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The Ultraviolet Follow-on Observatory (UFO)

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ABSTRACT

Prime Solutions Group, Inc. (PSG) in partnerships with Southwest Research Institute (SwRI), the University of Colorado at Boulder, the University of Illinois, and the Astronomy Association of Arizona (AAA) are proposing the development, launch and operation of a 12U CubeSat mission for stellar astronomy.

The stellar observatory mission will consist of a space-based UV/optical telescope system designated as the Ultraviolet Follow-on Observatory (UFO). This proposed CubeSat will be a 12U system housing a 250mm telescope and designed for a four-year plus mission timeline in high Earth orbit. A camera capturing simultaneous UV/optical observations will first be developed and tested on a ground-based telescope before being designed and integrated into the CubeSat. UFO will follow in the footsteps of the successful launch and operation of the Colorado Ultraviolet Transit Experiment (CUTE) and the planned launch of the Star-Planet Activity Research CubeSat (SPARCS) which are paving the way for this new era in CubeSat space-based astronomy. The operation of UFO (240nm to 390nm (UVC, UVB, UVA)) will expand on these missions. This will demonstrate that small telescope observations in the ultraviolet frequency can provide valuable data to the astronomical science community and will help fill a critical need in the observational ultraviolet astronomy gap until NASA's Large UV/Optical/IR Surveyor (LUVOIR) mission launches in the early 2040s timeframe.

1. Introduction

Astronomical photometry covers the range of the electrometric spectrum from ultraviolet (UV) at 200 nanometers (nm) through the visible portion into the near infrared (NIR) at 1500 nm. The UV portion of astronomy research reveals a wealth of information about hot and energetic processes in astronomical objects contributing valuable information to the scientific community. Due to atmospheric absorption, UV astronomy can only be successfully conducted outside the atmosphere in the space environment thus it is not the focus of many current or past astronomical investigations. Only a few current large space missions, such as the Hubble Space Telescope (HST) and the Neil Gehrels Swift Observatory cover the UV spectral range, some of them only in the near-UV (NUV). This UV research field is currently sparsely addressed but of scientific interest for the larger scientific community. With the growth rate of the use of small satellites such as SmallSats and CubeSats, the opportunity to provide means of research for UV astronomy are now becoming possible. With HST and Swift currently approaching end-of-life, we are beginning to enter a period without any good UV satellites in orbit, Yatsu et al. (2019). This proposed UV/Optical CubeSat project can provide good UV photometry in a very "general purpose" orbiting observatory. While this CubeSat is a prototype, a major goal is to keep it inexpensive and as such, it can easily be replicated to create a serial constellation of UV observing satellites that will help fill a critical need in the observational UV astronomy gap until NASA's Large UV/Optical/IR Surveyor (LUVOIR) mission launches in the early 2040s timeframe.

2. Background

As a review, CubeSats are a class of research spacecraft called nanosatellites. CubeSats are built to standard dimensions (Units or "U") of 10 cm x 10 cm x 10 cm. CubeSats can be configured in 1U, 2U, 3U, or 6U sizes where weigh is typically less than 1.33 kg (3 lbs.) per U, Loff, (2018). Typical CubeSat sizes are shown in Figure 1. The boundary between CubeSats and the next size SmallSat is normally 27U. In 1999, California Polytechnic State University (Cal Poly) Professor Jordi Puig-Suari and Bob Twiggs, a professor at the Stanford University Space Systems Development Laboratory developed the CubeSat specifications to promote and develop the skills necessary for the design, manufacture, and testing of small satellites intended for Low Earth Orbit (LEO). Academia accounted for the majority of CubeSat launches until around the 2013 timeframe, when more than half of launches were for non-academic purposes, and by 2014 most newly deployed CubeSats were for commercial or amateur projects, CubeSat Database (2022).

