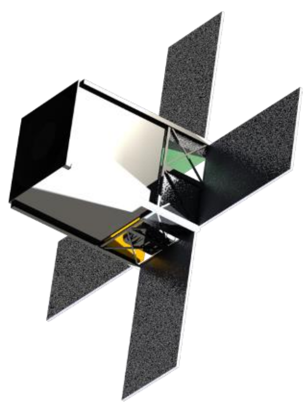
CubeSat Astronomy Network

Conceptual Study 2018



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Preface

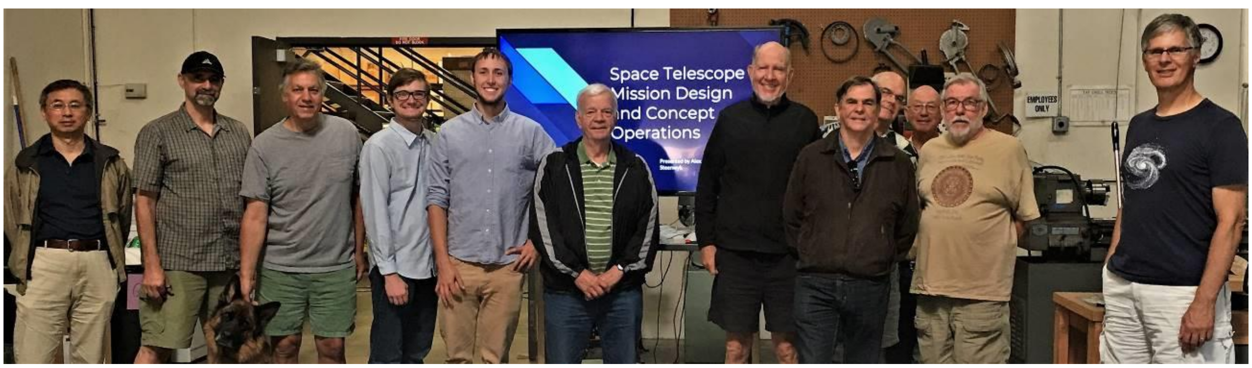
This study took place from June 23rd, 2018 to January 27, 2019. The authors thank PlaneWave Instruments for their generous support that made this study possible. We also thank the faculty and student members of PolySat at California Polytechnic State University, whose insight and assistance has been instrumental to the progress of this study.

We thank the Society for Astronomical Sciences for hosting a workshop on the CubeSat Astronomy Network on June 15, 2018, the Aerospace Engineering department of the College of Engineering at California Polytechnic State University in San Luis Obispo for hosting the second workshop for this study, especially Kendra Bubert, Dr. Amelia Greig, Dr. Eric Mehiel, and Joe Carpico.

Additionally, the authors thank the Alt-Az Telescope Initiative for the opportunity to present the findings of this study at their eleventh annual workshop, held in Portland from July 20th to July 22nd of 2018, and Dan Gray, Howard Banich, and Sidereal Technology, who graciously hosted the workshop and team members for the duration of the workshop.

Study team members, left to right: David Rowe, Charles Van Steenwyk, Alex Johnson, and Russell Genet

CubeSat Astronomy Network Workshop at the Society for Astronomical Sciences annual symposium, June 15, 2018, in Ontario, California.



CubeSat Astronomy Network Workshop at the 11th annual meeting of the Alt-Az Initiative in Portland, Oregon on July 22, 2018.

Contents

1. Summary

Research supported by astronomical observations is most efficient when there is a synergistic balance between a few large and many small telescopes. The small telescopes make the large telescopes more effective by providing follow-up and time-series observations, helping recruit and train the next generation of astronomers and instrumentalists, and serving as test beds for new instrumentation. The cost-effectiveness of small, ground-based research telescopes has been significantly enhanced through full automation and production-line assembly of robotic telescopes with apertures up to 1.0 meter.

Cost-effectiveness could also be increased with a synergistic balance between paid researchers (professional astronomers and their graduate students) and unpaid researchers (undergraduate students and citizen scientists). Over the past decade, the one-semester Astronomy Research Seminar has, with 150 papers and 500 coauthors to its credit, demonstrated the ability of undergraduate and high school student teams to conduct published astronomical research in a single semester. These teams are supported by a community of practice that includes professional astronomers, educators, and experienced citizen scientists, and by the nonprofit Institute for Student Astronomical Research (www.In4StAR.org).

Astronomical research is also most efficient when there is a synergistic balance between ground and space telescopes. Space telescopes, free from atmospheric scintillation, jitter, and blockage, can provide highly precise observations over a wide range of wavelengths. The proposed CubeSat Astronomy Network (CAN) could, at low cost, simultaneously improve the balance between large and small space telescopes, between space and ground telescopes, and between paid and unpaid researchers. Low cost could be achieved by taking advantage of CubeSat technology, no-cost NASA-supplied CubeSat launches, and the extensive use of undergraduate students in telescope design, fabrication, testing, operation, data analysis, and publication and presentation of research results.

A modest half-year conceptual study (summer and fall of 2018) has suggested that the most promising research areas for the CAN will be highly precise, multi-band, photometric observations of exoplanet transits, variable stars, etc. A 12-unit CubeSat (20x20x30 cm) is currently the largest CubeSat that can be readily tested at university facilities and launched at no cost by NASA. It could accommodate an ~20 cm telescope, camera, and CubeSat bus components such as a star tracker, reaction wheels, propulsion system, computer, batteries, radio, etc. Multiple telescopes in low-Earth orbit (LEO) would provide continuous target coverage. It is proposed that faculty-supervised undergraduate engineering and physics/astronomy students in the PolySat program at Cal Poly, in conjunction with students and faculty at other universities, would design, fabricate, and test the space telescopes. They would then operate the network once it is in space.

Observational time on the CAN, leading to published contributions to astronomical research, would be made available to undergraduate students, high school students, and citizen scientists nationwide. Their research could significantly advance our scientific knowledge. Published research helps students gain entry to graduate schools—often with scholarships. Publication also helps provide the motivational self-identity as scientists or engineers that many students need to navigate the long road to advanced degrees and a professional career. The

dozens of schools and thousands of students involved in the economical CAN and its published research would significantly advance both science and engineering education across the nation.

2. Concept

Synergy Between Large and Small Telescopes

This report describes a proposed future network of small, low-cost space telescopes that could be designed and produced in quantity by students, and also operated and utilized by students for published astronomical research. Before discussing this, however, it should be illuminating to consider a somewhat similar situation that has evolved over the past 35 years with respect to ground-based research telescopes. This evolution has led to two distinct but synergistic research communities that utilize very different telescopes.

On one hand, there is a community of paid professional research astronomers~~,~~ and their paid graduate assistants and post-docs, usually located at major research universities or institutes. They primarily employ large, one-off (unique) mountaintop telescopes for their research that cost tens or even hundreds of millions of dollars.

On the other hand, there is a growing community of volunteer (primarily unpaid) researchers that consists of undergraduate students and their full-time instructors (who are paid to teach, not to conduct research), students and their teachers at high schools, and citizen scientists (aka amateur astronomers). For their published research, they employ smaller, production, often fully robotic telescopes that cost a tiny fraction of the large mountaintop telescopes.

Large ground-based telescopes excel in the detailed study of faint objects at the edge of the observable universe, as well as high-resolution examination of specific objects. Small telescopes provide valuable astronomical research through time series, networked, and other observations that only the large numbers of smaller telescopes can provide—tasks which would be cost prohibitive for large telescopes. Small telescopes also continue to play a vital role in recruiting and training the next generation of astronomers and instrumentalists and serve as test beds for developments of novel instruments and experimental methods.

There is a synergy between large and small telescopes—an appropriate balance between the two. Yet the ever-rising initial and operational costs of large, cutting edge telescopes—absolutely necessary for the advance of astronomical science—has made it difficult over the past three decades for governmental institutions, such as the National Science Foundation (NSF), to also invest in purchasing and operating new state-of-the-art smaller telescopes. In fact, over the past several decades NSF has shut down many of the smaller, increasingly antiquated telescopes at their national observatories. Yet we needed to maintain a balance between large and small telescopes to preserve their synergy. For ground-based telescopes, the solution to this dilemma has been three-fold: the development of fully robotic telescopes, producing research-grade smaller telescopes in quantity, and engaging undergraduate and high school students in published research in an economical, large-scale manner.

Robotic Telescopes

The first solution, which began in earnest in the early 1980s by a group of unpaid amateur (citizen science) astronomers (who were professional engineers on their day jobs), was to totally automate telescopes and then entire observatories. This greatly reduced operational costs and also allowed telescopes to be located at prime sites without any significant cost penalty.

The Fairborn Observatory's automated telescopes have been in continuous operation for 35 years (since 1983). Currently there are 14 robotic telescopes at the Fairborn Observatory, ranging in aperture from 0.2 to 2.0 meters. They are all maintained in operational condition by a single person, Louis Boyd. It might be noted that telescope automation, which began with small telescopes, has been spreading to much larger telescopes.

Figure 1: Seven fully robotic telescopes at the totally automated Fairborn Observatory on Mt. Hopkins in the late 1980s. Remote access was via 9600 baud modems over the telephone lines. These seven telescopes specialized in high precision, time-series photometry. The first exoplanet transit was observed with one of the four 0.8-meter telescopes in 1999.

Production-Line Research Telescopes

The second solution was to greatly reduce the cost of manufacturing by producing smaller-aperture research telescopes in production quantity through the innovative transfer of technologies from large to small telescopes. This process is sometimes called reverse innovation (*Reverse Innovation,* Vijay Govindarajan and Chris Trible, 2012: Harvard Business Review).

The Alt-Az Initiative was founded in 2006 to catalyze the reverse innovation process from large to small telescopes. The Initiative's name emphasized the fact that while all recent research telescopes larger than 5-meters have employed alt-az mounts, smaller research telescopes seemed stuck on space-consuming and expensive equatorial mounts. Two student teams and faculty at California Polytechnic State University (Cal Poly), David Rowe at PlaneWave Instruments, and members of the Alt-Az Initiative developed an 18-inch direct drive telescope which led to the direct-drive, dual-Nasmyth-port, CDK-700 0.7-meter fully robotic research telescope manufactured in quantity by PlaneWave Instruments. Some 50 of these telescopes are now located at observatories around the planet. A larger, 1.0-meter version of this robotic research telescope has entered production.

Figure 2: The PlaneWave Instruments CDK-700 9.7-meter fully robotic telescope at Great Basin Observatory. This direct-drive, production telescope features dual Nasmyth ports and is an example of reverse innovation*.*

Figure 3: One key to cost-effective research is fully automated, production-line telescopes.

Large-Scale Published Undergraduate Student Research

The third solution was to harness undergraduate (and high school) student researchers in an economically efficient and reproducible manner to conduct the research. The Astronomy Research Seminars, which began a decade ago at Cuesta College, have now spread to a dozen schools. The pace of the seminar's expansion is rapidly accelerating. The original concept for the seminar was that undergraduate student teams should be able to complete scientific research projects in the same manner as professional research teams (including a paper submitted for publication) in a single semester or less. That this is possible has now been amply demonstrated by the Seminar's more than 150 published papers coauthored by some 500 students and their supporters.

In the Astronomy Research Seminars, each student team:
** Writes a research proposal and submits it for approval
** Manages their own research (with supervision as is the case with most professional research teams)
** Obtains and analyzes original data
** Writes a team paper (and rewrites it several times)
** Obtains an external review of their paper
** Submits their paper for publication to an appropriate community-of-practice journal
** Gives a public PowerPoint presentation or presents their results in a poster

To make this possible:
** Student teams conduct research within a well-established, pro-am community of practice
** The teams conduct their research in a narrow topic area to facilitate timely paper submission
** Nearly total focus is on producing a high quality published paper / students split up the work
** Their research is supervised (but not led or managed) by a research supervisor (instructor)
** The students are supported by experienced researchers, which can include professionals, amateurs, and former seminar students, all drawn from the relevant community-of-practice
** Students are provided with the *Small Telescope Astronomical Research Handbook,* videos, and examples of past student proposals and papers, all organized within a learning management system

By conducting complete research projects as members of an established community of practice, some students come to identify themselves as scientists. This identity can provide them with the *grit* many may need to complete their educational objective. In psychology, *grit* is referred to as a positive, non-cognitive trait based on an individual's passion for a particular long-term goal, coupled with a powerful motivation to achieve their objective. Being a coauthor of a research paper improves a student's chance of admission to their school of choice and obtaining a scholarship as a result of their demonstrated research experience. Completing a team research project also provides students with useful, transferable skills in team participation and leadership, project planning and management, data acquisition and analysis, technical writing and critical thinking, and presenting research results in public.

