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R^3: Thermal Imaging and Rapid Feature Detection for Small Satellites

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ABSTRACT

The Georgia Tech Center for Space Systems is developing the Rapid Reconnaissance and Response (R^3) mission to perform thermal imaging and feature detection for responsive space applications. Historically, thermal imaging missions have been limited to large spacecraft due to the size, complexity, and power utilization of cryogenically cooled infrared imagers; only recently have smaller alternatives emerged for orbital thermal imaging applications. The R^3 satellite utilizes a modified commercial off-the-shelf microbolometer, previously used in ground-based military applications, to perform thermal imaging of selected features. Because microbolometers are small, lightweight, low-power systems, they can be rapidly integrated with a flight system in response to an emerging need. Microbolometers have previously flown in space, but their susceptibility to the radiation environment of space is not well understood. The R^3 spacecraft will fly a radiation dosimeter to quantify the radiation environment of the spacecraft in low Earth orbit, and the health and performance of the microbolometer will be compared to the radiation total dose and single event effects. This will allow future instrument designers to utilize an appropriate amount of radiation shielding on the microbolometer to ensure adequate performance and minimize mass. The R^3 mission is also developing autonomous feature identification and geolocation algorithms for the microbolometer images. These algorithms will be utilized to quickly identify thermal features of interest, calculate their coordinates, and downlink these coordinates to the ground station. This paper describes the development of the R^3 mission and its operationally responsive space applications.

KEYWORDS: microbolometer, thermal imaging, responsive space

INTRODUCTION

As the need for operationally responsive spacecraft increases, the need for operationally responsive instruments and software capabilities also increases. Without the necessary tools and capabilities, it will be impossible for future spacecraft designers to adequately address the growing need for spacecraft that can be designed, fabricated, integrated, and launched quickly in response to a specific need or threat. In this spirit, the Georgia Tech Center for Space Systems has developed the Rapid Reconnaissance and Response (R^3) Mission to demonstrate the use of a lightweight thermal imager, test its performance under the harsh radiation environment of space, and employ on-board image processing algorithms to fully exhibit the responsive space capabilities of such a mission.

The Georgia Tech Center for Space Systems (CSS) was founded in 2008. CSS was created with the intention of encouraging student involvement in the full lifecycle of space flight projects and developing world-class research facilities for the design, development, and operation of advanced space systems. Engineering students are given the opportunity to gain flight experience, helping them to develop engineering intuition not easily obtain in a classroom setting. The CSS and the R^3 program are structured to develop well-rounded engineers with expertise in one or more engineering subsystems and a basis for system-level engineering intuition.

In December 2008, CSS was awarded an opportunity to compete in the University Nanosatellite Program

(UNP), funded by the Air Force Office of Scientific Research and the Air Force Research Laboratory. Principal Investigator David Spencer formed a design team from students in the Schools of Aerospace Engineering and Electrical and Computer Engineering. Georgia Tech partnered with Arizona State University for the design and fabrication of the imaging instruments for the project. The R^3 team members have been responsible for developing and implementing the processes and techniques necessary for future successful design programs; in addition, they have also helped to design and acquire the facilities and equipment for hardware fabrication and mission operations.

The University Nanosatellite Program is a two-year program sponsored by the Air Force Research Laboratory's Space Vehicles Directorate, the Air Force Office of Scientific Research, and the AIAA. The program offers the opportunity for students to design and build a nanosatellite in competition for a future launch slot. The current program, UNP-6, is currently in its second year, and the Georgia Tech entry has just finished its Critical Design Review.

MISSION AND SYSTEM DESCRIPTION

The R^3 mission is a thermal imaging mission, focused on the characterization of radiation environment effects on the microbolometer thermal imager, and detection and geolocation of thermal features of interest. In order to perform thermal imaging from a small spacecraft, the R^3 team, along with its partners at Arizona State University, is adapting a commercial off-the-shelf (COTS) microbolometer provided by Raytheon Vision Systems for space applications. A radiation dosimeter will be used to characterize the space radiation environment and compare it to the performance of the microbolometer. The R^3 satellite will process the thermal images from the microbolometer using on-board image processing and feature detection algorithms developed for the mission. Context images will be provided by a Point Grey Research Grasshopper visible camera.