The CubeSat Design Specification Rev.14.1 has been developed to help guide CubeSat construction, CubeSat Design Specification (2020). The CubeSat specification accomplishes several high-level goals, Call for CubeSat Proposals (2008). The main reason for miniaturizing satellites is to reduce the cost of deployment using the excess capacity of larger launch vehicles or a "ride share" option. The CubeSat design specifically minimizes risk to the rest of the launch vehicle and payloads making rideshare possible. Encapsulation of the launcher–payload interface takes away the amount of work that would previously be required for mating a satellite with its launcher. Unification among payloads and launchers enables quick exchanges of payloads and utilization of launch opportunities on short notice.

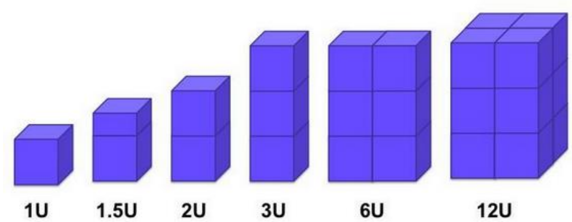

Figure 1. Buildup of CubeSat sizes utilizing 1U components (1U = 10cm x 10cm x 10cm)

2.1 Colorado Ultraviolet Transit Experiment

The Colorado Ultraviolet Transit Experiment (CUTE) is a 4-year, NASA-funded project to design, build, integrate, test, and operate a 6-unit CubeSat (30 cm x 20 cm x 10 cm). A cut-away is shown in Figure 2. CUTE is planned to have a 1-year nominal mission lifetime and was successfully launched in late September 2021, Launch of Cute (2022). It has completed commissioning processes and is now in scientific data operations. Using near-ultraviolet (NUV) transmission spectroscopy from 255 nm to 330 nm, CUTE is focusing on characterizing the composition and mass-loss rates of exoplanet atmospheres by measuring how the NUV light from the host star is changed as the exoplanet transits in front of the star and passes through the planet's atmosphere. Transit light curves created from CUTE observations will provide constraints on the composition and escape rates of these atmospheres and may provide the first concrete evidence for magnetic fields on extrasolar planets.

CUTE is designed to follow exoplanet systems of interest for several orbital periods to provide low resolution spectroscopy of critical atmospheric tracers (Fe II, Mg II, Mg I, OH) that are inaccessible from the ground.

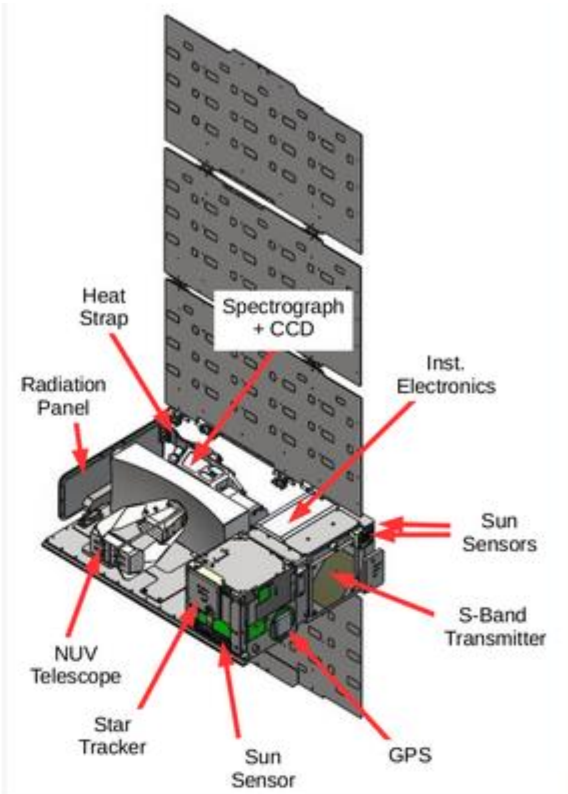

Figure 2. Cut-away CAD rendering of CUTE, with transparent top and sides to display the telescope and spectrograph. (Credit UC LASP)

CUTE was designed at the University of Colorado, Boulder and the Laboratory for Atmospheric and Space Physics (LASP) and built by Blue Canyon Technologies. Dr. Kevin France (co-author) is the Principal Investigator of the CUTE mission at LASP.

