NITTANYSAT—A STUDENT SATELLITE MISSION FOR *D*-REGION STUDY AND CALIBRATION OF RIOMETERS

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ABSTRACT

NittanySat is a nanosatellite currently under development that will be used to study variations in the *D*-region ionosphere and to provide calibration for ground-based riometers. The *D*-region will be investigated using measurements of the total ionospheric absorption of HF signals at three four?? frequencies transmitted from the ground to this small polar-orbiting satellite. The larger signal loss observed at the lower frequencies is due to ionospheric absorption and, thus, is comparable to what a riometer measures. The possibility for measuring at high latitude stations in Norway and Alaska will provide opportunities to study the *D*-region variations during geophysically active periods. Design considerations and initial simulations are presented. NittanySat is a participant in the 5th University Nanosatellite Program, which was established to train students in satellite systems.

1. INTRODUCTION

Satellite missions with student involvement ideally should have lead-times short enough for the participants to see the results of their endeavor. Consequently, such payloads are intentionally not too complex and will generally have a relatively short mission lifetime. Given these restrictions, scientific payloads for student missions must be found that - despite these limitations - will also have useful scientific yield beyond satisfying the engineering endeavor. The fact is that a satellite mission will undoubtedly extend beyond a single semester and even beyond the matriculation period of some students; thus, it provides another important learning experience in documenting work and passing on responsibilities.

The *D*-region of the ionosphere is one of the least monitored regions of the Earth’s atmosphere. This altitude region between 60 and 100 km is the most difficult to monitor because direct measurements with sensors are largely limited to rocket payloads. It is also the most important region for propagation in a significant part of the electromagnetic spectrum. The product of collision frequency and electrons density reaches a maximum in this height range. These collisions result in energy loss for any electromagnetic wave passing through the region. As the electron density increases, the absorption increases with higher frequencies being less attenuated than lower frequencies. The attenuation depends upon the number of electron–neutral collisions. Since the neutral density is relatively constant, and can be described reasonably well (within ~20%) by models, then the absorption provides a measure of the variations in electron density in the *D*-region.

A primary goal of NittanySat will be to investigate the *D*-region and characterize the ionization variations associated with energetic particles, x-ray events, polar cap absorption (PCA) events, winter anomaly conditions, and other features that influence the ionization in the *D*-region. As we approach the next solar cycle maximum in 2012, which is expected to be a relatively large one, the energetic events influencing the ionosphere will provide many interesting features to be studied. A study of the impact on communications links of these increases in *D*-region electron density will also be critical for improving our understanding of communications in the high latitude region. Another focus for the experiment is to investigate the variations in radio wave scintillation. Improved knowledge of both the absorption and the scintillation of radio waves are valuable applications expected from this project.

Riometers (relative ionospheric opacity meters) are ground-based instruments to routinely monitor the state of the lower ionosphere (*D*-region) at high latitudes. The principle is unchanged since the late 1950s, but much refinement has gone into details, notably so-called imaging riometers provide detailed information on the location of the disturbances in the *D*-region. One such imaging riometer has recently become operational near the Norwegian Andøya rocket range and has stimulated the present satellite mission, which will provide "space truth" for such installations.

1.1. University Nanosatellite Program

The NittanySat mission was selected as a participant in the University Nanosatellite-5 (NS-5) Program, which is a joint program between the American Institute of Aeronautics and Astronautics (AIAA), the Air Force Office of Scientific Research (AFOSR), and the Air Force Research Labs Space Vehicles Directorate (AFRL/VS). The objectives of the NS-5 program are to educate and train the future workforce through a U.S. student satellite design and fabrication competition, and to enable small satellite R&D, payload development, integration, and flight. An important aspect of the program is the ability to fly new technologies to validate their operation in a space environment. There are 11 universities participating in NS-5. All universities were provided grants of approx. US$110k over two years as seed money for their satellite development. If selected for launch, launch costs are provided by AFOSR.

2. NITTANYSAT OVERVIEW

NittanySat will investigate the variability of the *D*-region by measuring radio frequency absorption and scintillation caused by the enhanced ionization from energetic particles and plasma irregularities. The on-board receivers will measure the relative power received at the satellite of several HF frequencies from signals transmitted from ground stations located at high latitudes. To better understand the physical processes, an energetic particle detector and an *in situ* Langmuir probe will measure the ionization source of *D*-region variability.

