System Design of a Miniaturized Distributed Occulter/Telescope for Direct Imaging of Star Vicinity

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Abstract—**The Space Rendezvous Laboratory (SLAB) at Stanford is investigating the feasibility of a miniaturized distributed occulter/telescope system (mDOT) to directly image exozodiacal dust and Jovian exoplanets. The mDOT mission relies on formation flying in Earth orbit and promises a drastic decrease of the expected mission cost compared to large scale missions, such as NWO and Exo-S (NASA). The preliminary system design of mDOT, described in this paper, is complemented by concurrent novel studies of optimal formation dynamics and diffractive optics design. mDOT consists of a microsatellite carrying a 1 meter radius petal shaped occulter at a distance of 500 km from a 6U CubeSat carrying a 10 cm diameter aperture telescope designed to image at short visible and ultraviolet wavelengths. Following a systems analysis, based on the definition of mission requirements and a survey of CubeSat capabilities, the telescope spacecraft provides 80 days of operation with 50 W solar cells, 31 m/s of delta-v capability using cold gas thrusters. Together with ad-hoc relative metrology instruments, these are used for lateral alignment with the occulter spacecraft at 15 cm position control accuracy. The goal of the mDOT mission is to prove that a space telescope with an external star occulter can be miniaturized, greatly reducing the mission cost and complexity. As shown in this paper, the proposed mission has the capability to directly image the vicinity of nearby stars and, at the same time, prove that miniaturized space systems are capable of executing complex missions. mDOT can serve as a first-of-a-kind precursor, paving the way for larger missions with higher scientific return.**

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1. INTRODUCTION

To date more than a thousand exoplanets have been detected by indirect methods using their effect on the light of their parent star. However, only a few exoplanets have been detected by direct imaging. Direct imaging allows the properties of the planet to be deduced from spectral data and is not subject to the detection constraints of indirect methods. A promising candidate for direct imaging of exoplanets is a pair of an occulter and a telescope spacecraft, referred to as a distributed occulter/telescope (DOT).

DOTs have been the subject of a number of studies including NASAs New Worlds Observer, but the resulting mission designs are extremely large, requiring extensive inter-satellite separations and deployment in deep space. The Space Rendezvous Laboratory (SLAB) at Stanford is investigating the feasibility of a miniaturized DOT system to allow deployment of a pair of satellites in Earth orbit, drastically reducing the expected mission costs. In this paper, a system design for a Miniaturized Distributed Occulter-Telescope mission (mDOT) is proposed. mDOT would use an occulter at a distance of 500 km from a miniaturized telescope to image exozodiacal dust and Jovian exoplanets at short visible and ultraviolet (UV) wavelengths. Size and distribution of the exozodiacal particles are of scientific interest. Moreover, the distribution can indicate the orientation of the planetary system, as well as hint at hidden exoplanets. mDOT would help satisfy the goal identified in the Decadal Survey of characterizing zodiacal emission around stars [1].

The potential applications of CubeSats in distributed space science missions is a relatively understudied topic. CubeSats offer a cheap alternative to large monolithic satellite platforms, but due to their small size, they are limited in their utility. However, steadily improving capabilities of CubeSat components, especially in the Guidance, Navigation and Control domain, open new frontiers for CubeSat applications, like a DOT. Placing the telescope on-board of a CubeSat aligns with the objective to reduce the size, complexity and cost of the mission. While the scientific utility will be reduced as compared with large scale missions, mDOT will serve an important role as a technology demonstrator for DOT feasibility and CubeSat formation flying capabilities.

In this paper, we define the scientific goal, describe the payload and orbit necessary to fulfill the goal and then detail the design of the two spacecraft, with emphasis on the telescope spacecraft.

2. Mission definition

The goal of this mission is to study exozodiacal dust and exoplanets by direct imaging methods, while demonstrating the technology readiness of a miniaturized occulter/telescope spacecraft pair.

For mission definition, target stars are limited to ones with specific exoplanet size and distance from the star, brightness and spectral signature. Larger exoplanets closer to their stars are easier to image because they reflect more light. Unfortunately, small Earth-like exoplanets are impossible to observe with mDOT's 10 cm diameter telescope, because of their low brightness and short available exposure tiumes. Moreover, the exoplanets have to be located outside the inner working angle of the occulter in order to be seen by the telescope. Diffraction of light around the occulter imposes restrictions on the mission geometry and observation wavelength. Fortunately, limitations on observing exozodiacal dust are less stringent.

