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The Radio Aurora Explorer – A Bistatic Radar Mission to Measure Space Weather Phenomenon

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ABSTRACT

In this paper, we describe the Radio Aurora Explorer (RAX) and its space weather mission. RAX is a satellite mission funded by the National Science Foundation (NSF) to study space weather, and is a joint effort between SRI International and the University of Michigan. The primary mission objective is to study plasma instabilities that lead to magnetic field-aligned irregularities (FAI) of electron density in the lower polar thermosphere (80-400 km). These irregularities are known to disrupt trans-ionospheric communication and navigation signals. The RAX mission will use a network of existing ground radars that will scatter signals off the FAI to be measured by a receiver on the RAX spacecraft. The satellite is a 3kg CubeSat with a scheduled launch in late 2010. RAX is the first of the NSF-sponsored satellites to be manifested for a launch and represents a path forging activity for similar science missions conducted on nanosatellite vehicles.

INTRODUCTION

The Radio Aurora Explorer (RAX) is the first of several nanosatellites commissioned by the National Science Foundation (NSF) to study and extend our knowledge of space weather. In 2008, NSF hosted a workshop to explore the potential use of a specific nanosatellite form factor, the CubeSat [1], for novel space weather missions. Despite their obvious limitations in mass (less than 4 kg) and size (less than 10x10x30 cm) these small satellites offer potential advantages that compliment their larger forerunners. They provide the opportunity for fast implementation and deployment of sensors in space, for focused science missions that target a specific space weather phenomenon, and for increased multi-point measurements of space plasma parameters through coordinated and distribute satellites. Also, due to their low-cost, innovative missions with higher-risk are acceptable and encouraged [2]. Proposals to the NSF program included science missions to investigate upper-atmospheric, ionospheric, magnetospheric, and solar space weather research. Currently, the NSF funds six missions. RAX is the first of these missions with a scheduled launch in late 2010.

The RAX space weather investigation seeks to better understand the distribution and genesis of naturally occurring ionospheric irregularities by deploying the first known ground- to-space bistatic coherent-scatter radar system. Plasma irregularities are naturally occurring ionospheric structures that can significantly degrade the performance of satellite-based communication and navigation systems. As our economy and society becomes increasingly dependent on GPS and space-based communication, commerce and human safety can be threatened by even momentary system outages.

The RAX mission overcomes the limitations of existing measurements by using a novel bi-static radar experimental configuration. The ground-to-space bi-static geometry enables high horizontal and altitudinal resolution measurements of the auroral FAI. The high resolution is achieved through two factors: (1) the radar illuminating the irregularities has a narrow beam width, which is typical of all incoherent scatter radars (ISR), and (2) the radar-to-irregularity distance is short because the radar can be pointed at high elevation angles (as opposed to a monostatic radar pointed at very low elevation to meet the perpendicularity condition).

Beyond science and technology, RAX has a strong commitment to post-secondary and K-12 outreach. The RAX PIs hope to create a new class of opportunities for *student space physics experimentalists* by inviting graduate and undergraduate students to participate in a series of orbital radar experiment workshops, a once-in-an-academic-lifetime opportunity to influence mission science execution. Through fabrication, testing, operations, analysis, and discovery, the RAX mission will involve as many as 200 students, providing them with a broad skill set including engineering design, project management, scientific analysis, and community outreach. The RAX mission has already engaged K-12 students in high-altitude balloon field tests of critical RAX position and timing subsystems. By selecting to transmit telemetry data in the 70 cm amateur radio band and widespread propagation of modulation formats, RAX will engage a global community in tracking health, status, and science data streams on-orbit.

In the remainder of this paper, we provide an overview of the RAX mission. We summarize the scientific background and objectives, and describe our scientific method for measurements. We then discuss the RAX satellite design and conclude with a summary of mission status.

