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Recalibrating the Star Sensor: From the IBEX Satellite to the RENU Rocket

Joshua French
University of New Hampshire

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Recalibrating the Star Sensor: From the IBEX Satellite to the RENU Rocket

—Joshua French (Edited by Katy Sternberger)

Leaving behind a tail of fire, the Rocket Experiment for Neutral Upwelling (RENU) launched 215 miles into the Earth's aurora, carrying the second UNH-built star sensor ever to leave the surface of our planet on December 12th, 2010. The star sensor is a new and inexpensive twist on a star tracker, and first became successful on the Interstellar Boundary Explorer (IBEX) satellite after its launch in October 2008. Costing only $50,000 to produce, compared to the star tracker's price tag of up to half a million dollars, this device, designed and built by University of New Hampshire (UNH) scientists and engineers, with help from various undergraduates and high school students, will be valuable for reducing the cost of future NASA missions.

The star sensor views stars in front of the spacecraft in order to tell the spacecraft which way it is facing in the sky, just as explorers on naval vessels have used the North Star to direct their vessels throughout history. The expensive star tracker, on the other hand, takes pictures of all the stars in front of the spacecraft, then runs the pictures through a database. However, the new star sensor still needs to be tested in various settings before it can be produced commercially. The device was successful aboard IBEX, but what about on other types of spacecraft with different parameters? The purpose of my 2010 Summer Undergraduate Research Fellowship (SURF) was to help recalibrate the second UNH star sensor so it could be tested on the RENU rocket.

The author working on the star sensor in the Facility for Optical Calibration at Low Light Levels at the Institute for the Study of Earth, Oceans, and Space.

The IBEX satellite, shaped like a bus wheel, has a very stable rotation. Contrary to this, the RENU rocket, shaped like a pen, spins vertically upward and has nowhere near as stable a rotation. As a result, the rocket payload would likely begin the process of coning. Just as a top begins to wobble off its vertical axis after spinning for a short time, the RENU rocket wobbled around 1° from its vertical axis. Further, with RENU's increased spin rate—about once per second, compared to IBEX's once per fourteen seconds—the star sensor would need to capture data much more quickly. These two factors meant that the second star sensor, originally built as a spare for the IBEX mission, would need to be completely recalibrated for the rocket.

In the end, the star sensor was unable to gather any data aboard RENU, as there were difficulties providing power to the device after launch. Despite this downfall, recalibrating the star sensor for the RENU mission helped our team of scientists and engineers, as well as high school students and UNH alumni, to better understand what to expect from the device while in flight. Further, several unexpected issues arose which, when solved, allowed us to better understand the existing star sensor and its results on the IBEX satellite. Therefore, even though the RENU star sensor never had its chance to shine, the research leading up to its calibration will be instrumental in future star sensor missions.

In the Beginning, There Was IBEX

Since its launch on October 19, 2008, NASA's IBEX satellite has been collecting data about the edge of our solar system to create the very first map of the interaction of the Sun's environment with the interstellar medium beyond. The satellite depends heavily on two cameras telling it exactly which way it is facing in order to precisely determine the direction of incoming particles. In particular, the spacecraft required an error of less than 0.1° to accurately determine the direction of interstellar gas. During satellite construction from 2004 to 2005, the IBEX mission team drawing up specifications at NASA was not fond of the idea of having two star trackers aboard the satellite, one for each camera, due to their high costs. However, since the cameras required precision pointing to figure out exactly where the neutral atoms were coming from, each required its own pointing device. So, the IBEX team looked into other options. This is where Professor Eberhard Möbius and his team at UNH, several engineers and undergraduates came into play. NASA decided to keep one star tracker for the satellite and use an experimental star sensor on one camera.

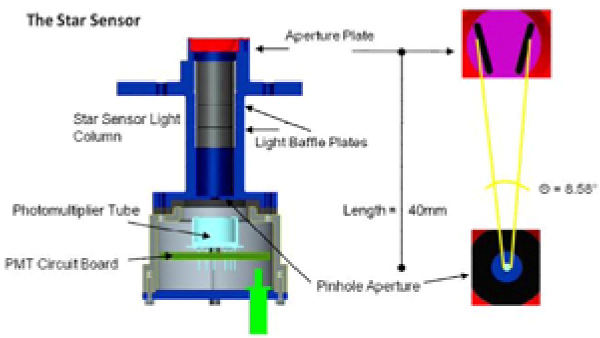

Figure 1: Diagram from O'Neill et al. (2009) outlining the basic operation of a star sensor. Starlight is captured through the two apertures and funneled through a pinhole to the photomultiplier tube. The entire device fits easily into the palm of a hand.

