EXOPLANETSAT: HIGH PRECISION PHOTOMETRY FOR EXOPLANET TRANSIT DETECTIONS IN A 
3U CUBESAT

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ExoplanetSat is a 3U CubeSat which will detect transiting “superEarth” exoplanets around bright, nearby sun-like stars. The ExoplanetSat prototype will focus on stars with low-mass planets (discovered by radial velocity planet-finding surveys)—planets which are not yet known to transit. No other current ground or space-based mission is capable of observing these systems, one star at a time, over long time periods with the required photometric precision to detect small planet transits. Eventually, many copies of the ExoplanetSat prototype and larger-aperture versions will be launched to survey the brightest sun-like stars in the sky for small, long-period planets like Earth.

ExoplanetSat will observe 55 Cancri e, a 2 Earth-radius planet transiting a bright sun-like star with an 18 hour period, as its validation case. Photometry with 40 part-per-million (ppm) precision is required to detect the 55 Cancri e transit with 7-sigma certainty. ExoplanetSat will achieve this goal through a novel two-stage pointing system capable of 20 arcsecond pointing (3 sigma). The system consists of a traditional reaction wheel and torque coil unit from MAI which provides coarse pointing to 120 arcseconds and a fine pointing piezoelectric stage which adjusts position of the focal plane to compensate for pointing drift. Such fine pointing is required to control the location of the star spot centroid on the detector to the same fraction of a pixel over many minutes to reduce noise from interpixel and intrapixel sensitivity variations. ExoplanetSat employs a hybrid focal plane composed of two CMOS detectors to perform three critical tasks: precision photometry for scientific measurements; “lost in space” attitude determination based on star patterns; and fine attitude control through rapid star centroid tracking.

ExoplanetSat has been awarded a launch through NASA’s ELaNa program. This paper will describe ExoplanetSat’s scientific mission, target selection, and the engineering innovations required to meet the science goals of the mission, with a focus on the optical payload and ADCS system.

I. INTRODUCTION

CubeSats have been a boon to university research engineering and education programs. With CubeSats, students at the undergraduate and graduate level have the opportunity to build real flight hardware and see their design through to launch. CubeSats are now beginning to evolve beyond educational tools to impactful science missions.

CubeSats offer a unique opportunity to scientists. Unlike general-purpose observatories and space science missions which can be shared between hundreds of observers, CubeSats can be tailored to a very specific science goal. CubeSats can contribute impactful science if a systems approach is taken to their design. Unlike traditional space systems where the scientific payload and spacecraft bus are developed in relative isolation from one another, CubeSats must be designed toward their scientific mission from the very beginning. ExoplanetSat is an example of such a mission. Each subsystem was designed specifically to achieve the scientific
II. SCIENTIFIC MOTIVATION

One of the main motivating goals of exoplanet science is the discovery of a planet like the Earth that may be capable of supporting life. ExoplanetSat will identify Earth-sized planets around nearby Sun-like stars. Once Earth-sized planets in Earth-like orbits around bright stars are identified, follow-up spectroscopy with more capable telescopes can determine the composition of their atmospheres.

In this paper, we discuss the ExoplanetSat prototype, which will search for transits of known planets discovered by the radial velocity method, as well as the long-term goal of an ExoplanetSat constellation which will survey all bright, nearby stars for transiting Earth-size exoplanets.

II.I Transiting Exoplanets

In recent years, hundreds of exoplanets (planets orbiting stars other than the sun) have been discovered. At the time of writing, the count stands at 838 planets (1). Several detection techniques are used to search for exoplanets. The radial velocity method measures small Doppler shifts of the star’s spectral lines caused by the star’s motion in response to a planet’s gravitational tug. The transit method uses time series photometry to detect the small change in brightness that occurs when a planet passes across the disk of its star and blocks some of the star’s light. Transit timing variations can also reveal additional unseen planets in the system through their influence on a transiting planet’s orbit. The microlensing technique also uses time series photometry to detect changes in the brightness of a background star as a foreground planet’s gravity creases a gravitational lens. Direct detection and imaging of planetary systems has been performed as well, but only planets far from their stars. Direct imaging is not yet feasible for planets in Earth-like orbits. This paper focuses on the transit method. Figure 1 shows the planets detected to date color-coded by the method used to detect them.