The basic structural design of the R^3 spacecraft emphasizes ease of fabrication and integration as well as structural integrity. The UNP guidelines restrict the spacecraft to a 50 cm x 50 cm x 60 cm envelope. A simple rectangular prism shape has been chosen in order to maximize surface area for the solar arrays and volume for internal components. In order to reduce mass while maintaining structural rigidity and support, the panels of the spacecraft will be made of Aluminum 6061 utilizing an isogrid design. This design also allows the plates to be designed and machined by students using Georgia Tech facilities and tools. Spacecraft component housings will be oriented in the spacecraft to ensure ease of integration and maintain the necessary center of mass and moments of inertia; the housings will be bolted directly to the panels for ease of manufacturing. Figure 1 shows a design of the internal structure of the spacecraft. The packaging density for this design is fairly low at 280 kg/m^2.

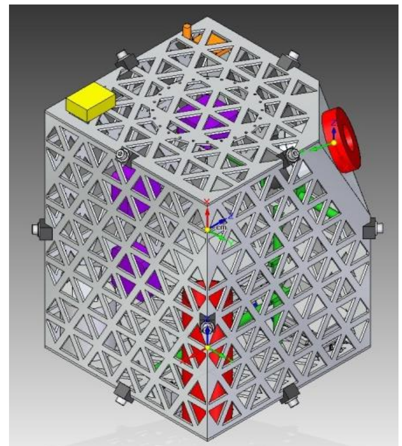

Figure 1: Internal Structure of R^3 Spacecraft

The R^3 spacecraft, although very small by commercial and military standards, possesses a great deal of functionality necessary to accomplish the imaging mission. To obtain targeted images of thermal features of interest, the R^3 spacecraft requires precise attitude knowledge and control. For fine attitude determination, a Valley Forge Composite Technologies Inc. star tracker will provide primary attitude knowledge. This offers attitude knowledge within 15 arc seconds in two axes and 70 arc seconds in the third. Primary attitude control during fine attitude mode will be performed by three 0.1 Nms reaction wheels with magnetic torquers providing desaturation. A coarse mode of attitude determination and control provides the capability to detumble upon separation from the launch vehicle and allows the spacecraft operate in a safe, lower power mode when imaging is not a priority. For the coarse mode, twelve Adcole Coarse Sun Sensors and a magnetometer will provide attitude knowledge. Attitude control will be provided by the three magnetic torquers, fabricated in-house at CSS. In addition to attitude knowledge, precise orbital knowledge is important for the geolocation of the thermal features, so a GPS system will be used for orbital information. The R^3 spacecraft will use the SGR-05U GPS unit manufactured by Surrey Satellite Technologies Limited, and a filter will provide orbital position accuracy to 10 m and velocity accuracy to 8 km/s.

On a small satellite such as the R^3 spacecraft, the production and distribution of power becomes a prime concern. In order to emphasize simplicity and robustness, the R^3 spacecraft will use body-mounted solar arrays for power production. Currently, Spectrolab Ultra Triple Junction (UTJ) solar cells are baselined for use on the solar panels. For power storage, the R^3 spacecraft will utilize 24 Sanyo N4000 Ni-Cd batteries, provided by the UNP. Again, to emphasize simplicity in design and reliability, the design team has chosen a simple Sun-regulated power bus for distribution and control. Although this presents some losses in efficiencies of the solar cells and distribution, it provides a robust system with lower part counts than alternative architectures. All of these design decisions combine to create a very tightly controlled power budget; the Electrical Power Subsystem (EPS) team has focused on lowering power usage among components and maintaining safe margins for the batteries.

Another important aspect of the R^3 mission is the Command and Data Handling (C&DH) of the spacecraft. Because of mass and volume considerations a centralized architecture was chosen for the majority of the C&DH work. Capitalizing on Georgia Tech's resources, the R^3 spacecraft will use an FCS20 flight control system, a combination board created by Adaptive Flight Inc., a partner and collaborator of Georgia Tech. The FCS20 was originally designed as a flight control system for atmospheric vehicles, such as small military remote-controlled helicopters, but is being adapted for space flight. It contains two boards, a processor board and a power/sensor board. The processor board contains a Field-Programmable Gate Array (FPGA), Digital Signal Processor (DSP), RAM, and flash memory. The DSP provides the basic computing for the spacecraft and serves as the main area on which the flight code will run. The FPGA serves as the I/O controller for the components of the spacecraft controlled by the C&DH subsystem. The power/sensor board possesses the power regulation system used for data lines in the C&DH system, Analog to Digital Converters (ADC), and physical I/O interfaces.