Professor Möbius' group had developed a very simple method for determining orientation based on the design of two slanted apertures and a pinhole 40 millimeters behind them. Each aperture is inclined at an angle, forming into the shape of a V. (See Figure 1) This V-shaped opening allows the star sensor to determine both the longitude and latitude of a celestial object. Behind the two apertures lie the two-millimeter diameter pinhole and the photomultiplier tube (PMT), a device that collects light and converts it into a readable voltage signal on the computer. This voltage signal is directly related to the number of photons (particles of light) that the PMT receives; and, as a result, a map of the sky can be created to analyze the positions of the stars.

Each point source of light, such as a star, appears as two triangular shaped signals as it moves horizontally across the V-shaped aperture. (See Figure 2) The signal it creates increases until it is fully viewed by one aperture, creating a maximum signal. Then it slowly moves out of sight of this aperture and repeats the process with the second aperture. This is how the two peaks are created. As a star passes at different heights across the V, the two peaks move closer or further apart on the computer and indicate the angle of elevation (latitude) of the spacecraft. (See Figure 3) Once the plans for the star sensor were finalized, two fully functional star sensors were built for the IBEX satellite, along with a single prototype.

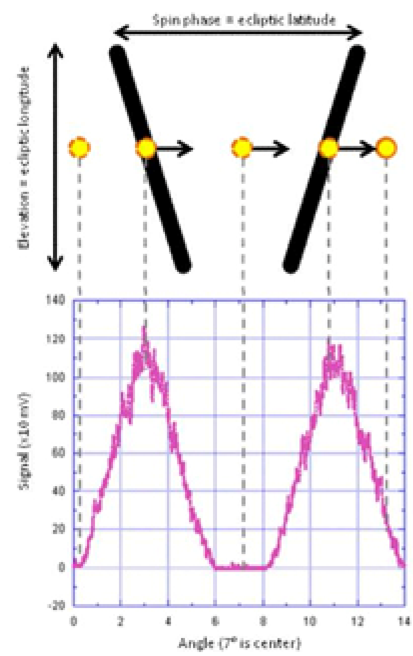

Figure 2: Diagram from Clark et al. (2009) illustrating a star passing from left to right over the two apertures. The result is two triangular-shaped voltage peaks. The brightness of the star determines the height of each peak, while the separation of the peaks corresponds to how high or low the star passed across the V.

Roughly twenty orbits, or 160 days, after the launch of IBEX, the star tracker showed that it wouldn't work when facing a bright source, such as the Earth or the Moon. Without knowing exactly when the spin cycle began and where IBEX was facing at that time, any data collected could not accurately be linked to a part of the sky. Since then, the star sensor has become the backup orientation device to determine where IBEX is facing at the start of each new spin cycle whenever the star tracker has problems.

The star sensor has been a success on IBEX since its launch, and testing it in this very stable spin setting, where it sees the same stars on each rotation, was an excellent first test. However, testing it in another setting would be necessary to prove that this economical device is a viable alternative to the expensive and complex star tracker systems now commercially available.

Preparing the Star Sensor for Flight aboard RENU

On December 12, 2010, a team of UNH scientists, led by Professor Marc Lessard, launched the four-stage sounding rocket known as RENU roughly 215 miles above Earth from Norway's Andøya Rocket Range. Unlike other scientific spacecraft that are slated for many years of scientific research in outer space, RENU was in space for only ten minutes. Funded by NASA's Sounding Rocket Program, RENU was intended to measure the complex, underlying physics behind the phenomena called neutral upwelling, where an upper layer of the Earth's atmosphere, or thermosphere, swells upward. This effect can interact with orbiting satellites and cause their orbits to decay slightly by inflicting friction on their movement.

Regardless of the scientific objectives of the mission, Professor Lessard offered Professor Möbius the opportunity to test the second of the two star sensors in a new environment aboard RENU, even though the sensor itself was not needed for the rocket's mission. The star sensor data would be cross-checked with data from a magnetometer, a device which determines the magnetic field strength and direction of the field lines coming out of the Earth. Professor Möbius knew this would be a great test for the star sensor and gladly accepted the offer. He advised me in my preparation of the SURF application and, once it was accepted, worked closely with me to prepare the star sensor for RENU. The goals of my SURF project were as follows:

- Confirm that the second star sensor still operated as expected, using tests from 2005-2006 made with the IBEX star sensor.
- Prepare the star sensor for the erratic coning motion of the RENU rocket and model this motion to predict how the star sensor would react.
- Recalibrate the RENU star sensor such that information could be processed more quickly, using data retrieved from the IBEX star sensor currently in orbit.