SCIENCE OVERVIEW

RAX is a plasma-sensing ultra-high frequency (UHF) radar mission developed in response to NSF's 2008 CubeSat-based Science Missions for Space Weather and Atmospheric Research. The RAX mission goals are to better understand the genesis and distribution of naturally occurring ionospheric irregularities [6]. Deploying the first known ground-to-space bistatic coherent-scatter radar system, the RAX mission will coordinate a network of megawatt-class ground-based radar observatories with an on-orbit CubeSat radar receiver to yield a unique scattering geometry (Figure 1) for characterizing the climatology and evolution of meter-scale ionospheric structures—features inaccessible to ground-based observation [5]. These globally observed ionospheric irregularities, driven by the interaction of naturally occurring strong electric fields and ionospheric plasma gradients, result from a chaotic interplay of solar magnetic and ultraviolet forcing of Earth's upper atmosphere.

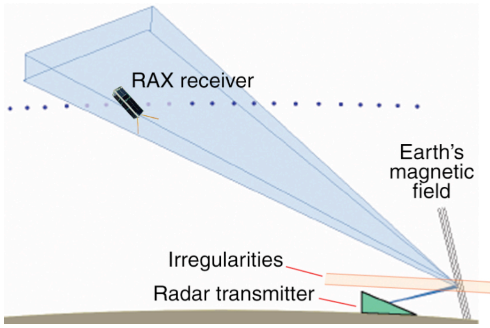

Figure 1 – Schematic drawing of the RAX mission radar geometry. A ground radar transmits radar pulses towards irregularities that are aligned with the Earth's magnetic field. The irregularities scatter these signals towards space. RAX will receive these signals, process them onboard, and downlink data to the science operations centers.

The RAX mission will investigate ionospheric irregularities to gain insight into several candidate causal mechanisms (plasma instabilities), only a few of which have been observed by ground-based research radars. By gauging the global spatial distribution of these ionospheric irregularities and their causal geophysical drivers, the RAX mission will advance the state of *space weather forecast*.

The itemized science objectives of the RAX mission are given by the questions below:

1. What is the altitude distribution of high-latitude ionospheric irregularities as a function of convective electric fields?

2. Which plasma waves are responsible for these irregularities?

3. To what extent are the irregularities field-aligned?

MISSION CONSTRAINTS

Design of the RAX mission began in 2008 with several constraints and programmatic requirements that shaped the nature of the project.

CubeSat Form Factor

First, all satellites in this NSF program are CubeSats, and therefore RAX must conform to the CubeSat standard [3]. Cal Poly and Stanford University developed the standard which defines several structural features of the satellite. The mission was allotted a 3U satellite, nominally with a volume of 10x10x30 cm and less than 3 kg. Thus, the science mission was crafted to utilize this resource-constrained satellite.

Launch Manifest

The second constraint (and also an opportunity) was a manifested launch opportunity on a US Air Force Space Test Program launch, STP-26, for the RAX mission. At program inception, the launch date was scheduled for December 2009 and the orbital parameters were a 650 km circular orbit at an inclination of 72 degrees. This resulted in two distinct sub-constraints. Design, build, test, and delivery of the RAX mission had to be done in less than 12 months. Also, at an altitude of 650 km, assessment of de-orbit properties was a prime driver for the satellite mass and structural properties. A 25-year deorbit time after mission life was achieved by fixing the RAX structure to a typical 3U and ensuring the mass was less than 3 kg.

MISSION DESCRIPTION

The RAX payload receiver design leveraged extensively the SRI design for NSF's Advanced Modular Incoherent Scatter Radar (AMISR). The RAX spacecraft bus design, in turn, grew out of the University of Michigan's (UMich) extensive experience with over ten small satellites, including several CubeSat missions. We describe the payload and spacecraft configuration, with focus on the position and timing subsystem (PTS), attitude determination and control subsystem (ADCS), electrical power system (EPS), flight central processing unit (FCPU) subsystem, communication subsystem (COMMS), and the instrument data processing unit (IDPU).

