Title: ExoplanetSat Constellation
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Need

The discovery of planets orbiting other stars (exoplanets) has empowered humanity to quantitatively search for the answer to one of the fundamental questions of our existence, "Are we alone?". Planets which orbit very bright stars are the best candidates for the thorough characterization needed for the detection of life, but current exoplanet-hunting surveys have not studied these bright, Sun-like stars. The ExoplanetSat Constellation will address this need by dedicating a fleet of small satellites to monitor each of the brightest Sun-like stars for Earth-sized transiting exoplanets. Other exoplanet detection methods, such as radial velocity monitoring, cannot currently detect small planets in long-period orbits and transit surveys conducted by large telescopes avoid bright stars because their intense light quickly saturates sensitive detectors. ExoplanetSat will fill a crucial niche in the multi-front campaign to detect and characterize exoplanets.

Mission Objectives

"Each member of the ExoplanetSat constellation shall be capable of detecting a transiting Earth-sized planet in the habitable zone of the brightest sun-like stars with a detection threshold of 7σ" (The exoplanet community has adopted 7σ as the gold standard for planet detection certainty. The 7σ requirement means that the depth of the transit is seven times the height of the noise on the transit light curve.)

Requirements (for each unit of the Constellation):

1. ExoplanetSat shall detect planets 1-3 times the diameter of the Earth.
2. ExoplanetSat shall detect planets in orbits in which planetary surface temperatures permit the existence of liquid water (planets within the habitable zone).
   - ExoplanetSat shall have a design lifetime of at least 24 months in order to detect two transits for Earth-sized planets. ExoplanetSat target stars shall be spectral type G or K and non-variable.
3. ExoplanetSat shall achieve a photometric precision of 10 ppm over 20 minutes for a 2.5 magnitude star. This is derived from the expected intensity drop of an Earth-Sun transit event of 1 part in 10,000 (100 ppm) and the criteria of a detection with 7σ S/N ratio (with margin).
   - Each continuous observation period must be at least 20 minutes per orbit.

Concept of Operations

Pre-launch: Complete design, build and test of ExoplanetSat unit, transport to launch facility. Design and construction will take place at MIT's Space Systems Lab (SSL). Testing will be conducted at SSL and Lincoln Laboratory.

Launch: Each ExoplanetSat unit will be loaded into Poly-PicoSat Orbital Deployer (P-POD). The P-POD is attached to a launch vehicle as a secondary payload. Batteries will be charged prior to launch. ExoplanetSat units will be launched into low-inclination Low-Earth Orbits (LEO) with periods of approximately 90 minutes. Solar panels will deploy upon P-POD separation. ExoplanetSat will be detumbled and begin nominal space operations.

Nominal Space Operations (for each member of the constellation): During orbital night, each ExoplanetSat unit will acquire its designated target star and begin capturing science images. Images are taken every second and stacked to create one minute exposures. Imaging will continue for at least 20 minutes. At the end of orbital night, the satellite slews to point solar panels normal to the Sun. During orbital day, the satellite charges its batteries and makes contact with the ground when a ground station is in view. At the end of orbital day, the satellite goes back into target star acquisition mode. This cycle repeats for every 90 minute orbit. Each satellite will target the same star each night unless it receives a command to change targets.

Ground Operations: MIT operates a set of three ground stations spaced regularly around the equator. All data is transmitted back to the MIT control center in the Space Systems Lab for coordination, interpretation, and high-level decision making. Any necessary commands are generated at MIT's control center and transmitted to all ground stations so that the ground stations can relay commands to the spacecraft when they are in view.

Key Performance Parameters

Science: In order to detect Earth-sized planets around Sun-like stars, each ExoplanetSat must be able to reach a photometric precision of 10 parts per million (ppm). This precision will allow the detection of a transiting 1 Earth-radius planet orbiting a Sun-sized star with a detection certainty of 7σ.

Attitude Control System (ACS): A major source of noise for precision photometry satellite missions is pixel nonuniformity. In order to mitigate this issue, light from the target star must be consistently collected by the same pixel(s). To accomplish this task each ExoplanetSat must control the pointing of the detector array to 1 arcsecond, which will hold the star's light spot stable to a fraction of a pixel. This fine pointing is accomplished by controlling the spacecraft attitude to 120 arcseconds and then controlling the focal plane array pointing to 1 arcsecond.

Lifetime: The primary goal of this mission is to detect Earth-sized planets that orbit in the habitable zone – the set of planet semi-major axes at the right temperature (as heated by the star) to permit the existence of liquid water. For Sun-like stars, planets in these orbits will transit approximately once every 12 months. A transit must be observed at least twice; therefore each ExoplanetSat must monitor its star for at least two years.