3. Potential Science Missions

Introduction

During the initial concept phase, the team identified astronomical knowledge gaps for science opportunities. Astronomical objects requiring either frequent follow-on observations or temporally large data sets were identified as prime candidates for a moderate-aperture space telescope network. While there are many opportunities for astronomical research, the primary science case for the CAN (as currently envisioned) is to make photometric time-series observations of variable stars, exoplanet transits, etc., some of which would be follow-up observations that would compliment space and ground-based missions, providing additional data and avenues for student research. Time-series photometric observations, as opposed to astrometric or spectral observations are appropriate thanks to having, respectively, less stringent pointing requirements and more photons (wide-band photometry as opposed to spectroscopy which spreads out the light). A non-exclusive list of science opportunities is identified in the following section.

Time-Series Precision Multi-Band Photometry

Although the capability for time-series photometry is not unique to space-based telescopes, the lack of atmospheric interference offered by operations in space permit levels of instrument precision and ranges of spectral coverage that cannot be achieved by similarly-sized ground-based instruments. Depending on sensor characteristics, photometric measurements may be readily performed from near-ultraviolet wavelengths to near-infrared wavelengths, with continuous spectral response capability for wavelengths over the entire bounded spectral range. Broadband image sensors from Teledyne e2v may be capable of offering such spectral ranges, and onboard filters can provide precision measurements over multiple independent photometric bands while utilizing a single sensing instrument. It should be noted that while CubeSat space telescopes (and the CAN) could also cover extreme ultraviolet wavelengths and beyond the near-infrared to longer wavelengths, we have left these options for later investigation. Targets of opportunity for one-time or limited repeatability measurements include existing cataloged objects, such as those observed by the Gaia mission and existing star catalogs.

Gaia

The European Space Agency's (ESA's) Gaia mission (origninally called the Global Astrometric Inteferometer for Astrophysics, but now just called Gaia) has taken high-fidelity data of nearly every star in our sky, making an extremely precise 3D map of the universe. It has taken sub-milliarcsecond accurate images of nearly every star brighter than 20th magnitude. This has produced a wealth of candidates for stellar observations and has opened the door to many potential stellar observation follow-on missions. One exciting area of research for the CAN is that in the field of double star observation, due in large part to the efforts of organizations such as the Astronomy Research Seminar. Double star analysis requires many data points collected for a long period of time to determine if the target pair is gravitationally bound or just an optical double – that is, aligning in the observer's line of sight to appear paired. Accurate images must be taken to show whether the parallax and radial velocities allow for the two stars to exist in a binary system. The population of stars imaged by Gaia is shown below, in Figure 4. Photometric analysis by a CubeSat-sized telescope platform is reasonable on roughly 1% of the GAIA stars, or about 10^5 stars. Working with this data set allows the platform to assist with other missions as well– additional observations of nearby cool, dim stars such as M-dwarfs would

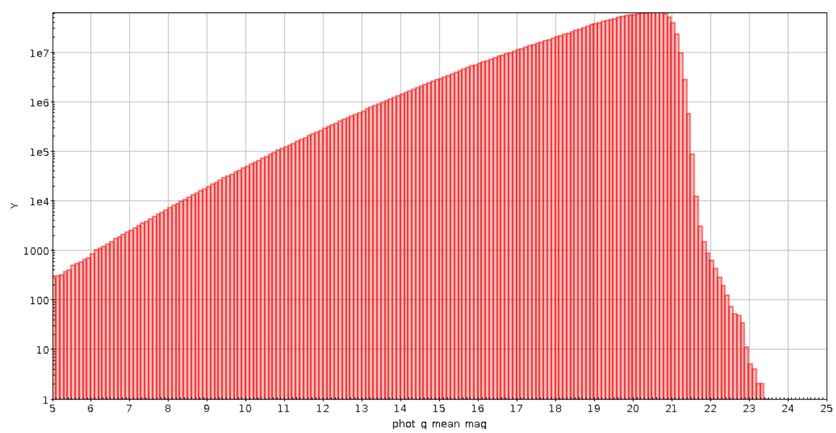


Figure 4: A histogram of Gaia data showing number of stars vs. apparent magnitude. Image credit: ESA/GAIA

provide increased precision in measurements intended for specific science such as exoplanet hunting.

Additional Time-Series Precision Multi-Band Photometry

Targets whose observation schedules require extended time-series measurements with a required temporal resolution (but can be scheduled to allow for occasional interruptions) are another viable candidate for observation by means of a space telescope network. Targets that may be occluded by the interfering signals from Earth, planets, or other *a priori* known sources of interference may be scheduled weeks to months in advance, permitting observation cycles during periods of minimal interference. Targets of opportunity for such science observations include long-period variable stars and active galactic nuclei.

Active Galactic Nuclei

There are approximately 10^3 active galactic nuclei brighter than 15^{th} magnitude, and thousands brighter than 17^{th} magnitude. The CubeSat Astronomy Network platform can perform photometry on many of these sources, giving student researchers the opportunity to extend their research capabilities. Future payloads, operating in the extreme ultraviolet or further out in the infrared, could facilitate even better characterization of the universe's continued evolution. The additional wavelengths could also be used to find out the conditions under which black holes become active or dormant, and how they shape their host galaxy. Because these observations are not time-critical, they could be performed concurrently with other observation sets.

Variable Star Observations

Variable star photometry could also be augmented by this platform. The American Association of Variable Star Observations (AAVSO) has been coordinating and archiving variable star observations for over a hundred years [1], and now have over 35 million observations on record. The majority of known variable stars are brigher than 13^{th} magnitude (mean 12.09) with a median value of 12.4^{th} magnitude. A majority vary in brightness by around 4-5 magnitudes with periods of several hours to days to months. Some variables may have smaller brightness variations and exhibit multiple periods [2], making precise measurments from space especially valuable.

The proposed space telescope platform's aperture selection provides the capability of observing the star targets on sufficiently short time frames to capture this data. In addition, it may be possible to get better photometry on dimmer stars [2] than is reliably possible for amateur ground-based observers. Of note: while all-sky surveys such as the Sloan Digital Sky Survey [3] capture many variable stars, it requires dedicated observations over many months to accurately classify many cases.

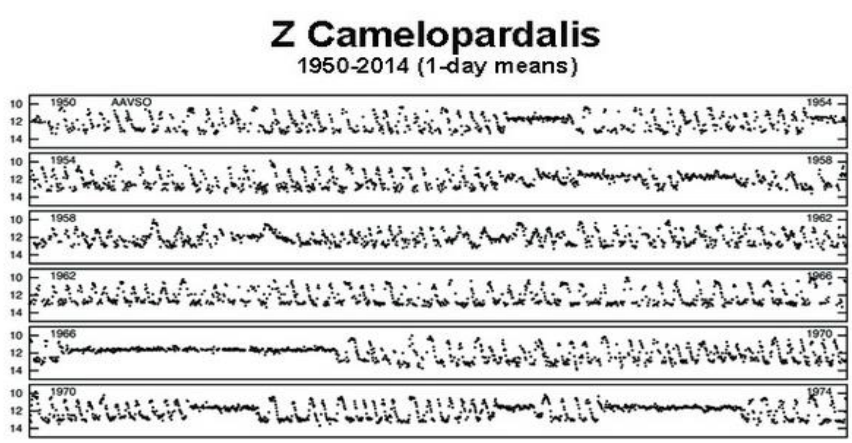


Figure 5: Historical image from the AAVSO catalog showing magnitude changes in Z Camelopardalis. Image credit: AAVSO

Rapid Follow-on Precision Multi-Band Photometry

Time-sensitive CAN observations may offer a level of rapid measurement that ground-based and existing space-based telescopes may be unable to provide. Rapid response and slewing times, enabled by a smaller imaging payload and platform, could facilitate the observation of targets of opportunity such as supernovae and asteroids. However, such rapid response capability is inherently limited by command uplink capability, as slew commands would either require line-of-sight communication or space-based relay systems to ensure rapid command receipt without reliance on direct line-of-sight communication.

Supernovae

The CAN provides the capability to rapidly slew and image these transient events, allowing for more complete light curve generation. Additional future payloads would allow for the possibility of far-ultraviolet and infrared observations as well. Only an estimated 50% of supernovae have associated light curves, and fewer still have light curves for multiple wavelengths [4]. In addition, within the context of undergraduate student work, adding the ability to analyze a supernova remnant with original observations enhances student education. Due to their nature, these events may be considered without additional cost or complexity due to their brightness and duration [5].

Continuous Time-Series Precision Multi-Band Photometry

If coverage capabilities permit, continuous observations of targets, with minimal interference from background sources such as the Sun, Earth, moon, and planets, would permit greater time coverage of targets, enabling time-sensitive observations without risk of eclipse from other sources. Follow-on observations of targets imaged by other missions may be achievable with such capabilities, and may even be possible through careful mission design, though mission orbits with less frequent launch windows, or orbits requiring onboard propulsion to achieve and maintain may be required to facilitate satisfactory observation conditions, which may result in increased system cost and operational constraints to facilitate the use of such systems. Further work may be determined to identify key technologies that would enable such missions, though constellation-based systems may prove effective at facilitating such continuous observation capabilities. Such targets of opportunity that could be observed with uninterrupted instrument coverage include exoplanet candidates observed by the Kepler, K2, and TESS missions, astroseismological targets, short-period variable stars, and near-earth objects.

Exoplanet Transits: TESS / Kepler Follow-on Mission

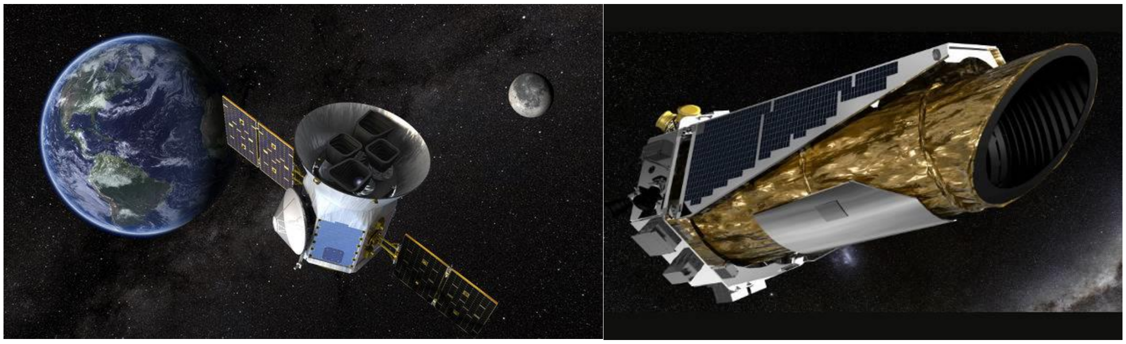


Figure 6: Concept models of the TESS and Kepler missions, on the left and right respectively. Images credit NASA

The NASA Kepler mission, launched in March 2009, was the first satellite dedicated to observing exoplanet transits. In doing so, it identified and cataloged exoplanet candidates detected in a limited area of the sky. Nine years into its lifetime, Kepler has shown that where we find stars, we find planets. It does this by staring deeply into a few select fields, targeting stars between 13^{th} and 16^{th} magnitude.

NASA's Transiting Exoplanet Space Satellite (TESS), launched in April 2018, is a space telescope intended to search for exoplanets that could be transiting more than 200,000 bright, nearby F- to M-dwarf stars. Unlike the Kepler mission, which searched a 105 $degrees^2$ field of view very deeply, TESS will use lessons learned about exoplanet abundance in its mission objectives. Its payload consists of four 10-centimeter aperture cameras that scan the entire sky for transits within 200 light years of Earth. Additionally, it targets M-dwarf stars, which make exoplanet detection simpler due to the higher relative change in brightness—the smaller stellar disk means proportionally more light is blocked during transit. Using equation 1 from Ricker et al. [6], it can be seen that a transit depth of around 300ppm is expected for an Earth-sized planet around a sun-sized star. Of the selected targets in the TESS target catalog, most are M-dwarf stars around 10-13^{th} magnitude, with $>10^5$ stars around 10^{th} magnitude. In order to achieve this, TESS utilizes a 16.8-megapixel MIT Lincoln Labs CCID-80 CCD in each of its four cameras. Each of the four cameras focuses a 24x24 degree square onto 15-micron pixels, allowing it to observe thousands of stars at once. The Student Space Telescope has a larger aperture and somewhat smaller field of view, allowing for more photometric sensitivity for similar targets due to a finer pixel scale. In addition, smaller pixel formats are being considered, such as the Teledyne e2v series detectors.

As its primary mission, TESS focuses on detecting short-period transits, and is designed to catch transits occurring with orbital period less than 27 days [6]. This represents an excellent opportunity for followup observations from the CubeSat Astronomy Network, as the capability to observe the same target for as many target orbits as necessary greatly enhances the capacity for science. More transit observations not only improves the probability of detection, but it also constrains the probable period and mass of the target. In addition, all exoplanets present in a system affect each other's orbits. This is represented by a periodic increase or slowdown of transit timing, even if no other bodies appear to transit the star. This functionality will allow CAN follow-on observations to potentially detect long-period targets either by transit or indirect effects, allowing for more terrestrial analogues to be discovered, helping to fulfill Kepler's fundamental research objectives.