Payload Receiver

To satisfy science goals, the RAX payload receiver (Figure 2) tunes and converts the radar echoes scattered off meter-scale ionospheric structures. These signals may be transmitted from any one of five terrestrial radar observatories. Received echoes are digitized at 14-bit resolution with 1 MHz sampling and are time–tagged for subsequent downlink. The receiver, a direct-conversion (homodyne) design using industrial-grade analog components, was employed to improve overall reliability and to minimize susceptibility to radiation and transient energetic particle events. The RAX receiver also exhibits extremely wide RF dynamic range (60 dB), rapid (10 μs) overload recovery, minimal power consumption (2.6 W), efficient internal heat dissipation, stable long-term frequency lock, and robust protection from electromagnetic interference (EMI).

The SRI payload was certified for integration into the UMich bus as a functional subsystem by successfully surviving a test regime that included accelerated-life RF testing, thermal/vacuum (T/VAC) forcing (–40° to 50° C), EMI screening, and vibration exposure per NASA General Environmental Verification Standard. The RAX receiver is currently at TRL 5 as a completed subsystem and demonstrated as operational in a relevant environment with low-vacuum, thermal forcing, and realistic EMI background.

SATELLITE DESCRIPTION

The RAX spacecraft bus provides attitude knowledge/control, timing, power, science downlink, and command telemetry in a 3U structure (Figure 3). RAX is compliant with the CubeSat standard except on two very minor points: the center of mass is slightly outside the desired center of volume, and the aluminium used on the structure is not the 6061 as required, but instead 5052-H32.

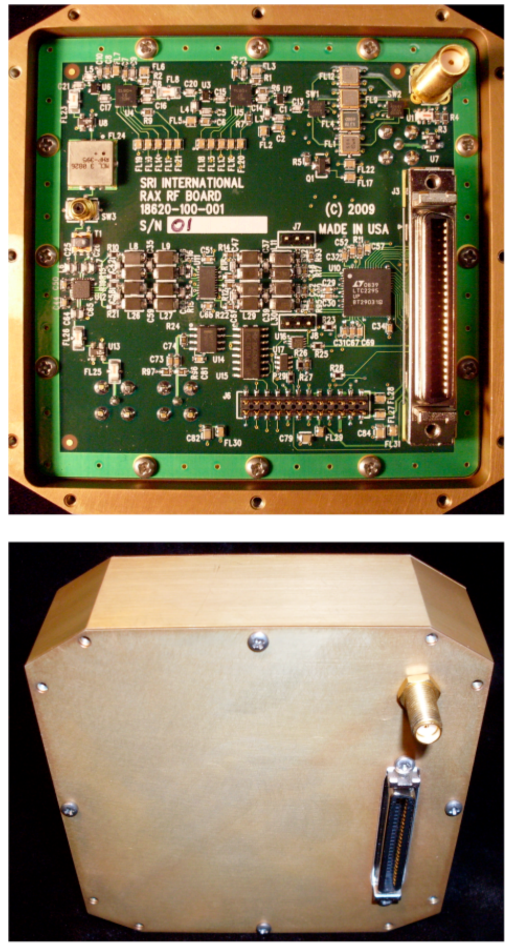

Figure 2 – The SRI payload receiver to be flown on the RAX satellite.

PTS. The RAX PTS provides spacecraft absolute position to the ADCS. The PTS also provides an expected 20m accurate position and 20ns accurate timing (relative to GPS pulse-per-second synchronization) to the RAX payload receiver as mandated by science requirements. These requirements are met with, an onboard GPS receiver and associated antenna, a real-time clock, and synchronization data encoded onto the ground radar pulse pattern. The time, position, and velocity information and uncertainties are combined in an optimal manner with a deterministic spacecraft dynamics model and associated Continuous-Discrete Extended Kalman filter developed at UMich. The PTS is at TRL 6.

