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Project Title – "Virtual Telescope for X-ray Observations"

1 Project Description

1.a Project Purpose

The success of NASA missions can be attributed to the Administration's ability to implement and develop new technologies. This is particularly true for NASA science missions where advances in spacecraft capabilities coupled with the development of advanced instrumentation have driven scientific discovery. In 2012 the National Research Council produced a study entitled *NASA Space Technology Roadmaps and Priorities - Restoring NASA'S Technological Edge and Paving the Way for an New Era in Space*. This report listed the development of X-ray optical systems with at least a factor of ten improved spatial resolution, while maintaining the current collecting area to mass ratio, as a game-changing technology. X-rays are linked to the Universe's highest energy phenomena and an order of magnitude increase in the spatial resolution would provide a window to the underlying physical processes of the high energy universe. This technology would enable high resolution imaging of the X-rays from solar flares and the detailed mapping of the X-ray production in energetic objects such as active galactic nuclei. The development of advanced X-ray instruments falls under the NASA -Space Technology Mission Directorate's Roadmap in Technology Area 08 under Technology 8.1.3: Optical Systems.

The Virtual Telescope for X-ray Observations (VTXO) program is a NASA EPSCoR project that includes researchers from New Mexico State University (NMSU) and the University of New Mexico (UNM) working in close collaboration with scientists and engineers at NASA's Goddard Space Flight Center (GSFC). VTXO addresses the cited need for high resolution imaging of X-ray sources with the development of a novel diffractive X-ray optical system. X-ray diffractive systems offers the advantage of finer angular resolution and reduced mass compared to the reflective optics currently employed on X-ray satellites (RHESSI and XRT). However, diffractive systems require very long focal lengths ($\sim$ 100 m), well beyond what is practical for a single spacecraft telescope. VTXO will demonstrate the feasibility of using two satellites, held in precise alignment by an advanced guidance, navigation and control system (GN&C), to achieve the required focal length (Figure 1).

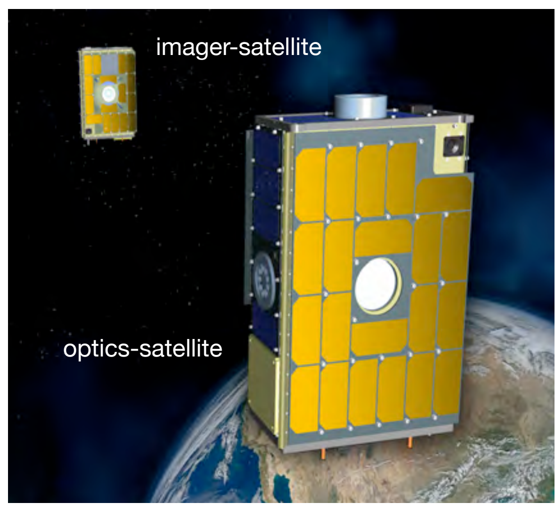

Figure 1: Schematic showing the alignment of the imager-satellite with the optics-satellite. The direction of the X-ray source target would be along the line of sight between the two satellites and out of the paper.

The use of CubeSats as a *cheaper, better, faster* platform to demonstrate new technologies and increase the Technology Readiness Level (TRL) of components and systems has gained the interest of NASA. VTXO will leverage expertise with CubeSats that exists within the collaboration to develop a technology demonstration mission using two 6U CubeSats. One CubeSat will carry the diffractive lens and the second an X-ray sensitive camera. The optics-satellite and the imager-satellite will be separated by a distance of $\sim$ 100 m, forming a *virtual telescope* that can be *pointed* at X-ray producing targets. VTXO will focus on the imaging of solar flares, but the technology developed as part of this project is applicable other astronomical sources as well.

VTXO is closely aligned with goals in NASA's Space Technology Mission Directorate (STMD) and Science Mission Directorate (SMD). The GN&C architecture developed for VTXO will combine multiple navigation technologies to autonomously perform both relative navigation and absolute alignment relative to an inertial source for the first time. This enabling technology is applicable to a number of next-generation space telescopes proposed to NASA, such as the Milli-Arc-Second Structure Imager and the New Worlds Observer. The scientific observations enabled by this technology support the two *Big Questions* from the Science Mission Directorate: *How Does the Universe Work?* and *What Causes the Sun to Vary?*.

New Mexico State University and the University of New Mexico have an established history in the development of small satellites. VTXO joins researchers from NMSU's Klipsch School of Electrical and Computer Engineering, Department of Mechanical and Aerospace Engineering and Department of Astronomy with UNM's Configurable Space Microsystems Innovations & Applications Center (COSMIAC) and Department of Mechanical Engineering. This New Mexico-based team will collaborate with GSFC to address some of the most challenging problems associated with the precision formation flying of satellites to enable a virtual telescope. The successful demonstration a virtual telescope will establish the State of New Mexico as one of the leading players in the development of virtual telescope systems, attracting highly qualified new students, strengthening connections to the NASA centers, and expanding the research infrastructure in New Mexico. The broad area of formation flying of satellites is a research priority of other New Mexico entities as well: Los Alamos National Laboratory, Sandia National Laboratory and the Air Force Research Laboratory's Space Vehicle Directorate. VTXO will undoubtedly lead to synergistic activities with these research centers.

VTXO involves close collaborations among students, faculty, and NASA researchers. It will lead to a cultivation of expertise in advanced GN&C design as well as instrumentation development for the detection of X-rays. VTXO will position New Mexico in a leadership role for the future generation of space-based telescopes.

1.b Goals and Objectives

The overarching goal of the VTXO program is to develop a space-based, X-ray imaging telescope with sub-arcsec angular resolution. VTXO addresses the technology development goals of STMD and enables scientific measurements that support goals in SMD.

VTXO features a diffractive optics design using a Fresnel lens deployed on one 6U CubeSat and the imaging device on a second 6U CubeSat. VTXO will develop the GN&C systems required to keep the two spacecraft in inertial (*astrometric*) alignment while collecting data. The *virtual telescope* concept has been studied by several groups. VTXO will advance the technology by advancing these studies to the hardware development stage and will take advantage of *build it – fly it* mindset of the CubeSat community as well as the large pool of Commercial Off The Shelf (COTS) parts available for CubeSats. VTXO will advance the Technology Readiness Levels (TRL) of several key technologies that impact future *virtual telescope* missions. The production of two flight-ready spacecraft is beyond the financial limits of the EPSCoR program. However, the goals listed below demonstrate how the VTXO program will make substantial progress toward the completion of flight hardware. Both the New Mexico collaborators and the GSFC collaborators will seek additional funding sources and collaborative arrangements to complete the spacecraft.

The specific goals of the VTXO program are described in this section. Each goal contains a sublist of objectives that will be met to guarantee the success of the project.

Goal (1) Guidance Navigation and Control: *Develop the GN&C, maneuvering technologies and algorithms needed to operate two 6U CubeSats in precise astrometric alignment..*

- Combine the GSFC's *Covariance Analysis Software Package* with navigation software from NMSU and UNM, to estimate relative motion between the 6U CubeSats.
- Quantify the performance requirements for the hardware related to the GN&C system and identify suitable candidate COTS parts.
- Implement the GN&C architecture in a simulation program that includes perturbations due to gravity, drag and solar pressure.
- Expand the simulation to include harware-in-the-loop (when possible) and verify the performance using an air bearing test stand.
- Migrate the the GN&C code to the on-board processor.

Goal (2) Instrument Development: *Develop and characterize the X-ray optical system (lens and camera) needed to image X-ray sources.*

- Utilize the GSFC Phase Fresnel lens analysis program to design a lens for solar X-ray observations suitable for use in the 6U form factor.
- Explore the capability of 3D printing techniques to determine viability for Phase Fresnel Lens manufacturing.
- Build the proto-flight imaging system based on the Teledyne Imaging Sensor, a hybrid CMOS sensor. (ASIC readout and control electronics)
- Design the thermal control system for the imager.

- Perform an end-to-end test of the system at the GSFC X-ray facility.
- Develop a simulation of the system's expected on-orbit performance.

Goal (3) Bus Design: *Design and construct the spacecraft bus and evaluate mission profiles.*

- Develop mass, power, communications and Δv budgets for the mission.
- Design and fabricate the 6U structures and solar arrays.
- Identify through trade studies the appropriate Command and Data Handing, power and communication subsystems. Include the requirements of the GN&C subsystem
- Develop an STK model to simulate various mission profiles using the constraint set introduced by the definition of the subsystems.

Goal (4) Promote Educational Excellence: *Train students in the technical areas of mechanical, electrical and aerospace engineering along with astronomy and physics.*

- Recruit three graduate students to work for VTXO and use their research as topics for Master's Theses or PhD Dissertations.
- Involve up to five undergraduate students in all aspects of the project.
- Encourage all students to pursue NASA internships, especially those that provide opportunities for the students to work with the collaborators at GSFC.
- Provide advising, mentoring and career guidance to students involved with VTXO. Encourage them to pursue advanced degrees and employment opportunities within NASA and the commercial space industry.

Goal (5) Foster Collaboration: *Develop robust research partnerships within New Mexico and beyond.*

- Seek out researchers in New Mexico's universities and national laboratories (Sandia, LANL and AFRL) whose interests overlap with those of VTXO.
- Build on existing collaborations with GSFC to include researchers at other NASA centers to strengthen the relevance of the VTXO project to NASA's technology and scientific priorities.