2.2 Star-Planet Activity Research CubeSat (SPARCS)

Arizona State University's Star-Planet Activity Research CubeSat (SPARCS) is a NASA-funded astrophysics mission, devoted to the study of the UV time-domain behavior in low-mass stars, ASU SPARCS (2022). It is a 6U spacecraft where the solar power panels extend like wings from one end. The deployed on-orbit configuration is shown in Figure 3.

Low-mass stars are important targets in the search for exoplanets residing in the habitable-zone. Over its scheduled 1-year mission, SPARCS will stare at approximately 10 stars in order to measure short term- (minutes) and long term- (months) variability simultaneously in the near-UV and far-UV. The SPARCS scientific payload consists of a 9-cm reflector telescope and two high-sensitivity 2D-doped CCDs. The payload will be placed on a Sun-synchronous terminator orbit, allowing for long observing stares for all targets. Launch is expected to occur in the 2023 timeframe.

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Figure 3. Illustration of SPARCS in orbit and operational parameters. (Credit ASU School of Earth and Space Exploration)

SPARCS will also be capable of "target-of-opportunity" ultraviolet observations for the rocky planets in M-dwarf habitable zones soon to be discovered by NASA's Transiting Exoplanet Survey Satellite (TESS) mission. This will provide the needed ultraviolet context for the first habitable planets that the James Webb Space Telescope will characterize.

2.3 Ultraviolet Follow-on Observatory

A search of literature shows in addition to the missions above, there are several Earth orbiting UV CubeSat telescopes in the discussion stage but no funded projects. To help bridge the observing gap between the end-of-life of the CUTE and SPARCS missions and the launch of LUVOIR, a follow-on CubeSat mission is being proposed, the Ultraviolet Follow-on Observatory or UFO. This proposed CubeSat will be a 12U system housing a 250mm telescope. A series of three CubeSats are being proposed where each is designed for a four-year plus mission timeline in high Earth orbit. The continuation of the CubeSats observing timeline will fill the approximate 15-year observing gap described above. A camera capturing simultaneous UV/optical observations will first be developed and tested on a ground-based telescope before being designed and integrated into the CubeSat. A dichroic beam splitter or mirror has been selected for separating out the UV from the optical wavelength. Separate duplicate cameras will then be used for image capture.

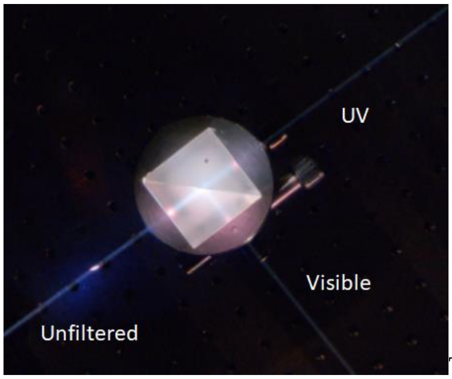

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Figure 4. Dichroic beam splitter for separating UV and optical wavelengths

The operation of UFO will expand on the previous missions and demonstrate that small telescope observations in the ultraviolet can provide valuable data to the astronomical science community and will help fill a critical need in the observational ultraviolet astronomy gap until LUVOIR becomes operational, NASA GSFC (2022).

3. Program Objectives

The primary science objective for this project is to provide simultaneous observational data in the UV wavelength range of 280nm to 390nm (UVB to UVA) for ground based and 240nm to 390nm (UVC, UVB, UVA) for space based. The optical wavelength range of both systems will be 400nm to 750nm. Because it is small aperture, it can handle "bright" objects and events that are beyond the bright limit of larger satellites.

The secondary objective is to provide synergy with ground-based amateur and university level observatories. Systems at this level can provide excellent time-series photometry and spectroscopy of bright targets that are out of range for larger observatories. Science mission objectives are broken out by the following areas.

Solar System

- Venus. Observations will fill continuous observations gap between NASA missions

- Pluto. Observations of atmosphere via stellar occultations.