Figure 1 - Exoplanets detected to date. Radial velocity and transit have produced the majority of detections.

An exoplanet “transits” when it crosses the disk of its host star from the perspective of an observer. Even the largest telescopes cannot spatially resolve the disk of stars other than the Sun, so an exoplanet transit cannot be observed in the same way as the recent transit of Venus. Rather, an indirect measurement must be made. The transiting exoplanet blocks a portion of the host star’s light as it passes in front of the star. This results in a small change in the star’s apparent brightness which can be measured by telescopes either on the ground or in space. The change in the star’s brightness is equal to the planet-star area ratio. Transit light curve data (see Figure 2) provides a measurement of an exoplanet’s radius and orbital period. When this data is coupled with a mass measurement from radial velocity observations, the planet’s mean density can be calculated as well. The planet’s density can be used to infer its composition.

Figure 2 - Transit light curve. The depth of the transit corresponds to the ratio of the planet area and star area. The length between transits is the planet's orbital period. Image credit: John Johnson.

ExoplanetSat is a targeted search mission which will observe individual bright Sun-like stars (visual magnitude < 7) for transit signatures. The first
The low cost of CubeSats enables such observations to detect planets with Earth-like periods (0.5 – 2 years). The eventual ExoplanetSat prototype will observe stars with known high-quality photometry unhindered by the Earth’s atmosphere, and conduct observations for longer durations than is feasible with existing in-demand space observatories.

NASA’s Kepler observatory is a space-based telescope that can provide much better photometric precision than ground-based telescopes. Kepler has detected thousands of transiting planet candidates (some smaller than Earth) and will likely add many more to that list. Kepler is designed to point at one patch of sky for many years and monitor the brightness of ~150,000 stars simultaneously. This large sample is critical to Kepler’s statistical goal of determining the frequency of Earth-sized planets in the galaxy. The Kepler field stars are relatively dim and far away to prevent detector saturation. These dim stars are not good candidates for spectral follow-up.

Other space-based observatories are capable of high-precision transit photometry on bright stars and have produced excellent transit results. The Spitzer telescope was used to detect the transit of 55 Cancri e, a ~2 Earth radii exoplanet orbiting a 7$^\text{th}$ magnitude star with a period of 18 hours (2), (3). For reference, the $6^\text{th}$ magnitude is generally considered the limit for a star that can be observed from Earth’s surface with the naked eye.

Existing space observatories can perform highly specific, short-duration observations (as Spitzer did with 55 Cancri e), but the high demand for observing time precludes longer duration observations to detect planets with longer orbital periods. The ExoplanetSat prototype will observe stars with known RV planets for weeks to months due to the uncertainties in transit time predictions. The eventual ExoplanetSat constellation will use one spacecraft per star to conduct observations over several years in order to detect planets with Earth-like periods (0.5 – 2 years). The low cost of CubeSats enables such observations even though the probability of a transit detection for each individual star observed is low.

**II.III High Precision Photometry**

The ExoplanetSat prototype will measure the light curve of 55 Cancri to a precision of 43 parts per million (ppm) over the duration of the transit. This precision represents a transit detection significance of 7$\sigma$ for this planet. In the exoplanet community, a transit detection is generally not considered reliable until it reaches the 7$\sigma$ certainty level. Figure 3 shows a simulated light curve of the 55 Cancri e transit with 43 ppm precision over the transit. 55 Cancri e was chosen as ExoplanetSat’s demonstration target because of its bright host star (V = 5.95), small transit signal (~400 ppm), and short orbital period (18 hours). The transit of 55 Cancri e is a well-characterized signal that will be used to refine ExoplanetSat’s data processing pipeline.