1.c Project Content

1.c.i Project Overview

Historically, discoveries in astronomy and astrophysics have been enabled by advances in instrumentation. These advances often take the form of improved resolution or access to different parts of the electromagnetic spectrum, both of which provide information about the underlying physical processes. The VTXO use of a diffractive optics system operating in the X-ray regime has the promise of enabling scientific discoveries in the area of the physics of solar flares.

The current state-of-the-art, in terms of angular resolution, for solar observations is on the order of 1 arcsecond (arcsec). This resolution was achieved with the X-ray Telescope (XRT) on the Hinode (Solar-B) spacecraft (Golub et al., 2007; Weber et al.. 2007). However, XRT's typical resolution is 18 arcsec over the energy range from 0.2-10 keV. The optical system used a grazing-incidence mirror configuration that required each X-ray to undergo two reflections. The angular resolution of reflective system is dominated by the surface quality of the mirror (surface figure). The *Ramaty High Energy Solar Spectroscopic Imager* (RHESSI) achieved an angular resolution on the order of 2 arcsec for X-rays with energies on the order of a few keV (Lin et al., 2002). RHESSI uses nine rotating modulation collimators coupled to germanium detectors to time-modulate the incident X-ray flux. The image is then reconstructed on the ground. It is unlikely that either of these X-ray imaging techniques can be modified to achieve substantially better angular resolution. In fact, it has been pointed out by Davila (2011) that conventional optics cannot achieve X-ray angular resolutions below 0.1 arcsec due to manufacturing limits on the surface figure.

In contrast to reflective or refractive optics where the shape of the lens is used to bend the radiation, diffractive optics work by breaking up incoming waves into a large number of waves, which recombine to form completely new waves. Diffractive optics focusing relies on the phase or amplitude modulation of the radiation. The radiation is transmitted through the optical element at a normal incidence. This results in a very thin lens that has more relaxed manufacturing tolerances and is less sensitive to the optical alignment of the system. Often the resolution of such systems approaches the fundamental maximum resolution limit describe mathematically in Equation 1, where λ is the wavelength and d is the diameter of the lens and θ is the diffraction-limited angular resolution.

$$\theta = \frac{1.22\lambda}{d} \tag{1}$$

An intriguing attribute of diffraction-limited optical systems is that for a given angular resolution, the diameter of the lens decreases with decreasing λ. For photons in the X-ray regime, the diameter of the lens can be small compared to reflective systems with the same resolution. Table 2 shows the lens diameter needed to achieve a diffraction limited angular resolution of 0.01 arcsec. For the X-ray wavelengths, the requirement on lens diameter is very compatible with the dimensions of a 6U CubeSat. It is remarkable that such a small system can improve the angular resolution by over an order of magnitude over current systems. This highlights the potential impact that the development of VTXO can have on improving the imaging capabilities for X-rays and driving the scientific discoveries enabled by this technological advancement.

For VTXO we will use a Phase Fresnel Lens (PFL) design which offers substantially higher efficiency (near 100%) compared with the earliest diffractive optical devices, Fresnel Zone Plates (Soret, 1875), that focus by blocking unwanted phases (11%). In fact,

Band	Energy	Wavelength (λ)	Diameter (d)
Optical	0.7 eV	1.6μm	40 m
Optical	2.5 eV	500 nm	13 m
X-ray	6 keV	0.2 nm	0.5 cm
Hard X-ray	100 keV	12 pm	0.03 cm

Table 2: Lens diameter required to achieve an angular resolution of 0.01 arcsec.

PFLs offer a higher efficiency compared to many reflective designs. This translates to an inherent higher relative sensitivity for PFL systems, which is critical for the detection of weak signals often encountered in X-ray measurements (Skinner, 2001, 2002). PFLs have two drawbacks. The first is that they are inherently chromatic. This means that they will be able to image a fairly narrow range of X-ray energies. Therefore PFLs are better suited to measure narrow line radiation. For solar studies this is not a serious concern since measurements of line radiation contain useful information on the physical environment. One could even conceive, for future missions, of having a set of lenses that could be rotated through to match different energies in much the same way filter wheels are used in other parts of the spectrum. The second drawback is that the focal length of the PFL system scales with the photon energy. For the X-ray regime, this translates to a ∼100 m focal length, which can only be achieved with the *virtual telescope* technique.

Because of the chromatic behavior of PFL systems, the desired energy range for the X-ray observation must be selected before the lens is designed. As noted by Dennis (2012) an energy of 6.7 keV, corresponding to the Fe XXV line emission, is an excellent candidate. This is the strongest and most prominent line in the iron group. It provides information on the hottest plasma generated in a solar flare and its broadening is an indication of the turbulence generated from interactions with non-thermal electrons. The resolution of VTXO will allow the structure of the magnetic loops on the Sun to be resolved for the first time.

1.c.ii Phase Fresnel Lens Telescope Development

The PFL telescope is comprise of two elements, the PFL lens and the imager or camera. VTXO will address the fabrication of both of these item. The lens design will be based off the preliminarily work done by Krizmanic (NASA Partner).

A Phase Fresnel Lens is composed of a circular diffraction grating with the pitch of the N concentric annuli becoming smaller in a prescribed manner as the radius of the lens increases. The radial profile of each annulus, or Fresnel zone, is exactly matched to the optical path needed to coherently concentrate incident radiation into the primary focus (Miyamoto, 1961). Coherent imaging leads to focused flux gains $\sim N^2$ where N is the number of Fresnel zones in the lens. The thickness of material is varied in each Fresnel zone from zero to a maximum thickness of $t2\pi$, the length required to obtain a 2π phase shift for the material at a specific photon energy. From the point we can determine an

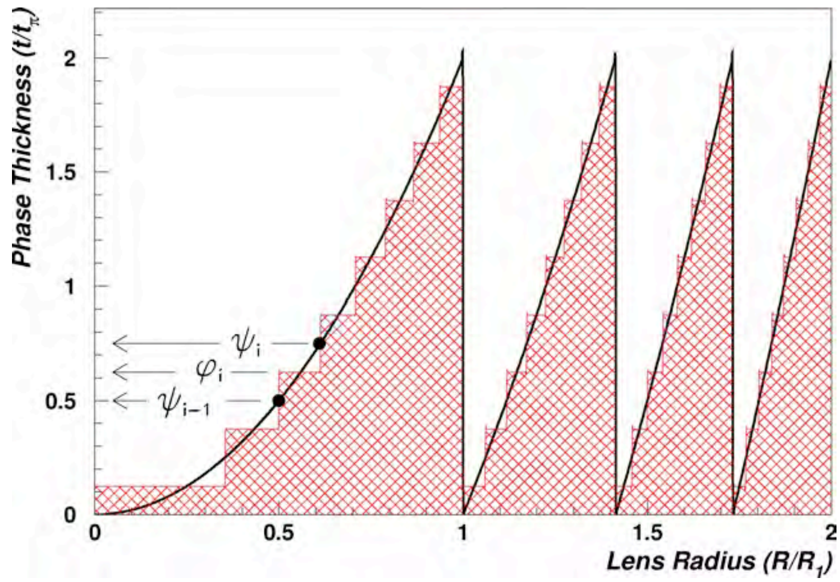

Figure 2: shows the stepped profile of the first 4 Fresnel zones. The solid curve is the ideal function.

expression for the thickness of the profile for Fresnel zone and a function of the radius. The index of refraction of a material can be expressed as a complex term:

$$n^* = 1 - \delta - \beta i \tag{2}$$

Where the imaginary term represents the absorption my the medium. As the photons travels through the material they are attenuated and their phase is retarded. The attenuation term is dependent on the thickness, t, and is represented as a multiplicative exponential:

$$e^{-t(4\pi\beta)} \tag{3}$$

The amount the phase is retarded by the same thickness is given by:

$$\phi = 2\pi t\delta/\lambda \tag{4}$$

This allows the thickness for a 2π phase change to be expressed at $t_{2\pi} = \frac{\lambda}{\delta}$. The " lens maker" equation for PFL is:

$$t(r) = t_{2\pi}\ modulo\left[\frac{r^2}{2f\lambda}, 1\right] \tag{5}$$

Figure 2 illustrates the stepped profile of the first 4 Fresnel zones generated by this equation.