- Asteroids

- Trans Neptunian Objects

Exoplanets

- Planetary eclipses

- Atmospheric detections

Stellar systems

- Globular clusters

- Open clusters

- Contact binaries

- Eclipsing binaries

Galactic

- TBD

The general astronomical community

- Provide access for advanced amateur, university faculty and professional astronomers to conduct follow-up observations of objects of interest.

- Allow astronomers to conduct original research.

- Provide opportunities for graduate students to perform original research.

3.1 A Benefits/Cost Ratio (BCR)

The Benefit-Cost Ratio (BCR) is an indicator used in industry that shows the relationship between the relative costs and benefits of a proposed project. An analysis was conducted to determine the benefit of the UFO project in relation to other systems.

3.1.1. Science BCR

The science results and benefits of any observational system are difficult to quantitively measure. An approach taken here is to determine the cost of a published paper in a peer reviewed journal as the ratio of cost of system operations over the number of papers. Table I shows the results of comparing the HST and the Las Cumbres Observatory (LCO) against the estimated cost for the UFO project.

Table 1: Benefit-Cost Ratio of UFO compared to other observatory systems.

System	Operations Cost ($M)	No. Peer Review Articles	Cost/Paper Ratio ($K)
Hubble Space Telescope	$16,000	18,000	$888.89
Las Cumbres Observatory	$44.37	431	$102.95
UFO	$11.14	323	$34.47

Table 1 is based on the assumptions that the UFO total project cost is approximately $11.14 M and that the number of published papers is 75% of what has been accomplished with the LCO system. This preliminary analysis shows a very good potential payback for science results for funds invested.

3.1.2. Education BCR

A similar analysis was carried out for estimating the cost for reaching students in both the high school, college, and university level. The AAA will be taking the lead in developing the educational and public outreach events.

Table 2: Benefit-Cost Ratio of Educational Aspects of UFO.

Event	Cost per Event	No. Students Reached	Cost/Student Ratio ($)
High School Seminar	$3,000	14,000	$4.50
University	$3,000	1,400	$15.00

For a relatively small amount of funds, high school and university level students can be reached with introduction of STEM related activities.

3.2 Engineering Objectives

Model-based Systems Engineering (MBSE) is a formalized methodology that is used to support the requirements, design, analysis, verification, and validation associated with the development of complex systems. In contrast to a more traditional document-centric engineering approach, MBSE puts models at the center of system design. The increased adoption of digital-modeling environments during the past few years has led to increased adoption of MBSE. In January 2020, NASA noted this trend by reporting that MBSE, "has been increasingly embraced by both industry and government as a means to keep track of system complexity." Shevchenko (2020).

A model support tool which supports this MBSE approach has been selected for the UFO project. The Innoslate modeling environment offers a full lifecycle software for model-based systems engineering, requirements management, verification and validation, plus DoDAF with a powerful ontology at its core, Innoslate MBSE Tool (2022).

3.3 Education Objectives

As first introduced in 3.1.2 above, education is a major emphasis for this project. Education objectives include the following:

- Provide education opportunities to AAA members and the general public regardless of ethnic origin, cultural beliefs, or socioeconomic status
- Provide opportunities for high school, community college and university students to become involved in a multi-year project which can lead to high school science projects, community college special project courses and university level Capstone projects.
- Provide observational data to university faculty and professional astronomers to conduct original research in their areas of expertise.
- Provide observational data and guidance to amateur astronomers and students to conduct original research and publish their findings.
- Provide synergy between UV satellite data with ground-based data that is achievable with college and semi-professional observatories.
- Provide synergy of satellite UV photometry observations with ground-based spectroscopy.

The AAA will take the lead in emphasizing the importance and interaction of education and public outreach.

4. CubeSat Design

The CubeSat Design Specification Rev.14.1 specifies the basic design and major components for CubeSats. A basic design of the UFO CubeSat consists of the 12U bus structure, deployable solar panels for power generation and containing the 250mm optical telescope. An example configuration is shown in Figure 5.