Based on a trade between occulter size, spacecraft separation distance, available observation time and typical star emission spectrum, observation wavelength of 175-325 nm has been selected. Therefore, stars which are bright at this specific wavelength are desirable targets. In addition, stars near the ecliptic north and south make better candidates, because due to the relative orbit of the telescope and the occulter, holding alignment of the two spacecraft requires less propellant.

Beta Pictoris was used as a reference target, because exozodiacal dust surrounding it has already been detected in infrared wavelengths, and complementary UV measurements would be scientifically interesting. With enough propellant, mDOT could even image multiple targets, but observing one is the baseline for mission success.

The two spacecraft are designated mDOT A and mDOT B, the former carrying the telescope and the latter the occulter. The system design of mDOT A, the telescope spacecraft, is challenging and novel because of its CubeSat form and requirements on alignment keeping, for which mDOT A is responsible. Therefore, this paper is focused primarily on the mDOT A system design.

Requirements

Three top level requirements were derived from the mission statement. The first describes the scientific objectives, the second the technology demonstration goal and the third enforces the operations aspect.

Direct imaging—mDOT shall observe exozodiacal dust around at least one target using direct imaging. As mentioned in the motivation section, direct imaging of exozodiacal dust and exoplanets has been limited to date. Discovering interesting phenomena with mDOT could be used as a case to explore them further with more advanced telescopes.

Occulter/Telescope concept—mDOT shall increase the technology readiness of formation flying starshades.

Cost—mDOT shall cost less than $100M. This requirement serves to prove that mission of scientific and technological utility can be executed on shorter time scales and for less money than traditional missions.

3. Payload design

Occulter

The occulter will be designed as a petal shaped nulling interferometer, illustrated in Figure 1. The theory for this type of starshade is explained by Cash [2]. The occulter will be optimized for the observation wavelength which is 175-325 nm, in the UV spectrum. The design of the occulter shape itself is a complex problem, and was addressed by the authors in a concurrent study [3]. This study describes the procedure used to identify feasible occulter geometries given a specified suppression level, shadow size and inner working angle. First, a simplified model of star/planet systems is presented and variations of the required suppression level with varied dimensions of the target system are explored. Next, dependence of performance metrics (contrast, maximum shadow radius and Fresnel number) on the size of the occulter is shown. Then, the paper presents a model of the diffraction behavior of the telescope and describes the formulation of the optimization problem used to generate occulter geometries. Finally, performance results generated using this optimization formulation are presented for various inner working angles, separation distances, occulter radii and observation wavelengths. These results can serve to inform the target selection. For the reference mission, the parameters are the following: 1) occulter radius of 1 meter and separation of 500 km; 2) resulting inner working angle around 400 milliarcseconds; 3) shadow diameter of 20 cm with contrast for light suppression of 10^{-6}; 4) 16 petals with manufacturing tolerance at 20 microns. Although these last manufacturing parameters are similar to a large-scale occulter, they are easier to achieve at small sizes.

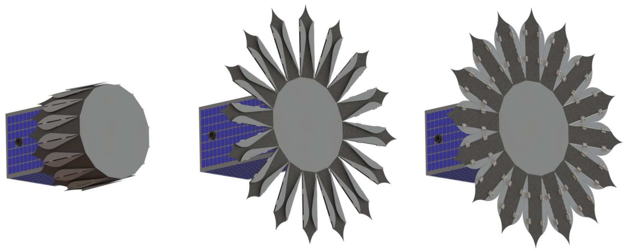

Figure 1. Petal shaped occulter design. Three stages of the 16-petal starshade deployment are depicted. [3].

Telescope

The telescope size is limited by the CubeSat standard. Therefore, the primary mirror can be at most 10 cm in diameter. Increase in the telescope size to 20 cm would provide better scientific results, but such design decision would greatly raise the cost of the mission, due to the necessary increment in size of the occulter, increase in spacecraft separation and abandoning the world of affordable CubeSat parts. CubeSat telescopes are a reasonably mature and space-tested technology, used for example by Planet Labs satellites for Earth imaging. The required detector size is not large, because it is diffraction limited, but a detector around 10 megapixels is desirable, because the telescope can double as a navigation instrument, which benefits from a larger field of view. This Charge-Coupled Device (CCD) detector will have to be cooled to reduce noise. Moreover, the telescope structure needs to be kept stable to ±10 K to prevent distortions from thermal expansion. A filter needs to be present to only allow the selected wavelength to impact the detector. As this is a preliminary system design, detailed optical design of the telescope was not explored yet and for the purpose of this paper the telescope is assumed to be a 2U sized unit.