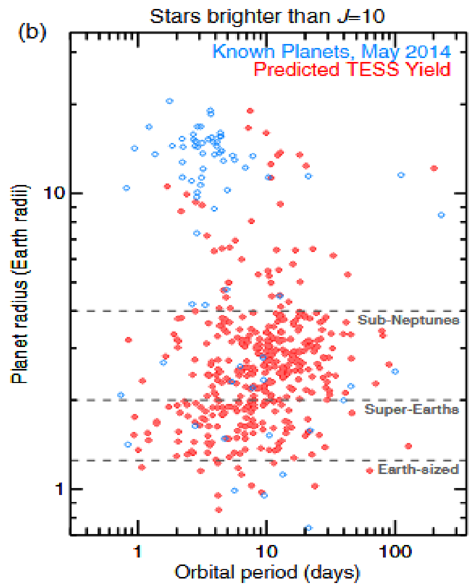


Figure 8: Planet radius vs orbital period for J magnitude >10 stars. This plot shows known and predicted exoplanets, with the majority having P<100 days. Image credit:

Asteroseismology

Asteroseismology is another possible CAN research area enabled by rapid temporal sampling. The TESS mission notes that for the rapid exposures achieved by their platform, it is possible to detect oscillations in stellar activity that indicate seismic activity. The TESS mission is expected to detect pressure-mode (p-mode) oscillations on stars brighter than 7.5^{th} magnitude. With approximately 4 times the detector area, it is reasonable to believe that the CAN can perform similarly on somewhat dimmer stars. It is estimated that the baseline space telescope described later in the report can achieve 1 mmag sensitivity/precision for similarly bright stars to TESS. This would allow CAN to obtain precise photometric asteroseismology on thousands of stars for p-mode oscillations [7]. Doing so would allow a reduction in the errors associated with other missions discussed in this report, such as classifying temporal variation in stars~~.~~ For M-dwarf stars, such as those chosen for exoplanet targets, better characterization of intrinsic variation will allow for more accurate, less time-consuming observational sets.

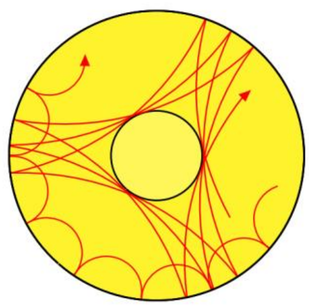


Figure 9: A graphic depicting how seismic waves could propagate through the stellar envelope. Image credit: Wikipedia

NEO/NEA Close Approaches

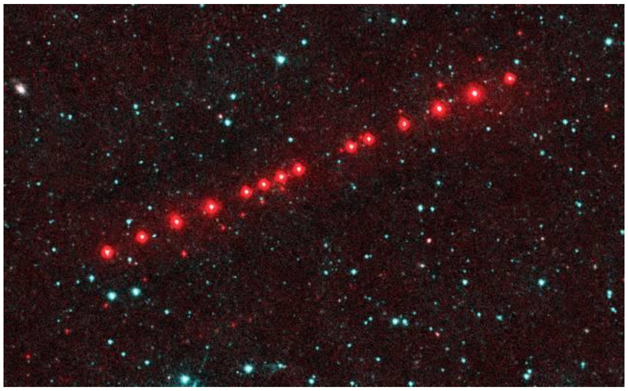


Figure 10: An example of a minor body track on the background field. Image credit WISE/NEOWISE

Due to the low albedo and varying phase angles of near-earth objects, it is expected that the CAN will be able to perform asteroid close approach imaging when the object is at around 100m in diameter and within 5 lunar distances from earth. Further, it will be capable of imaging objects around 30m in diameter while within 1 lunar distance. The CAN will be able to assist with albedo and light curve measurements during such events, providing a more complete picture of our own solar system.

4. CubeSat Space Telescopes

Introduction

To accomplish the above-mentioned science objectives, it is proposed that a network of small space telescopes be constructed, deployed, and operated for the intended purpose of producing astronomical data to supplement the capabilities of ground-based robotic systems currently used for student astronomical research. To maximize scientific capability and minimize program cost, the team decided to investigate the feasibility of seeking student involvement in developing a network of small-satellite space telescopes as the baseline space-based asset for gathering astronomical data. Such a system would be best developed and implemented with an initial single unit operating as a proof-of-concept before launching future units, allowing the system to flexibly expand in response to future interest in augmented network capabilities.

Introduction to CubeSat Spacecraft

According to the CubeSat Design Specification [8], “the primary mission of the CubeSat Program is to provide access to space for small payloads.” Furthermore, the purpose of the original CubeSat Project was “to provide a standard for design of picosatellites to reduce cost and development time, increase accessibility to space, and sustain frequent launches.” It is estimated that over 800 CubeSats have been launched since the original specification was published, shown in the figure below. Part of their increased prevalence in space mission development is owed to their low cost, ease of construction and assembly per standard specifications, and outreach events and conferences held to support and present the current state of CubeSat development, such as the annual CubeSat Developer Workshop hosted at California Polytechnic State University in San Luis Obispo.

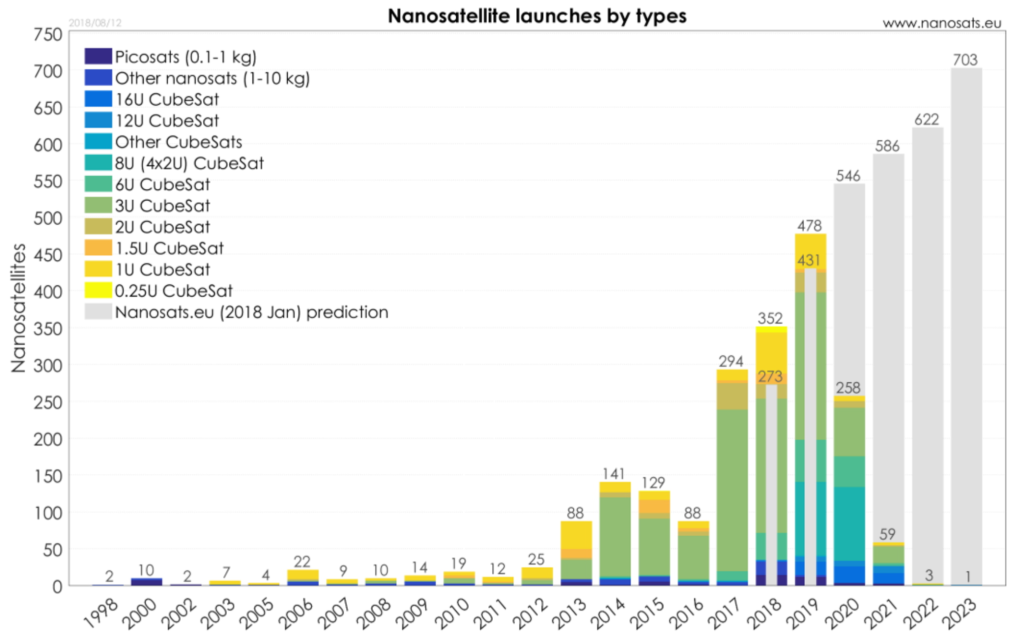


Figure 11: Nanosatellite launches by type since 1998. Data provided by Nanosats.eu. [39]

Spacecraft designed according to the CubeSat standard are normally designed to satisfy a set of size and weight constraints, depending on the size of payload system that the bus is designed to operate. Typically, these standard constraints are characterized by the relative size of the spacecraft itself, using a reference size and mass of a “1U” CubeSat as a reference. A 1U CubeSat bus, for example, is required to be no heavier than 1.33 kg and takes up a cube-shaped volume of 10 centimeters by 10 centimeters by 10 centimeters. Larger CubeSat bus sizes are specified by the number of 1U CubeSats required to roughly equal the same volume of the larger bus, e.g. a “6U” bus measures roughly 30 centimeters by 20 centimeters by 10 centimeters, the equivalent volume of six “1U” CubeSats. An illustration of the CubeSat bus size nomenclature is shown in the figure below.

To minimize launch costs, CubeSat missions ordinarily are launched as secondary payloads, and launch service providers, upon receiving a CubeSat integrated with a standard mechanical deployer, will integrate the deployer assembly to the upper stage of the launch vehicle. Each CubeSat form factor has standard constraints on maximum size and maximum weight to ensure conformance with launch provider requirements, deployer integration

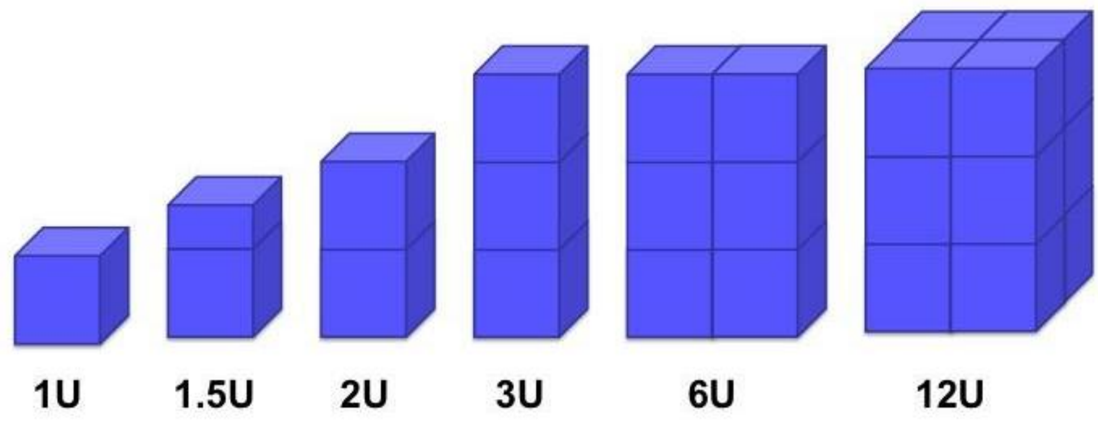


Figure 12: Standard CubeSat bus configurations. The 1U bus dimensions are 10 cm x 10 cm x 10cm. [42]

requirements, and reduce the risk of mission failure. For the proposed program application of CubeSat-based space telescopes, many components and systems required for implementation are commercially available off-the-shelf, such as the guidance and navigation system components required for spacecraft fine pointing and slewing, although custom components and systems can be acquired from many of the same firms that supply off-the-shelf components at the price of increased development costs.

Student Involvement

Largely due to the efforts of Dr. Jordi Puig-Suari and other key individuals at California Polytechnic State University in San Luis Obispo, the university's College of Engineering hosts the PolySat laboratory, an on-campus multidisciplinary research lab that has access to facilities and equipment to perform CubeSat design, assembly, integration, and testing. The lab's efforts have resulted in six successful launches of spacecraft designed, constructed, tested, and integrated using PolySat's facilities. It is possible to minimize development costs by promoting student involvement in program and mission definition, and PolySat's capabilities in aiding in development, construction, and testing of system elements have been deemed feasible for the achievement of the CAN's program objectives. Multilateral involvement with other organizations, however, will not be discounted during the course of system development.

NASA Supplied Launches

Additionally, there are potential sources of funding that may be available during program development and implementation that would make the proposed program more feasible. For example, NASA's CubeSat Launch Initiative can provide the cost of launch for space missions, provided that the supplied spacecraft abides by NASA's requirements, which also include the requirements of the launch service provider. Pricing for larger payloads is estimated for low-

Earth-orbit and geosynchronous-transfer-orbit launches for a launch in 2019 in the figure below from Spaceflight Industries [9].

Note that the price to send containerized payloads (CubeSats) varies from a LEO launch to a geosynchronous transfer launch by as little as a factor of 2.6 for 6U up to a factor of 3.1 for

DETAIL	CONTAINERIZED			SATELLITE CLASS							
PAYLOAD TYPE	3U	6U	12U	50kg	100kg	150kg	200kg	300kg	450kg	750kg	1000kg
LENGTH (CM)	34.05	34.05	34.05	80	100	100	100	125	200	300	350
HEIGHT/DIA (CM)	10	10	22.63	40	50	60	80	100	150	200	200
WIDTH (CM)	10	22.63	22.63	40	50	60	80	100			
MASS (KG)	5	10	20	50	100	150	200	300	450	750	1000
PRICE-LEO	$295	$545	$995	$1,750	$3,950	$4,950	$5,950	$7,950	$17,500	$22,000	$28,000
PRICE-GTO	$915	$1,400	$2,750	$4,600	$8,400	$9,800	$11,200	$14,000	CALL	CALL	CALL

Pricing in thousands (USD)

Figure 13: Pricing (in thousands of USD) information on estimated satellite launch costs using Spaceflight Industries' launch services. Note the lack of pricing options for geosynchronous orbits, due to the need for onboard propulsion for CubeSats to achieve a stable geosynchronous orbit.