Figure 5. CubeSat with solar panels deployed. (Credit Knapp 2019)

A corresponding cutaway showing the internal components is shown in Figure 6.

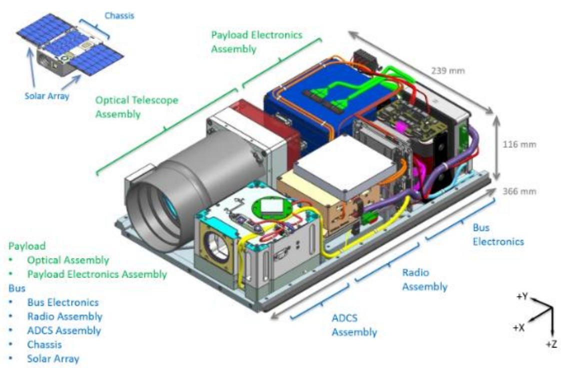

Figure 6. Cutaway diagram showing optical telescope and subcomponents. (Credit Knapp 2019)

As shown in the cutaway diagram, the typical CubeSat bus consists of about 1/3 bus electronics, Attitude Determination and Control System (ADCS) and payload assembly respectively. The 12U size of the UFO is driven by the 250mm telescope.

4.1 Satellite Bus

Defining a standard bus, developing standard hardware components using commercial off the shelf components and a standard spacecraft frame simplifies the development of picosatellites. The CubeSat development will provide a standard spacecraft frame, a spacecraft controller, radio transceiver, attitude determination and control, solar cells, batteries, and an interface for a payload.

As a subsidiary of Raytheon Technologies, Blue Canyon Technologies, is a complete end-to-end spacecraft company and a leading provider of turnkey small satellite solutions, including nanosatellites, microsatellites, and ESPA-class satellites. Initial discussions have taken place with Blue Canyon technologies for the development of the bus assembly. Other avenues for bus engineering and development are available to include the University of Colorado and SwRI Boulder facility.

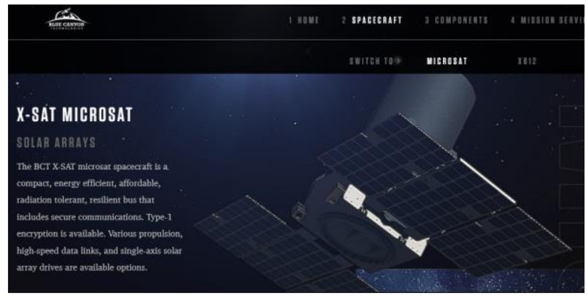

Figure 7. Blue Canyon Technologies is one possible CubeSat bus manufacturer.

4.2 Optical Telescope

The main scientific instrument on UFO is the telescope system. Aperture Optical Sciences (AOS) designs, develops and manufactures optics for satellite imaging and communications systems. AOS develops aspheric mirrors for high energy lasers and specialize in the use of Silicon Carbide materials for extreme performance applications.

The AOS CC series is the new generation of high-performance telescopes for CubeSats, supporting 3U, 6U and 12U applications. Extensive use of Silicon Carbide (SiC) provides a telescope that is inherently athermal and low mass, ensuring consistent imaging performance and lowering launch costs. Custom solutions with apertures to 250 mm are available.

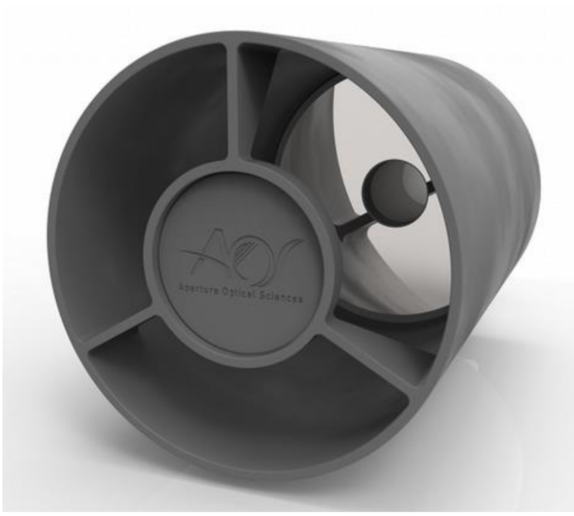

Figure 8. Aperture Optical Sciences 250mm CC Series telescope.