NittanySat has a number of primary and secondary objectives, which are discussed herein. While the primary objectives are fixed at this point, the secondary objectives are still under review.

2.1. Primary Objectives

1. Measure the plasma characteristics and phenomenology of the high latitude *D*-region ionosphere.
2. Measure the amplitude and variability of the radio frequency absorption at several HF wavelengths caused by absorption in the *D*-region ionosphere.
3. Measure the amplitude and locations of the scintillations on radio frequencies at high latitudes.
4. Correlate the absorption effects on RF communications with energetic particle flux and local plasma environment.
5. Calibrate ground based riometers using RF absorption data collected.

2.2. Secondary Objectives

1. Demonstrate the use of UV-curable material to rigidize an inflatable gravity gradient boom.
2. Measure the dynamics of an inflatable gravity gradient boom.
3. Demonstrate responsive-space capabilities through frequency flexibility and science augmentation using reconfigurable software defined radio (SDR).

2.3. Design Concept

The four different design phases of the project are concept and definition, design and prototyping, fabrication and verification, and integration and validation. The time span to have a completed and functional nanosatellite is only two years. The project began in January 2007 and is to be completed by January 2009. Launch and start of the mission phase will not be until after this time.

Fig. 1 provides a view of the current design concept for NittanySat. NittanySat is to fit in a volume smaller than 60×60×50 cm with a mass less than 50 kg. On the bottom of the satellite, is the LightBand deployment system, and boom deployment orifice. Stowed antennas, which are deployed early in the mission, are located on four sides for both the science and the communications systems. On the top of the satellite, a high energy particle detector is located. The satellite is almost completely covered with solar cells in order to provide sufficient power for electrical requirements.

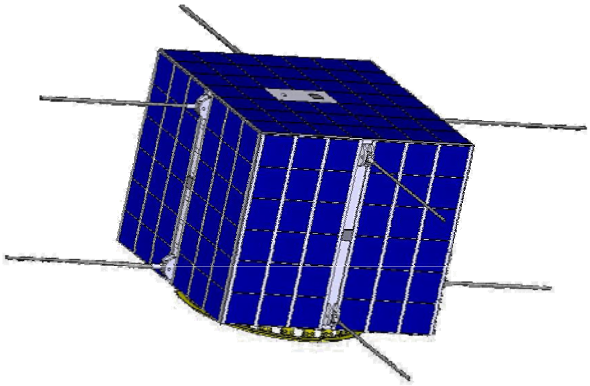

Figure 1. NittanySat Design Concept

NittanySat is requesting a circular polar low earth orbit at an initial altitude of ~600–1000 km. After launch, the payload will be in an inert state, meaning the batteries will not be charged. After separation from the launch vehicle, the batteries will be charged and the antennas will deploy to permit updates of satellite health to be downlinked. Next, the active attitude control system will orient the payload to deploy the boom to achieve gravity gradient stabilization. Once the payload is gravity gradient stabilized, science operations can commence.

As NittanySat's science mission is to investigate radio wave absorption at high latitudes, several transmitting ground stations are necessary. The presently anticipated sites for these stations are Poker Flat in Alaska, U.S.A. (run by the University of Alaska at Fairbanks), and the University of Tromsø in Norway. The transmitting ground stations will have a field of view comparable to the imaging riometer IRIS (KIL), in Kilpisjärvi, Finland, or AIRIS (AND) on Andøya, Norway, which measure over a zenith angle of approximately 65°, providing measurements over a 130° solid angle. The data collected from NittanySat will help to calibrate riometers, such as IRIS.

During science operations (explained in more detail in Section 4), when NittanySat passes over a ground station (Fig. 2), one on-board receiver will be in a listening mode searching for the reference signal. This signal will use a modulated code to identify it as the correct transmitting station, and not an unwanted signal. Once this signal is located, all of the scientific instruments will turn on and data will be collected.