Because the telescope has to image objects which are very faint, stray light entering the telescope has to be minimized. This can be done either by shielding the telescope and occulter from sunlight, or by operating in Earth's umbra. The requirement on delta-v for alignment during the observation increases by a factor of 4-6 when imposing the umbra constraint. Nevertheless, it is still in the realm of feasibility of CubeSat propulsion, and it is easier to implement than the shielding scenario. For the purpose of the system design, mDOT is assumed to carry out the observations in eclipse.

It is also important to keep the telescope pointing stable during the entire exposure time (around 1000 s). If the telescope pointing is not kept stable enough, the image would travel across multiple pixels and degrade the results. This issue is investigated further in the system design.

4. ORBIT

The mDOT satellites require an orbit with a high apogee, corresponding to a low acceleration, which helps with fuel efficiency. Additionally, the orbit has to allow an observation time at the order of 1000 s in the umbra, requiring either a Geosynchronous Transfer Orbit (GTO) or a Highly Elliptical Orbit (HEO). The two spacecraft will orbit at identical orbital periods with specific differences in orbital elements, which realize an inter-satellite separation of 500 km mainly in cross-track direction (i.e., orbit angular momentum vector) during scientific observation. The nominal absolute and relative orbits depend on the selected target, as the two spacecraft have to align with the target star when passing through Earth's umbra. The inter-satellite separation is allowed to drift along the line-of-sight by ±5 km (1% of baseline) to minimize the required delta-v. A conceptual visualization of the orbits is provided in Figure 2.

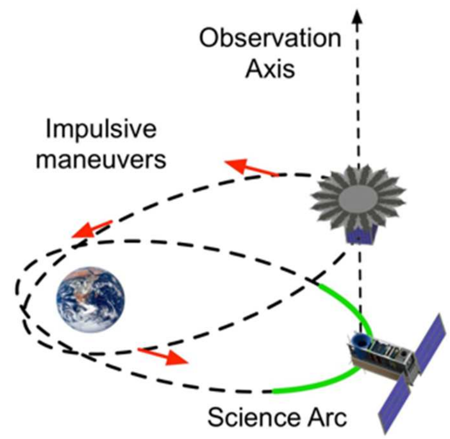

Figure 2: Telescope and occulter orbits with quasi-continuous control during the science phase (green) and impulsive control during reconfiguration phase (red) [4]

The initial orbit of mDOT A for the reference mission to image Beta Pictoris is given in Table 1. The orbit is designed as a GTO with its apogee aligned with the target, as illustrated in Figure 2. The orbital period is 10.6 h. The parameters $\Delta\omega$ and $\Delta\Omega$ represent the differential argument of perigee and longitude of ascending node, respectively, between mDOT A and mDOT B.

Table 1. Initial orbit elements for reference mission [5]

a	e	i	ω	Ω	$\Delta\omega$	$\Delta\Omega$
24500 km	0.72	39°	89.3°	357.3°	1.4°	-2.6°

The details of the formation design are presented in a concurrent study by the authors [4], [5]. In these two papers, the relationship between the delta-v cost of the mission and the absolute and relative orbits of the telescope and occulter is analyzed. The study first demonstrates that spherical gravity is the dominant contribution to relative acceleration by several orders of magnitude. Using this finding, the delta-v cost of three mission phases is assessed: orbit acquisition phase, forced motion control for observations (science phase), and formation reconfiguration phase, to produce an estimated delta-v cost of the entire mission.

The orbit acquisition delta-v is assessed by considering the mechanical energy differences between the initial and desired orbits. To assess the delta-v cost of the observation phase, the instantaneous delta-v cost is expressed as a function of the formation geometry. This allows the selection of optimal orbits and the analytical integration of the perturbing acceleration to compute the delta-v cost of the finite observation. The formation reconfiguration problem is solved through a closed-form quasi-optimal maneuvering scheme which is reiterated to take into account all relevant conservative and non-conservative perturbations [6]. The delta-v requirement on the mission varies in orders of magnitude depending on the number of targets and their selection. For the single target Beta Pictoris reference mission, the requirement is about 85 m/s for formation acquisition, 10 m/s for reconfiguration and 5 m/s for formation keeping.