The CC Series telescope system is designed for simplicity and economy – but with its all-ceramic construction it can outperform more typical refractive designs by providing broadband, thermally insensitive performance. The standardized architecture with generalized specifications is intended to define baseline performance specifications. CC series telescopes require only minimal customization to meet customer defined mission requirements.

5. Ground Station Support

The Amazon Web Services (AWS) Ground Station is a fully managed service that lets you control satellite communications, process data, and scale your operations without having to worry about building or managing your own ground station infrastructure. Satellites are used for a wide variety of use cases, including weather forecasting, surface imaging, communications, and video broadcasts. Ground stations form the core of global satellite networks. The AWS Ground Station allows direct access to AWS services and associated infrastructure including a low-latency global fiber network.

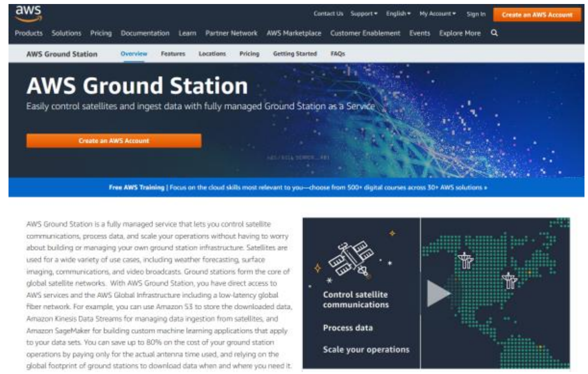

Figure 9. AWS ground station services will provide UFO command and telemetry.

Satellite command and telemetry will be provided by the AWS Ground Station network.

5.1 Target Querying and Prioritization

The spread of telescopes around the world has greatly increased the opportunities to observe all astronomical events. The light from celestial objects can be sampled with greater frequency and for longer durations when observations are passed from one telescope to the next. The Las Cumbres Observatory has been developed to provide access to astronomical telescopes located around the world to enable both amateur and professional astronomers to take advantage of transients which are astronomical phenomena whose duration can range from seconds to several years.

Figure 10. The Las Cumbres Observatory provides a system of fully automatic target querying, observing and image distribution.

The heart of LCO operations is its dynamic observation scheduling system. Working without human intervention, LCO's internet-based scheduler takes requests for observations from scientists and observers, deconflicts competing requests and conditions at each telescope site, directs individual telescopes to make the desired observations, and compiles the results. Scientists can make requests for observations at any time as the scheduler updates the entire network plan about every 5 minutes.

Figure 11. LCO's automated system allows internet sign-on, request of targets for observation, querying and deconflicting of targets, imaging and distribution of results.

The network operates around-the-clock where calibration observations are made during daytime. Observing schedules are stored at site, so telescopes can continue observing even when an external link is interrupted. Within minutes of the camera shutter closing at the telescope, the science data are calibrated and sent to the science archive for retrieval by the scientists.

The LCO system is being investigated as to whether UFO can integrate into the current LCO infrastructure and take advantage of synergism between the two systems. Discussions with the LCO team are being initiated.

6. Launch Support

The CubeSat Launch Initiative (also known and rideshares) provides opportunities for small satellite payloads built by universities, high schools and non-profit organizations to fly on upcoming launches, NASA CubeSat Launch Initiative (2022). Through innovative technology partnerships, NASA provides these CubeSat developers a low-cost pathway to conduct scientific investigations and technology demonstrations in space, thus enabling students, teachers, and faculty to obtain hands-on flight hardware development experience. CubeSat rideshares are constrained to CubeSats 12U and smaller. The plans for UFO are to take advantage of the rideshare thus the sizing of UFO being restricted to size 12U.