Figure 3 – The RAX satellite fully integrated.

ADCS. Mission science goals require that the RAX spacecraft attitude be determined to within ± 7° so that received radar pulse power can be properly calibrated. Accurate spacecraft position knowledge from the PTS is used to determine the local Earth magnetic field vector and the position of the Sun relative to RAX. Attitude is determined by combining this knowledge with six miniaturized magnetometers, nine sun sensors, and an inertial measurement unit. This data is post-processed with the Kalman filter, and the resulting lab-tested ADCS attitude determination accuracy is better than 5°. Attitude control, provided by a longitudinal permanent magnet and two orthogonal hysteresis strips, provides 7° authority with minimal oscillation and is judged sufficient to accomplish the RAX science objectives. The ADCS is currently at TRL 5.

EPS. RAX EPS is comprised of solar panels, a battery system, and associated regulation and conditioning circuitry. The battery system consists of a 7.4 V, 4.4 Amp-hour Li-Ion pack that is housed in an aluminum frame and secured to a PCB. The PCB measures battery state and links the battery to the spacecraft bus. The EPS provides a controller for maximizing energy throughput from the solar panels to the battery (44 W max but with an on-orbit average expected of 6W) and a bus regulation system with sufficient margin to ensure regulated 3.3V and 5V output for all mission phases. The load set-point of the EPS controller is statically set to extract maximum power output from the panels based on preflight orbit simulations. Internal sensors measure voltage, current, and temperature within the battery, solar panels, and bus controller. The EPS was designed, built, and tested by UMich for improved safety and reliability over available off-the-shelf solutions. The EPS has survived vibration and T/VAC testing. The EPS is currently at TRL 5.

FCPU. The UMich-built RAX flight computer , is responsible for all phases of subsystem and payload command and control, and implemented using an MSP430 from TI. An off-the-shelf real-time operating system is used with RAX specific low-level drivers and application code developed at UMich and SRI, which provide the necessary mode flexibility required by RAX throughout all mission phases: uplink command reception, science data acquisition and buffering, science data processing mode, and science downlink mode. The MSP430 was selected due to its flight heritage, low power consumption, relatively low cost, and access to previously developed processor compatible code. The FCPU is judged to be at TRL 5.

COMMS. The FCPU board was designed to host an S-band transceiver, which will be used for 70 kbps science data downlink at 2.4 GHz via a small UMich-designed patch antenna. RAX also implements an UHF transceiver as an uplink command receiver and as a redundant downlink science transmitter. The UHF transceiver will operate in the amateur band and will share the quad turnstile antenna used for the RAX payload radar receiver. The COMMS is currently at TRL 5.

IDPU. The IDPU is a Linux-based processor running at 500 MHz that post-processes onboard radar data. For each experiment, 1.5 GB of data is generated, much greater than RAX's downlink capabilities. Various science modes that utilize GPS-based time tagging, radar encoded time synchronization, and satellite motion parameters are used to process radar data and reduce downlink requirements.

METHODOLOGIES

Given the schedule, form-factor, and cost constraints present during mission inauguration, the RAX team adopted several design strategies and approaches to accommodate the constraints.

University-Class Mission

The RAX mission is a university-class mission as described by Swartwout [4]. NSF's combination of science and educational goals enabled our team to consist primary of graduate and undergraduate students. Over fifty students have been involved from UMich and other schools.

Student effort is supported by intense PI involvement and oversight. PI's have an active role in designing, building and testing of RAX. This provides the proper structure and motivation to harness student capabilities and energy, while providing many in-situ, immersive educational opportunities that go well beyond typical class room interactions.

In addition, periodic consultants were integrated into the team to provide specialized expertise when needed. This included design support on the EPS and radio systems.