The first task to complete in early June 2010 was to verify the older test results from the IBEX star sensor to confirm that the second star sensor was still working as expected. For this, the rotary table we used in our dark testing room, which rotated the star sensor in front of a point source of light, needed to be sped up in order to simulate the faster spin the star sensor would experience in space aboard the RENU rocket. However, a problem quickly arose when we needed to select a wavelength range of light in order to test the star sensor.

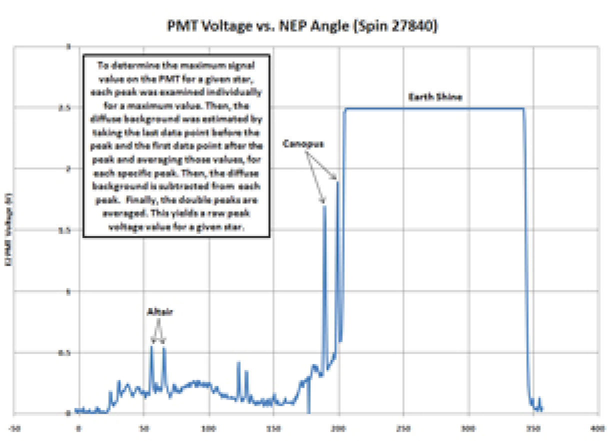

Figure 3: Data taken from the 26th orbit of the IBEX satellite. These measurements were taken over the course of the roughly 14 seconds it takes IBEX to spin around 360 degrees on its axis. As can be seen here, stars Altair and Canopus have been identified; Canopus is brighter and produced a larger signal on the star sensor. The brightness of the scattered light from the Earth, so bright that it actually causes the PMT to max out, can be seen towards the right.

Each individual photon's energy corresponds to a certain color (or wavelength). The light-emitting sphere we used (called an integrating sphere) can measure exactly how much energy it releases, but we first needed to specify a wavelength range (or color range), as the detector of the star sensor responds to different wavelength ranges with different signal readings. It was important to use the same exact range that was utilized during preparations for IBEX, but we could not immediately verify what it was. For assistance, we contacted Morgan O'Neill, a UNH graduate who had worked extensively with the IBEX star sensor, who came from the Massachusetts Institute of Technology to help us. After searching through some old documents and computer files, we found the wavelength band we needed, and then could verify that the star sensor was working well within expectations.

A second problem arose when we tried to speed up the rotary table to simulate the faster spin of the RENU environment. We soon realized that the fastest speed it could reach was about half of the speed we required, but we had to settle for that.

Next, we moved on to analyzing the IBEX star sensor data to better prepare the RENU sensor for flight performance. In 2009, Project SMART students, high school students that worked together to tackle real UNH space science problems, had found roughly nine stars that the IBEX sensor clearly and definitively measured. Using the double peaks that the star sensor produced for these stars, I was able to calculate and graph each star's maximum voltage signal with respect to its magnitude, or brightness to the human eye. Although this was a great step, it was ultimately inconclusive for one very important reason: different stars, although appearing to have the exact same brightness to the human eye, look very different to the PMT because many stars give off different ranges of light. Our eyes collect only what is called the "visual range" of light, which are the normal everyday colors we see. However, stars give off many ranges of light we cannot see, such as microwave, infrared, or radio. The PMT in the star sensor collects a different wavelength range of light than our eyes do. Therefore, we needed a way other than magnitude to relate the signals from the PMT to the brightness of the stars.

Using known values of the stars we were interested in, such as their radius and temperature, I calculated the total output energy of each star for the specific wavelength range we needed for our PMT. Further, I calculated what the star sensor would be expected to read from these stars, taking into account that a star becomes much fainter as you move away from it. As light expands out from a source, the photons spread out, and we only receive a small fraction of the original photons emitted from the star's surface. This gave me a rough model of what our star sensor should read, in terms of voltage, when it reached space.

Once all these tasks had been completed to recalibrate the star sensor, it was placed on board the RENU rocket in preparation for launch.