5. TELESCOPE SPACECRAFT DESIGN

State-of-the-art and upcoming CubeSat capabilities across subsystems were surveyed. Then, requirements of the mDOT mission were identified and compared to the capabilities. After verifying that the mission is not fundamentally impossible, a preliminary design was drafted. Finally, specific parts were selected for each subsystem.

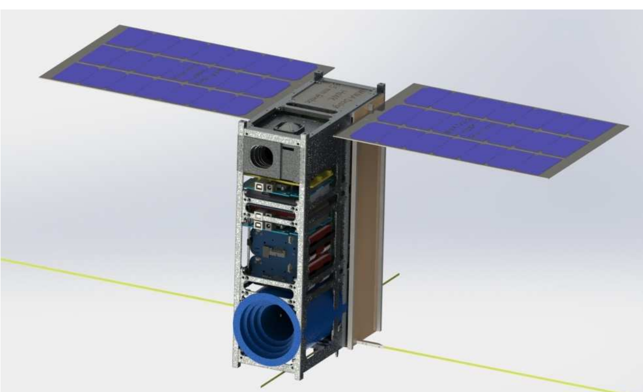

Figure 3. mDOT A design

Guidance, Navigation, and Control

In order for the starshade to remain effective in blocking the star light, the telescope has to remain in its shadow. This constraint mandates a requirement of formation flying accuracy of 15 cm laterally and 5 km in line of sight.

Table 2. Blue Canyon Technology XACT attitude control unit characteristics [7]

Specification	Performance
Spacecraft Pointing Accuracy (1-sigma)	± 0.003° for 2 axes ± 0.007° for 3rd axis
Spacecraft Lifetime	3 Years (LEO)
XACT Mass	0.85 kg
XACT Volume	10 x 10 x 5 cm (0.5U)

Attitude control—The specific pointing requirement depends on the mission phase. During the science phase, mDOT A will be pointing the telescope toward the occulter spacecraft, mDOT B. During reconfiguration phase, mDOT A has three roles: 1) downlink collected data; 2) estimate the relative position of mDOT B; and 3) recharge its batteries. During the data transfer, the antenna needs to be pointed toward the ground station. This task will only take a fraction of the reconfiguration phase. When the transmission is completed, mDOT A will point the telescope to mDOT B and estimate its position, while rotating around the free axis to maximize solar exposure. It is also important to prevent damage to the telescope from sun exposure, so mDOT A will have to adjust its attitude when the occulter becomes too close to the sun in angular distance.

The sensors selected to satisfy the requirement above are sun sensors, a star tracker and a three axis gyroscope. These sensors are all combined in the Blue Canyon Technology XACT unit, whose specifications are given in Table 2. Reaction wheels have to be used as actuators rather than magnetorquers, because magnetic field is too weak at GEO/HEO altitudes. The XACT unit features three reaction wheels providing the pointing accuracy outlined in Table 2. It is also possible, but not necessary, to use thrusters for attitude control. The lifetime of the unit is specified as three years in LEO, but further analysis is necessary to assess the effect of GEO/HEO environment on the unit and other components.

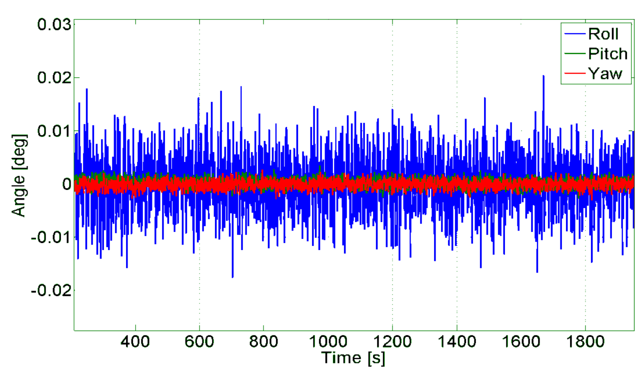

Figure 4: Attitude control simulation

Unfortunately, as seen from the simulation in Figure 4, even a custom attitude control system cannot keep the maximum pointing drift of the telescope under the required 50 mas. Therefore, the telescope will further stabilize the image on the detector using a piezo controlled tilt-tip mirror. This is a common method of fine stabilization on large telescopes [8].