Envelope (mass/volume): The P-POD system requires the satellite to fit within a 34 cm by 10 cm by 10 cm volume envelope, weighing less than 5 kg (Puig-Suari, Turner, Ahlgren, 2001).

Space Segment Description

Each ExoplanetSat in the initial constellation will be identical. See **Orbit/Constellation Design** for details on constellation extensions. Specifications for subsystems are listed below.

Optics

The Optics subsystem uses a f/1.4 85mm lens will focus light from the guide and science stars onto the optical array. The optical detector array will consist of a charged coupled device (CCD) to detect light from the science target star and six complementary metal oxide semiconductors (CMOS) to detect light from the guide stars. A baffle around the lens will block stray light.

Avionics

The avionics subsystem is composed of four main components: a 32-bit microcontroller, FPGA, SDRAM memory, and FLASH memory. The FPGA will be dedicated for processing CMOS and CCD images while the microcontroller handles ACS's attitude estimation control loops and all other housekeeping processes. • The SDRAM memory module will be reserved primarily for the FPGA's memory requirements and FLASH will be primarily responsible for storing all CCD science images.

Communications

The communications subsystem consists of two patch antennas connected to one 900MHz model via a splitter. The antennas are oriented at right angles to each other to increase coverage and prevent loss of communication due to tumbling (loss of attitude control). With limited computing and data storage resources, data downlink of 13.4Mbits per 90 minute orbit is required. This data total accounts for all science imaging as well as telemetry and margin.

Power

ExoplanetSat uses solar panels to collect power during orbital day and batteries to store power for use during orbit night (when imaging takes place). The power is generated by four deployed solar panels (see Fig. 1) and one body-mounted panel. The solar array generates a maximum of 30 Watts. Two batteries store power for use during orbital night.

ACS

The Attitude Control System architecture of ExoplanetSat is a crucial subsystem since very precise pointing is required to meet the science objective of 10 ppm photometric precision. Fine pointing is obtained via a two-stage approach. Coarse control is achieved through reaction wheels and torque coils for desaturation. A magnetometer and rate gyroscope will be used for sensing and estimation. Several modes of coarse control will be used throughout the orbit, but fine control will only be used during orbital night to take science data. Fine control is achieved through the use of a moving stage that adjusts the horizontal and vertical position of the detector array to keep the target star centered with subpixel accuracy. Guide star positions provide sensor input for the fine control stage.

Thermal

The thermal architecture of ExoplanetSat is crucial for maintaining an even CCD temperature to keep dark current to a minimum. Because of restrictions on power, mass, and volume, no active thermal control will be used. Cold straps, radiators, and insulation will provide required thermal stability. Thermal sensors will be attached to critical components in order to monitor temperatures throughout the spacecraft.

Structure

ExoplanetSat is a triple CubeSat, so it must conform to the mass and volume envelope of the CubeSat standard (see **Key Performance Parameters**). The structure must support all of the necessary components without adding significant mass to the satellite while also withstanding launch loads and maintaining an acceptable fundamental mode frequency. Figure 1 shows the current CAD model of the structure and attached internal components. The primary structural material will be aluminum. Mass will be minimized wherever possible by the use of cut-outs.

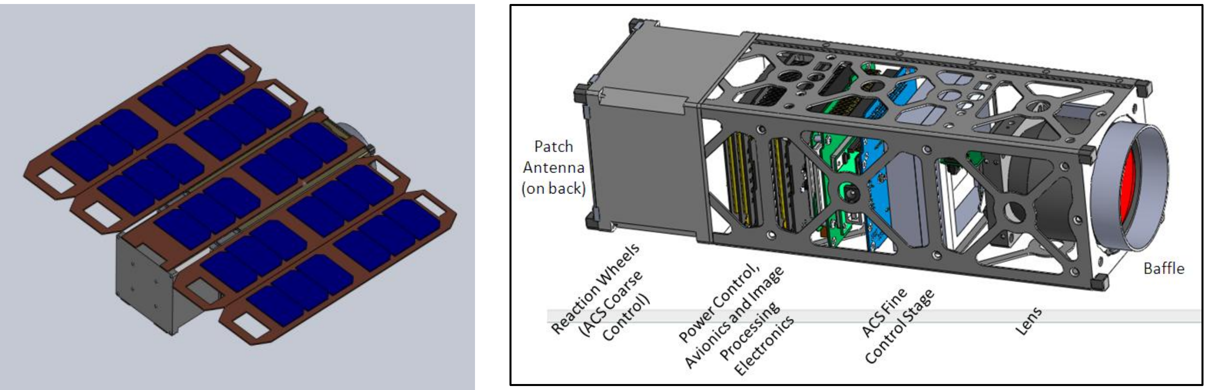

Figure 1 ExoplanetSat CAD model, showing deployed solar panels and internal components.