3U. The ratio of launch costs for a 12U CubeSat between a GTO and a LEO launch trajectory is roughly 2.7. It is important to note that rideshare pricing is not shown for GEO launches due to the necessity for onboard propulsion to achieve a geosynchronous orbit. Due to restrictions on the use of pyrotechnic devices aboard CubeSats by launch service providers, any onboard propulsion would require a non-igniting propulsion system to achieve the necessary change in velocity for a stable synchronous orbit. Such electric propulsion systems would require at least several months of continuous operation to achieve a circular orbit, during which time the craft would necessarily pass through the Van Allen radiation belt and receive a larger total dose of ionizing radiation than if the craft were operated at lower altitudes. Given the frequency of launch opportunities to LEO, the lower launch costs, and the heritage of NASA-launched CubeSat missions to LEO, the development of a LEO-based mission has been investigated.

University Testing Facilities

Although there are commercial vendors that offer payload integration and CubeSat assembly, integration, and testing services, a number of universities also possess the facilities and personnel required to perform many of these services for CubeSats. PolySat has provided these services for its own past flown missions and is capable of providing many of the same services required for this proposed program.

Per *An Advanced Standard for CubeSats* [10], the testing and integration schedule recommended for a launch environment testing for a 12U CubeSat spacecraft consists of a fit check, thermal vacuum testing, random vibration and mechanical shock testing, separation testing, and launch vehicle integration.

For verifying the fit of the 12U payload to a canisterized satellite dispenser (CSD), the 12U payload is integrated into the dispenser. According to Planetary Systems Corporation, a nine-month lead time is recommended for acquisition of a non-custom CSD.

Thermal vacuum testing is then conducted on the complete assembly according to United States Air Force Space and Missile Systems Center Standard SMC-S-016, Section 6.3.9. The facilities available to PolySat may be sufficient to carry out this testing for 12U CubeSat configurations, though the testable temperature range may be restricted between -40 Celsius to +40 Celsius. Required testing capabilities will be ultimately driven by the launch service provider, but integrated systems testing requiring broader temperature capabilities may require an alternative testing facility or refurbishment of existing facilities.

Random vibration testing is conducted according to NASA's GSFC-STD-7000 environmental testing standard. PolySat's facilities are deemed sufficient to perform this testing process for 12U CubeSat configurations, though any testing specifications may need approval.

In the event of successful deployment testing and documentation, the unit is then delivered to the launch service provider for integration to the launch vehicle. Any additional testing required by the launch service provider will be specified as part of the documentation and coordination process with the provider.

Off-the-Shelf Components

Due to the increased prevalence of CubeSat systems in the past decade, several firms have been developing components and systems for CubeSat space systems, often already qualified for vacuum operations and characterized for radiation tolerance in an environment similar to that encountered in a LEO orbit. To verify the suitability of non-space-qualified components, separating testing of those systems is usually accomplished by a CubeSat developer, or contracted to a firm or organization, such as a research center, in order to confirm the component or system's performance for a CubeSat mission. Some types of component and subsystem testing can be performed using Cal Poly's existing facilities, but other types of testing, such as radiation performance testing and optical system testing, may require facilities beyond what can be provided by PolySat. Further work is required to characterize such dependencies on external resources.

By minimizing the use of custom components and systems, students involved in the development of space telescopes can minimize the amount of time spent fabricating systems whose performance in the proposed orbit environment is already well characterized. Some CubeSat systems, such as transceivers, batteries, solar panels, and attitude determination and control systems, are available commercially from suppliers. Aerospace suppliers that supply systems for larger satellites have also begun supplying systems and components suitable for CubeSat systems. Making use of commercially-off-the-shelf components can reduce the scope of testing required for individual space telescopes, since the verification required for space-qualified component performance will not need to be as comprehensive as testing for a nonqualified custom component, especially for components with flight heritage [11]. This can therefore minimize component, subsystem, and system level failures at lower cost, ensuring mission success while remaining cost-effective.

12U CubeSat Configuration

Due to the size constraints that CubeSat systems must satisfy, it was decided to characterize the limitations on aperture size that would be imposed by utilizing a CubeSat spacecraft bus to house the instrument. Per discussions with members involved with PolySat, it was determined that a 12U sized CubeSat bus was the largest bus size that PolySat could reasonably assemble, test, and integrate, limiting the maximum aperture size for an imaging instrument for such a spacecraft to no more than 20 centimeters in diameter.

Specifications and deployer options are being developed for larger format CubeSat configurations, such as 27U bus sizes (30 centimeters by 30 centimeters by 30 centimeters), shown in the figure below.

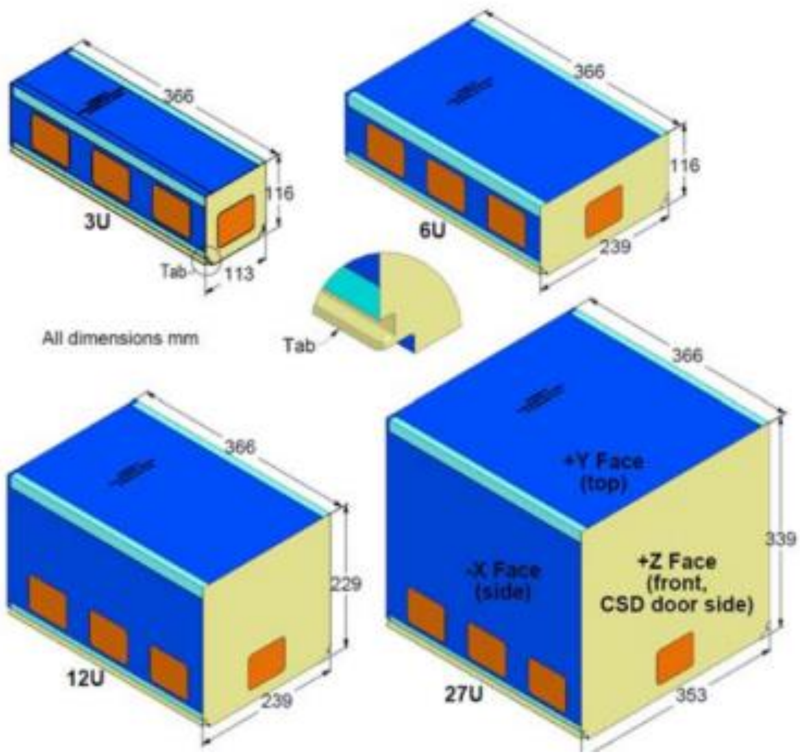


Figure 14: Diagram of large format CubeSat bus configurations. Dimensions shown are per the specifications of Planetary Systems Corporation; requirements may vary between dispenser providers. [40]

Such bus configurations could allow larger aperture space telescopes to be developed, but it is not known if such large bus sizes would be viable candidates for the CubeSat Launch Initiative. Furthermore, it is not well characterized what upgrades, if any, would be needed to ensure that PolySat could perform testing and fabrication for such larger bus configurations, and partnership with other test facilities may be required. Some small satellite system firms, such as

Blue Canyon Technologies, offer a microsatellite-sized bus capable of launch via integration to a specially-designed payload adapter, which allows launch of a payload larger than a CubeSat as a secondary payload. However, launch costs for such a larger spacecraft may not be covered by a program like the CubeSat Launch Initiative, so an alternative source of funding for launch costs for larger missions may be required for future implementation.

Due to the constraints imposed on 12U dimensions and mass properties by dispenser manufacturers, 12U CubeSats are restricted from being no more massive than 24 kilograms and can be sized no larger than 21.91 centimeters by 23.9 centimeters by 36.59 centimeters, according to *An Advanced Standard for CubeSats* [10]. While other requirements for the 12U configuration compatible with a dispenser supplied by Planetary Systems Corporation are similar to those imposed on other CubeSats and space systems, these constraints drive the maximum size of optical payload that can be integrated into a 12U bus.

Potential for Quantity Production

Due to the limited expected lifetime for CubeSat systems, space telescope replenishment must be considered for program lifetimes expected to last longer than the lifetime of a single space telescope. Consequently, a space telescope bus design that could be manufactured in quantity, instead of a singly-produced design, would make replenishment or refurbishment of space telescopes as they reach the end of their operational life and are safely disposed more viable for the proposed program. Furthermore, improvements in production technology and CubeSat technology over the course of system operations could be leveraged to improve system performance as new system iterations are developed and tested. This key consideration shall be considered during system development.

Making use of off-the-shelf components that could be purchased in bulk could allow for parallel production and integration, potentially allowing for launch as a constellation, after sufficient testing and verification of system performance via demonstrator missions and flight testing [11].

If telescope science requirements can be satisfied using a common optical telescope assembly with an instrument mount capable of supporting a range of types of imaging sensors, optical assemblies could be produced in quantity, allowing different space telescopes with different instrument loadouts to be developed and integrated into the larger system. However, the size constraints of the CubeSat bus constrain the optical assembly geometry, unless technologies such as deployable optics can be utilized to permit the use of a wider range of imaging payloads.

5. Orbit Considerations

Introduction

To better characterize system performance with respect to the orbits of CubeSat Astronomy Network spacecraft, a number of orbital environments were considered in the course of designing the conceptual system. Geocentric orbits, especially orbits that could be achieved by a CubeSat launching as a secondary payload, were considered for the system instead of interplanetary orbits, as mentioned below. Although interplanetary orbits offer observation environments less contaminated with background signal from the Earth and Moon, insufficient data is available to characterize the near-term availability of such rideshare opportunities for interplanetary orbits, due to the entire prior heritage for such flights consisting of two 6U CubeSats launched onto a Mars flyby orbit in 2018 [12]. However, potential expansion to such orbits should be closely considered as more small satellite interplanetary missions launch.

Orbital Altitude Considerations

For considering geocentric orbit altitude and its effects on system sky coverage capability, two principal orbital regimes were considered for system location: high-altitude, long-period geocentric orbits, and low-altitude, short-period orbits. Based on launch availability for as a secondary payload, two principal orbital geometries at low earth orbit (LEO) and geosynchronous (GEO) altitudes were considered. Although CubeSat systems have not been deployed to geosynchronous altitudes, and commercial off-the-shelf components would likely need to be tested to verify performance in the radiation environment characteristic of geosynchronous orbits, such orbits could allow for long uninterrupted cadence series of observations of targets. Some CubeSat missions are being developed and plan to be launched to GEO orbits in the next few years, such as the Air Force Research Laboratory's ASCENT mission, which aims to better characterize the suitability of CubeSat systems in the GEO environment [13].

Low earth orbits commonly used for CubeSat systems include orbits achievable via deployment from the International Space Station and sun-synchronous orbits. Sun synchronous orbits, as exemplified in the figure below, are orbits whose trajectories precess about the Earth's inertial reference frame at the same rate as the Sun's angular position during the course of a full solar orbit. This permits a constant angle between the Sun's inertial position and the orbital plane to be maintained during orbital operations. Such an orbit would be advantageous because the orbital orientation with respect to the Sun can be maintained such that a satellite experiences little to no eclipse of the Sun, allowing constant solar power generation and little temperature variation during the spacecraft's mission.

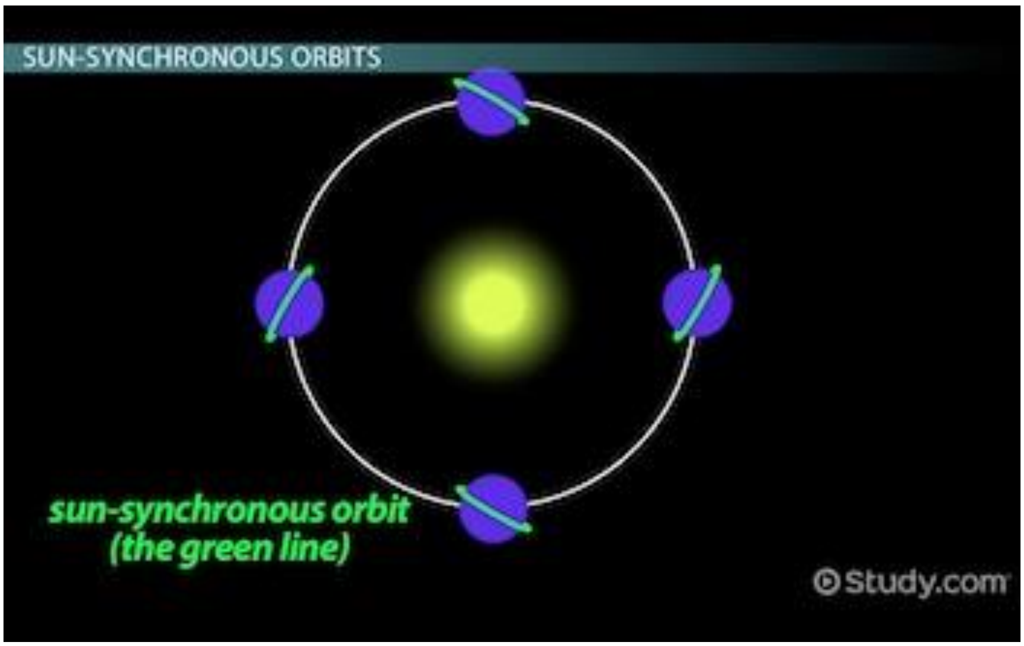


Figure 15: Illustration of sun-synchronous orbit precession throughout Earth's annual orbit. Note that orbital orientation is preserved throughout the course of the year and can be achieved for orbits at different angles with respect to the Sun than the one depicted above. [41]

By comparison, launches via deployment from the International Space Station place spacecraft into a similar orbit to the station. Relative time in eclipse, orbital disturbances, and other orbit considerations may prove disadvantageous for operations in such an environment. Additionally, operating at altitudes that would degrade below the altitude of the International Space Station place an upper limit on the operational lifetime for such a mission. However, at least one similar mission, ASTERIA, deployed into a similar orbit [14]. Further work may be required to characterize the science capabilities and constraints imposed by operating in a similar orbit.