![Figure 3 - Simulated data for 55 Cancri e transit. This data set represents 10 transits of the planet that have been folded together for improved precision. Figure credit: Rachel Bowens-Rubin.](image)

High photometric precision can only be achieved by carefully characterizing and mitigating a variety of noise sources in the imaging system. The most relevant noise sources for ExoplanetSat are photon (Poisson) noise, dark current, read noise, and pixel non-uniformity (both between pixels and within a single pixel). Photon noise is due to the quantum nature of photons and the uncertainty in their arrival time. Photon noise is the square root of the photon flux, so collecting more photons drives down the photon noise (increases the measurement SNR).

Dark current is composed of electrons generated by thermal processes in the detector rather than arriving photons. Dark current is strongly dependent on temperature and can be mitigated to an extent by minimizing the temperature of the detector. Dark current can also be subtracted through the use of dark frames but the dark noise remains since dark current

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**Figure 3 - Simulated data for 55 Cancri e transit. This data set represents 10 transits of the planet that have been folded together for improved precision. Figure credit: Rachel Bowens-Rubin.**
is a Poisson process with associated Poisson noise. Read noise is a fixed characteristic of the detector used, although it may have a small temperature dependence. Finally, each pixel has a slightly different sensitivity to arriving photons, creating an uneven gain pattern across the detector.

Interpixel and intrapixel variations are of particular concern for ExoplanetSat and a significant engineering effort has been devoted to the problem. If the image of a star on the detector shifts slightly due to errors in spacecraft pointing, the change in gain caused by uneven pixels can slightly reduce the measured flux and appear to be a transit. For this reason, ExoplanetSat must have very stable pointing to prevent the star spot from wandering around the focal plane. The ExoplanetSat ADCS system is capable of controlling the location of the target star centroid to within 1/10th of a pixel.

Additionally, the target star spot will be intentionally defocused and spread over several pixels. This provides an averaging effect which mitigates the effect of small motions of the target star centroid.

II.IV Observation target selection
ExoplanetSat’s primary observational target is 55 Cancri e. Observations to fulfill the technology demonstration part of the mission will be carried out over approximately 1 month. Once this primary goal has been achieved, ExoplanetSat will move on to its extended science mission.

ExoplanetSat will observe additional bright target stars (V < 8) that host low-mass planets (M < 25 M_Earth). While the minimum masses of these planets have been measured via the radial velocity method, it is not known if these planets transit. Planets in this mass range are referred to as super-Earths or exoNeptunes. Planets less massive than Neptune but more massive than the Earth (“mini-Neptunes”) are (so far) the most common found in the Kepler dataset (4). Mini-Neptunes are of great interest to astronomers and planetary scientists because of their frequency and because their formation is not fully understood. There is no analog for mini-Neptune planets in the solar system. Discovering the transit of even one mini-Neptune planet around a bright star would be a significant result.

Table 2 (see Appendix) lists the complete current target list for ExoplanetSat’s extended mission. The target list will evolve as additional discoveries are made by radial-velocity planet-finding surveys like HARPS (5).

Table 2 includes columns for estimated radii of each planet based on an assumed composition. These radii are plotted in Figure 4. Radii were calculated using formulas found in (6). Assuming a composition of pure iron (Fe), we obtain the smallest possible radius for each planet. The minimum radius for each planet will allow for a definitive negative result for each star – if the star is observed with sufficient precision to detect the minimum mass planet but no transit is observed, we can conclusively state that the planet does not transit. The other compositions included in the table are MgSiO3 (perovskite) and pure water (H2O). These calculations do not include atmospheres, but thin atmospheres will have a negligible contribution to planet radius.