Krizmanic (NASA Partner) has used this equation in the fabrication of small (3 mm) lenses on silicon using a gray-scale lithographic technique (Krizmanic et al., 2009) . These lenses where then tested at the GSFC facility. Figure 3 shows a photograph of the PFL along with the image from the very first test run. Building from this technique. VTXO will design and fabricate a larger, 10 cm lens for use on the CubeSat mission. VTXO will have to explore alternative techniques the achieve a lens of this size. State-of-the-art 3D printing facilities now can produce feature sizes small enough to meet

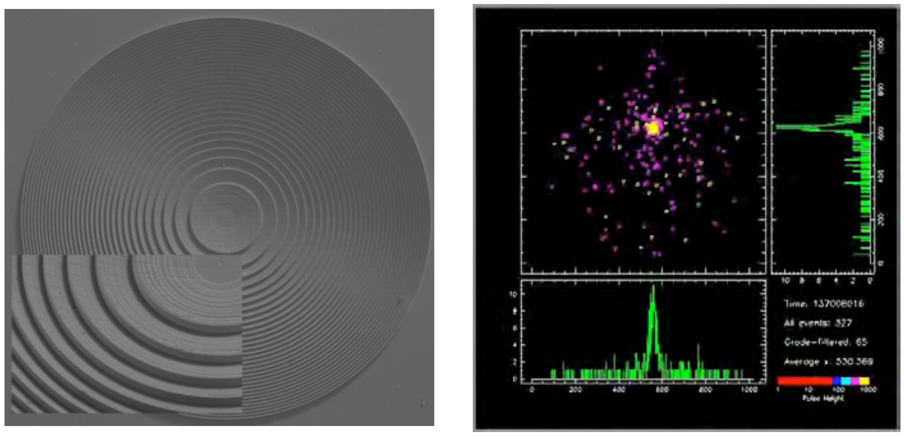

Figure 3: *left:* Photograph of the 3 mm PFL tested at 8 keV. The inset shows a zoom of the inner part of the Fresnel profile.*right:* The âĂŸfirst lightâĂŹ results showing 8 keV x-rays imaged by a PFL at the GSFC facility

the need for PFL lens. The 3D fabrication technique will be verified using the process established at GSFC.

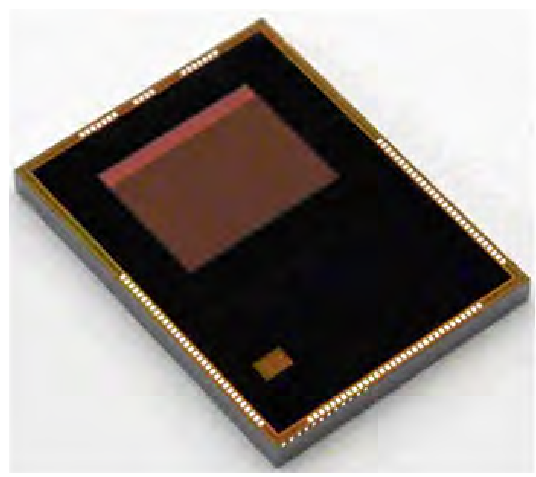

Figure 4: Photograph of the Teledyne H1RG-18 Hybrid detector that will be used in the design of the VTXO imager.

VTXO will also address the design and fabrication of the X-ray imager. The imager will be based on the Teledyne H1RG-18 Hybrid CMOS detector (HCD). HCDs are used because the randomly addressable pixel readout allow only the pixels of interest (one that have registered X-rays) to be readout. In contrast CCDs require all the pixels to be readout, resulting in longer readout times. Other advantages HCDs have over CCDs are: lower power, lower readout noise, they are inherently radiation hard and more robust against micrometeoroida. HCDs, unlike CCDs, can be operated without a mechanical shutter. A silicon photon converter of thickness $\sim 100\ \mu$m will be places in front of this array to provide high efficiency for the detection of X-ray in the 6 KkeV range. This system will have to be temperature regulated using a thermo-electric-cooler. The system will be readout with a ASIC chip designed at NMSU. NMSU will also address the packaging of the system for operation on the 6U CubeSat. Figure 4 show a figure of the H1RG-18 detector.

1.c.iii Guidance, Navigation and Control

Attitude Determination and Control Subsystem: The Attitude Determination and Control System (ADCS) is a vital sub-system among spacecraft systems, as it enables critical attitude maneuvers such as pointing, re-orientation, and stabilization. The ADCS system consists of the attitude determination and estimation component, and the attitude control system Corporation. and Wertz [1978]. A novel mechatronics approach is proposed by Amit Sanyal (NMSU) for spacecraft ADCS that fuses information from optical and inertial sensors of a commercial-off-the-shelf (COTS) smartphone, which is also used as an onboard computer Viswanathan et al. [2015a]. This approach uses the smartphone's inbuilt accelerometer, magnetometer and gyroscope as an Inertial Measurement Unit (IMU) for attitude determination, and Variable Speed Control Moment Gyroscopes (VSCMG) for attitude control. The primary motivation for using an open source smartphone is to create a cost-effective, generic platform for spacecraft attitude determination and control, while not sacrificing on performance and fidelity. The PhoneSat missions of NASA's Ames Research Center demonstrated the application of COTS smartphones as the satellite's onboard computer with its sensors being used for attitude determination and its camera for Earth observation Marshall et al. [2011]. More recent satellites in the Phonesat series, Phonesat 2.4 and 2.5, successfully utilized smartphones for attitude control using reaction wheels Bell [2013]. University of Surrey's Surrey Space Centre (SSC) and Surrey Satellite Technology (SSTL) developed STRaND-1, a 3U CubeSat containing a smartphone payload Bridges et al. [2011], Kenyon et al. [2011].

Evolution of smartphones have been remarkable in the past few years with sophisticated processors, higher order system architecture, and high quality sensors integrated into a compact unit. These smartphones can be used as onboard CPU for operations of complex mechatronic systems like spacecraft with internal actuators. Some advantages of using smartphones onboard are: (1) compact form factor with powerful CPU, GPU etc.; (2) integrated sensors and data communication options; (3) long lasting batteries that reduce total mass budget; and (4) cost-effective and open source software development kit. The ADCS mechatronics architecture comprises of a COTS smartphone running stock Android OS with self-contained ADCS routine, an ADK microcontroller board, ESC units along with the motor driven VSCMG arrays. This architecture is shown in Figure 5. The standalone mechatronics architecture performs the task of state sensing through embedded MEMS sensors, filtering, state estimation and implementation of feedback control law, to achieve the desired control objectives while maintaining active uplink/downlink with a remote ground control station.

Attitude Control using VSCMG Array: The cubesat spacecraft's attitude will be controlled by VSCMG actuators. The novel VSCMG design (patent pending) given in Sanyal et al. [2013], Prabhakaran et al., Viswanathan et al. [2015b] will be adopted in this research. This design relaxes simplifying assumptions used in most of the existing literature on (VS)CMGs Hughes [1986], Wie [2008], McMahon and Schaub [2009], Tokar and Platonov [1979]. These assumptions impose constraints on the design and manufac-

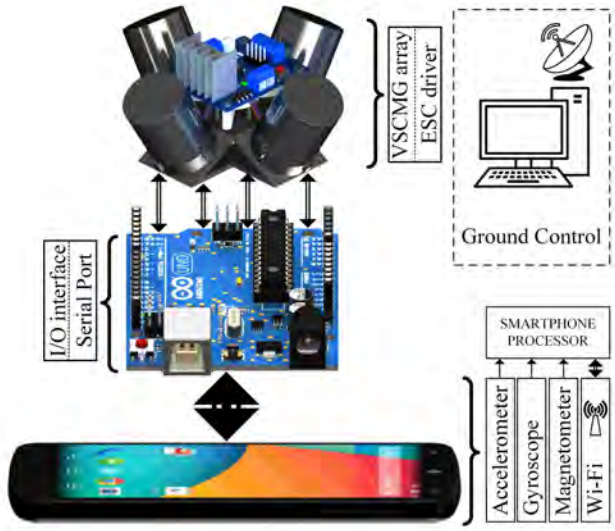

Figure 5: Hardware architecture of smartphone based ADCS

turing of VSCMGs, like perfect alignment of flywheel with gimbal axis and the flywheel having perfect axial symmetry. As our VSCMG model does not make these assumptions, it increases the system's adaptability (tolerance of misalignments and manufacturing defects) and scalability and decreases development costs. The attitude kinematics and dynamics of the spacecraft is given by $\dot{R} = R\Omega^{\times}, \dot{\Pi}_b = \Pi_b \times \Omega + (u \times \Omega - \dot{u}) = \Pi_b \times \Omega + \tau_{cp}$, where R is the attitude (rotation matrix from spacecraft bus frame to inertial frame), Ω is the angular velocity vector, Π_b is the angular momentum of the spacecraft bus and $\tau_{cp} = u \times \Omega - \dot{u}$ is the control torque generated by the "internal" momentum u from the VSCMGs. The total angular momentum of the spacecraft is

$$\Pi = \Pi_b + u, \text{ where } \Pi_b = \Lambda(t)\Omega \text{ and } u = \mathcal{B}\dot{\Gamma}, \tag{6}$$

where $\mathcal{B}$ is a control influence matrix that depends on the locations and orientations of the VSCMGs in the cubesat bus, and $\Lambda(t)$ is the overall time-varying inertia matrix of the spacecraft expressed in the cubesat bus frame. The hardware architecture of the VSCMG array ensures that $\mathcal{B}$ is non-singular, while the control software ensures that τ_{cp} provides three-axis control for all attitude maneuvers.