The telecommunications subsystem of the R^3 spacecraft is a vital design concern, as an imaging spacecraft with low power production and small size provides a challenge for data return. Specifically, the pairs of images taken by the microbolometer and the visible camera create a significant amount of data that must be returned. Currently, CSS possesses a single ground station, so the spacecraft must be prepared to downlink several hours of data in only a few minutes of overpass each day. To accomplish this, the spacecraft will use RD Labs' S-Band Transceiver for Microsat platform. This small COTS transceiver possesses high data rate-capabilities, low weight and cost, and variable modulation formats and frequency bandwidths. Due to the volumetric constraints of the UNP regulations and the wide beam width necessary for the spacecraft, a patch antenna was selected for communications; an S-Band patch antenna from SSTL will be utilized in this case. In order to ensure data return success, a detailed link budget analysis has been performed to ensure link reliability. The winner of UNP6 will be placed in a LEO orbit of unknown altitude, eccentricity, and inclination. Therefore, the Telecommunications team, along with the Mission Design Team and C&DH team, has performed a detailed study of the data return capability of the spacecraft spanning a broad range of potential orbits.

UNP has imposed a strict 50 kg limit on the spacecraft, so the R^3 team has tightly controlled the mass budget. Trade studies between mass and performance have been continuously updated throughout the design process in order to maximize spacecraft value. Contingencies for all parts have been based upon conservative estimates – 15% for parts to be procured, 10% for parts to be procured that possess detailed test documentation, and 5% for parts that have been procured and weighed. A summary of the R^3 spacecraft mass breakdown can be seen in Table 1.

Table 1: Mass Breakdown Summary

Component	Mass (g)
Microbolometer Sensor	150
Microbolometer Lens	1,840
Microbolometer Coupler	115
Visible Camera	120
Visible Camera Lens	52
Radiation Dosimeter	138
ADCS	7,899
Structure	14,292
C&DH Subsystem	1,128
Power Subsystem	7,527
Communications Subsystem	1,440
Thermal Control	1,000
Miscellaneous	5,000
Total	40,700
Margin (%)	18.60%

MICROBOLOMETER

The Georgia Tech team has partnered with Arizona State University, under Dr. Phil Christensen's lead, to produce the primary instrument for the R^3 mission. Dr. Christensen is a leader in the development of space-based infrared imagers; he currently serves as the Principal Investigator for the Mars Thermal Emission Imaging System (THEMIS) instrument on Mars Odyssey. Under Dr. Christensen's direction, several Arizona State students have developed the preliminary design of the thermal instrument for the R^3 mission, an adapted COTS microbolometer. Microbolometers are widely used in ground-based applications, including on military helmet-mounted infrared imagers and rifle scope imagers. Microbolometers have also been used for space applications, including as a part of the THEMIS instrument.[1] The DARPA Orbital Express Mission also used a microbolometer array onboard the Autonomous Space Transport Robotic Operations (ASTRO) spacecraft. ASTRO utilized the microbolometer to detect its sister satellite NextSat's thermal signature to aid in autonomous rendezvous and docking.[2] The microbolometer bears many features that make it valuable for space-based applications, specifically for operationally response space uses. On previous infrared imaging missions, spacecraft were required to use large, cryogenically cooled imagers. These cryo-cooled systems are very high mass, power-hungry, and costly. Although they are very accurate, they are cannot be used for small satellite operations or responsive space applications due to their complex design and long integration and testing schedules. Microbolometers can provide a valuable alternative for small spacecraft with short development and integration times.

A microbolometer is essentially a Focal-Plane Array (FPA) of individual pixels, each measuring infrared radiation. Specifically, the microbolometer uses a radiation-absorbent material that is thermally sensitive to changes in infrared levels. The change in temperature of the absorbent material is correlated to the change in IR radiation, and is calculated using the absorbent material's heat capacity and the thermal conductance of the structure holding the absorbent material.[3] For sensitivity, it is important that the absorbent material is thermally isolated from the rest of the integrated circuit to ensure reliability. Developments in microelectromechanical systems (MEMS) technologies have allowed these absorbent materials to be suspended micrometers above the rest of the device. This has led to a reduction in size of individual pixels, allowing for greater resolution of the devices. This method of thermal isolation replaces more traditional types of thermal isolation, such as cryogenic cooling used in large infrared imagers.

The microbolometer used by the R^3 mission is the Uncooled Infrared Camera Engine UE640, produced by Raytheon Vision Systems (RVS). It has previously been used for helmet-mounted infrared imagers. The specifications for the microbolometer can be seen in Table 2. The microbolometer will be paired with a commercial infrared lens from Ophir Optronics to form the thermal imager. A picture of the microbolometer can be seen in Figure 2.