![Figure 4](image)

**Figure 4** - Calculated planet radii for ExoplanetSat extended target list. The planetary radii are plotted against the V-magnitude of their host stars (horizontal axis).

The estimated radius value for each planet was used to calculate the expected its expected transit signal. The expected transit signal divided by 7 gives the precision requirement for a 7σ detection of a planet transit. The next step was to determine which planets on the target list ExoplanetSat could detect at the 7σ level. This precision is not per point but rather for the aggregated transit light curve. Given the expected duration of each planet’s transit, the required per point photometric precision was calculated. Longer-duration transits are beneficial because they allow for more data collection and therefore higher overall precision. Figure 5 shows the results of these calculations.
**Figure 5** - Detectability of ExoplanetSat targets in 1 planet transit. Note that there are 3 icons for each planet on the list. The requirement for an iron planet is plotted as a black circle, the requirement for a perovskite planet is plotted as a red circle, and the requirement for a water planet is plotted as a blue circle.

ExoplanetSat’s total noise over an integration time of 10 seconds is indicated by the solid black line. The open circles represent the noise per measurement required to reach the overall required precision for a $7\sigma$ detection. Each planet appears three times on the plot – one circle each for a composition of iron (black), perovskite (red), and water (blue). If a planet’s circle falls above the black line, ExoplanetSat is able to detect that planet with $7\sigma$ certainty by observing only one transit. Planets that fall below the black line may still be detected, but multiple transits must be observed and folded together to achieve the necessary precision. For planets with long periods, this may not be practical within ExoplanetSat’s 2 year design lifetime. Note that any black circle on Figure 5 that lies above the black curve represents a planet whose transit ExoplanetSat will be able to detect no matter the planet’s composition. If a transit is not observed for such a planet, the planet does not transit and its inclination can be constrained.

**II.V Star Visibility and Transit Window Analysis**

ExoplanetSat will be limited to observations during orbit night. As the Earth moves around the sun, some stars will no longer be accessible to ExoplanetSat due to their proximity to the Sun. Using AGI’s Satellite Tool Kit (STK), ExoplanetSat’s access to each of the target stars was computed. Table 1 lists the assumptions used for these calculations.

**Table 1** - Parameters used in STK simulation to determine ExoplanetSat’s access to each target star.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit altitude</td>
<td>500 km</td>
</tr>
<tr>
<td>Orbit inclination</td>
<td>45°</td>
</tr>
<tr>
<td>Orbit eccentricity</td>
<td>0</td>
</tr>
<tr>
<td>Lighting condition</td>
<td>Umbra only</td>
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<tr>
<td>Lunar exclusion angle</td>
<td>30° from telescope boresight</td>
</tr>
<tr>
<td>Min Earth grazing angle</td>
<td>22°</td>
</tr>
<tr>
<td>Simulation duration</td>
<td>1 year</td>
</tr>
</tbody>
</table>

**Figure 6** shows access time for each star on the list as computed by STK using the parameters in Table 1.

When combined, the coverage times for each star add up to nearly 100% visibility. At least one target star is always available for ExoplanetSat to observe. This is a result of the near-random distribution of bright stars across the sky.

The likely time of transit will also be taken into account in ExoplanetSat observation scheduling. The expected time of transit can be calculated from each planet’s orbital parameters. These parameters are extracted from radial velocity data and there may be large error bars on the values. These error estimates are used to calculate a transit window which represents the most likely period of time when a planet may transit. The combination of these windows with star visibility produces an observation schedule. An example is shown in Figure 7 for one exoplanetary system. Figure 8 shows the transit windows for all of the targets.
During gaps when no transits are visible, ExoplanetSat will collect baseline photometry on any available targets. The baseline flux level of each star must be measured so that the depth of the transit (if/when it occurs) can be measured accurately. Baseline measurements of each star will also reveal any periodic or aperiodic fluctuation in the star's light that could affect transit measurements.

