within this code space, we can schedule commands and bypass the SD card when downloading data. This allows us to download science data, as it is stored on the PIM and IDPU after an experiment. Still in work is the ability to store spacecraft telemetry and log GPS data.

Debugging attempts and the development of the reconfigurable code took approximately one month. Science data from experiments performed before the SD failure was downloaded on February 17, and experiments resumed on February 20. The exact cause of the failure is still unknown. Possibilities under consideration include a radiation-induced failure, or thermal expansion. When the failure occurred, the FCPU temperatures had been gradually increasing as eclipse time decreased. The FCPU temperature was approximately 30°C at the time of the failure. This temperature is well within bounds of thermal-vacuum testing performed before flight. Full details of the failure and recovery will be presented in future work.

3.3 Nominal Operations

The main activities within nominal spacecraft operations include scheduling and processing experiments; scheduling other events such as radar receiver noise floor characterization, logging GPS data, and collecting high frequency telemetry data; and down linking data. We normally upload a schedule to RAX-2 once per day which includes time-tagged commands for the next 24 hours. When we are not performing an experiment or related activities, we download data to the University of Michigan and SRI ground stations, as well as the global amateur radio community.

Figure 7 shows the cumulative sum of data downloaded (MB) over the mission. After spacecraft checkout, data was downloaded at a fairly steady rate until the SD card failure on January 16. The lull around December 25 is due to the holiday break. If no science data or results from specific events were available for download, portions of the stored beacon history were downloaded. On January 16, the download rate decreased due to the inability to schedule downloads. From January 16 to February 17, the data collected is only beacons decoded real-time. Capabilities were gradually restored after the SD anomaly, and the ability to schedule downloads over the global HAM community was restored around April 10, resulting in the significant increase in data return.

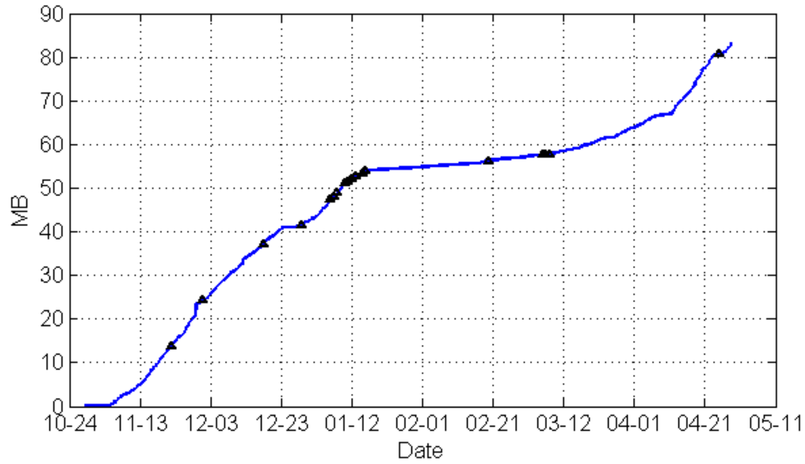

Figure 7. Cumulative sum of data received (MB) versus time. The markers in the plot indicate the dates that experiments were performed. By November 13, we were regularly downloading data. The lull around December 25 corresponds to a break for the holidays. The SD card failure on January 16 resulted in a much slower data collection rate due to the inability to schedule downloads. Capabilities were gradually restored after the failure, and on April 10, the significant increase in download rate is due the restored ability to schedule downloads and utilize the global amateur radio community.

4 SCIENTIFIC RESULTS

The principal science objective of the RAX mission is to understand the microphysics of plasma instabilities that lead to field-aligned irregularities (FAI) of electron density in the ionosphere between altitudes of 80 and 400 km. FAI are driven by solar wind and magnetospheric electromagnetic forcing. Although it is currently possible to detect and identify FAI, the details of the irregularities, e.g. their spectrum, amplitudes, and magnetic field alignment, and how these quantities vary as a function of the driving forces, are unknown. The unique radar scattering geometry of the RAX mission, composed of the ground-based transmitter and satellite-based receiver (discussed in Section 1), enables high resolution characterization of FAI. The primary science product of the mission is the intensity of the irregularities as a function of the electron density, electron temperature, ion temperature, magnetic field-alignment, and altitude. The intensity is measured by RAX, the electron density and temperatures are measured by the ISR, and altitude and magnetic-field alignment can be computed from the spacecraft position and magnetic field orientation. Details of the scientific mission can be found in [5].