Table 2: Microbolometer Operating Specifications

Parameter	Value
Overall Mass (kg)	1.73
Peak Power Dissipation (W)	2
Spatial Resolution (m) from 500km altitude	124
Noise-Equivalent Differential Temperature (mK)	60
Pixel Pitch (µm)	25
Spectral Range (µm)	7.5 to 13.6
Frame Rate (Hz)	40
Field of View	9.1° x 6.8°
Ground Footprint (km)	79 x 60
Array Size (pixels)	640 x 480

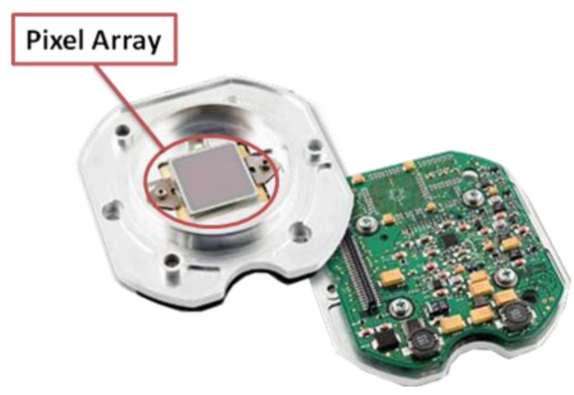

Figure 2: RVS Uncooled Microbolometer (Original Image: Raytheon)

As previously mentioned, there has been little use to date of microbolometers in space applications. There is a great need to provide flight heritage of such systems and to provide information about the performance of these instruments in space. Specifically, the performance of such instruments when subjected to the radiation dosages of spaceflight is not fully understood. Single Event Upsets (SEU) and Total Ionizing Dose

(TID) are two commonly used metrics to evaluate the amount of radiation a spacecraft experiences; both play significant roles in reducing the performance and lifetime of electronics. Although ground-based radiation testing can provide partial answers about the susceptibility of microbolometers to space radiation, it is still vitally important to test them in space.

Radiation Testing of Microbolometer

In order to better understand the effects of radiation upon the microbolometer, the R^3 spacecraft will fly a radiation dosimeter to quantify the radiation environment experienced by the spacecraft. The R^3 team has partnered with Dr. Peter McNulty to fly the Dosimetry Intercomparison and Miniaturization Experiment-1 (DIME-1) onboard the R^3 spacecraft. The DIME-1 board was developed by Dr. McNulty and Clemson staff for the NASA Goddard Space Environment Testbed Project. Dr. McNulty serves as the Principal Investigator for the experiment, which seeks to characterize the radiation environment, including total dose, displacement damage, and SEUs while aboard the Demonstration & Science Experiments (DSX) spacecraft.

DIME-1 uses several types of dosimeters to measure radiation. Three units of Electrically Erasable Programmable Read-only Memory (EEPROM) will be used to measure the total dosage of radiation over time; as radiation affects the dosimeter, the voltage signal to the memory slowly changes individual bits' states. They will also be used to track SEUs over time. Two sizes of EEPROMs will be used to capture the effects of different energies of radiation. Radiation-Sensing Field-Effect Transistors (RadFET) will also be used to measure total radiation dosage. The RadFETs contain varying levels of aluminum and tantalum shielding, in order to evaluate the effects of shielding on the dosimeter.[4] A picture of DIME 1 can be seen in Figure 3.

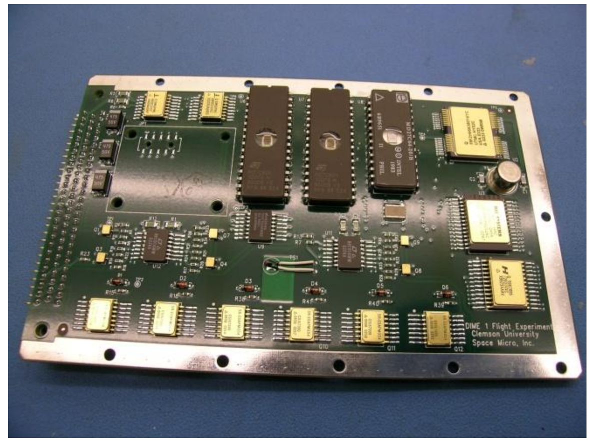

Figure 3: DIME 1 Board (Image: McNulty)

The DIME-1 board will be placed in close proximity to the microbolometer and should provide an accurate quantization of the radiation effects the microbolometer experiences. During flight operations the microbolometer will be calibrated periodically to measure performance. Once radiation data from the dosimeter and performance data from the microbolometer have been downlinked to the ground station, post-processing will evaluate the effects of radiation. This correlation will help future instrument designers to design radiation shielding and predict the lifetime of the instrument.