III. EXOPLANETSAT DESIGN

ExoplanetSat's design has been specifically tailored to the science goals described above. The optical payload and ADCS system are not separate from one another as with traditional spacecraft systems. The ExoplanetSat focal plane performs both science measurement and star camera/star tracking functions. Figure 9 highlights the close interaction of all of ExoplanetSat's subsystems.

III.1 Optical Payload

ExoplanetSat's optical payload consists of a commercial lens, a CMOS detector, and a stray light baffle. Photometry will be performed in a broad band spanning the visible range (~400 nm to ~1000 nm).

ExoplanetSat's optic is an f/1.4 85 mm lens. This lens provides a large aperture (6.7 cm) for efficient photon collection. A commercial product was chosen to reduce cost and development time. This particular product, the Zeiss Planar T* 1.4/85 ZF-I, was successfully modified for use in space by researchers at the University of Utah and Naval Research Laboratory (NRL) for use on the International Space Station (7). The wide field of view (~660 square degrees) provided by this refractive optic is necessary for the star camera/tracker portion of the ADCS system as well.

ExoplanetSat employs a CMOS detector rather than a CCD for science measurements. In the past, CMOS detectors were not commonly used in astronomical applications due to poor quantum efficiency and high read noise. Recently, CMOS detectors have evolved significantly and are now a reasonable choice for a high-precision detector. ExoplanetSat’s science imager, the HAS-2 from ON Semiconductor, is designed specifically for star tracker applications. The HAS-2 has a quantum efficiency (maximum) of 45% and its read noise is 75 e-/pixel/read (8).

Though CMOS detectors are not yet equivalent to the best astronomical CCDs, they do offer other benefits that are critical to ExoplanetSat. First, CMOS readout electronics are much more compact than CCD readout electronics. CCD readout electronics would break ExoplanetSat’s volume budget. CMOS detectors are designed for room temperature applications, so they do not require cooling to the same extent as CCDs. With a
CubeSat’s limited power budget, adding a thermoelectric cooler (TEC) to the ExoplanetSat design to accommodate a sensitive CCD was a nonstarter from a power and volume perspective. CMOS technology is also generally more tolerant to radiation than CCDs. Radiation induces charge transfer inefficiencies in CCDs, significantly reducing their performance. CMOS detectors are read out at the pixel, so there is no need to transfer charge across the detector. The HAS-2 imager is guaranteed up to 42 krad and has been performance tested up to 300 krad (8). Finally, the ability to read out windows of a CMOS detector at different rates has enabled ExoplanetSat’s hybrid science/ADCS focal plane design.

The ExoplanetSat composite focal plane contains two CMOS detectors. The larger detector, the HAS-2, is a 1 megapixel sensor with 18 micron pixels. The lower portion of the HAS-2 (shown in lavender in Figure 10) will be used for science measurements. The upper portion (light blue) will function as a star camera. The star camera will be capable of “lost in space” attitude determination anywhere on the sky. Star camera attitude estimates will be used for initial attitude acquisition after detumbling and for target acquisition.

The smaller detector is a 860 x 640 pixel imager from e2v. This detector has smaller pixels (5.8 microns) and therefore provides more accurate centroid measurements. The e2v detector will be used primarily for star tracking in fine pointing mode.

IIIII Attitude Determination and Control (ADCS)

ExoplanetSat’s attitude control system is composed of two stages: a coarse pointing stage and a fine pointing stage. Coarse pointing is provided by a customized MAI-400 from Maryland Aerospace. The coarse pointing control loop can achieve 3-axis stability to approximately 1 arcminute (9). The MAI-400 unit includes three reaction wheels for 3-axis control and torque rods for momentum dumping and detumbling. It also integrates a sun sensor and takes input from a magnetometer placed elsewhere in the spacecraft as well as a GPS unit. Figure 11 shows the block diagram for the ExoplanetSat control system.