Attitude Estimation using Smartphone Sensors: In Izadi and Sanyal [2014], an estimator for rigid body attitude and angular velocity without any knowledge of the attitude dynamics model, is presented using the Lagrange-d'Alembert principle of variational mechanics. This variational estimator requires at least two inertially known vectors as well as the angular velocity measured in the spacecraft-fixed coordinate frame. A first order discretized estimation scheme for computer implementation is also presented using discrete variational mechanics. A second order time-symmetric discretization was also obtained in Viswanathan et al. [2015a]. Vector measurements obtained from optical and inertial sensors include the geomagnetic field from the magnetometer, gravity direction from the accelerometer, and star pattern measurements from the camera. In addition, rate gyros give the angular velocity vector. The variational estimator of Izadi and Sanyal [2014] is obtained by applying the Lagrange-d'Alembert principle to the Lagrangian $\mathrm{L}(\hat{R}, U^m, \hat{\Omega}, \Omega^m) = \frac{m}{2}(\Omega^m - \hat{\Omega})(\Omega^m - \hat{\Omega}) - \Phi\Big(\frac{1}{2}E - \hat{R}U^m, (E - \hat{R}U^m)W\Big)$. in the presence of the Rayleigh dissipation term $\tau_D = D(\Omega^m - \hat{\Omega})$. Here $(\hat{R}, \hat{\Omega})$ are estimates of (R, Ω), U^m are the direction vectors and Ω^m are the angular velocity measurements from the ADCS sensors, $m > 0$ and D is a positive definite gain matrix. The resulting variational estimator fuses the sensor measurements and gives a robustly stable estimator that is robust to uncertainties in the measurement noise and attitude dynamics. This estimator was compared with some state-of-the-art attitude estimation schemes that have known instabilities, including the commonly used multiplicative extended Kalman filter (MEKF), in Izadi et al. [2015].

Spacecraft Formation Flying Navigation and Control:
Navigation during Close Proximity Spacecraft Formation: One of the challenges of autonomous formation flying is that the available information for each agent (spacecraft) consists of periodic communications due to the fact that the agents in these networks may not communicate their intents or objectives continuously. To perform conformance monitoring (i.e., to verify whether the agent is adhering to the objectives) and intent inference, each agent needs to estimate the state of the other agents. Kalman filtering is one of the methods that is widely used in flight mode estimation. However, Kalman filtering techniques are restricted in the sense that they have to wait for the next discrete time interval to update their mode estimation. Hence, these techniques need rapid updating. The hybrid hidden Markov model (HHMM) algorithm proposed by Asal Naseri (UNM) is based on hidden Markov models and is able to detect changes that occur in an asynchronous fashion, that is, between update intervals. This leads to a decrease in the required refresh rate and in turn a decrease in the required power. Thus, given the HHMM λ and a sequence of observations T_{obs}, we can determine the probability that the observations are generated by the model. Furthermore, given the model λ and a sequence of observations T_{obs}, we can determine the most likely state sequence in the model that produces the observations using a continuous adaptation of the Viterbi Algorithm. This HHMM algorithm will be coupled with a dynamics model-free relative state estimation scheme obtained recently by Sanyal (NMSU), to estimate the relative pose (position and attitude) between the cubesats and their relative velocities based on optical measurements, and lidar measurements if available. This model-free estimation scheme generalizes the attitude estimation scheme outlined earlier, to relative pose estimation using only optical measurements during close proximity formations. This model-free (relative) state estimator could also be used to update the models in the HHMM algorithm based on optical measurements. When measurements are sparse and during limited communications, the model-based Kalman filter algorithm due to Neerav Shah (GSFC) will be used to propagate relative states and error covariances between measurements Calhoun and Shah [2012].

Relative State Control for Spacecraft Formation: Relative state control for formation keeping and other formation maneuvers will be based upon the coupled relative pose control scheme by Amit Sanyal (NMSU), outlined in Lee et al. [2015]. This approach, which is not standard in the astronautics community, is necessary and useful for close proximity formations because of two reasons mainly: (1) the translational and rotational dynamics are coupled due to natural effects (gravity, solar radiation, atmospheric drag, etc.), as well as body-fixed thrusters; and (2) communications (optical, lidar, radar) is coupled to the relative pose states between the spacecraft in formation. The standard model-based control approaches in spacecraft formation flying assume that the spacecraft is a point mass for relative translational states, while the spacecraft are modeled as rigid bodies for their (relative) attitude states. These approaches therefore suffer from the limitation that there is no feedback between the (relative) attitude states and the relative translational states in the control scheme. Therefore, if an attitude actuator was to malfunction, the control scheme for the relative translational states (position and relative velocities) would not naturally take this into account when firing body-fixed actuators. This necessitates ground communications to "close the loop" and ensure safe operations when such malfunctions occur. On the other hand, the relative state control scheme for spacecraft formation flying detailed in Lee et al. [2015] considers the coupling between the attitude and translational motion states in the control design process itself. As a result, the control scheme is “more autonomous", robust and stable, compared to the standard approaches currently used.

1.c.iv Bus Design

A great amount of detailed work and planning are required to turn a concept for a mission into flight-ready hardware. VTXO collaborators from UNM and NMSU will address both of these issues under the general heading of Bus Design. Figure 6 show some of the facilities that are available within the collaboration for the construction of the 6U CubeSat, along with an example of a CubeSat that was built at COSMIAC. For each of the VTXO 6U CubeSats (imager-satellite and optics-satellite), detailed mass, power, communications and maneuvering (Δv) budgets will be established. Each time a new component is selected by the telescope design group or GN&C group it will be evaluated based on its impact to these budgets. The power budget is of particular importance since both satellites have operational attitude requirements that will not always be compatible with optimal power generation via the solar panels.

Both of the 6U satellites will use an aluminum exoskeleton for the principle support structure. Both of the structures will be designed and fabricated in New Mexico. The arrangement of the solar panels, which are attached to the exoskeleton, and the supporting Electrical Power Systems (EPS) will be included as part of the bus design.

Each of the satellites will share subsystems that are common to most CubeSat missions, such as the Command and Data Handling system and the communication system. These systems will be addressed with COTS parts, which are available through the CubeSat economy.

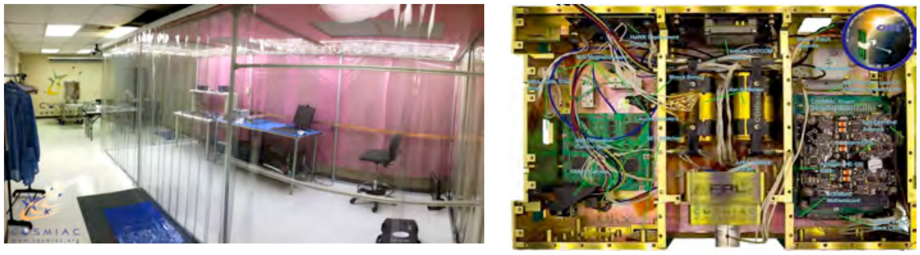

Figure 6: *left:* The cleanroom facility at COSMIAC. This is one of two cleanrooms that will be used for the VTXO project. *right:* Photograph of the ORS Squared satellite built at COMSIAC. This is a 6U CubeSat built as part of a project between NASA, UNM and AFRL

Both satellites, and in particular the imager-satellite, have thermal requirements that must be addressed through modeling of the thermal characteristics of the satellites and their space environments based on their orbits. A model build in STK will address this topic and provide input that can be fed back into the mission operations and planning as well as the communications link budget.

1.d Partnerships and Interactions

The **collaboration goal** of this effort is to foster long-lasting relationships between NMSU and UNM, and NASA GSFC. It leverages jurisdiction resources such UNM's COSMIAC facility, NMSU's SmallSat Laboratory and through our Educational Partnership Agreement, the AFRL Space Vehicles Test Facility. We can demonstrate past interactions among the proposing team members, and expected ones that VTXO will make possible and formalize.

Past interactions: NMSU and UNM-COSMIAC have collaborated together on several proposals to build CubeSat class satellites. We have exchanged students via summer programs and have worked together on educational programs such as the FPGA Laboratory at NMSU. NMSU has a long standing relationship with GSFC that includes work in both the areas of Cosmic Ray Physics and Solar Physics. Current collaborative efforts include the analysis of solar events (flares and SEPs) using the PAMELA and Fermi satellites. UNM-COSMIAC has a long standing collaboration with several NASA Centers including GSFC and Glenn Research Center. These collaborations focus on the development and testing of electronics for space missions.

Planned interactions: One of the great strengths of VTXO is that it will enable deeper collaboration between the UNM Mechanical Engineering (ME) and the NMSU Aerospace Engineering (AE) programs. Both of these programs have experts (Co-I Sanyal and Co-I Naseri respectively) in the field of satellite GN&C and it will strengthen the capability of the jurisdiction to have these two departments working together. VTXO also will build two new external relationships. The first joins the GN&C expertise in New Mexico with the Attitude Control Systems Engineering Branch at GSFC (NASA Partner Shah). The second pairs the low-power ASIC design capa-

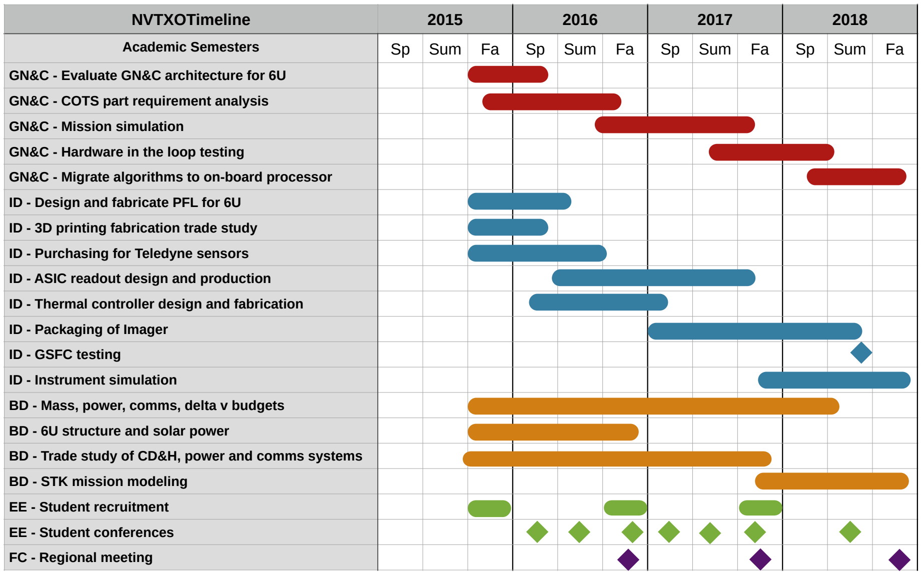

Figure 7: Schedule showing the activities associated with each of the VTXO goals. The schedule is build around the academic year and takes into account the cadence of the time demands placed on students and faculty. In the figure, the following abbreviations are used: GNC. Guidance Navigation and Control, ID - Instrument Development, EE - Educational Excellence, FC - Foster Collaborations

bilities at NMSU (Co-I Tan) with the Astrophysics Science Division (NASA Partner Krizmanic) working on novel semiconductor detectors, related technologies, and VLSI electronics for space-based applications.