Several key parameters describe major differences between geosynchronous orbits and sun-synchronous orbits, as shown in the table below. Note the higher electron flux and free space path loss at GEO altitudes compared to sun-synchronous orbits, which directly affect system lifetime and communications, respectively.

Table 1. Differences Between Geosynchronous and Low Earth Sun-Synchronous Orbits

Parameter	*% of Full Sky Not Occluded by Earth*	*Maximum Eclipse Time*	*Minimum Orbital Period*	*Best Case Free Space Path Loss at 437 MHz*	*Integral of Trapped Electron Flux (> 1 MeV) [e-/cm^2/s]*	*End of Life Plan*
LEO Sun-Sync (~400 km Altitude)	65 %	37 minutes	93 minutes	135 dB	1.8441e+03 (From SPENVIS, AE-8)	Reentry
GEO	99.2 %	64 minutes	1440 minutes	176 dB	4.2978e+05 (From SPENVIS, AE-8)	Boost to graveyard orbit

While the relatively wider instrument area of accessibility of a GEO orbit may improve the science capabilities of a CubeSat space telescope system, there are several operational challenges associated with ensuring mission success from a GEO orbit. As shown in the figure below, nanosatellite systems have no heritage in GEO orbits, though there are missions such as ASCENT that are intended to be launched into GEO. The relative abundance of nanosatellite systems in LEO orbits, by comparison, is largely due to the abundance of launch opportunities to LEO that offer capabilities for rideshare launches to be a viable deployment method for

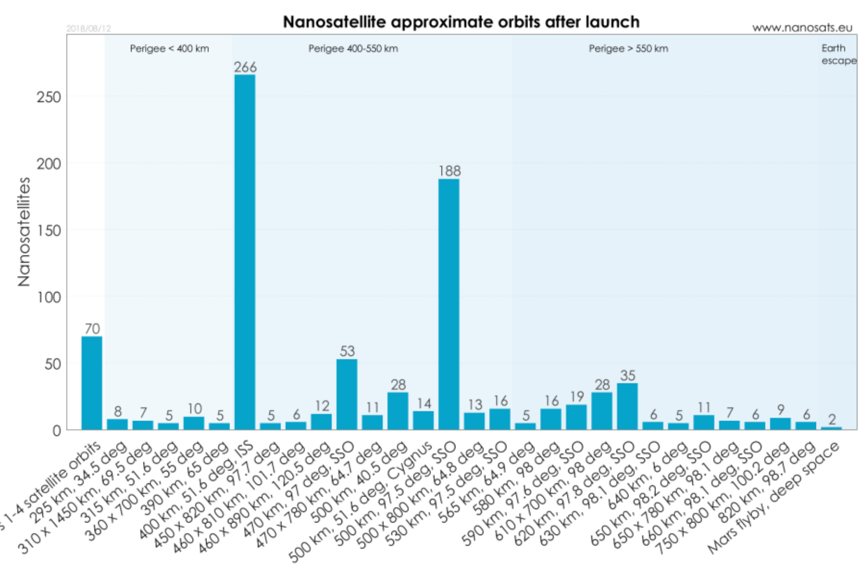
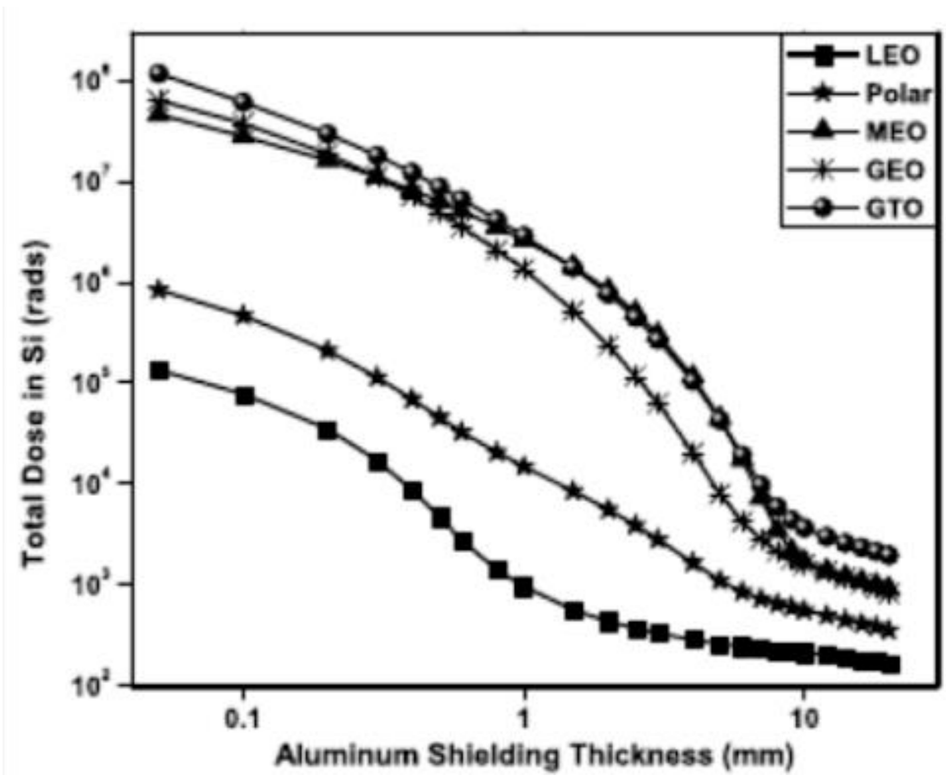


Figure 16: Graph of nanosatellite orbits upon launch. Data obtained from nanosats.eu. [39]

CubeSat systems. In contrast, opportunities for rideshare launches into higher altitude orbits, while not impossible or infeasible, are demonstrably less utilized by CubeSat systems.

The radiation environment in GEO poses another significant concern for system robustness and operational lifetime. Per the figure below from Samwel et al. [15], it is anticipated that a 12U craft in GEO would either experience approximately at least an order of magnitude higher total ionizing dosage than a craft in LEO, or would require an order of magnitude thicker radiation shielding in the spacecraft bus to receive the same annual dosage as a craft in LEO. Note that a polar orbit is more representative of a sun synchronous orbit than the "LEO" mission in the table. Orbits more distant than GEO tend to have more severe radiation environement in the absence of a protective magnetosphere in their operational environment.



Orbit	Inclination	Orbital perigee	Orbital apogee
LEO	28.4^0	597 km	618 km
Polar	98.5^0	724.7 km	839.3 km
MEO	56.2^0	19988.6 km	20375 km
GEO	0.0405^0	35774.7 km	35797.8 km
GTO	18.0115^0	338.5 km	34536.5 km

Figure 17: Graph of total ionizing dosage for various one-year orbits. Orbit properties are shown below. Note the logarithmic total dosage scale in silicon.

Continuous Target Coverage from LEO Orbit

Due to the time-sensitive nature of certain observation targets and the need for space-based observation systems to complement the capabilities of ground-based observation systems, the capability of continuous field coverage for a target over the course of several hours was investigated as a feasible system requirement. Sky coverage capability is directly coupled with system orbit geometry, especially for lower altitude orbits where target imaging capabilities may be impaired due to interfering signal from the Earth, Moon, or other celestial bodies. Since interplanetary orbits require greater launch costs and occur less frequently, launch as a secondary payload into an interplanetary orbit was not deemed practical for the achievement of program objectives. Near-Earth geocentric orbits, therefore, were considered more appropriate than other orbits for the proposed system.

To achieve continuous coverage of a stellar target over the course of several hours, two alternative methods were considered: continuous dwell time with a single space telescope, and distributed overlapping coverage of a target with multiple different instruments. The former either requires targets and orbit geometries that avoid eclipse and stray light from Earth and Lunar albedo, such as long-period, high-altitude geocentric orbits with less interference due to Earth eclipse, or restricting instrument accessibility from pointing towards stray light sources if there is the possibility of eclipse or interference during a given imaging cadence cycle. The latter requires the use of a constellation of space telescopes for the continuous observation of a particular stellar target throughout the cadence series, but does not necessarily require restricting the instrument access area from targets eclipsed by the Earth. Variations in instrument performance may result in some variability in measurements taken during a given cadence series. However, telescope sky access capability is not the sole deciding factor for selecting orbits for the proposed space telescope network.

To provide constant coverage of stellar targets in a sun synchronous orbit, a minimum of three equally-spaced imaging spacecraft are required to slew to a desired field in the night sky, per Figure 18. Deployment of spacecraft into a single orbital plane can be accomplished by a single launch, but onboard propulsion would be required to space out the telescopes after deployment and maintain each telescope's orbital position after achieving orbital spacing. Electrical propulsion systems sized for a CubeSat spacecraft may permit station-keeping capabilities for several years, but such performance will need to be verified in the course of system design. More spacecraft in a given orbital plane formation could be supplied, but refined analysis of stray light effects may be required to adequately characterize the effects of additional spacecraft. Theoretically, cadence series imaging of stellar targets from a geosynchronous orbit is achievable for a period of at least eight hours without interference from Earth eclipse effects.

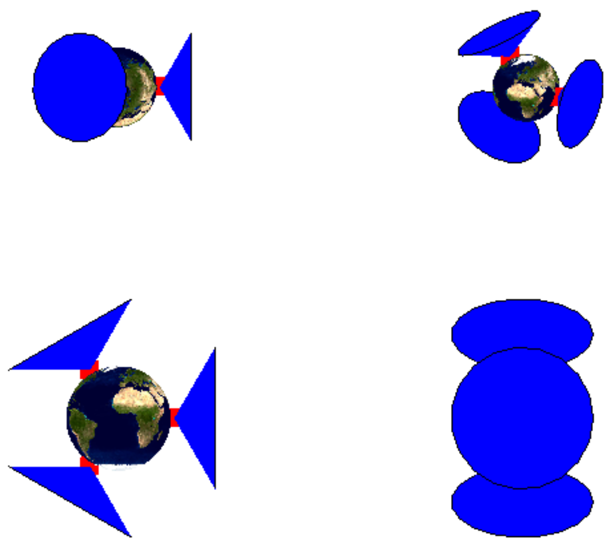


Figure 18: Illustration of a theoretical constellation of three space telescopes in a circular low earth polar orbit. The blue cones are representative of theoretical instrument access areas to illustrate theoretical worst-case regions of imaging capability for their telescopes, but do not necessarily represent true sky coverage capability. If the instruments have baffles and stray light control to enable imaging operations within 15 degrees of the Earth's functional horizon, then any theoretical stellar target in the celestial sphere can be imaged by at least one instrument, regardless of orbit orientation. Other sources of interfering signals may limit imaging operational effectiveness, not shown here.

6. Conceptual Space Telescope Design

Introduction

A conceptual design for a 12U space telescope for operations in a low earth orbit is described below. An 18.5 centimeter aperture imaging payload is the baseline imaging payload enclosed in the bus.

Optical Assembly Design

A conceptual design for a corrected Ritchey-Chretien telescope was designed for use in the CubeSat Astronomy Network. The instrument was designed to perform photometric imaging in a spectral band ranging from 0.4 micrometers to 1 micrometer, though instruments designed for ultraviolet and infrared imaging could be considered for future designs. The 185-millimeter aperture instrument is capable of being enclosed within a 12U CubeSat bus, and the f/4.03 instrument focal number enables a wide instrument field of view for performing visual-band photometry. A visualization of the proposed optical configuration, generated in the ray tracing software TraceXP, is shown below.