While arcminute level pointing is significantly higher than most CubeSats in the past have achieved, it is not sufficient for ExoplanetSat’s photometry goals. To achieve the required pointing precision, ExoplanetSat uses a second fine pointing control loop to stabilize the target star centroid. ExoplanetSat’s fine pointing control stage consists of a piezoelectric actuator that rapidly adjusts the position of the focal plane itself based on input from the star tracker. The fine pointing control loop tracks star centroids on the ADCS portion of the HAS-2 detector and the e2v detector and corrects for detected deviations by commanding the piezoelectric stage to adjust the position of the focal plane. Figure 12 shows the effect of the fine pointing control loop on the position of a simulated star centroid.
ExoplanetSat’s attitude sensing suite includes a ComTech Aero/Astro sun sensor, a 3-axis MicroMag3 magnetometer, a GPS receiver from Surrey Satellite Technologies, and the star camera/tracker located on the focal plane. During the detumbling phase of the mission, only the sun sensor and magnetometer will be used. At high angular rates, the star camera cannot centroid stars accurately. Once ExoplanetSat is under full control, the star camera will be used to provide absolute attitude updates which will be used to correct for drift and errors in the other sensors.

ExoplanetSat is able to achieve much higher pointing precision than any current or planned spacecraft in its weight class (as shown in Figure 13). The two-stage pointing system has many potential applications including laser communication, improved Earth imaging, and formation flight.

### III. Avionics

The Exoplanetsat avionics system is designed to be capable of handling the mission’s precision pointing requirements within a reasonable volume and cost envelope. To accomplish this, we choose to develop a system that utilizes a mix of off-the-shelf and custom components. Using off-the-shelf components affords the advantage of existing designs to quickly create a prototype flight system. Later, in the flight version of the spacecraft, the components may be upgraded to custom versions that are more compact.

The heart of the avionics system is a Virtex4QV FPGA containing a PowerPC CPU hard core. An FPGA was selected for the processor to meet the high performance requirements of the image processing algorithms. The internal CPU will handle most of the mission logic. It can be made to operate at 700+ DMIPS. This is substantially better than one known rad-hard alternative, the RAD750 by BAE Systems Electronics Solutions, which runs at 266+ MIPS. Given this comparison, we expect our choice of processor to be easily capable of keeping up with all the satellites data processing requirements. However, the FPGA will allow us to offload some data intensive tasks such as image processing, data acquisition, and control feedback. Unloading of the processor should also permit running the CPU at a lower frequency. Since the total power consumption is proportional to the frequency, we expect this reduced rate will result in a noticeable power savings for the satellite (although power is also proportional to the amount of logic performed by the FPGA fabric, so a small portion of those savings will end up negated). Additionally, since the chosen FPGA is radiation-tolerant, the prospect of long missions or high orbits is open to consideration without requiring a complete system rewrite.

In the present design, a custom external interface board connects the flight computer to all the off-the-shelf external components. This board provides any conversion logic as well as the appropriate connector pinouts for the MAI, EPS, camera, and other subsystems. Except for the imager, all of these devices have been procured in their commercially available packages. The flight computer board containing the primary FPGA was designed by Andrews Space, Inc. to meet the requirements of high-performance CubeSats. This made it a strong candidate for the rapid development of our own algorithms in a configuration that was very similar to our planned flight model.

The imager is controlled by a second, nearly identical FPGA. This board, the Imager Electronics Board (IEB), is a custom board designed by Draper Laboratories that also provides the stable power supplies for accurate imaging, and a differentially
adjustable mounting platform for our dual imager focal plane. In the future, the imager, flight computer, and interface boards can easily be merged with the interface board to save space and power. For development purposes, the current separation enabled parallel development of the flight computer software, the imager controllers, the state estimation algorithms and imager performance testing. By designing the IEB and flight computer around a common component, these boards can be merged with minimal extra effort.