Future possibilities: Sandia National Laboratory, Los Alamos National Laboratory and the AFRL Space Vehicles Directorate all have a strong interest in the formation flying of satellites. These represent opportunities for future collaborations in this area. These three research facilities also have very active summer research programs for both graduate and undergraduate students that can be utilized to provide additional education and career development opportunities for VTXO's students.

1.e Timeline

Figure 7 shows the schedule of actives for VTXO over the three year time period of the grant. A start date of 1 September 2015 has been assumed. The schedule is build around academic semesters to take to account the time periods (summers and between semesters) when students and faculty have more time to devote to research activities.

1.f Sustainability

As described in Section 1.d, the planned and future partnerships will create many sustainable opportunities. VTXO has a huge potential to advance research competitiveness in New Mexico, not only in the three-year EPSCoR award period, but well into the future. The GN&C systems needed to carry out the precision formation flying of satellites represent a major advance in a technology that will enable many future missions and projects. The experience gained through VTXO will place the jurisdiction's researchers in an excellent position to take on major roles in the development of future NASA *virtual telescope* missions both on the GN&C-engineering side and the instrument development side. It is very easy to envision the VTXO program maturing into a SMEX or MIDEX class NASA mission.

Many specific possibilities exist for supplemental funding to continue and expand the scope of VTXO. As described in Section 1.d, SNL, LANL and AFRl all have a keen interest in developing formation flying capabilities. NMSU and UNM have an excellent track record with funded research collaborations with these institutions. Extending these collaborative efforts to include aspects from the VTXO program is very likely. On a smaller scale, the National Science Foundation (NSF) budget for CubeSat programs is increasing as is the role of CubeSats in science missions. Partnerships that couple expertise developed through VTXO with new science objectives are very likely. Finally, students will be encouraged to pursue scholarship and internship possibilities through NMSGC, SNL, LANL, AFRL and NASA.

1.g Dissemination

Project results and progress will be disseminated in standard ways with refereed publications in appropriate journals (check with AMIT) and at national and international conferences (AMIT). Regular team meetings and Skype calls will keep all members aware of the status of VTXO. Partners at GSFC will be invited to participate in the meetings and calls. The close collaboration with GSFC will ensure that NASA is aware of the project status and results. In particular, collaborator Shah at GSFC will assist with identifying appropriate dissemination channels at NASA. A project website will also be set up to collect information on team members, results, publications, and serve as the VTXO data access entry point for the community.

1.h Evaluation

The key milestones described in Section 1.e will serve the metrics to assess the progress of the VTXO program. Targets such as conference presentations, publications, and selected follow-on funding proposals are external and objective means of evaluating the project's success and will be recorded in all reports. Other evaluation outcomes for the project and their metrics are:

1. *Contribute to and promote the development of research infrastructure in New Mexico in areas important to NASA's priorities.* Metrics: Number of participating partners, university faculty, and students; evidence of how EPSCoR activities have furthered jurisdiction priorities; financial commitment from jurisdiction and participating institutions (student fellowships, faculty hires, awards, etc.); extent to which collaborations with NASA partners have evolved and strengthened.

2. *Work in close collaboration with the New Mexico Space Grant Consortium (NMSGC)*

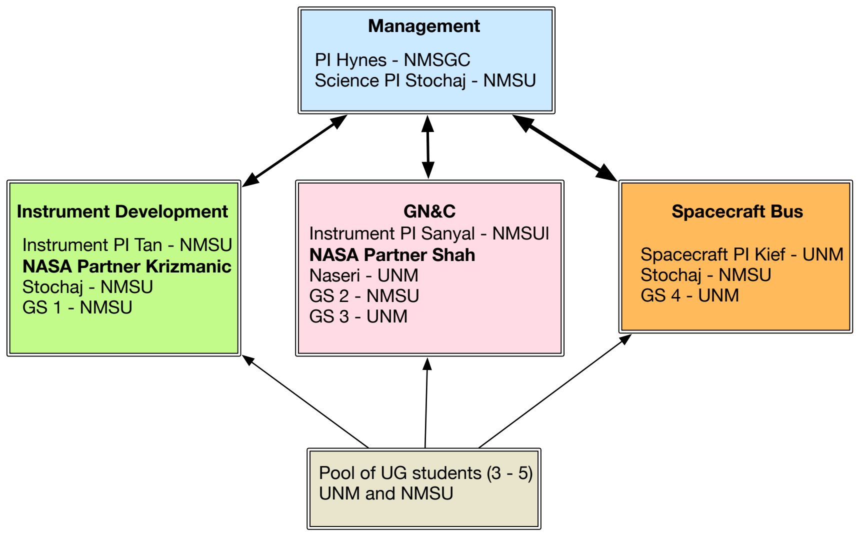

Figure 8: Management and collaboration structure for the VTXO EPSCoR project. The figure links collaborators with each aspect of the project. NASA Partners are indicated in bold type. GS refers to Graduate Student and UG refers to UnderGraduate students.

to promote rigorous STEM training, workforce development, and diversity. Metrics: Number of graduate qualifying and MS exams passed; number of student-participant graduates; number of student talks and presentations given at NMSGC and non-NMSGC events; number of publications with student authors, number and gender/ethnicity of students participating in program research.

Continuous refinement and improvement of our work plan will also be a key consideration in demonstrating the effectiveness of this program. As students will be employed with NASA EPSCoR funds, we will institute mechanisms for assessing their performance, including recording publication contributions and long-term tracking of future employment in STEM-related fields in industry or academia. Student data such as the number of participants who are underrepresented minorities and/or female will also be collected and distributed to the NMSGC and compiled in its reports. PI Hynes will provide evaluation reports and assessment of these metrics, along with feedback and strategies to increase program efficiency and success regarding science and education goals.

1.i Management

The management structure of the VTXO collaboration team is illustrated in Figure 8. Team meeting and regular Skype calls will ensure that all member are on task and informed.

• **Administrative PI: Dr. Patricia Hynes**, Director of the New Mexico NASA EPSCoR Program and of the New Mexico Space Grant Consortium. Hynes will oversee the project management, and collect all project evaluation data and provide feedback to the Co-Is on its progress toward its benchmarks, particularly regarding student participation, sustainability, and partnerships.

• **Project PI: Dr. Steve Stochaj**, Professor of Electrical and Computer Engineer at

NMSU. Stochaj has a background in instrumentation and small satellites. Stochaj will oversee all aspects of the instrument development and construction of the satellite bus. He will manage the recruiting, hiring, and mentoring of the NMSU graduate student and the undergraduate students. He will organize meetings and Skype calls.

• **Spacecraft Bus PI: Dr. Craig Kief**, Deputy Director ofConfigurable Space Microsystems Innovations and Applications Center (COSMIAC) at UNM Expertise: satellite design, power systems, communications systems, reconfigurable computing, radiation tolerant electronics. Kief will manage the development of the spacecraft bus and oversee operations at COSMIAC.

• **Instrument Development PI: Dr. Wei Tan**, Assistant Professor of Electrical and Computer Engineering at NMSU. Expertise: low power ASCI design. Tan will manage the the design and packaging of the camera system. He will oversee a graduate student and an undergraduate student.

• **GN&C PI: Dr. Amit Sanyal**, Associate Professor of Mechanical and Aerospace Engineering at NMSU. Expertise: Attitude control and determination. Sanyal will lead the development of the GN&C system and will manage the graduate student and undergraduate students from NMSU, work on the GN&C system.

• **GN&C PI: Dr. James McAteer**, Assistant Professor of Astronomy at NMSU. Expertise: Solar Physics. McAteer will develop the goals and procedures for the solar observations. He also will guide in the design of the PFL to optimize the science yield.

• **GN&C Co-I: Dr. Asal Naseri**, Associate Professor of Mechanical Engineering at UNM. Expertise: Guidance, navigation and control systems. Nisei will work on the the development of the GN&C system and will manage the graduate student and undergraduate students from UNM, work on the GN&C system.