Microbolometer Applications for Responsive Space

The utilization of microbolometers for space applications provides a myriad of advantages to designers looking to meet the challenges of responsive space missions. Most importantly, the relative size of the microbolometer makes it advantageous for smaller responsive space operations. The use of a traditional cryo-cooled IR imager forces the designer to implement a very large and expensive satellite expected to take years to develop. The main reasons for this spacecraft size constraint are the mass, volume, and power requirements of traditional systems.

For comparison, examine the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) flown on the NASA Terra satellite. ASTER is a very powerful multi-spectral infrared imager. It utilizes three types of infrared imagers to very precisely image the infrared radiation of Earth; the Visible and Near-Infrared Radiometer (VNIR), Short-wave-infrared Radiometer (SWIR) and Thermal Infrared Radiometer (TIR) make up the instrument suite. Each imager measures several smaller spectral ranges for a very complete and precise measurement of the infrared environment. The SWIR and TIR are cryogenically cooled, using mechanical Stirling cycle coolers.[5] Although the ASTER imager provides a great deal of precision and science value, it does not come without a heavy tradeoff in mass and power requirements. Table 3 shows the general specifications of ASTER.[6]

Table 3: ASTER Imager Specifications

Parameter	Value
Overall Mass (kg)	352
Peak Power Dissipation (W)	650
Spatial Resolution (m)	90
Noise-Equivalent Differential Temperature (mK)	300
TIR Spectral Range (μm)	8.13 to 11.7
Absolute Accuracy (K)	< 3K
Peak Data Rate (Mbps)	89.2

One can easily see the relative advantages and disadvantages of the R^3 microbolometer in comparison with the ASTER imager. The microbolometer provides less precision and spectral range in measurement of the infrared environment, but it allows for much greater flexibility in spacecraft design. At less than 1% of the mass and power consumption of the ASTER imager, the microbolometer has the potential to reach a wide variety of responsive space needs.

One of the most critical requirements of responsive space needs is turn-around time for design, fabrication, and integration of spacecraft. The large mass, power, and volume requirements of the cryo-cooled thermal imagers dictate a design, integration, and system test schedule spanning years, effectively precluding these systems from consideration for responsive space missions. Large spacecraft with complex power, telecommunications, and data handling systems require a great deal of oversight and schedule margin. In addition, the necessary test procedures for a cryo-cooled system also prevent responsive applications. The testing time alone for the cooling system could be greater than the maximum allowable time to design and fly a system for a specific responsive space need.

On the other hand, the low mass of the microbolometer, its functional simplicity, and its modest power requirements make it a strong candidate for responsive space missions. A 50 kg satellite such as the R^3 spacecraft is well equipped to sustain such an imager, and spacecraft of this size are much more capable of being designed, fabricated, and integrated in short periods of time to meet responsive space time constraints. The relative simplicity of such an instrument also makes it ideal for time-constrained missions. Although there is currently no space-qualified microbolometer that can truly be called "Plug-and-Play," the MEMS manufacturing techniques used to create such devices have eliminated the most time-intensive portion of thermal imager I&T, the active cooling system.[7] It is entirely likely that the next generation of microbolometer designed by ASU and Georgia Tech will allow Plug-and-Play integration capabilities.

Another aspect of the microbolometer that makes it suitable for responsive space applications is the imager's relatively low cost. Because the R^3 microbolometer is adapted from COTS terrestrial technology, it can dramatically lower the development cost, compared to thermal imagers. Utilizing the microbolometer from RVS and a commercial infrared lens from Ophir brings the development and procurement cost of a thermal imager down to thousands of dollars, rather than millions of dollars for large imagers such as ASTER. The overall cost savings associated with designing a spacecraft around a small imager such as a microbolometer should also be examined. Small satellites such as the R^3 spacecraft should require a complete Design, Development, Test and Evaluation (DDT&E) cost on the order of several million dollars. For comparison, the Terra satellite is estimated to have cost $1.3 billion.