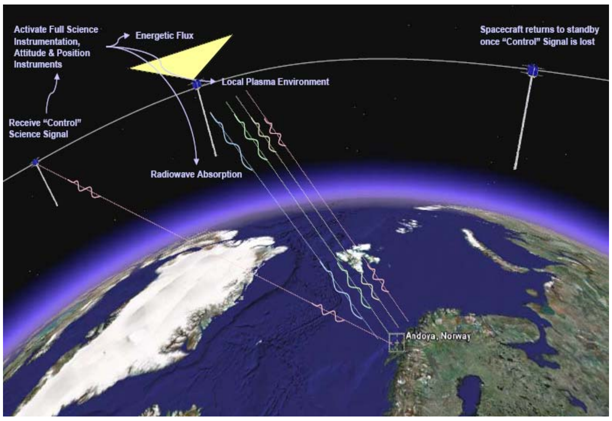

Figure 2. NittanySat Concept of Operations.

Along with the scientific investigation, NittanySat will perform several engineering demonstrations. One such demonstration is to obtain gravity-gradient stabilization via an inflatable UV-curable boom. Three air-core magnetic torquers will be used for the active attitude control system. The coils will be energized in a specific manner around orbit to orient the payload to the proper orientation for deploying the gravity-gradient boom.

The NittanySat pyroless deployment system is another engineering demonstration. The system is composed primarily of shaped memory alloy actuators, which use a pulse of current through this wire causing the actuators to contract. These mechanisms will be used to deploy the antennas and the door of the gravity-gradient boom.

3. RIOMETERS

A riometer is essentially a stable receiver that monitors the signals originating from cosmic radio noise sources. The simplest design consists of an upward-looking antenna, e.g., a three-element Yagi. Imaging riometers - such as the new one at Andøya, Norway - consist of an array of antennas that can be phased in such a way that narrow beams with different look directions are formed. In absence of an ionospheric layer that absorbs electromagnetic waves such as the ionosphere's *D*-region, the received signal strength undergoes a diurnal variation due to the different regions of the sky "seen" by the antenna over the course of a day. This so-called quiet day curve (QDC) is strictly a function of sidereal time, geographic latitude, and the antenna pattern; therefore, the QDC ideally can be calculated based on maps of sky noise [1]. In reality, however, the QDC is determined at regular intervals (e.g., weekly) by superimposing diurnal variations of the received HF flux (consecutive days shifted by 4 minutes) and establishing the high-signal envelope [2]. Fig. 3 shows the QDC for two riometers (wide and narrow beam) located at Kilpisjärvi, Finland, at about 70°N latitude. The differences between the corresponding curves can be readily explained by the real antenna patterns deviating from ideal ones. Furthermore, these actual antenna patterns can change due simply to humidity at the ground or snow cover impacting the reflective properties of the ground.

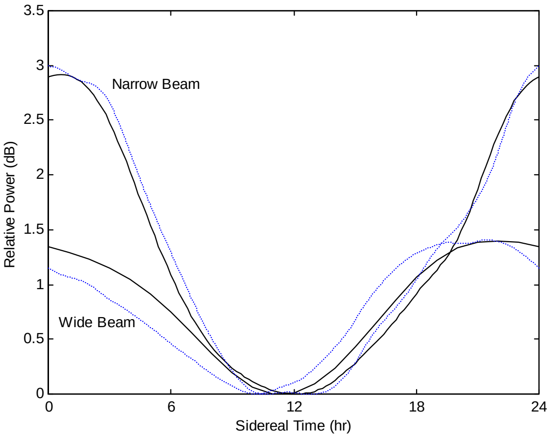

Figure 3. Simulated and observed variation of received power (QDC) for a narrow beam riometer and a collocated wide beam instrument at Kilpisjärvi, Finland. A winter period was chosen to assure absence of solar ionizationduring the whole day (dotted lines: empirically determined QDCs, solid lines: theoretical variation) [3].

The observed intensity of the HF signal does not always follow the QDC, but may have dips that can be ascribed to absorption of the radio wave by enhanced electron densities in the ionosphere. Fig. 4 shows a whole day of observed radio flux at 38.2 MHz together with the empirically determined QDC. Riometer absorption is, by definition, signal loss relative to the QDC. Variations of the received noise signal of the order of 0.05 dB (~1%) can be resolved by modern riometers, but the absorption measurement desired is the ratio to the normal diurnal variation (QDC). Hence, an accurate establishment of the QDC is of paramount importance, notably when one wants to measure small values of riometer absorption.