• **NASA Partner: Dr. John Krizmanic**, Associate Research /Staff Scientist Universities Space Research Association NASA/GSFC Expertise: PFL design, novel semiconductor detectors, related technologies, and VLSI electronics for space-based applications. Krizmanic will coordinate the development of the telescope system.

• **NASA Partner: Neerav Shah** , Aerospace Engineer Organization: Code 591, Attitude Control Systems Engineering Branch, Applied Engineering and Technology Directorate Expertise: Guidance, navigation and control systems. Shah will coordinate the development of the GN&C system.

1.j Prior NASA EPSCoR Research Support

Results of Prior NASA EPSCoR Research Results of Prior NASA EPSCoR Research NASA EPSCoR award number: NNX09AP76A; Amount: $694,181.00; Title: New Mexico Solar and Stellar Seismology; Period of support: 8/1/09-5/31/14 The objective of this program was to build the infrastructure needed for New Mexico to become nationally competitive for grants in the fields of solar and stellar seismology. Our goals are closely connected to NASA Strategic Goal 3B "Understand the Sun and its effect on

Earth and the solar system" and the NASA program "Living with a Star". Below is a discussion of completed work and student achievements in each of the project's three targeted areas. A major goal of our proposal was: "To develop research infrastructure in solar and stellar seismology among New Mexico's universities (NMSU, UNM), national laboratories (LANL, NSO, AFRL) and the New Mexico Space Grant Program." To meet this objective NMSU pledged to hire two faculty in project related areas. In this regard NMSU has exceeded its commitment since it has hired three new faculty members. The AFRL Center for Excellence in Space Weather now recognizes NMSU, the New Mexico Institute of Technology, and the University of New Mexico (UNM) as important sites to meet their future workforce needs. It has signed a memorandum of understanding for joint educational and research efforts with each of these universities. The University of New Mexico is our EPSCoR partner. AFRL has already sent staff members to participate in their teaching programs. At the request of the New Mexico Space Grant Consortium our group sent representatives to the dedication ceremony of Spaceport America in Upham, NM. Dr. McNamara has completed an on-line text on human spaceflight that includes a new section on NASAâĂŹs efforts to stimulate the development of a U.S. commercial space flight industry.

NASA EPSCoR award number: NNX11AQ35A; Amount: $748,716.00 ; Title: Proximity Operations for Near Earth Asteroid Exploration; Period of support: 9/1/11-8/31/14 Research has been continued on developing methods and analyses to support close proximity operations about asteroids. At least two of these were transitioned to funded proposals from the NASA NSTRF program. Probably the most important finding of this research project is that the "point mass model" for a spacecraft that is much smaller and much less massive than the NEA it is exploring, is completely wrong in predicting the trajectory of the spacecraft. For (relative) attitude estimation, was recently accepted in the journal Automatica, which is the flagship journal of the International Federation for Automatic Control (IFAC) and is the highest impact journal on controls worldwide. Future work will consider utilizing the attitude-orbit coupling to control the orbital trajectories of spacecraft exploring NEA using propellant-less attitude control only. This aims to enhance the research infrastructure at an MSI within the New Mexico EPSCoR jurisdiction; establish our collaboration as leaders in instrument development and field demonstration; produce flight-qualifiable instrumentation necessary for astrobiological investigations. This will enable our participation in planetary science flight programs and strengthen the NASA-related technical and human resources capabilities within the State of New Mexico. This developed a state-of-the-art orbital mechanics 3D visualization laboratory which is funded by his recent grant from AFOSR. This laboratory will be used for the current project as well as serving as an outreach tool for visiting K-12 students at New Mexico State University.

NASA EPSCoR award number: NNX09AP69A; Amount: $732,016.00; Title: New Mexico Exoplanet Spectroscopic Survey Instrument (NESSI); Period of support: 8/1/09-7/31/14 The goal of this project is to build a unique near-infrared spectrometer expressly suited for observations of exoplanet atmospheres; develop a stable hardware platform and data extraction and reduction pipeline for analyzing the data; deploy NESSI at the MRO 2.4m telescope to obtain dedicated observing time and start an exoplanet survey; employ students and postdocs in all parts of the design, assembly and testing of the system, and offer time for student observing in the 3rd year of the proposal to learn how to obtain and reduce exoplanet data; form a cross-disciplinary team of scientists within/outside NM to prepare for the interpretation phase of NESSI data and to participate in workshops in NM. The NESSI team successfully designed, built and deployed the NESSI instrument at the MRO 2.4m telescope. While initial commissioning activities were delayed for more than one year for reasons associated with a delay in hardware funding and then a subsequent MRO 2.4m telescope failure, we were finally able to commission NESSI initially from March 29-April 5, 2014. Deployment of NESSI at the MRO 2.4m telescope took place in March-April and June, 2014. Proposals have been submitted internally within JPL and to NASA to support survey work with NESSI once commissioning is completed. We have employed more than half a dozen undergraduate students, two graduate students, three postdocs and several professional staff directly at the Magdalena Ridge Observatory Interferometer in the design, integration and assembly of NESSI and its associated software. We were unfortunately unable to engage students at other institutions in the State in the potential use of NESSI for other types of science (not strictly exoplanet science, but also spectra of other objects or imaging) as commissioning was not completed during the project period. Funds for this part of the project are left unspent. Improvements in jurisdiction research and development infrastructure as a result of the NESSI project include: a more complete and well-developed instrument laboratory at NM Tech that is part of the MRO and is housed in Workman Center; a team of undergraduate and graduate students who worked with professional observatory staff, engineers and external technical vendors to specify and develop components for NESSI; a more mature operations model for the MRO 2.4m telescope including the ability to change out instrumentation to accommodate NESSI runs; development of a multi-object spectrometer and wide-field imager which will have applications for many fields in astrophysics. Increased financial commitment from the jurisdiction, industry and participating institutions as part of the NESSI project include: engineering expertise and assistance by several of the MRO Interferometer staff ; industry participation to develop NESSI components in collaboration with the NESSI PI and team; assistance to assemble and deploy NESSI from several groups including vendors and investigators at JPL and Caltech; interest from several institutions to use NESSI at the MRO 2.4m including faculty at NM Tech, researchers at JPL, NRAO, Yale and University of Massachusetts âĂŞ Lowell. There have not been any reordered institutional priorities within New Mexico Tech as a result of the development of NESSI as commissioning has not been completed and therefore regular observing with NESSI has yet to come to fruition.

NASA EPSCoR award number: NNX08AV85A; Amount: $250,000.00; Title: Exploring Surface Texture and Reflectivity of Cave and Related Surface Environments as Harbingers for Life; Period of support: 6/21/12-6/20/14 The primary goal of the project is to develop and enhance research capabilities at Navajo Technical College (NTC), a designated Minority-Serving Institution (MSI) in the New Mexico EPSCoR jurisdiction. To achieve this goal, we developed a program to explore cave and nearby surface environments using two novel and complementary techniques that will elucidate the relationship between rock surface roughness, reflectivity, and the presence of biomarkers indicative of extant or extinct life. This investigation addresses two of the fundamental questions that guide NASA's solar system exploration program: What are the characteristics of the solar system that lead to habitable environments? And how and where could life begin and evolve in the solar system? The project and goal are directly aligned with NASA's FY2011 Strategic Goals: To enable MSI faculty and NM EPSCoR jurisdiction researchers to conduct NASA's space science research; to share NASA with the public, educators, and students of New Mexico to provide opportunities for New Mexicans to participate in NASA's Mission. This program is making significant contributions to NASA's Science Mission Directorate (SMD), specifically in the Solar System Exploration Division. This project has high relevance to the New Mexico EPSCoR jurisdiction as our field site for Year 2 was located within the State of New Mexico. The NMSU-NMT-NTC team met in May 2013 to plan the summer 2013 field expedition. The first field measurements for this project were made in July 2013. Additional faculty from NTC were added to the faculty team to enhance research capabilities in multiple departments at NTC and to reach a broader range of students.

NASA EPSCoR award number: NNX14ZHA001C; Amount: $729,273.00; Title: Jovian Interiors from Velocimetry Experiment in New Mexico (JIVE in NM); Period of support: 7/17/14-7/16/17

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3 Biographical Sketches

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Relevant Experience:
Dr. Stochaj has over 30 years of experience in the development and flight of particle detectors on both space-based and balloon platforms. He serves as the US spokesperson for the PAMELA cosmic rays experiment and severed at the PI for the WiZard Balloon program, a large international collaboration (six balloon campaigns). Stochaj has worked on a number or projects with NASA-GSFC and is currently working with the Heliophysics Branch on the measurement of Solar Energetic Particle events. He has overseen the completion of seven Ph.D.s and 25 M.S. degrees.

Dr. Stochaj is the PI for the NMSU University NanoSat program and oversees the research activities of 28 undergraduate and four graduate students. This program serves as the pilot program for NMCCT and has attracted a large number of female and minority students. During the first 20 months, three students have been motivated to make the transition to graduate school. The program also employs two students from the College Assistance Migrant Program (CAMP) program.