There are seemingly endless possibilities allowed by very small, low-cost, thermal imaging satellites that could not previously be met. Individually, these satellites could be fabricated, integrated, and launched within months to identify specific threats or examine particular features of interest that are time-sensitive. As a mobile fleet of imagers, a group of thermal imaging satellites could provide a wealth of real-time information about a number of important features or thermal phenomena. For example, the R^3 team has studied images taken by the ASTER imager concerning coastal currents such as the Gulf Stream. Although the R^3 microbolometer could not provide the same level of fidelity as the ASTER imagers, a fleet of spacecraft similar to R^3 could provide a detailed understanding of the changes in coastal current patterns over time. Instead of a single overpass of a feature per day as is possible with ASTER, a fleet of small spacecraft would have overpass frequencies on the order of every few hours. Alternatively, these same spacecraft could turn their attentions to a military feature of interest. The thermal signature development over time of a specific threat could be very valuable to the military for intelligence planning. Potentially, a fleet of these spacecraft could even provide a first-alert system for missile launches, as the resulting heat generated from a launch will provide a significant "hot flash" for thermal imagers. No matter the application, small, inexpensive satellites with low development times present a wealth of possibilities for thermal imaging missions that were not previously possible.

THERMAL FEATURE DETECTION ALGORITHMS

In addition to the development of the microbolometer for space applications, the R^3 team is also seeking to develop methods of autonomous feature detection and geolocation of thermal features of interest for the spacecraft. The algorithms necessary to process the microbolometer's thermal images, identify thermal features, and calculate the feature's coordinates will be programmed as a module within the R^3 flight software. This will allow for an autonomous processing of images necessary to meet responsive space needs. Two main algorithms have been developed for the purpose of feature detection, the Blobber algorithm and the Edge Detection algorithm. These algorithms can be combined as appropriate for the thermal feature of interest.

Blobber Algorithm

The Blobber algorithm, so named for its use of large "blobs" of pixels, is used to identify thermal features that have very similar thermal infrared intensity levels. There are several steps involved in the process that work to identify features that fall within several constraints. First, the image's matrix representation is screened to identify only those pixels that fall within a certain thermal intensity threshold. These thresholds will be determined through extensive testing of existing thermal images, based on the type of thermal feature of interest. For example, the thresholds necessary for tracking of the Gulf Stream will differ from the thresholds for wildfire identification; these will be determined by evaluation of existing images of each type of feature.

Once all pixels falling outside of the intensity thresholds have been filtered out, the algorithm seeks to identify areas of contiguous pixels. All remaining pixels are tested for neighboring pixels that have similar intensities; the groups of pixels that remain are labeled as numbered blobs. This technique helps to filter out individual pixels that fall within the thresholds but do not represent specific features. This process must be iterated through several times to ensure all blobs are identified by a single group number. Once this has been accomplished, blobs are filtered out according to blob size thresholds. Again, these thresholds depend upon the type of thermal features to be tested for and will be established through extensive testing prior to full implementation. The area thresholds help the algorithm to only identify features that are of a proper size; if large Gulf Stream movements are the feature of interest, small features like land formations must be filtered out.

An example of the results of the Blobber algorithm can be seen in Figure 4 and Figure 5. Figure 4 is an ASTER image of the ocean off the coast of North Carolina. By itself, it qualitatively shows the boundary between the cool ocean water and the warmer water affected by the Gulf Stream, but it lacks clarity and definition. Once the Blobber algorithm has processed the image, it becomes much clearer. Figure 5 clearly shows the thermal boundary between the two distinct volumes of ocean water. The Blobber algorithm has filtered out smaller variations in temperature and even the small portion of land in the top left corner.