III. IV Other Subsystems

Thermal Control

Thermal control is critical for the ExoplanetSat science payload. Though CMOS detectors are less sensitive to temperature than CCDs, higher temperatures necessarily produce higher dark current and therefore higher dark noise. For high-precision photometry, the temperature of the focal plane should be kept as low as possible. Temperature stability is equally critical to maintaining a low noise level. The effects of temperature variability on both short and long term scales on the noise performance of CMOS imagers generally has not been sufficiently studied for the needs of ExoplanetSat. Ongoing laboratory testing will address this issue (see section IV).

Since active cooling is not an option due to power and volume constraints, the focal plane must be carefully isolated from the hot parts of the satellite. All focal plane attachment points well be insulated with a low thermal conductivity material. This strategy will significantly reduce the temperature swings that the HAS-2 will see as ExoplanetSat goes from orbit day to orbit night. Further temperature stabilization will be implemented with active heating elements. Rapid transitions between orbit day and night do not allow enough time for the spacecraft’s temperature to reach an equilibrium point. In order to preserve as much observing time as possible, resistive heaters will be used to hold the focal plane at whatever temperature is has after 5 minutes in orbit night. This set temperature is not the lowest possible temperature for the focal plane, but thermal isolation will ensure that the set temperature is well below 20° C. With a stable temperature throughout observations, the effects of thermal noise will be easier to reduce through post processing even if the overall thermal noise is slightly higher.

Power

ExoplanetSat will use Clyde Space’s EPS system and solar panels. Each solar panel holds 7 Spectrolab (28.3% efficient) solar cells. ExoplanetSat will have two body-mounted solar panels and 4 deployed solar panels (see inset Figure 9, top right). The deployed panels will form two two-panel wings on either side of the spacecraft. The wings combined with one body-mounted panel will generate approximately 30 W (beginning of life).

ExoplanetSat must perform two power-intensive operations during orbit night: image acquisition and fine pointing. Due to these requirements and a 2 year design lifetime, ExoplanetSat requires 70 Wh battery capacity. Two Clyde Space 30 Wh battery packs will be used in combination with a 10 Wh battery pack to meet this requirement.

Communications

ExoplanetSat will communicate in the S-band. Higher frequency communication than the typical UHF/VHF used by CubeSats is required for ExoplanetSat because of the high volume of science data that must be downlinked. The ExoplanetSat communication system is composed of two patch antennas (placed orthogonally) and L3 Com’s Cadet radio.

ExoplanetSat will communicate with the OSAGS ground station network (10). The Open System of Agile Ground Stations (OSAGS) is a network comprised of three equatorial ground stations. The ground stations are located in Cayenne, Kwajalein, and Singapore. Each station is equipped with a 2.3 m dish operating at 2.025 – 2.120 GHz (uplink) and 2.200 – 2.300 GHz (downlink). These stations were constructed to support the High Energy Transient Explorer (HETE-2) mission (11). The control center for the OSAGS network is located at MIT and MIT has retained the right to use the OSAGS network for new spacecraft.

Structure

ExoplanetSat’s structure will be customized. As shown in Figure 9, ExoplanetSat logically breaks down into 3 sections. The MAI-400 is self-contained and will connect to the end of the ExoplanetSat structure. The science payload will also be a self-contained unit. The structure supporting the payload unit will attach to the central portion of the CubeSat. This central portion (avionics unit) will contain all of the necessary PCBs. The modularity of the payload module and the MAI-400 will allow easy access to the avionics module for testing and debugging purposes. This modularity also allows for payload testing independent of the spacecraft avionics.

IV. TESTING

Intensive simulation work as well as lab hardware testing has been performed for ExoplanetSat’s critical subsystems: ADCS and the optical payload.
testing is ongoing and is quickly approaching the final goal of an integrated imaging/ADCS/avionics test.