Due to the snapshot nature of each experiment, which last five minutes as RAX passes over the radar station, and the probability of geophysical activity at a given time being low, a large number of experiments are needed to detect backscatter from FAI. The first detection of scatter from FAI occurred March 8, 2012 [9]. The experiment was conducted with PFISR, and the resulting RTI is shown in Figure 8. Radar echo from FAI is seen in the boxed region of the plot, just above the direct radar beam. A zoomed-in portion of the portion of the data containing the radar echo is shown in Figure 9. In this plot, the dashed black line shows the range delay corresponding to echo from FAI at an altitude of 100 km, and the red line is a fit to the peak intensity of the measured scatter. Figure 10 shows FAI altitude, signal-to-noise ratio (SNR), and magnetic aspect angle corresponding to data along the red line of Figure 9. In this experiment, radar scatter was measured from irregularities at altitude between 80 and 115 km.

This experiment has provided unprecedented characterization of FAI. The irregularities are located with an altitude resolution of 3 km and sub-degree resolution in aspect angle, which is a first for aural region measurements. The measurements from this experiment as well as many future RAX experiments will enable improved characterization of meter-scale ionospheric irregularities. Preliminary analysis of this experiment can be found in [9], and a thorough analysis is in progress. In addition to the processed data, we are downloading raw radar measurements from the time periods of interest for further analysis.

In the weeks following this experiment, space weather was relatively calm, so we focused on downloading the raw measurements rather than performing more experiments. Geomagnetic activity increased on April 24, and the next experiment took place on April 25, 2012. Scatter from FAI was detected in this experiment as well, and analysis of the data is in progress.