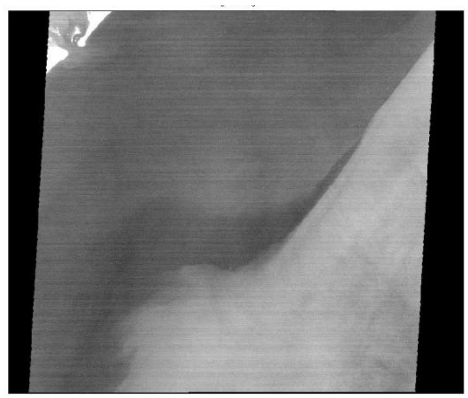

Figure 4: Original ASTER Image of Gulf Stream

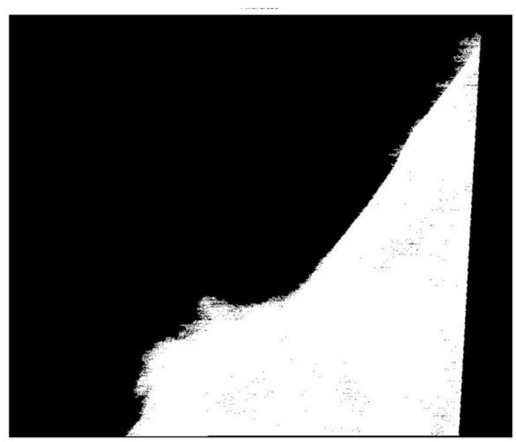

Figure 5: ASTER Image after Blobber Application

The final step in the Blobber algorithm is the geolocation of the feature. Two approaches have been developed for geolocation, depending upon the application. The first approach is the calculation of the "center of brightness" of the contiguous blob. Similar to calculating the barycenter of a mass, the Blobber algorithm assigns weights to each pixel's location according to its thermal intensity. The weighted locations are summed and used to determine the center of brightness. It is important to note that the center of brightness may not fall within the blob if the blob is not convex, but it will still provide valuable information about the location of the feature. Utilizing the spacecraft's orbital position knowledge from filtered GPS data and the spacecraft's attitude knowledge, it is possible to determine the coordinates of the feature. An example of the center of brightness identification can be seen in Figure 6 and Figure 7. Figure 6 shows another image from ASTER, this one of a wildfire in the Angeles National Forest in California, falsely colored to enhance identification. Figure 7 shows the same image after the Blobber algorithm has processed it and identified the center of brightness. A second approach for geolocation is simply to calculate and store the coordinates for every pixel contained within the blob. For the tracking of large, broadly-distributed features such as the Gulf Stream in Figure 5, this approach is favored.

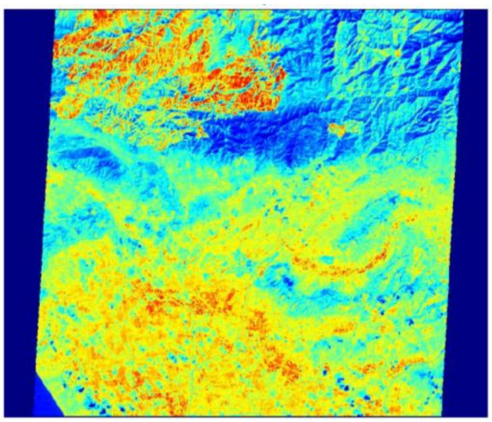

Figure 6: False Color ASTER Image of Wildfire

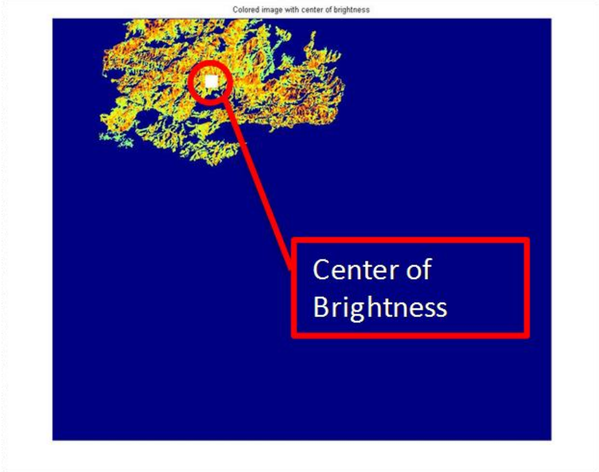

Figure 7: Color Image of Wildfire after Blobber Application

Edge Detection Algorithm

The second algorithm under development for the R^3 mission is the Edge Detection Algorithm. While the Blobber algorithm focuses on the relative similarities between nearby pixels, the Edge Detection algorithm focuses on the sharp changes between neighboring pixels. This is especially applicable to features with well-defined boundaries, such as coastlines and man-made objects.

For the R^3 spacecraft algorithm, edge detection is accomplished through gradient-based calculations. The algorithm applies calculus to identify edges: the larger the first derivative, the swifter the change in value. The algorithm calculates the gradient of each pixel, using independent calculations of the change in each direction. In this case, the algorithm uses two Sobel operators, one for the horizontal direction and one for the vertical direction.[8] The absolute values of the two resulting calculations are summed to create a single intensity value for each pixel, and the image is redrawn using these values for the grayscale intensity. This method helps to clearly identify the boundaries between different geographic features.

An example of the application of the Edge Detection Algorithm can be seen in Figure 8 and Figure 9. Figure 8 shows an ASTER image of the South Carolina coastline. Figure 9 shows the same image after being processed by the algorithm. The edges of the coastline are much clearer in the second image and, given geolocation information, can be used to precisely track the coastline changes over time.