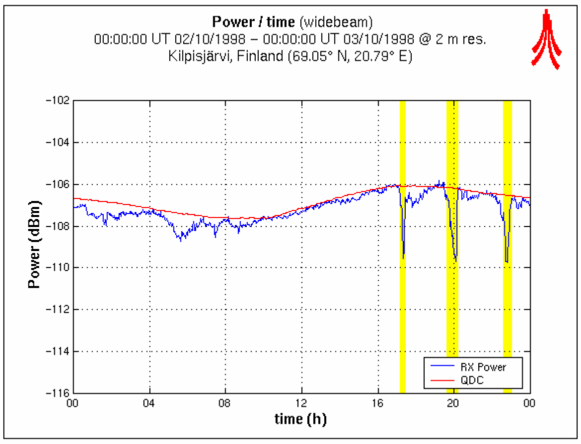

Figure 4. Measured variation of 38.2-MHz sky noise together with the (empirically determined) quiet day curve (http://www.dcs.lancs.ac.uk/iono/iris/).

4. SCIENCE MISSION CONCEPT

The NittanySat mission aims to provide insight into the variations in the high latitude *D*-region, the propagation of radio waves (both absorption and scintillation), and provide support for the interpretation of several ground-based riometers. The mission will conduct the ABEX (absorption experiment) to explore an “inverse riometer” technique. The setup consists of transmitter stations located at high latitude, and near the riometer stations of interest. These transmitters radiate to the satellite in a polar orbit, where the signal variations are recorded at three different frequencies. The horizon of a receiver at the anticipated altitude (~600 - 1000 km) covers a very large area. The nanosat’s receivers could potentially pick up unwanted emitting stations from a radius of at least 3000 km; therefore, our transmitter stations will be identified by the satellite receivers from other transmitted signals by using a recognition code.

The ionospheric plasma is a dispersive medium, which means that the absorption is dependent on frequency f, with a dependency of the form $1/f^2$. Hence, observation of signal amplitudes of two or more frequencies allows the extraction of ionospheric absorption from other factors influencing the signal amplitude. These other factors are principally,

(a) The distance between transmitter and receiver,
(b) The imperfect orientation of the receiver antenna along the line-of-sight, and
(c) The misalignment of the orientation of the antenna relative to the polarization at the point of the reception.

Factor (*a*) is the easiest to account for since the distance can always readily be calculated from the orbit parameters. Factor (*b*) is minimized by feeding the on-board receivers from the same linearly polarized antenna (length ~30 cm); hence, any signal degradation due to imperfection in antenna orientation or changing distance affects all frequencies in the same manner, i.e., by the same frequency-independent factor. However, in order to assure optimum received signal the satellite will be stabilized by a gravity-gradient boom in such a way that always the same side of the satellite points towards the Earth and, hence, the transmitters. The satellite’s attitude control system will determine the pointing of the antennas to within a few degrees. The presence of the Earth’s magnetic field causes the ionosphere to exhibit dual refractive indices (birefringence), which consequently leads to a rotation of a linearly polarized wave after traversing the ionosphere, known as Faraday rotation. To get around this problem, the ground transmitters will radiate circularly polarized waves, which arrive with that same polarization irrespective of the degree of Faraday rotation suffered in the ionosphere. The linearly polarized receiving antennas will ideally measure the received signal independent of the satellite’s orientation, factor (*c*).

The ground segment consists of four transmitters of about 100 W output each, radiating at frequencies between 10 and 60 MHz (exact values are currently being determined in a trade study) into circularly polarized antennas. The receivers, or the ground transmitters, will be programmed to account for: (1) the Doppler shift (as much as ±3 kHz within 65° field of view), and (2) to check the radio noise level. One operating mode is planned to switch from zero to 10% and to full power in order to test levels of unwanted signals originating from other transmitters and sources. In another simpler concept, the frequency may be swept to fully cover the conceivable Doppler shift. Preferably, the frequency deviations of the receivers or the transmitters would be matched to track the expect offset or indeed to the exact frequency the receiver detects. The lowest frequency may be perhaps 10 MHz, making this arrangement more sensitive by a factor of 5 to 15 than a standard riometer operating in the 30 to 40 MHz range. This is important when measuring small absorption (which the imaging riometers can potnetially resolve); larger absorption (e.g., 1 dB at 38.2 MHz) will usually be associated with similarly enhanced electron density at the F-region peak. In this case, 10 MHz will likely be below the F_2 critical frequency and, therefore, not be able to penetrate the ionosphere to reach the satellite, and in this case, the next higher, but less sensitive, frequency will provide the absorption information. Since the inverse riometer measures total absorption, the "quiet day absorption" can be determined by subtracting that which the ground based riometer measures once it is properly calibrated (after accurately determining the QDC). Given a circular polar orbit at ~1000 km, then the satellite will come within 30° off zenith for about 15 minutes every day (more often for high latitude stations); at other times the ground transmitters and the two receivers of the lower frequencies will be off, and the satellite will be in a hibernate mode awaiting its wakeup signal from the higher HF frequency used. The receiver for the highest frequency (e.g., 50 MHz) will always be the first to "see" the ground transmitter and will be used to switch on the other receivers.