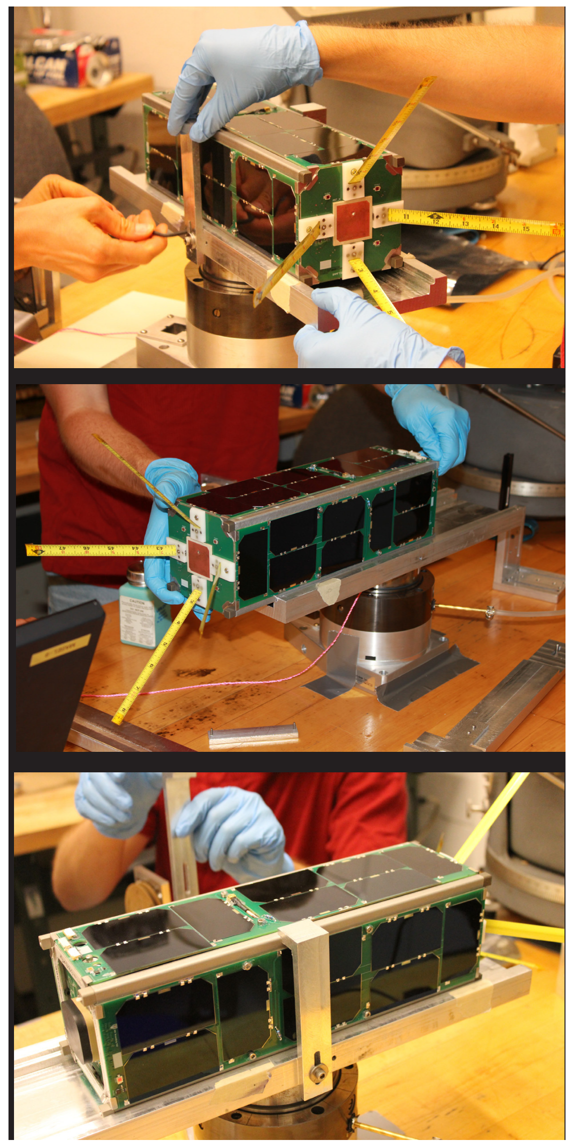

Figure 4 – Inertia and mass property measurement of RAX.

Continuous Improvement Model

Given the uncertainty in a launch date, the RAX team developed a method to both meet pending launch-related deadlines as well as take advantage of delays in delivery to improve and enhance mission capabilities. This *continuous improvement model* (CIM) produced several flight ready satellites that were later reworked to enhance functionality and science yield.

As with typical space missions, requirements were developed to satisfy mission goals. A minimum-effort mission was developed to meet these goals that utilized simple attitude control methods and extensive use of off-the-shelf components for the first launch deadline in December 2009. As the launch slipped, improvements were made that included advanced GPS position and time synchronization. Some emerging technologies, such as three-axis active attitude control, were not implemented in the final design due to schedule constraints. While 3-axis control would have enhanced communication and science collection capabilities, it was not required and hence not fully developed for this first mission.

SUMMARY

The first RAX satellite, RAX-1, is complete and awaiting launch on the Space Test Program's STP-S26, a Minotaur IV launching from Kodiak Island. It is expected to launch in late 2010. RAX-1 has passed stringent launch and payload readiness reviews chaired by the US Air Force. RAX-1 will operate in full science collection mode for at least one year pending nominal satellite performance. Beyond the baseline science operation, ad-hoc science experiments will be performed and the satellite will transition to an educational testbed for students.

A second satellite identical to RAX-1 has been built and tested as well. It is in storage until a second launch opportunity is available. If a second launch is sufficiently in the future, it will be deintegrated and upgraded to include faster communication and processing capabilities.

The RAX mission offers an excellent opportunity to push the state of the art in science studies while training the next generation of space scientists and engineers. The science products from this mission are expected to provide novel insight into space weather processes that have been impossible to measure before with existing technology. Numerous students have capped their educational experience with RAX mission work and the on-orbit flight operations and data analysis of RAX is expected to train many additional students as well.

ACKNOWLEDGEMENTS

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