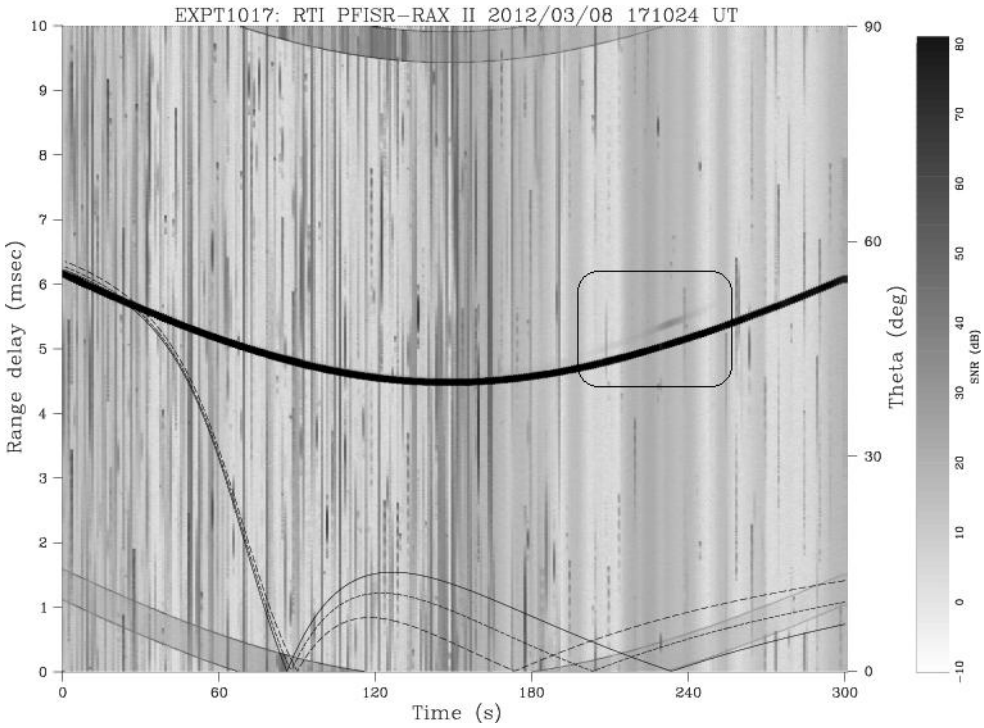

Figure 8. Range-time-intensity plot from the RAX-PFISR experiment conducted March 8, 2012. As in Figure 6, the strip of saturated signal is a side lobe from the direct radar pulses. Radar scatter from FAI is seen in the boxed region above the direct beam. The thin solid, dotted, and dashed lines show the aspect angles of scattering for the altitudes of 100, 200, and 300 km, respectively.

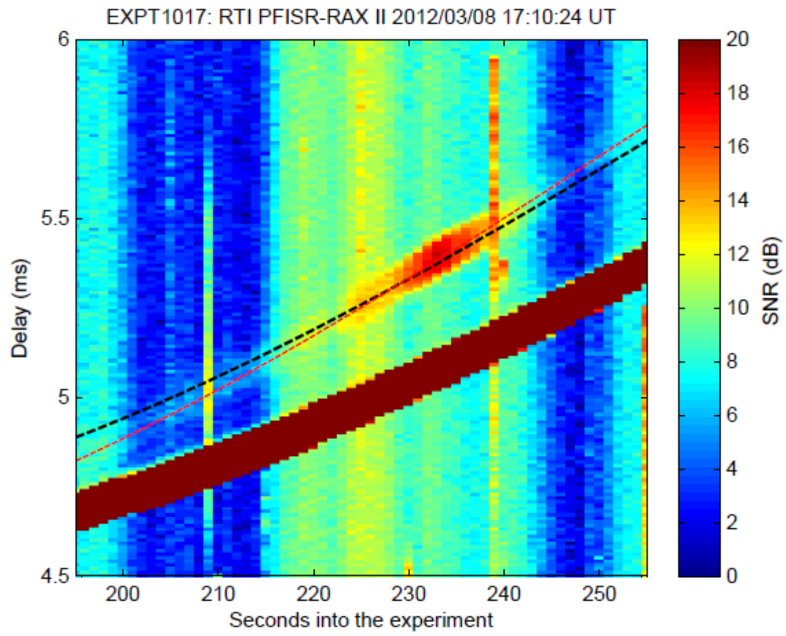

Figure 9. Zoomed-in portion of Figure 8 between 190 and 260 seconds. The black line is the expected range delay corresponding to FAI at an altitude of 100 km. The red line is a visual fit to the maximum intensity of the radar scatter.