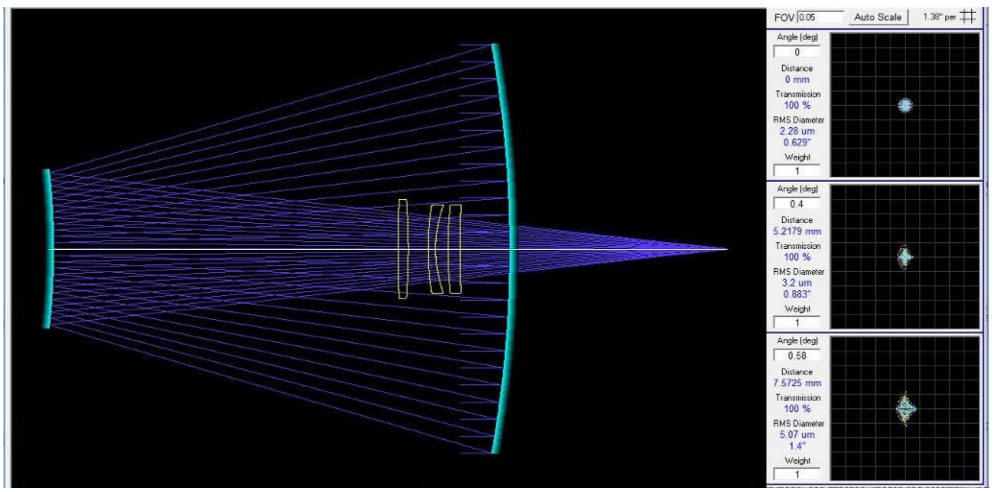


Figure 19: TraceXP window showing optical ray trace and optical performance of the payload.

Key parameters for the visual band photometric optical assembly are shown in the table below, though many of these parameters are dependent on the instrument parameters described further below.

Table 2. Key Parameters for Optical Baseline Payload

Parameter	*System Aperture Diam. [mm]*	*System Focal Length [mm]*	*System f/#*	*System FOV [degrees]*	*Full Field RMS Spot Diam. [um]*	*Full Field RMS Spot Diam. [“]*	*Percent Secondary Obscuration [%]*
Value	185	746.77	4.037	1.16	5.07	1.4	38.9

A Solidworks model of the optical configuration is shown below. Fused silica reflective elements are suitable for vacuum applications, and Corning 7980, used in the corrector lenses, is known to be used in vacuum applications, minimizing the risk of optical element outgassing, though thermal vacuum testing may be required to verify operational optical performance.

Figure 20: Solidworks rendering of the optical payload and imaging instrument.

Theoretical photometric performance on a variety of target magnitudes with different single-frame exposure times are shown in the figure below, with the key parameters for this analysis presented in Appendix B.

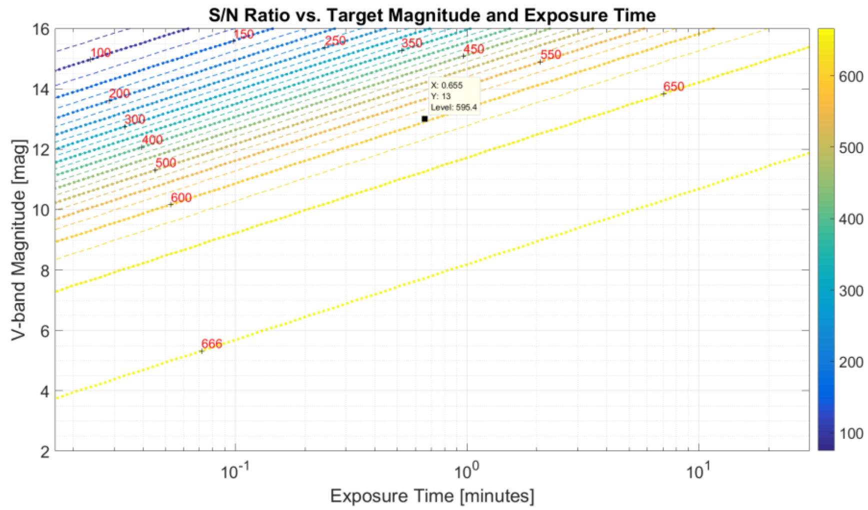


Figure 21: Estimated payload signal to noise ratio with respect to target visual band magnitude and exposure time. Note the peak signal to noise ratio of ~660 due to the finite flat-fielding accuracy. Note the logarithmic x-axis for exposure time.

Preliminary Baseline Instrumentation

One specific imaging instrument investigated for the space telescope was a space-qualified four-megapixel 3DCM734-1 CMOS camera sensor from 3D Plus. The sensor is available in either a Bayer filter configuration or a monochromatic configuration, though the monochromatic configuration is more suitable for astronomical applications, and is rated for a total ionizing dose of at least 40 kilorads. The sensor is integrated to an onboard FPGA and storage module for preliminary image processing such as averaging, adding, and multiple windowing [16]. The 5.5 micron pixel pitch sensor is capable of imaging in either 10 bit or 12 bit modes, with varying frame rates achievable in either mode from 7 frames per second to 16 frames per second and outputs images via LVDS output. A graph of the sensor's spectral response depending on monochromatic configuration is shown below.

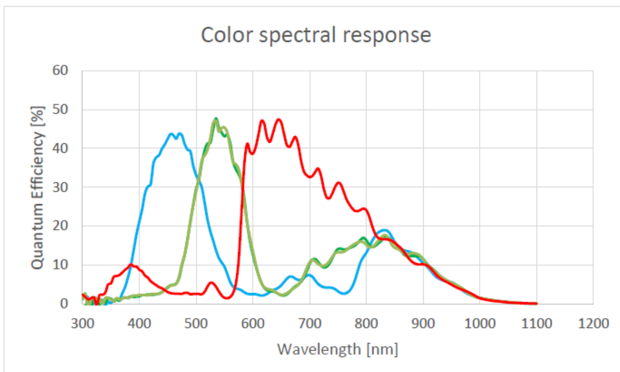


Figure 22: 3D Plus CMOS space camera spectral response. Colors correlate to red, green, and blue Bayer configuration pixels, respectively. The green curve was used to characterize system performance. Monochromatic configurations use one of the respnse curves shown above.

A similar-sized sensor offered by Teledyne e2v is the CCD47-10 [17], a 1024 by 1024 pixel full-frame CCD imaging sensor. With a pixel pitch of 13 microns, an approximately equivalent instrument area is offered, with superior broadband wavelength responsivity than the 3DCM734-1. Larger potential sensors are available from e2v, such as the CCD42, but would require further analysis to verify the feasibility of full-field imaging using the current optical configuration. A figure of this sensor's spectral response is shown below. Note the higher

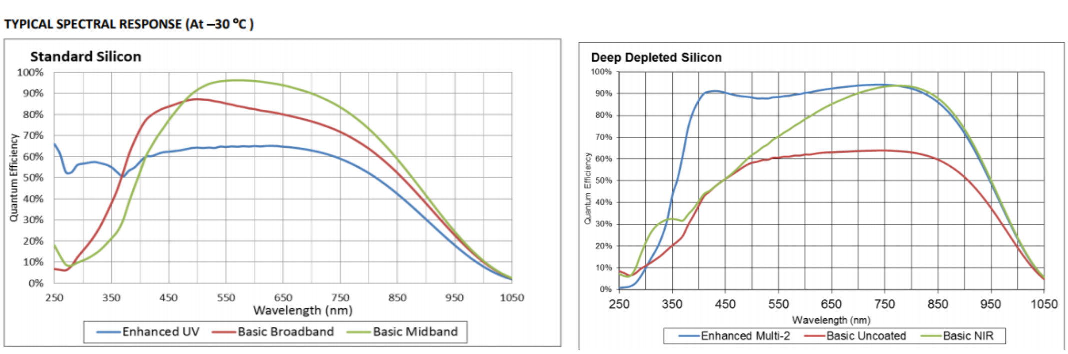


Figure 23: Teledyne-e2v CCD47-10 NIMO back-illuminated sensor spectral response, for two different substrate configurations and different surface coatings.

performance over a broad wavelength range compared to the above CMOS sensor.

Although CCD systems have more heritage in astronomical applications, recent strides in CMOS sensor development have made them more competitive with CCD sensors in certain applications. However, CMOS sensors suffer from nonuniform response due to inconsistent analog-digital conversion between pixels, despite their relatively higher readout rate. However, CMOS sensors allow the selected readout of sub-fields of the entire sensor, and the 3DPlus CMOS camera head is capable of windowing multiple areas of a full frame for independent readout. This capability is not available to CCD sensors, as they require the readout of a full frame from the sensor due to their architecture. Additionally, the independent readout capability of CMOS sensors offers antiblooming capability, minimizing noise and crosstalk due to overexposure. The low readout noise capabilities of CMOS sensors also make them advantageous for rapid integration times, which has been leveraged to increase fine pointing accuracy for the ASTERIA mission [18].

Options for Future Instrumentation

To determine the feasibility of imaging instruments that could provide spectral resolution not achievable by ground-based instruments, other space-qualified instruments were investigated as possible options for future telescopes. Instruments with infrared and ultraviolet imaging capabilities have been proposed for use in CubeSat-based space missions, though there are other space-qualified instruments that may be suitable for payload development that have not been integrated and flown in previous CubeSat missions.

If a feasible thermal configuration can be designed, an instrument capable of imaging in infrared up to M band (4.7 micron) could be integrated into a suitable optical payload. Teledyne Imaging Sensors' H1RG sensor has recently been qualified for space applications to a Technological Readiness Level of 9 [19]. At least three different variants of this focal plane array are documented in TIS's specifications, with cutoff wavelengths of 1.75 microns, 2.5 microns, and 5.3 microns, with effective operating temperatures of 120 kelvin, 77 kelvin, and 37 kelvin, respectively.

It is not expected that an instrument required to have an operating temperature below 80 kelvin could achieve and maintain this temperature through passive cooling alone, and some manner of active cooling would be required. Lockheed Martin has been developing a small cryocooler intended for use in a CubeSat imaging platform [20], but the estimated cold temperatures it is being designed for range from 105 to 150 kelvin. Future technological development or a custom design may be required to develop a feasible thermal configuration for a mid-wave infrared imaging instrument. Additionally, ITAR restrictions on some infrared sensors may restrict system launch options from considering non-U.S. launch providers.

For obtaining imaging data in ultraviolet bands, space-qualified CCD sensors can be used for imaging wavelengths from the visible band to near-ultraviolet wavelengths. At least two proposed CubeSat missions, CUTIE [21] and CUTE [22], intend to perform ultraviolet astronomy surveys using CCD sensors manufactured by Teledyne e2v, and are proposed to be capable of imaging at limiting wavelengths of 240 to 260 nanometers in ultraviolet bands. Other sensor systems, such as electron-multiplying CCDs and multichannel plate instruments, may enable further expansion of ultraviolet imaging, down to wavelengths as short as 150 nanometers, such as the payload configuration for the proposed SPARCS mission [23], although such a short wavelength was not considered in the initial baseline optical design. For specialized operations in the near ultraviolet, the predicted payload performance is shown in the figure below. Further optimization of this payload could offer improved optical performance in the near ultraviolet band without compromising performance at longer wavelengths.

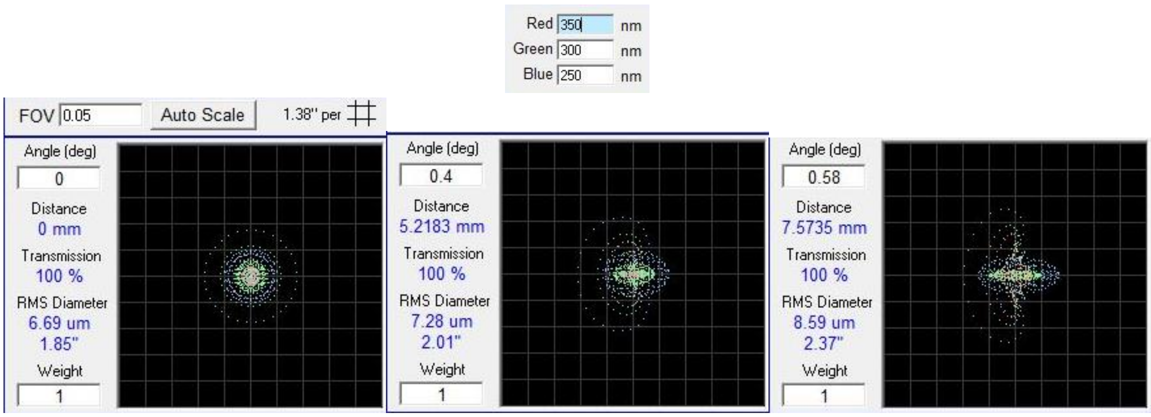


Figure 24: Near ultraviolet performance of baseline optical payload.

Bus Design Considerations

Introduction

To satisfactorily accomplish the science goals while meeting safety and launcher requirements, bus design was considered from an early stage. Several key driving requirements were identified as shown in Table 3. During the initial analysis, each subsystem was considered to ensure that current commercial capabilities can satisfy science needs. The individual subsystems are described in detail below.

Subsystem Considerations

Communications Subsystem

The communications subsystem will enable ground communication with the space telescope, permitting image, science, and telemetry data to be downlinked from the spacecraft, while permitting target schedules and commands to be uplinked. Hardware selection for this subsystem is dependent on the required data rate for downlinking data from the telescope. Several options have been investigated.