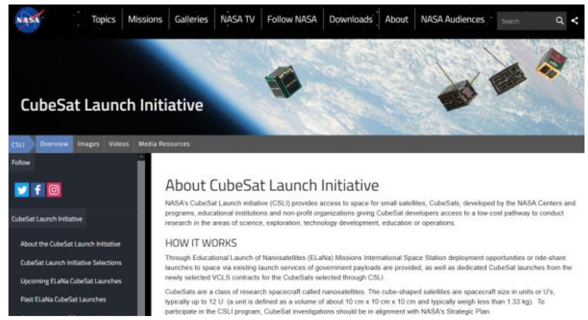

Figure 12. NASA launch initiative provides opportunities for CubeSat rides to low Earth orbit. Rideshares are constrained to 12U maximize size.

7. Pro-Am Science

Astronomy is one field of science where amateur astronomers can perform cutting-edge science research. These activities are usually in the form of partnering with professional astronomers in pro-am collaborations. Thanks to their ability to move and observe when and where they choose, amateurs are also often better at tracking asteroids or hunting for new supernovae than many pros. Amateurs are also branching into spectroscopy, splitting starlight into its constituent wavelengths to study the composition of stars and other celestial objects

This UFO project is designed with pro-am astronomy research as one of the primary objectives. As the system becomes operational and knowledge of research opportunities become widely known, it is anticipated that many professional-amateur relationships will be established and flourish.

8. Project Team Organization

In order to execute this program, a series of partnerships have been established with a select set of engineering and science organizations. This mix of expertise ensures that the probability of mission development and execution is maximized. This partnership organization includes the following profession organizations.

8.1 Prime Solutions Group, Inc.

PSG is a professional engineering services company with a legacy in Intelligence, Surveillance & Reconnaissance (ISR) technology. Leveraging deep experience and expertise in synthetic aperture radar (SAR) processing, core skills in complex system-of-systems engineering, and cutting-edge applied research and development in image-based machine learning, PSG helps solve the 21st century challenges faced by both private industry and government organizations. PSG is the prime contractor and system integrator for the UFO project. It's staff includes multiple decades of experience in project management and mission execution.

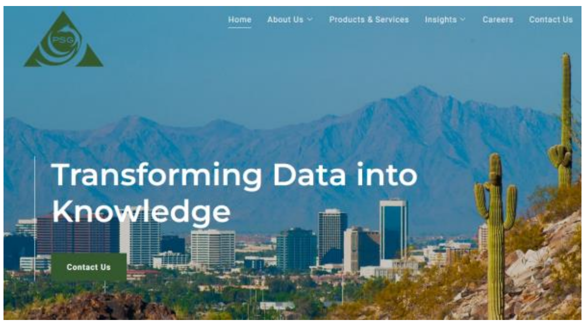

Figure 13. Prime Solutions Group is located in Goodyear, Arizona.

8.2 Southwest Research Institute

Southwest Research Institute (SwRI), headquartered in San Antonio, Texas, is an independent, nonprofit, applied engineering and physical science research and development organization with over 3000 employees. The Institute's Planetary Science Directorate has over 100 employees and is located in the Exeter Building at 11th and Walnut in downtown Boulder, Colorado.

The Space Science and Engineering Division's goals are excellence in space research and the expansion and deepening of SwRI's space research efforts. Areas of research and development include:

- Space Studies
- Planetary Physics
- Planetary Atmospheres and Surfaces
- Lunar Origin and Evolution
- Solar Physics
- Solar System Dynamics
- Astronomy
- Computer Systems
- Space Operations
- Space Technologies
- Mission Operations

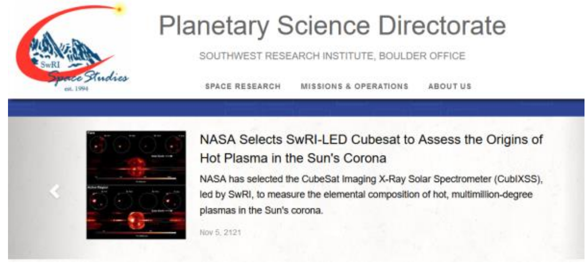

Figure 14. SwRI Planetary Science Directorate

8.3 University of Colorado, Boulder

The Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado Boulder (CU) began in 1948. UC is the world's only research institute to have sent instruments to all eight planets and Pluto.