The PSU ground station will provide the telemetry data downlink and a daily opportunity to check on the health and performance of NittanySat, while providing an opportunity to study x-ray flare ionization and winter anomaly conditions. The ground-based transmitters at four frequencies between 15 and 100 MHz will be selected from simulations to be performed. One upper frequency in the 50 to 80 MHz range would serve as a reference frequency since it would not be significantly affected by D-region absorption. The primary absorption data would then be derived by forming the ratio of two frequencies using a reference frequency above 50 MHz. The transmitted signals will be measured by narrowband receivers on NittanySat. A telemetry link back to the ground will provide the information on measured signal strength, as well as satellite monitors and other data on engineering systems. Several sets of high-latitude measurements and one or two sets of mid-latitude data can be obtained each day. An optimum condition would place the satellite in an 800-km-circular polar orbit and result in long data tracks over several thousand kilometers; however, a range of orbit parameters are considered, as this should not severely limit launch opportunities. The uplink transmission of the higher reference frequency would also serve as the command to turn on experiments and transmit the real-time data to the telemetry ground station.

5. RELATIONSHIP WITH ROCKET RESEARCH

The scientific investigation being pursued by NittanySat has its genesis in prior rocket investigations. Shown in Fig. 5 are specific absorption profiles for several electron density profiles measured by one of us (Friedrich) using sounding rockets. Receivers of the same architecture as the ABEX instrument have flown numerous times on sounding rockets. NittanySat will provide a "space truth" for these types of measurements.

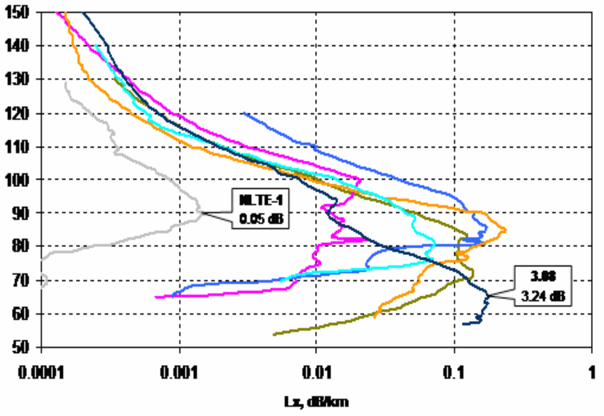

Figure 5. Specific absorption of some electron density profiles that were determined by sounding rockets. Clearly, the bulk of the absorption originates in the 70 to 90 km regio.

6. SUMMARY

The NittanySat mission will notably provide a valuable test of the newly established imaging riometer located near the Andøya Rocket Range. In addition, already established riometers such as the one in Fairbanks, Alaska or Kilpisjärvi, Finland, or indeed any other riometer whose operator wants to participate, will benefit from this mission. It should be noted that the NittanySat mission can arrange to add other ground stations; the only limitations are imposed by satellite power and data capacity. The current team is developing template ground-station designs that could be easily replicated for use at other locations.

Even though this description, and the original proposal have been strongly influenced by faculty advisors, the student team has been growing and is now shouldering most of the burdens for the activities. The students will conduct the formal Preliminary Design Review in August 2007, the Critical Design Review in January 2008, and they will fabricate the instruments, satellite hardware, sub-systems to prepare for satellite delivery in January 2009. They will also perform the activities associated with testing, calibration, integration, flight preparation, data analysis, data interpretation, and reporting of results.

7. REFERENCES

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