Table 3: Key subsystem requirements for bus design

Subsystem	Requirement	Solution	Additional Comments
Communications	Data Rate	S-band upgrade/image processing	Applies requirement to C&DH for onboard data processing
Attitude Determination and Control (ADC)	Pointing	Mission dependent	Mission dependent
	Stability	Mission dependent	Maintain pointing on target
	Desaturation	Magnetorquer	Propulsive system reduces system lifetime
C&DH	Onboard Processing	Additional hardware	Selection not made yet
Power	Power Generation	Deployable Solar Panels	Deployables add complexity, but solutions exist
Thermal Control	Focal Plane Temperature	Limit Conductive paths, insulate from internal radiation	Mission dependent
Structures	Center of Mass Location	Add mass to telescope tube	

S Band

S-Band represents an attractive option and allows for data downlink with minimal impact on science. 2 Mbps is achievable for readily available equipment and allows for an imaging duty cycle of around 50%, per Appendix A. This is the recommended solution for data collection backbone. Preliminary analysis suggests that for a small number of satellites in a constellation, there should be as many ground stations as there are satellites. Furthermore, a number of commercial options exist in this band for extending both pass frequency and duration. One such example is the KSAT network [24] which allows for S-band access on polar orbits 1-2 times per orbit, or every 45 minutes.

Laser Communications

Laser communications promises to provide much higher data rates than traditional radio communications systems. The OCSD mission [25] has demonstrated downlink speeds of over 100 Mbps in its primary mission. This option would drastically reduce the amount of time needed to downlink data and reduces the number of ground stations necessary as well as increasing the possibility for science.

VHF/UHF Band

The VHF/UHF band is not considered as a downlink option due to the low practical data rates that are achievable; on the order of 1-10 kpbs. This results in at best one image per downlink pass without significantly reducing science data quality. However, VHF/UHF bands are adequate for command uplink and to act as beacons.

Command & Data Handling Subsystem

A number of commercially available boards may be used for the command and data handling because the communication subsystem provides a more restrictive cap on the data generation than does the computer system. Most off-the-shelf options contain enough processing power to run a payload system, Linux-based operating system, and flight code; these options can additionally provide enough storage for science data without requiring onboard processing.

Attitude Determination and Control Subsystem (ADCS)

The attitude determination and control subsystem is responsible for controlling the spatial pointing and slewing of the space telescope based on commands from the onboard guidance system. Fine pointing at targets for performing observations will be required to minimize signal interference due to jitter of the image focused on the science instrument's sensor, and the XACT module manufactured by Blue Canyon Technologies [26] has been investigated as a viable component for performing this system's function. The XACT module is equipped with two onboard star trackers for fine attitude knowledge, and onboard reaction wheels will be capable of slewing the spacecraft with a maximum possible slewing speed of 10 degrees per second. Further analysis will be required to characterize the jitter requirements for spacecraft designed to satisfy the science objectives of the system.

To achieve finer pointing than can be achieved by spacecraft attitude control systems, a potentially viable solution utilized for similar CubeSat missions, such as the ASTERIA mission from NASA's Jet Propulsion Laboratory, is active stabilization. A CMOS sensor with a high frequency readout capability would serve as an effective sensor for such a controller, and actuators such as tip-tilt mirrors and piezoelectric-actuated image sensor assemblies have been proposed as such image stabilization mechanisms. The ASTERIA mission [18] payload utilized active sensor stabilization with piezoelectric actuators to achieve finer pointing than could be achieved by the reaction wheels and attitude control system alone, though further refinement of the space telescope's pointing capabilities without active image stabilization will determine if such stabilization is required for the proposed space telescope network. Additionally, image registration of subsequent exposures can be leveraged on large samples of stacked images, though this performance may be constrained by the capabilities of CubeSat-sized image processing systems.

Thermal Subsystem

The thermal control subsystem's primary purpose is to maintain spacecraft hardware within a specified temperature range for performance or survival. For best imaging, the payload should be kept cold to reduce the amount of thermal noise. Cubesats routinely record external temperatures between -10 and +45 C, so the payload camera must be kept thermally isolated from the bus as much as possible [27]. This can be achieved by a combination of passive insulation and cold biasing to below the target temperature by attaching dedicated radiators.

Heaters are then used to maintain a precise temperature, as is done on ASTERIA [18]. Thermoelectric coolers are also capable of removing heat from components using the Peltier effect, allowing for precision temperature control [28]. For components that require higher temperatures than ambient, such as during eclipse, heaters may be used to maintain operating conditions.

Power Subsystem

The power subsystem must keep the spacecraft operational for all phases of the mission and should be sized for end-of-life (EOL) considerations. Expected power requirements for invidual subsystems are listed in Table 4 below. Single-deploy solar panels on a 12U can generate power in excess of 65W, and more complicated geometries available can generate sufficient power on smaller platforms [29], [30]. If the solar panels do not point towards the sun during science missions, the platform can also use battery power as needed and will have a dedicated recharge cycle outside of science. The batteries are sized based on eclipse time and expected lifetime.

Table 4: Key parameters for power consumption

Subsystem	Component	Power ON (W)	Additional Comments
Communications	LG Antenna	10	
	Transceiver	5	
Thermal Control	Coolers	10	
	Heaters	1	
C&DH	Computer	5	Selection not made yet
GNC/ADCS	Star Tracker	1	Available data sheet
	IMU	1.5	Available data sheet
	Sun Sensor	0.007	Available data sheet
	BCT XACT Module	10	Available data sheet
	GPS	0.5	Available data sheet
Total		44.007 (Peak)	

Characterizing the tradeoffs between communication data rate, onboard storage requirements, onboard processing requirements, and the power required for all these operations and considerations remains a high-priority action item for further defining the system concept.

7. CAN Development Program

PolySat Involvement

PolySat students under faculty supervision would perform space system design, assembly, integration, testing, and program-level operations. PolySat is a student-run research lab located on-campus at California Polytechnic State University in San Luis Obispo. The lab provides opportunities for students to acquire hands-on experience in developing, assembling, and operating satellites designed per the CubeSat standard. PolySat has spent over a decade partnering with research organizations, such as NASA’s Goddard Space Flight Center and

NASA’s Earth Science Technology Office in order to offer multidisciplinary research and development project experience to students interested in developing CubeSat systems [31].

Design

It is anticipated that a relatively small team of undergraduate and graduate students, working with guidance from academic and industry professionals on an advisory basis, could complete a preliminary design and a finished detailed for a Student Space Telescope demonstration mission if sufficient funding could be acquired. Students with prior experience in space systems engineering, mission design, and subsystem design disciplines would be particularly valuable for ensuring constant development progress, and they should be capable of self-organization and project management without requiring constant direct supervision by dedicated industry or academic personnel. A team of at least ten experienced students may be sufficient for detailed system design, with careful selection of candidates and team members to provide the unique necessary skillsets for detailed design.

Assembly

Upon completion of preliminary design and progression into detailed system design, a similarly-sized team should be capable of assembling a demonstrator spacecraft for launch. For performing qualification system testing, an engineering prototype unit would be assembled and tested according to the CubeSat Design Specification. The estimated amount of time required for fabrication of flight hardware is expected to last two years.

8. Operations

Introduction

The proposed CubeSat Astronomy Network program organization and operational approach are presented below.

Operational Consortium

The CubeSat Astronomy Network program is fundamentally intended to offer astronomical research opportunities to students. Because of this emphasis on student end use, and in order to reduce development and operational costs for the program, it was decided to promote student involvement in designing, analyzing, testing, and operating system elements that would be utilized in the program. It is anticipated that a consortium of participating universities and research organizations would allow the benefits of low-cost access to space for astronomical research to be most fully realized; such a dedicated organization would be effective at determining, prioritizing, and scheduling compelling scientific targets for system observation. The role of observation prioritization and scheduling for the end use of students to utilize for astronomical research would be the key system allocation within the overall system architecture.

NASA Launches and Potential Involvement

A number of external organizations and programs have been identified as potentially valuable partners, and some have been identified as valuable potential sources of funding and support. Several NASA programs and research centers would be capable of lending support in the achievement of the proposed program's objectives.

NASA's CubeSat Launch Initiative [32], which releases annual Announcements of Opportunity for CubeSat-scale missions, provides development and planning support to payloads which demonstrate their merits and capabilities in achieving the agencies objectives, and will cover launch costs for eligible missions.

NASA's Ames Research Center has also been identified as another promising organizational partner for the proposed program. NASA's Small Satellite Technology Program (SSTP), a major program managed within NASA's Space Technology Mission Directorate, offers SmallSat Technology Partnerships, which permit collaboration with universities for technology development and demonstrations [33].

NASA's Jet Propulsion Laboratory (JPL) has been involved in several nanosatellite-based space missions and has recently launched a CubeSat-based astronomy space mission called the Arcsecond Space Telescope Enabling Research in Astrophysics, or ASTERIA [14]. Potential collaboration, due to JPL's prior experience with similar missions, would be highly desirable for ensuring program success.

For program funding, several NSF programs have been identified as viable candidates for involvement. Astronomy and Astrophysics Research Grants may be utilized for funding undergraduate research efforts utilizing the proposed system, though it is not known how suitable the scope of designing and constructing the system would align with the prior scope of work funded via those grants, due to their focus on student research applications. Several other NSF programs, such as the Research Experience for Undergraduates and Research in Undergraduate Institutions programs offer potentially viable research awards.

Ground System and Communications

For the duration of the program, the operators must be able to establish contact with satellites for data and health checkups. Ground stations must be included in an effective manner to facilitate these operations. For the initial demonstrator mission, the primary facility in use could be the PolySat ground station, located in San Luis Obispo, California. In order to achieve the required data rates, the ground station would need to be upgraded to communicate in the S-band (2-4GHz). This is achievable with off-the-shelf systems and does not represent a large upfront cost [34].

For future expansion, a network of ground stations will be required. There are several available. The most attractive consists of partnering with other universities and academic research facilities. This falls squarely within the goals of the program, to extend the opportunity to do scientific research to undergraduate institutions. Currently, several partnerships exist in several forms: university partnerships for single missions routinely provide access and use of each others' capabilities. Other options include purchasing time on government dishes, such as NASA's Near-Earth Network [35], or communicating with other satellites which act as relays, such as the GlobalStar network [36].

Baseline Link Budget

In order to ensure that data may be downlinked, a baseline link budget has been implemented as is shown in Appendix A. This preliminary budget shows that the link is expected to close for reasonable pointing errors and commercially available systems on both the transmitter and receiver ends. The hardware used consists of the ISIS S-band ground station for receiver, an Endurosat patch antenna for transmit, and a Blue Canyon XACT module for pointing errors.

Operational Modes

During nominal operation, each satellite in the CAN will route through standard modes of operation. Each satellite is powered off before launch and may only be activated at minimum 30 minutes after deployment from the dispenser, either through timer or acquisition of command signal. After deployment and initial checkout, the primary mission may begin. The following section describes what each mode may look like for a satellite in the constellation.

Launch (unpowered)

During launch the system will not perform any function as required by the launch provider.

Post deployment mode

This mode will consist of attitude determination, solar panel deployment, and deployment of any additional peripherals. During this time the batteries will be charged until acceptable levels for data collection.

Recharge mode

When necessary, the satellite will orient itself so that its solar panels face the sun, recharging the batteries. During this time onboard desaturation will spin down the reaction wheels to acceptable levels so that science may continue.

Science Mode

Imaging of targets occurs in this mode. The satellite will slew towards its previously-selected targets and take exposures. While new exposures are being taken, images may be processed and analyzed onboard. Data is then stored ~~in~~ onboard ~~storage~~. As necessary, the system may perform sensor calibration and store the results for later analysis.

TX/RX Mode

In this mode, the satellite will downlink data to the ground station. This includes telemetry, calibration, images, and diagnostic data. At this time, the next observation set will be uploaded for the next round of science data. As telemetry comes in, the operator may force a specific mode (i.e. recharge mode if batteries drain more quickly than anticipated).

Safe Mode / Safe Tumble Mode

This mode occurs whenever the satellite fails a health check. This is triggered by any one of a variety of watchdogs that compare current operations to safe mode triggers. Depending on the type of failure, this can be mitigated autonomously, but must be logged and downlinked in the next transmit phase.

Observing Time Allocation

To schedule and prioritize observations, students will submit proposals to a time allocation committee, similar in structure and function to ground-based observatories. If a proposal's intended observations are deemed feasible and necessary, a scheduling algorithm will append those observation times and targets to a systemwide observation schedule and determine the required operations to facilitate observation by one or more telescopes as necessary. A diagram of the user proposal flow is shown below.