IV.I ADCS Testing

Tests of the fine pointing control loop have been conducted on an air bearing at MIT. The air bearing testbed (illustrated in Figure 14) consists of an air-levitated platform holding the Zeiss f/1.4 85 mm lens, a CMOS detector, the MAI-200 (older version of the MAI-400), and an avionics box. A computer monitor served as a star field. The MAI-200 was used to introduce disturbances into the air bearing platform. This testing successfully verified fine pointing control simulations (simulation results shown in Figure 12).

Figure 14 - Air bearing test setup for ExoplanetSat ADCS fine control loop testing.

Figure 16 shows the results of the air bearing test. The left panel shows a star centroid location with the fine pointing control turned off. The right panel shows the improvement in pointing when the fine pointing loop is active. The air bearing test demonstrated that the fine control loop could achieve a pointing precision of 8 arcseconds (3σ) (12).

IV.II Payload Night Sky Testing

The ExoplanetSat science payload has been tested both in the lab and in the field. Though there are significant differences between astronomical observations from the surface of the Earth and from space, there is still significant benefit to testing ExoplanetSat’s camera on real stars.

A payload testing campaign was conducted in April 2012 in New Mexico. New Mexico was chosen for its predictably clear, dark, and dry skies. The ExoplanetSat payload module, which consists of the Zeiss lens, HAS-2 detector, e2v detector, and IEB, was mounted on a tracking telescope mount. Over the course of 5 nights, the ExoplanetSat payload module observed both stable and variable stars. Figure 15 shows a light curve generated by the ExoplanetSat payload unit for W UMa, an eclipsing binary system. Eclipsing binary stars have lightcurves similar to transiting planets, but the change in brightness is much larger and therefore easier to detect. The data was reduced using standard astronomical techniques including detrending of variations caused by temperature. The photometric precision of the fully reduced light curve was 500 ppm/hour. This precision is likely to improve significantly with thermal control and an improved data reduction process.

Figure 15 - Light curve of eclipsing binary star W UMa from data taken with ExoplanetSat payload unit. The light curve begins just after secondary transit and ends at the beginning of primary transit. The blue data points are a reference star used for differential photometry. The downward trend in the blue data is the result of increasing airmass as the star approaches the horizon. The red and white points are data from the target W UMa. These two curves represent slightly different reduction techniques used on the same data.

Figure credit: Dr. Brice-Olivier Demory
The payload unit used for field testing did not have the capacity for thermal control, although it did have temperature sensors for thermal measurement. The lack of thermal control introduced significant drift into the photometric measurements which, despite some success with detrending from temperature sensor readings, decreased the overall precision. The most important lesson learned from payload field testing is the critical importance of a stable thermal environment. Future field tests are planned with a full thermal control and monitoring system.

V. FUTURE WORK

Current work is focused on payload thermal testing and component radiation testing. Thermal testing will allow characterization of the HAS-2 noise response to temperature variations and temperature extremes. This data will be used to develop a data processing pipeline which can minimize the noise introduced by thermal variations. CMOS photometry is a new paradigm and requires the development of new techniques to extract useful results.

As described in Section III.III, the avionics system includes some customized hardware. Not all of this hardware is radiation hardened. Testing of imager power supplies will be carried out at the Massachusetts General Hospital (MGH) Proton Beam facility to assess the potential for dangerous current spikes under various levels of radiation.

Another near-term goal for ExoplanetSat is an integrated test of the payload, avionics, and ADCS system on an air bearing testbed.

ExoplanetSat has been awarded a launch slot through NASA’s ELaNa program. After the flight of the ExoplanetSat prototype, we hope to build copies of the prototype and launch them to carry on ExoplanetSat’s observations. Additional copies of ExoplanetSat could observe the same star and would effectively increase the collecting area of the observatory. This would allow observations of smaller planets or dimmer stars. Using multiple ExoplanetSats to search for ever-smaller planets is particularly exciting because the driving motivation for ExoplanetSat is to discover an Earth-sized planet orbiting a bright, very nearby sun-like star.

References