Figure 8: ASTER Image of South Carolina Coastline

Figure 9: ASTER Image after Edge Detection Processing

Algorithm Application to Responsive Space

The use of on-board thermal image processing algorithms provides several applications for operationally responsive space. In the case of a spacecraft designed and flown to detect a specific thermal feature, the algorithms may be fine-tuned enough to provide accurate identification and geolocation of these specific items of interest. The coordinates of a particular feature can then be autonomously downlinked to interested parties or vehicles. In particular, the use of unmanned aerial vehicles (UAV) and autonomous underwater vehicles (AUV) in conjunction with such spacecraft capabilities is particularly interesting. The coordinates of particular features of interest could be directly communicated to such autonomous vehicles for more detailed reconnaissance and imaging. The Georgia Tech R^3 team plans to exhibit some of these capabilities during its mission, using an autonomous helicopter designed and built by the UAV Research Facility at Georgia Tech. Alongside the spacecraft's geolocation capabilities, autonomous vehicles could be used to great effect for wildfires and specific military applications.

Alternatively, if a fleet of spacecraft with these feature detection capabilities was operational for general use, other applications are possible. The feature detection capabilities of the spacecrafts could be used to evaluate the movement of coastlines over time, specifically applicable to flooding and hurricane damage control and evaluation. These capabilities can also be used to track the Gulf Stream and other ocean eddies over time, in order to better predict weather patterns for the US Air Force and the National Weather Service. Finally, the relatively easy method of changing thresholds to change which features are identified allows for in-orbit changes to detection priorities, as needs develop.

CONCLUSION

The R^3 spacecraft, as designed by a team of Georgia Tech students, seeks to advance the capabilities of small satellites to perform thermal imaging missions suitable for responsive space applications and science data collection. The design and implementation of a microbolometer as a small, low-cost, easily-integrated instrument will provide new opportunities for thermal imaging, and the valuable information gleaned from the radiation study will help future designers to properly design and account for the effects of space radiation. The on-board image processing algorithms developed for the mission will help to demonstrate the capabilities of the thermal imager and allow for rapid identification of thermal features of interest. Along the way over sixty students will be exposed to real world design, analysis, fabrication, and testing of spacecraft. The important practical lessons learned from this project will go far to supplement the students' strong classroom educational experience at Georgia Tech and will hopefully provide the next generation of spacecraft designers with the necessary tools for success.

The R^3 mission is in the midst of the two-year UNP program. Currently, the components for the spacecraft are being procured from vendors or fabricated in Georgia Tech facilities. The imaging instruments are under development at Arizona State University. Integration and testing of the components will begin in April 2010 and continue until December 2010. The R^3 team will go through its Proto-Qualification Review in August 2010 and Flight Competition Review in January 2011. If the R^3 mission is chosen as the winner of the flight competition, the spacecraft will be delivered for environmental testing at AFRL's test facilities in the summer of 2011, for a probable launch in 2012. If this does not occur, the R^3 team will seek alternative launch opportunities for the spacecraft.

Acknowledgements

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References

1. Silverman, S. and P. Christensen. 2006. "Successful Mars remote sensors, MO THEMIS and MER Mini-TES," *Acta Astronautica*, Vol. 59, Issues 8-11, October-December 2006.
2. Timmons, K.K. and J.C. Ringelberg. March 2008. "Approach and Capture for Autonomous Rendezvous and Docking," *Proceedings from 2008 IEEE Aerospace Conference*, Big Sky, MT.
3. Bhan, R.K. and R.S. Saxena. November 2009. "Uncooled Infrared Microbolometer Arrays and their Characterisation Techniques," *Defense Science Journal*, Vol. 59, No. 6.
4. McNulty, P.J., K.F. Poole, and M. Fennell. 2009. "The DIME Suite of Dosimeters," *RADECS 2009 Proceedings*, September 9, 2009.
5. Fujisada, H., F. Sakuma, A. Ono, and M. Kudoh. 1998. "Design and Preflight Performance of ASTER Instrument Protoflight Model," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 36, No. 4, July 1998.
6. Abrams, M. and S.J. Hook, 1995. "Simulated ASTER Data for Geologic Studies," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 33, No. 3, May 1995.
7. Christensen, P.R., B. Jakosky, and H. Kieffer. 2004. "The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission," *Space Science Reviews*, Vol. 110, No. 1-2, January 2004.
8. Jensen, J.R. 2005. *Introductory Digital Image Processing: A Remote Sensing Perspective*, Pearson Prentice Hall, New Jersey.