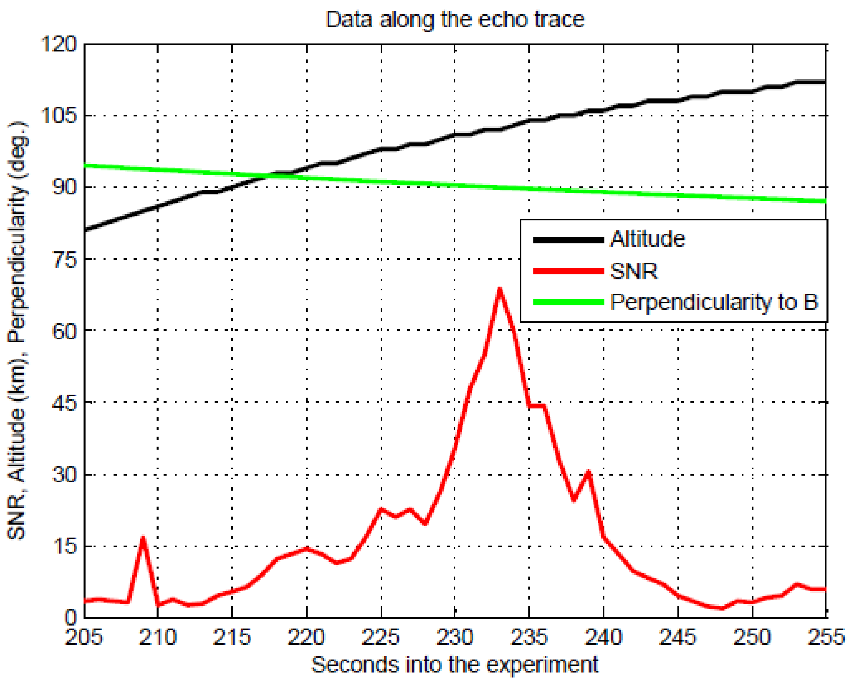

Figure 10. This plot shows FAI altitude, SNR, and aspect angle along the red line of Figure 9, which is a fit to the maximum intensity of the radar echo. Radar scatter was caused by FAI between the altitudes of 80 and 115 km. The angle shown in the plot is a measure of magnetic-field alignment. The maximum intensity of the scatter signals corresponds to an angle of 90°, where the Bragg wave vector is exactly perpendicular to the geomagnetic field lines.

5 SUMMARY

The RAX-2 spacecraft uses a novel, bi-static radar configuration to characterize magnetic field-aligned irregularities of electron density in the ionosphere. These irregularities are known to disrupt communication and navigation signals between Earth and space. The spacecraft continues the scientific mission started by RAX-1. RAX-2 corrected the solar panel failure of RAX-1, and launched on October 28, 2011, less than a year after the RAX-1 launch. After a successful spacecraft checkout, scientific operations began on November 22, 2011. With the exception of an SD card anomaly that occurred in January, 2012, the spacecraft has been performing well on-orbit. As of April 25, 2012, 19 radar experiments have been carried out. Experiments on March 8 and April 25 detected radar scatter from FAI, and will enable an unprecedented characterization of the ionospheric irregularities.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] J. Cutler, M. Bennett, A. Klesh, H. Bahcivan and R. Doe, "The Radio Aurora Explorer – A Bistatic Radar Mission to Measure Space Weather," in *AIAA/USU Conference on Small Satellites*, Logan, UT, 2010.

[2] J. W. Cutler, J. C. Springmann, S. Spangelo and H. Bahcivan, "Initial Flight Assessment of the Radio Aurora Explorer," in *AIAA/USU Conference on Small Satellites*, Logan, UT, 2011.

[3] T. Moretto, "CubeSat Mission to Investigate Ionospheric Irregularities," *Space Weather,* vol. 6, 2008.

[4] H. Bahcivan and J. W. Cutler, "Radar and rocket comparison of UHF radar scattering from auroral electrojet irregularities: Implications for a nanosatellite radar," *Journal of Geophysical Research,* vol. 114, 2009.

[5] H. Bahcivan and J. W. Cutler, "Radio Aurora Explorer: Mission science and radar system," *Radio Science,* vol. 47, 2012.

[6] J. W. Cutler and H. Bahcivan, "The Radio Aurora Explorer - A Mission Overview," *AIAA Journal of Spacecraft and Rockets.* In preparation.

[7] J. C. Springmann, A. J. Sloboda, A. T. Klesh, M. W. Bennett and J. W. Cutler, "The attitude determination system of the RAX satellite," *Acta Astronautica,* vol. 75, pp. 120-135, 2012.

[8] J. C. Springmann and J. W. Cutler, "Initial Attitude Analysis of the RAX Satellite," in *AIAA/AAS Astrodynamics Specialist Conference*, Girdwood, AK, 2011.

[9] H. Bahcivan, J. W. Cutler, M. W. Bennett, B. P. Kepmke, J. C. Springmann, J. Buonocore, M. Nicolls and R. Doe, "First measurements of radar coherent scatter by the Radio," *Geophysical Research Letters,* 2012. In preparation.