LASP seeks to maintain and improve the capability to pursue key science questions using experimental, laboratory, theoretical, and information systems approaches. LASP is dedicated to building and maintaining a unique synergism of expertise in space science, engineering, and spacecraft operations. The progressive development and use of innovative technologies and continuing participation in new research initiatives will help ensure a strong leadership role for LASP into the future.

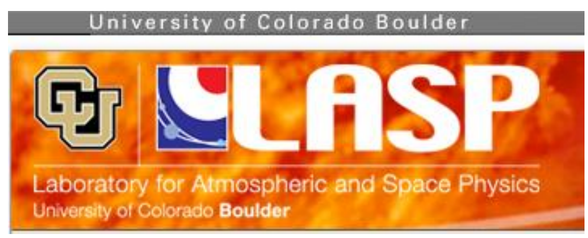

Figure 15. University of Colorado Laboratory for Atmospheric and Space Physics

8.4 University of Illinois

The goal of the University of Illinois Astronomy-Physics group in the Chemistry Department is to enhance society's ability to understand the Universe through the application of scientific problem solving. The university provides opportunities to learn about the universe through the courses which are offered, the scholarship of the faculty, Star Parties, disabilityfriendly support, and community updates of upcoming astronomical phenomena.

Figure 16. University of Illinois at Springfield.

8.5 Astronomy Association of Arizona

The Astronomy Association of Arizona is a nonprofit 501(c)3 organization. Their vision is to create an environment where anyone, regardless of ethnic origin, cultural belief or socioeconomic status, succeeds in meeting their personal astronomical and education goals through state-of-the-art learning activities and unsurpassed membership benefits. Mission statements include the following:

- To engage and educate those of all interest levels and to provide the highest quality of astronomical science to our community and beyond.
- Provide formal and informal education programs for both beginners and experienced astronomers.
- Encourage member participation regardless of their level of interest.
- Create and support programs to increase skills, broaden knowledge and focus on studies and research in specialized astronomical sciences.

The Association is located in Buckeye, Arizona.

Figure 17. The Astronomy Association of Arizona is a 501(c)3 nonprofit organization dedicated to bringing astronomy and space science to the general public.

9. Project Funding

The Astrophysics Research and Analysis Program (APRA) under the NASA Research Opportunities in Space and Earth Sciences (ROSES) solicits basic research proposals for investigations that are relevant to NASA's programs in astronomy and astrophysics and includes research over the entire range of photons, gravitational waves, and particle astrophysics. Awards may be for up to four years' duration. APRA investigations may advance technologies anywhere along the full line of readiness levels, from Technology Readiness Level (TRL) 1 through TRL 9.

Proposals relevant to the APRA program are those that address the best possible (i) state-of-the-art detector technology development that is directly applicable to incorporation in future space astrophysics missions; (ii) science and/or technology investigations that can be carried out with instruments flown as suborbital-class payloads on balloon-borne, sounding rocket, CubeSat, or other platforms; or (iii) supporting technology or laboratory research that are directly applicable to space astrophysics missions.

The APRA funding mechanism is the source being investigated to develop the UFO program.

10. Conclusion

A 12U CubeSat containing a UV telescope is being proposed as a follow-on mission to both current the CUTE and SPARCS satellites. This CubeSat, designated as UFO, is being designed to have a mission timeline of at least 4 years after achieving science commission operations. A series of three satellites with an overlap in observing operations will be deployed to fill the UV observational gap until LUVOIR is launched in the early 2040s timeframe.

11. Acknowledgements

I would like thank Joe Marvin, president of Prime Solutions Group, for allowing me to pursue the area of CubeSat research and development, an area currently outside of PSG's area of expertise. I would also like to thank the executive committee of the AAA for supporting me in developing the aspects of the project and the involvement necessary to get the project concept defined.

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