Education:
Ph.D. Physics, University of Maryland, 1990
B.A. Physics & Mathematics, Franklin and Marshall College, 1983

Professional Experience:
2013–present Distinguished Achievement Professor, New Mexico State University
2005–2012 Professor, New Mexico State University
2001–2005 Associate Professor, New Mexico State University
1995–2001 Assistant Professor, New Mexico State University

Research publications involving student research projects:

1. *Analysis on H spectral shape during the early 2012 SEPs with the PAMELA experiment*, M. Martucci, M. Boezio, U. Bravar, R. Carbone, E.R. Christian, G.A. De Nolfo, M. Merge', E. Mocchiutti, R. Munini, M. Ricci, J.M. Ryan, A. Sotgiu, S. Stochaj, N. Thakur, O. Adriani, G.C. Barbarino, G.A. Bazilevskaya, R. Bellotti, E.A. Bogomolov, M. Bongi, V. Bonvicini, S. Bottai, A. Bruno, F. Cafagna, D. Campana, P. Carlson, M. Casolino, G. Castellini, C. De Donato, M.P. De Pascale, C. De Santis, N. De Simone, V. Di Felice, V. Formato, A.M. Galper, A.V. Karelin, S.V. Koldashov, S. Koldobskiy, Y. Krutkov, A.N. Kvashnin, A. Leonov, V. A. Vacchi, E. Vannuccini, G. Vasilyev, S.A. Voronov, Y.T. Yurkin, G. Zampa, N. Zampa, V.G. Zverev, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, **742** (2014) 158.

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Relevant Experience:
Craig Kief is the Deputy Director of the Configurable Space Microsystems Innovations & Applications Center (COSMIAC) at the University of New Mexico. These duties include responsibility of contractor and graduate student work and research as well as budget preparations, management and reporting. Mr. Kief has taught many short courses in the areas of requirements analysis and Verification, Validation and Accreditation for Air Force and commercial customers. These courses have improved students' skills for accurately identifying requirements for large scale projects and for developing verification and validation techniques for measuring product quality in deliverables. He is the Program Manager for the ORS Squared CubeSat Satellite scheduled to be delivered to ORS in 2014. This joint AFRL/NASA/ORS 6U spacecraft is designed to perform a wide range of space experiments including magnetometer and dosimeter projects for Space Weather Analysis. He is responsible for all aspects of this satellite design, including all environmental testing.

Education:
The University of New Mexico, Computer Engineering
Community College of the Air Force, Electrical Engineering Technology, AA 1996

Professional Experience:
Deputy Director, COSMIAC (Research Faculty at the University of New Mexico)
Senior Systems Engineer, Aegis Technologies
Program Manager, Air Force Operational Test and Evaluation Center, United States Air Force

Selected Publications:
Kief C, Zufelt B, Matar B. Developing TodayâĂŹs New Technologist Using Reconfigurable Solutions. ASEE Gulf Southwest Annual Conference; Tomas Rivera Conference Center. 2012, 4 April âĂŞ 6 April

Androlewicz J, Buffington R, Kief C, Erwin R, Crane J, Avery K, Lyke J. Software- Defined and Cognitive Radio Technology for Military Space Applications. 2011 Wireless Innovation Forum Conference on Communications Technologies and Software Defined Radio (SDR'11 - WInnComm), Washington, DC. 2011; 29 November - 02 December

Kief C, Lange C. GENSO Presentation. 2011 Summer CubeSat DevelopersâĂŹ Workshop, Logan, UT. 2011; 06 - 07 August

Burns R, Chacon Z, DeRaad W, Ierides A, McCullough M, Ortega M. Lightning Spectrometer for Ionospheric Disturbances. 2011 IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting. 2011;July

Ierides A, Suddarth S, Kief CJ, Burns R, Ortega M. Satellite-Based Monitoring System for Ionospheric Disturbances. 13th International Ionospheric Effects Symposium, Alexandria, VA. 2011;June

R. T. James McAteer
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Relevant Experience:
Dr. McAteer works in solar physics and space weather research. He has over 14 years experience in studies of solar flares, coronal mass ejections and their affects throughout the heliopshere. He focuses on effectively combining ground- and space-based data to enhance our knowledge of the structure and changes in the Sun's atmosphere. He has supervised 6 PhDs, is currently PI of both NASA ROSES and an NSF (Career) grant , and teaches a graduate course on solar physics and space weather at NMSU. He has acted as a reviewer on NSF CubeSat panels, and is a founding member of the Solar Image Processing Workshop series, designed to encourage interdisciplinary research.

Education:
Ph.D., Astronomy, Queen's University Belfast, 2004
MSci., Physics with Astrophysics, Queen's University Belfast, 2000

Professional Experience:
2010–present: Assistant Professor, Astronomy Department, New Mexico State University
2008–2010: Marie Curie Fellow, Physics Department, Trinity College Dublin
2004–2008: NRC Research Associate and STEREO scientist, NASA GSFC
2004: Leverhulme Trust fellow, Queen's University Belfast
1997–1998: National Research Council Resident Research Assoc., NASA/GSFC

Selected Recent Refereed Publications (* denotes student-led publication):

Reep, J., Bradshaw,S.J., McAteer, R.T.J. (2013). On the sensitivity of the GOES flare classification to properties of the electron beam in the thick target model. *ApJ*, **778**, 76.

McAteer, RT.J., Bloomfield, D. S. (2013). The Bursty Nature of Solar Flare X-Ray Emission. II. The Neupert Effect. *ApJ* **776**, 66, doi:10.1016/j.icarus.2014.01.029.

McAteer, R.T.J., et al. (2005), Observations of HÎś Intensity Oscillations in a Flare Ribbon. *ApJ* **610**, 1101.

Andic,A., McAteer, R.T.J. (2013) Remote Oscillatory Responses to a Solar Flare , **772**, 64.

Milligan, R.O., McAteer R.T.J., Dennis, B., Young, C.A. (2011). Evidence of a Plasmoid-Looptop Interaction and Magnetic Inflows During a Solar Flare/Coronal Mass Ejection Eruptive Events *ApJ* **713**, 1392.

Amit K. Sanyal
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Relevant Experience:
Dr. Sanyal has several years of research experience on dynamics modeling, navigation and control of spacecraft, robots and unmanned vehicles. His research publications include robust control, state estimation and formation control for spacecraft and unmanned vehicles, proximity maneuvers involving robotic spacecraft, multibody dynamics models for spacecraft and underwater vehicles with internal actuators, multibody dynamics and control of humanoid robots. He is a member of the IEEE technical committees on Aerospace Control and Nonlinear Control, and past member of the AIAA Guidance, Navigation and Control technical committee. He is a Co-I on a NASA EPSCoR project on proximity operations for near-Earth asteroid exploration. His research group has 5 PhD students and one MS student.

Education:
Ph.D., Aerospace Engineering, University of Michigan, 2004
M.A., Mathematics, University of Michigan, 2005
M.S., Aerospace Engineering, Texas A& M University, 2001
B.Tech., Aerospace Engineering, Indian Institute of Technology, 1999

Professional Experience:
2010–present: Assistant Professor, Mechanical and Aerospace Engineering, NMSU
2007–2010: Assistant Professor, Mechanical Engineering, University of Hawaii
2005–2006: Post-doctoral Research Associate, Mechanical and Aerospace Engineering, Arizona State University

Selected Recent Refereed Publications (* denotes student-led publication):

A. K. Sanyal and J. Bohn, "Finite Time Stabilization of Simple Mechanical Systems using Continuous Feedback," to appear in International Journal of Control, doi: 10.1080/00207179.2014.974675.

D. Lee, A. Sanyal and E. Butcher, "Asymptotic Tracking Control for Spacecraft Formation Flying with Decentralized Collision Avoidance," to appear in AIAA Journal of Guidance, Control and Dynamics, 2014, doi: 10.2514/1.G000101.

D. Lee, A. Sanyal, E. Butcher and D. Scheeres, "Almost Global Asymptotic Tracking Control for Spacecraft Body-Fixed Hovering near an Asteroid," Aerospace Science and Technology, vol. 38, pp. 105-115, 2014.

M. Izadi* and A. K. Sanyal, "Rigid Body Attitude Estimation Based on the Lagrange-d'Alembert Principle," Automatica, vol. 50 (10), pp. 2570-2577, 2014.

D. Lee, E. Butcher and A. Sanyal, "Optimal mixed impulsive and continuous thrust trajectories to the interior Earth-Moon L1 Lagrange point," Advances in the Astronautical Sciences, vol. 148, pp. 3963-3982, 2013.

Wei Tang
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Relevant Experience:
Dr. Wei Tang has over 7 years of experience in integrated circuit design, implementation, and testing. He has successfully demonstrated several low power sensing and radio systems using novel asynchronous design methods. He is a member of IEEE. Currently he is the Principal Investigator of a NSF project of asynchronous sensing and wireless communication.

Education:
Ph.D., Electrical Engineering, Yale University, 2012
M.S., Electrical Engineering, Yale University, 2009
B.S., Microelectronics, Peking University, 2006

Professional Experience:
2012–present: Assistant Professor, Klipsch School of Electrical and Computer Engineering, New Mexico State University
2007–2012: Research Assistant, Yale University
Selected Recent Refereed Publications (* denotes student-led publication):

Al-Azzawi*, H.; Hong Huang; Misra, S.; Wei Tang (2014). On using compressed sensing for efficient transmission & storage of electric organ discharge. *Circuits and Systems (ISCAS), 2014 IEEE International Symposium on*, pp.1616-1619,
doi: 10.1109/ISCAS.2014.6865460.