Recalibration, Collaboration, and Disappointment

Unfortunately, the separation of the nose cone of the RENU rocket, upon launch, cut off power to the star sensor. After all of our calibration work, the star sensor was not successfully tested and no data was collected. However, this is often the risk that scientists take with space instrumentation, and any mistakes or errors during the process teach us new ways to improve our technology for the future.

Over the course of the last six years, several groups of people have collaborated to produce the star sensor. Most notably, George Clark and Morgan O'Neill, undergraduates at the time, worked extensively with UNH engineers and scientists to prepare the star sensor from scratch. During the analysis of IBEX star sensor data, Project SMART results became very useful when determining which stars to use. (Project SMART, which stands for Science and Mathematics Achievement through Research, is an annual UNH summer institute, during which students enrolled in the 10th or 11th grade learn about the research process with UNH faculty and graduate students.) Finally, countless engineers and faculty have assisted in many small and big ways on this project, lending a hand whenever needed.

Collaboration on scientific missions such as these is extremely important due to the fact that research would not be where it is today without support from one group or university to another. As an undergraduate researcher, I have learned to work with different research groups around me and to never be afraid to ask them for assistance when needed. Specifically, working with the RENU star sensor, I learned a great deal about collaboration and how to work efficiently with others, even when they may have minimal knowledge about my project in general. Working with the star sensor was truly the culmination of my undergraduate research at the University of New Hampshire. I learned a great deal about the stresses of research life and how to continue fighting through the work even when things are not going the way you may have expected.

I wholeheartedly express my thanks to Professors Möbius, Lessard and Kucharek; research scientist Brent Sadler; engineer Paul Riley; the Space Science Center and the Hamel Center for Undergraduate Research for this research opportunity. I am certain it has better prepared me for graduate school and research in my field as a whole.

References

Clark, G. “Analysis of the Diffuse Background Components towards Efficient Use of the IBEX- Lo Star Sensor for the Interstellar Flow Direction Determination.” B.S. Thesis U. of New Hampshire, 2009.

Lessard, M., J. Clemmons, K. Lynch, P. Kintner, and G. McHarg. “Rocket Experiment for Neutral Upwelling (RENU).” Mission Proposal, 2008.

Lühr, H., M. Rother, W. Köhler, P. Ritter, and L. Grunwaldt. Thermospheric Up-Welling in the Cusp Region: Evidence from CHAMP Observations.” *Geophys. Res. Lett.*, *31*, 6805, 2004.

O’Neill, M. “Precision Pointing in the Sky for IBEX Interstellar Flow Observations - Use of the Moon with the IBEX-Lo Star Sensor.” B.S. Thesis U. of New Hampshire, 2009.

To read more in this issue about the star sensor and the UNH team who developed it, go to the commentary by George Clark and Morgan O’Neill and to the Mentor Highlights *profile of Professor Eberhard Möbius.*

Author Bio

Joshua R. French*, of Burrillville, Rhode Island, has been interested in space science all of his life. French, who is pursuing the astronomy option of the Bachelor of Science in physics degree, will graduate in May 2011. As a member of the University Honors Program, several research groups, and multiple performing ensembles as a trumpet player, he has kept a busy schedule but made time for his star sensor research that was funded by a Summer Undergraduate Research Fellowship. Joshua feels a great sense of accomplishment knowing that the star sensor he worked on flew in space. “There is a lot of pride with knowing that something you worked so hard on will be helping to solve real world problems,” he said. Consequently, this was a very fulfilling research experience. “I learned a great deal about the stresses of research life and how to continue fighting through the work even when things are not going the way you may have expected,” he said. He is confident that his experience will help him as he prepares to study aerospace engineering in graduate school.*

Mentor Bio

Dr. **Eberhard Möbius** *professor of physics and the department chair of physics, has served at the University of New Hampshire since 1990. When not teaching, he is an experimentalist, meaning that he is involved in designing, building and testing instrumentation used on spacecraft, and then analyzing the resulting data to “understand what is going on in space.” The American Geophysical Union recently honored him by naming him a Fellow.*

Dr. Möbius was surprised by and proud of the amount of work that Joshua accomplished despite his busy schedule. “Joshua still managed to come back with new results, although he had his time filled to the max,” he said. Dr. Möbius has mentored many undergraduate students in the past, including George Clark and Morgan O’Neill, who provided the basis for Joshua’s research. He has found that it is important for students in the field of physics to learn to write for a broad audience. “As a scientist or engineer, we have to be able to communicate with the public,” he said. He also stressed the importance of collaboration on a project such as Joshua’s, saying, “We would not be able to function without extensive collaboration.”