Orbit/Constellation Design

The ExoplanetSat Constellation (1st wave) will consist of 24 individual ExoplanetSat units. They will operate independently and communicate with the ground individually. Four of the ExoplanetSat units shall be designated as dedicated, meaning that they will observe target stars with high declinations (above 60°) which are observable for nearly a full year. A high declination star is visible for the entire year because the target is never obscured by the sun. The remaining 20 ExoplanetSat units shall be designated as team units, working in groups of 5 to continuously observe a single low declination star for the season in which the star is visible. Each team of 5 shall observe a different star each season as stars move in and out of the visible range. Low declination stars are close to the ecliptic plane (the earth's orbital plane) and therefore cannot be observed for a significant portion of the year because they are too close to the sun. This visibility problem cannot be mitigated with a low earth orbit system. The five members of each team shall improve data collection by maintaining coverage of the target star for 24 hours per day because of orbit staggering which will keep at least one of the team members in orbital night at all times.

Implementation Plan

Cost and Organization: Significant design work and some prototyping have been conducted by members of MIT's SSL. Partnerships with Draper Laboratory and Lincoln Laboratory have added technical expertise to the project. Table 1 shows the current budget estimate for the first ExoplanetSat unit (based primarily on component costs).

Table 1 Subsystem Costs for ExoplanetSat Prototype

Systems	$7,500
Operations	$21,000
Power	$70,000
Structures	$15,000
ACS	$170,000
Optics	$14,800
Communications	$5,000
Avionics	$5,000
Total	$308,300

Labor costs are minimal for this student-driven project since the majority of design and manufacturing work will be conducted by graduate and undergraduate students with supervision from professors in several departments. The cost of subsequent ExoplanetSat units is expected to fall because the infrastructure created for the prototype can be reused and testing will not be as extensive.

Risks:

1. Volume overrun. Fitting all necessary components into the highly restricted volume has been an ongoing challenge. Uncertainty in some component specifications adds to this risk. If volume cannot be controlled, science may be compromised.
2. Achieving required photometric precision. Uncertainty in noise budgets (especially regarding thermal control) as well as unanticipated noise sources on-orbit.
3. Development/delivery of required components. Some components are still in development and may be delayed significantly or may not perform as expected.
4. Cost. Funding for testing and extensive prototyping is uncertain. Funding for units beyond the prototype/demonstration model has not been obtained.
5. Launch opportunities. ExoplanetSat's required low-inclination orbit constrains useful launches. Not all vehicles carry P-PODs. Obtaining enough launches for the Constellation will be challenging.

Schedule: The initial concept development and preliminary design phases of ExoplanetSat are complete. Table 2 shows a high-level schedule starting at the current state of design. The third wave of the ExoplanetSat Constellation (described in **Constellation Sustainability** has not been included because the schedule becomes highly uncertain at long timescales.

Table 2 ExoplanetSat Constellation Schedule

Finalize prototype design	May 2011
First flight model complete	December 2011
Launch of 1st flight model	2012 (depends on available launches)
Construction/launch of 3U constellation	2012-2014
Design of 2nd wave (6U)	2012-2013
Construction/launch of 2nd wave	2014-2016

Constellation Sustainability: The target list for the ExoplanetSat Constellation is limited by the size of the aperture in the current design. In order to have a high probability of detecting at least one transiting planet, more stars must be surveyed. Beatty & Seager (2010) showed that 1000 stars would need to be surveyed in a blind search for transiting planets in order to have 95% confidence of detecting more than one planet. This number can be reduced to 250 stars out of the initial 1000 if stars with spin axis inclinations near 90° (high probability of transit if a planet is present) are preferred and others are rejected. The first wave of the ExoplanetSat Constellation would consist of the triple CubeSats as described in this proposal and could observe ~20 stars. A second wave would use a six-unit (6U) CubeSat design to double the diameter of the telescope aperture and extend the magnitude limit to approximately V =6, adding approximately 60 stars to the initial target list. A third wave of satellites with still larger apertures will be needed to complete the constellation by extending the magnitude limit to V = 7. Then, over 1000 stars will be available for observation (although only ~250 of those stars will actually be observed) ensuring a high probability of detecting a planet.

References:

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