Harris, M.*; Salazar, E.; Guth, R.; Nawathe, V.; Sharifi, M.; Wei Tang; Misra, S. (2013). Wireless sensing framework for long-term measurements of electric organ discharge. *Biomedical Circuits and Systems Conference (BioCAS), 2013 IEEE*, pp.53-56,
doi: 10.1109/BioCAS.2013.6679638.

Tang, W.; Osman, A.; Kim, D.; Goldstein, B.; Huang, C.; Martini, B.; Pieribone, V.A.; Culurciello, E. (2013). Continuous Time Level Crossing Sampling ADC for Bio-Potential Recording Systems. *Circuits and Systems I: Regular Papers, IEEE Transactions on* vol.60, no.6, pp.1407-1418.
doi: 10.1109/TCSI.2012.2220464.

Dongsoo Kim; Goldstein, B.; Wei Tang; Sigworth, F.J.; Culurciello, E. (2013). Noise Analysis and Performance Comparison of Low Current Measurement Systems for Biomedical Applications. *Biomedical Circuits and Systems, IEEE Transactions on*, vol.7, no.1, pp.52-62.
doi: 10.1109/TBCAS.2012.2192273.

Shoushun Chen; Wei Tang; Zhang, Xiangyu; Culurciello, E. (2012). A 64 x 64 Pixels UWB Wireless Temporal-Difference Digital Image Sensor. *Very Large Scale Integration (VLSI) Systems, IEEE Transactions on.* vol.20, no.12, pp.2232-2240.
doi: 10.1109/TVLSI.2011.2172470.

5 Letters of Commitment

From: **John Krizmanic** john.f.krizmanic@nasa.gov
Subject: Letter of Support and some pre-proposal comments
Date: January 22, 2015 at 7:40 AM
To: Steven Stochaj sstochaj@nmsu.edu, Shah, Neerav (GSFC-5910) neerav.shah-1@nasa.gov

JK

Steve:

I am writing this letter to express my enthusiastic endorsement of the pre-proposal "Virtual Telescope for X-ray Observations" to be submitted to the NASA EPSCoR CAN NNH15ZHA003C solicitation. I support this project and if the pre-proposal is selected by the committee I will provide a full letter of support.

From their inception, CubeSats offer a unique educational opportunity for students in the fields of space science and instrumentation as well as aerospace engineering. Additionally, CubeSats have been recognized as a low-cost path for developing technologies and scientific mission concepts. An example of this is the X-ray Virtual Telescope System (VTS) that uses two spatially separated CubeSats to form a long focal length X-ray telescope, with optics on one CubeSat and an X-ray imaging detector on the other, as detailed in your pre-proposal.
The potential of formation flying to enable new astrophysics missions has long been recognized by the scientific community, and a measure is given by the number of proposed, formation-flying astronomy missions detailed in the scientific literature, e.g. XEUS, SIMBOL-X, DUAL, MASSIM, MAXIM, and FRESNEL. These missions are all based using long focal length optics to form a virtual telescope yielding orders of magnitude improvements in sensitivity and angular resolution, thus providing a pathway to revolutionary studies of astrophysical phenomena. ASD scientists at GSFC have developed lightweight, X-ray Phase Fresnel Lenses (PFLs) and have demonstrated near diffraction-limited imaging in the laboratory. This PFL research has proved to be an exceptional test-bed studying the physical phenomenon of diffraction and offers a unique student educational opportunity. The development of high-performance X-ray optics coupled to the realization of precision formation flying technology represents significant advances in achieving NASA's long-term goals. This is reflected in NASA's 30 year Astrophysics Roadmap, which explicitly states that lightweight X-ray optics and formation flying are critical future technologies.

In the recent past, ASD scientists have teamed with GSFC heliophysicists and engineers in the Guidance, Navigation, and Control (GN&C) group to develop CubeSats to form a VTS, eventually using PFLs. The results of past ASD-sponsored GSFC/IMC mission studies have demonstrated that even with large (> 1000 km) satellite separation, robust scientific missions are feasible, but need breakthrough technology development in GN&C and in astrometric alignment, e.g. how to point the VTS at an astrophysical target of interest with the required spacecraft control and positional knowledge. Your proposed VTS development offers the opportunity to make breakthrough advances in these critical areas of formation flying and validating them via astrophysical scientific measurements.

In closing, I would like to re-iterate my strong support for your EPSCoR pre-proposal. This development will be a crucial step to bring formation flying and the next generation of X-ray optics to a higher state of maturity, which will enable future, revolutionary astrophysics missions. The fact that the development of these cutting-edge technologies will be performed with a very high level of student involvement will provide a unique program to train the next generation of scientists and engineers.

Dr. John Krizmanic
Senior Scientist
CRESST Astroparticle Physics Group Leader
CRESST/USRA/NASA/GSFC

From: **Shah, Neerav (GSFC-5910)** neerav.shah-1@nasa.gov
Subject: Re: Draft of VT preprposal
Date: January 21, 2015 at 6:18 PM
To: Steven Stochaj sstochaj@nmsu.edu, Krizmanic, John F. (GSFC-660.0)[USRA] john.f.krizmanic@nasa.g
Cc: GSFC-DL-591-Managers gsfc-dl-591-managers@mail.nasa.gov, Woodfork, Dennis W. (GSFC-5900) dennis.w.woodfork@nasa.gov

Dr.Stochaj,

I would like to offer my strong support of the pre-proposal, ³Virtual Telescope for X-ray Observations,² you plan to submit to the NASA EPSCoR FY2015 Cooperative Agreement Notice NNH15ZHA003C. If your institution selects this proposal for submittal to NASA HQ, I will submit a complete endorsement letter from the Mission Engineering and Systems Analysis (MESA) Division at NASA¹s Goddard Space Flight Center.

The potential of formation flying to enable new astrophysics and heliophysics missions has long been recognized by the scientific community, and a measure is given by the number of proposed, formation-flying missions detailed in the scientific literature, e.g. EUV Imaging of the Sun, Solar Coronagraph, Proba-3, TPF, NWO, XEUS, SIMBOL-X, DUAL, MASSIM, MAXIM, and FRESNEL. These missions all require a long focal length to form a virtual telescope yielding orders of magnitude improvements in sensitivity and angular resolution, providing a pathway to revolutionary studies of space science.

The MESA division has collaborated with scientists in heliophysics and astrophysics to develop the requisite Guidance, Navigation, and Control (GN&C) requirements and technologies on the CubeSat-scale to demonstrate a dual-spacecraft virtual telescope. These studies have shown that a CubeSat-scale virtual telescope can achieve arc-minute-level alignment over a long separation distance. The fundamental GN&C technology is the astrometric alignment sensor, which optically detects a cooperative target with
respect to inertial space. Demonstrating this sensor on the CubeSat-scale allows us to better understand how it works and thus be better prepared to scale the sensor up to a full-size science mission, such as the ones listed Above.

Student involvement will provide a unique program to train the next generation of scientists and engineers. These students will be the leaders of tomorrow¹s technologies and training them now is a wonderful opportunity. This development is a crucial step to bring formation flying and the next generation of optics to a higher state of maturity enabling a revolution in space missions. In closing, I would like to re-iterate my strong support for the ³Virtual Telescope for X-ray Observations² pre-proposal.

Best Regards,
Neerav

--
Neerav Shah

8 Facilities and Equipment

8.a New Mexico State University

The facilities for the SmallSat Laboratory at New Mexico State University encompass 100 m^2 of laboratory and office space, including an assembly building. Facilities include test instrumentation, workstation, a small machine shop, and a 4 m^2 cleanroom. The Lab also hosts several student offices. The adjacent building houses the NMSU Satellite Ground Station. The ground station is capable of tracking and downloading satellite data in the 144MHz and 400MHz bands.

The project has access to the Manufacturing Technology and Engineering Center and the Innovation Space to support the design and fabrication needs. The Physical Science Laboratory at NMSU is well equipped with electronic, mechanical and thermal design and simulation tools, a CAD-integrated machine shop, electronics and detector assembly areas, thermal and vacuum chambers, clean rooms and clean benches, and well equipped detector laboratories. The facilities are available to the NMCCT projects.

8.b University of New Mexico

The Configurable Space Microsystems Innovation Applications Center (COSMIAC) is a University-affiliated research center that specializes in the areas of aerospace technology, defense research, and educational outreach. It contains 9 full-time researchers and 10-15 students as of CY14. COSMIAC is a space Research Center under the School of Engineering at the University of New Mexico (UNM). COSMIAC has a unique blend of researchers, scientists, engineers, staff and students that work on space technologies such as design and implementation of digital systems for satellites, radiation hardening testing and mitigation, dynamically reconfigurable systems and cognitive radios. Recently, we have added 3D printing (aka Additive Manufacturing) technologies for space, including entirely 3D-printed CubeSats. COSMIAC staff and students have DoD security clearances.

The COSMIAC laboratories contain advanced equipment devoted to this effort (laboratory benches, high speed oscilloscopes and digital analyzers, spare satellite parts, an advanced soldering station and five workstations with digital and electrical simulation tools as well as mechanical design tools with two 3D printer stations). The Spacecraft Development and Integration Laboratory has a 1.5 m $\times$ 2.5 m cleanroom for spacecraft integration and test. The space Physics Laboratory has a Helmholtz cage for testing attitude control systems. The roof top ground station is capable of tracking and downloading satellite data in the 144MHz and 400MHz bands.