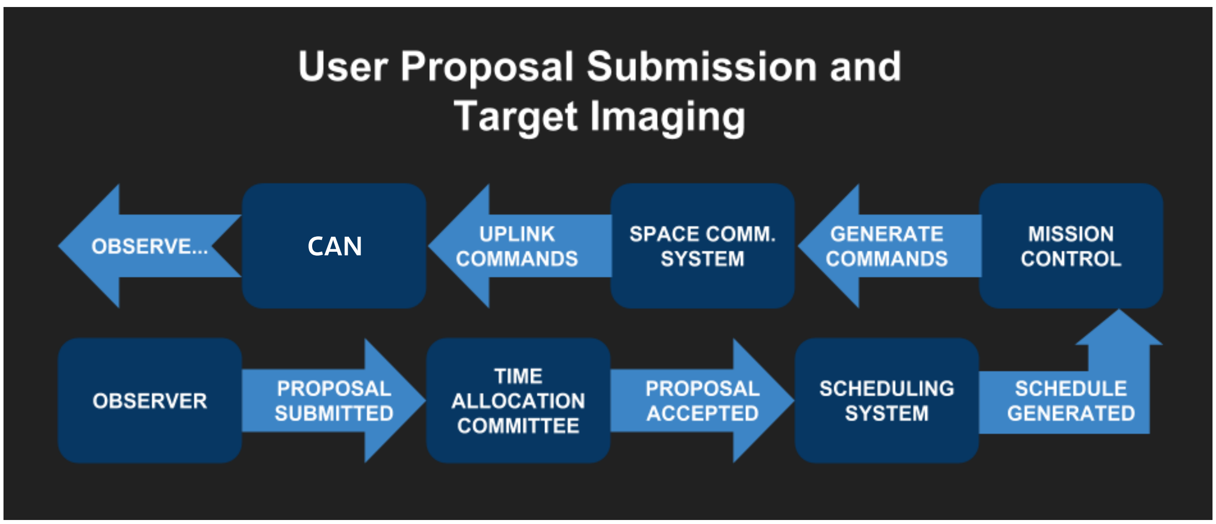


Figure 25: Observer proposal submission and observation process flow.

Science Data Flow and End User Access

In order to make data access simpler, it is worth considering cloud-based storage solutions such as Amazon Cloud. This costs a negligible amount ($60/yr per 1TB) and could provide a platform for students from all over the world to access data quickly and reliably. In addition, telemetry and health data could be easily visualized using open-source software: OpenMCT is already used for missions at PolySat and has heritage for satellite operations [37].

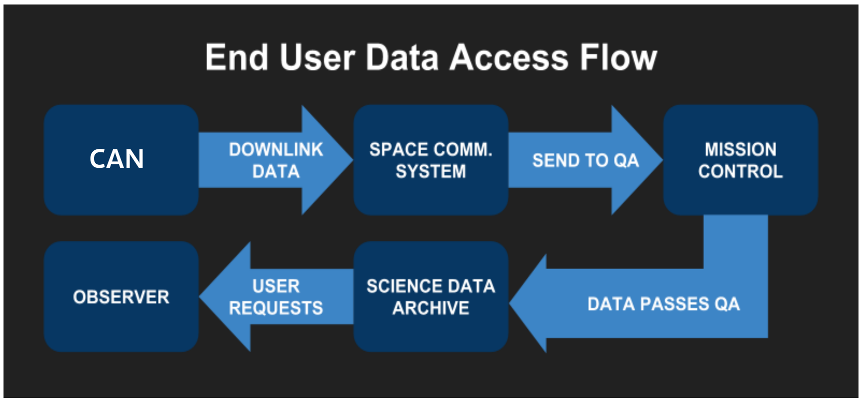


Figure 26: End user data access process flow.

For end users to access science data obtained by the network, data obtained and verified by the network would be uploaded to a science data archive after verification of successful data obtainment, as shown in the figure above.

End of Life Plan

The CubeSat specification requires that all missions not pose a threat to other spacecraft or to human lives. To that end, each satellite must show a plan to deorbit in under 25 years or at the expected end-of-life. The current orbit selection of 500-600 km sun-synchronous orbit will result in a baseline satellite lifetime of 10-20 years before orbit decay. Other options for end-of-life disposal also exist, such as deployable drag sails to increase the effect of atmospheric drag. A similar option includes orienting the spacecraft such that the solar panels maximize drag and maintaining that attitude until orbit decay. Finally, if onboard propellants are utilized, the system could burn any excess to force itself down into lower altitudes. All of these options show that the system could safely meet end-of-life criteria.

9. Proposed Program

Schedule

Program development is proposed to consist of four phases of development up until system deployment, operation, and replenishment or program completion.

Phase One consists of concept formulation and analysis as detailed in this current report. This report is part of Phase I.

Phase Two will consist of an approximately ten-month study, with a CubeSat Astronomy Network Workshop to be held at Cal Poly in San Luis Obispo. The final deliverable for Phase Two will consist of a preliminary design review for the proposed CubeSat Astronomy Network, along with supporting documentation. It is anticipated that a final report of the preliminary design could be made avilable before the end of 2019.

Phase Three will consist of detailed design, fabrication, testing, integration, and deployment of a demonstrator system, with demonstrator operations taking place for one year to verify system performance and generate preliminary science data before full system implementation. During this phase, a critical design review would likely be required before progression into flight hardware fabrication and testing, and ground station development and testing. Before flight hardware integration, readiness reviews to verify operational readiness and flight readiness would take place. Once the demonstrator spacecraft has been integrated to its deployer and delivered to the launch service provider, the provider would integrate the payload to the vehicle, and launch the system. Upon successful deployment and performance of on-orbit checkout and ground system checkout, the system would proceed with mission operations. It is anticipated that Phase Three would take about 3 years.

Phase Four would involve conducting mission operations and replenishment or expansion of the existing system, including adding new spacecraft with potentially expanded capabilities capable of supplementing initial science capabilities. Constellation deployment and operation, with the associated fabrication, testing, integration, and deployment would take place during this time, and peak science productivity could be achieved with complete system deployment. It is expected that sustained system operation during Phase Four could continue for several decades if funding could be obtained to sustain such a program, though further work may be required to expand system capabilities to maximize system longevity. It may be possible to perform a system refurbishment review at the end of Phase Four to implement an improved system with future technologies, or the existing system could continue operation with replenishment until the end of life when in-orbit hardware is safely disposed.

Cost Estimate

A rough cost estimate for proposed program elements is shown in the table below. The data shown below do not necessarily reflect the final actual cost of the system. “PolySat” refers to CubeSat development services that can be provided by PolySat with student involvement, and “CSLI” refers to launch costs that can be covered by acceptance as a CubeSat Launch Initiative mission candidate. Operational and maintenance costs have yet to be determined. Cost values with an asterisk (*) represent order-of-magnitude estimated one-time non-recurring costs per unit, and do not necessarily represent the true total cost of the system.

Category	Item	Cost (est.) [$M]	Source
Development	Concept Development	0.5*	
Per Unit	Components	0.5*	
	Fabrication	0.01*	
	Assembly	0.1*	
	Testing	0.1	
	Integration to Deployer	0.01*	
	Launch to LEO SS Orbit	1.0*	http://spaceflight.com/schedule-pricing/#pricing
	Total (+50% margin)	2.58	
	Total (w/ CSLI launch and 50% margin)	1.58	
Full Constellation (3 satellites)	No CSLI Launch	7.74	
	w/ CSLI Launch	4.74	
Ground Segment	PolySat Ground Station Upgrade	0.061	https://www.cubesatshop.com/product/full-ground-station-kit-s-band/

10. Conclusion

Due to the potential value of demonstrating the feasibility of the technology and science capabilities of the proposed program, it is recommended that system development and feasibility analysis proceed over the course of the next year. It is further recommended that a team of undergraduate students be organized and tasked with developing a preliminary design for the proposed system and present their findings.

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Appendices

Appendix A

Item	Units	Source	Value	Comment
Frequency	GHz	Input	2.5	S band, based off of ISIS ground station
Transmit Power	Watts	Input	4	Input
Transmit Power	dBm	10 log(P)	36	Calculated - adjusted from dBW to dBm
Transmit Line Loss	dBW	Input	-1	Assumed
Transmit Antenna Beamwidth	deg	Input	71	Based off of Endurosat patch antenna specs
Peak Transmit Antenna Gain	dBi	Input	6	Based off of Endurosat patch antenna specs
Transmit Antenna Pointing Offset	deg	Input	7.1	Assume 10% Beamwidth (SMAD) - Orbit/Gimbal/ADCS
Transmit Antenna Pointing Loss	dB	Eq. (13-21)	-0.1	Assumed pointing error (XACT achievable)
Transmit Antenna Gain (net)	dBi	Gpt + Lpt	1	Calculated - Sum of gains
Equiv. Iso. Radiated Power	dBW	P + Ll + Gt	1	Calculated - Sum of gains
Propagation Path Length	km	Input	1500	Given - Orbit (L1 + furthest distance during orbit)
Space Loss	dB	Eq. (13-18a)	-168.1	Calculated - Orbit
Propagation and Polarization Loss	dB	Fig. 13-10	-2.2	Assumed
Receive Antenna Diameter	m	Input	2	Based off of ISIS ground station
Peak Receive Antenna Gain	dBi	Eq. (13-23a)	35.4	Based off of ISIS ground station
Receive Antenna Beamwidth	deg	Eq. (13-19)	1	Calculated - Dish Geometry
Receive Antenna Pointing Error	deg	Input	0.1	Assumed 10% Beamwidth
Receive Antenna Pointing Loss	dBi	Eq. (13-21)	-0.1	Assumed pointing
Receive Antenna Gain	dBi	Grp + Lpr	35.3	Calculated - Sum of gains
System Noise Temperature	K	Table 13-10	320	Assumed
Data Rate	kbps	Input	1670	Calculated - Data per day, found below
Eb/No (1)	dBi	Eq. (13-13)	17.3	Calculated - Link Equation
Carrier-to-Noise Density Ratio	dB-Hz	Eq. (13-15a)	79.5	Calculated - C/No Equation
Bit Error Rate		Input	10^5	Assumed
Required Eb/No (2)	dB	Fig. 13-9	9.6	BER-Mod Figure, based on coding

Implementation Loss (3)	dB	Estimate	-2	Assumed
Margin	**dB**	**(1) - (2) + (3)**	**5.7**	**Typical (4-7)**
Time Overhead	**min**	**Orbit**	**5**	**Assumed**
Data per day	**Mb**	**Payload**	**500**	**Cadence - Assumed Compression 2:1**

Appendix B
Key Parameters for Photometric Signal to Noise Analysis

Parameter	Value	Units
Primary Mirror Diameter	18.5	cm
Secondary Mirror Diameter	7.2	cm
Pixel Scale	1.52	arcsec / pixel
Point Spread Function FWHM	0.63	arcsec
Pixel Aperture Diam.	6	pixels
Read Noise	10	e-/s/pixel
Dark Current	2	e-/s/pixel
Sky Background	24	Magnitude / arcsec^2
Flat-fielding Error	0.15	% of signal
Filter Trans. (450-650 nm)	60	%

Appendix C
Example Pass Times

Access Start (d-m-y)	Access start (hh:mm:ss)	Access End (d-m-y)	Access End (hh:mm:ss)	Duration (s)
25 Sep 2018	7:32:14 PM	25 Sep 2018	7:44:38 PM	743.76
25 Sep 2018	9:09:54 PM	25 Sep 2018	9:15:40 PM	345.991
26 Sep 2018	4:46:54 AM	26 Sep 2018	4:52:04 AM	310.438
26 Sep 2018	6:17:37 AM	26 Sep 2018	6:29:58 AM	741.083
26 Sep 2018	7:54:38 AM	26 Sep 2018	8:04:03 AM	564.334
26 Sep 2018	6:02:25 PM	26 Sep 2018	6:11:57 PM	571.848
26 Sep 2018	7:36:33 PM	26 Sep 2018	7:48:53 PM	739.794
26 Sep 2018	9:14:34 PM	26 Sep 2018	9:19:27 PM	293.628
27 Sep 2018	4:50:43 AM	27 Sep 2018	4:56:43 AM	359.915
27 Sep 2018	6:21:53 AM	27 Sep 2018	6:34:17 AM	744.761
27 Sep 2018	7:59:13 AM	27 Sep 2018	8:08:10 AM	537.382
27 Sep 2018	6:06:34 PM	27 Sep 2018	6:16:29 PM	595.228
27 Sep 2018	7:40:53 PM	27 Sep 2018	7:53:08 PM	734.873
27 Sep 2018	9:19:21 PM	27 Sep 2018	9:23:08 PM	227.28
28 Sep 2018	4:54:36 AM	28 Sep 2018	5:01:18 AM	402.006
28 Sep 2018	6:26:09 AM	28 Sep 2018	6:38:37 AM	747.5
28 Sep 2018	8:03:49 AM	28 Sep 2018	8:12:16 AM	507.126
28 Sep 2018	6:10:44 PM	28 Sep 2018	6:21:00 PM	616.245
28 Sep 2018	7:45:14 PM	28 Sep 2018	7:57:23 PM	728.975
28 Sep 2018	9:24:24 PM	28 Sep 2018	9:26:31 PM	126.668
29 Sep 2018	4:58:32 AM	29 Sep 2018	5:05:51 AM	438.819