Position control—The task of the position control system is to establish and maintain alignment of mDOT A with mDOT B and the target star during science phase to ensure good starlight suppression. It also has to provide absolute and relative orbit information so that propulsive adjustments can be made during the reconfiguration phase. The reconfiguration capability is delegated to mDOT B, because of mass and volume limitations of mDOT A. This will also allow the use of a different, higher thrust propulsion system based on conventional cold-gas thrusters on mDOT B.

Because Global Navigation Satellite System (GNSS) satellites reside in Medium Earth Orbit (MEO) and transmit toward the Earth, regular GNSS navigation is not available in the GEO/HEO orbits selected for mDOT. However, orbital information can still be extracted. This method has been shown possible both in theory [9] and in the laboratory [10], giving absolute orbital position accurate to 100 m. Combining these GNSS navigation solutions obtained by mDOT A and mDOT B provides a navigation accuracy of about 141 m (1σ) in relative position. A novel GPS unit designed by NASA for the Magnetospheric Multiscale Mission (MMS) provided relative navigation solutions with errors of 7 m and 1 cm/s for position and velocity respectively in a simulation [8]. In addition, analyses conducted by the authors for the PROBA-3 formation-flying mission show how carrier-phase differential GPS can still be accurately performed during the perigee of a high elliptical orbit [11]. The carrier-phase differential GPS has been space tested on the PRISMA mission [12]. The resulting centimeter-accurate relative position can be numerically propagated to the apogee with uncertainties below 100 m.

Table 3. Navigation methods

Accuracy	Method	Range / FOV	Noise floor (3σ)
Coarse	GNSS	Whole orbit	100 m
Medium	Star tracker and beacon	10° x 12°	50 m (36’’/2)
Fine	Telescope and beacon	400’’ x 400’’	0.1 m (0.2’’/2)
Ultra-Fine	Wavefront sensing	20 cm	1 cm

After acquiring a GNSS fix, mDOT A will have to communicate directly with mDOT B to calculate the relative position of the two spacecraft. Then, it will use its star tracker to measure and minimize the angular distance between the target star and a beacon on the occulter. Then, it can use the telescope to determine the angular distance even more accurately, as illustrated in Figure 5. In order to provide fast feedback, two detectors will share the telescope optics through a beam splitter. One detector will operate in UV, using long integration times, to image exozodiacal dust and exoplanets. The second detector will operate in a longer wavelength (visible), which leaks through the occulter, using a fast scanning mode. This second detector will be used for navigation both outside and inside the shadow.

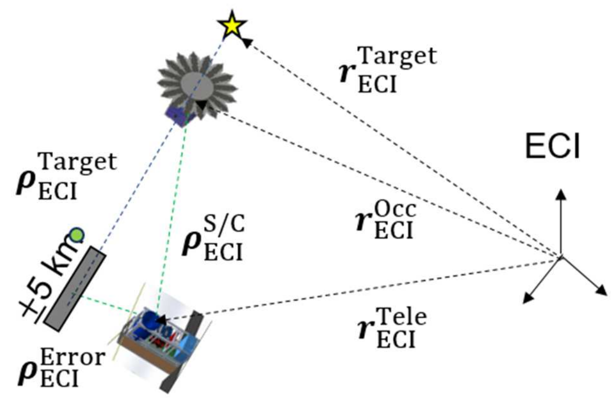

Figure 5. Angles-only navigation using the mDOT A telescope instrument

Knowing the inter-satellite separation from GNSS, this angular distance can be converted to lateral distance of the telescope from the target-occulter axis, which has to be minimized when the spacecraft is entering science mode. Assuming that the telescope CCD sensor will have 2 megapixels per side and a field of view of 400’’, it can measure the angular distance between the occulter and the target down to the diffraction limit (0.2-0.6’’, depending on wavelength). While this method does not provide enough overlap to enter the shadow (0.4’’), the diffraction limit can be circumvented by taking multiple measurements, averaging and finding the angular distance of the centroid of the star and centroid of the occulter as they appear on the detector. This can increase the accuracy by a factor of 10. Once the telescope is in the occulter shadow, the spacecraft will use wavefront sensing to analyze the image of the occulted star and adjust its position to fully cancel the Poisson spot in the center. The angles-only homing concept is illustrated in Figure 5. Simulations show a delta-v requirement of about 0.3 m/s per orbit, which is well within the capability of the propulsion system presented in the following section, for the entire mission duration.

Alignment control will be carried out by a high I_{SP}, low thrust propulsion subsystem to maintain alignment during science phase. The details of the propulsion subsystem are presented in the following section.

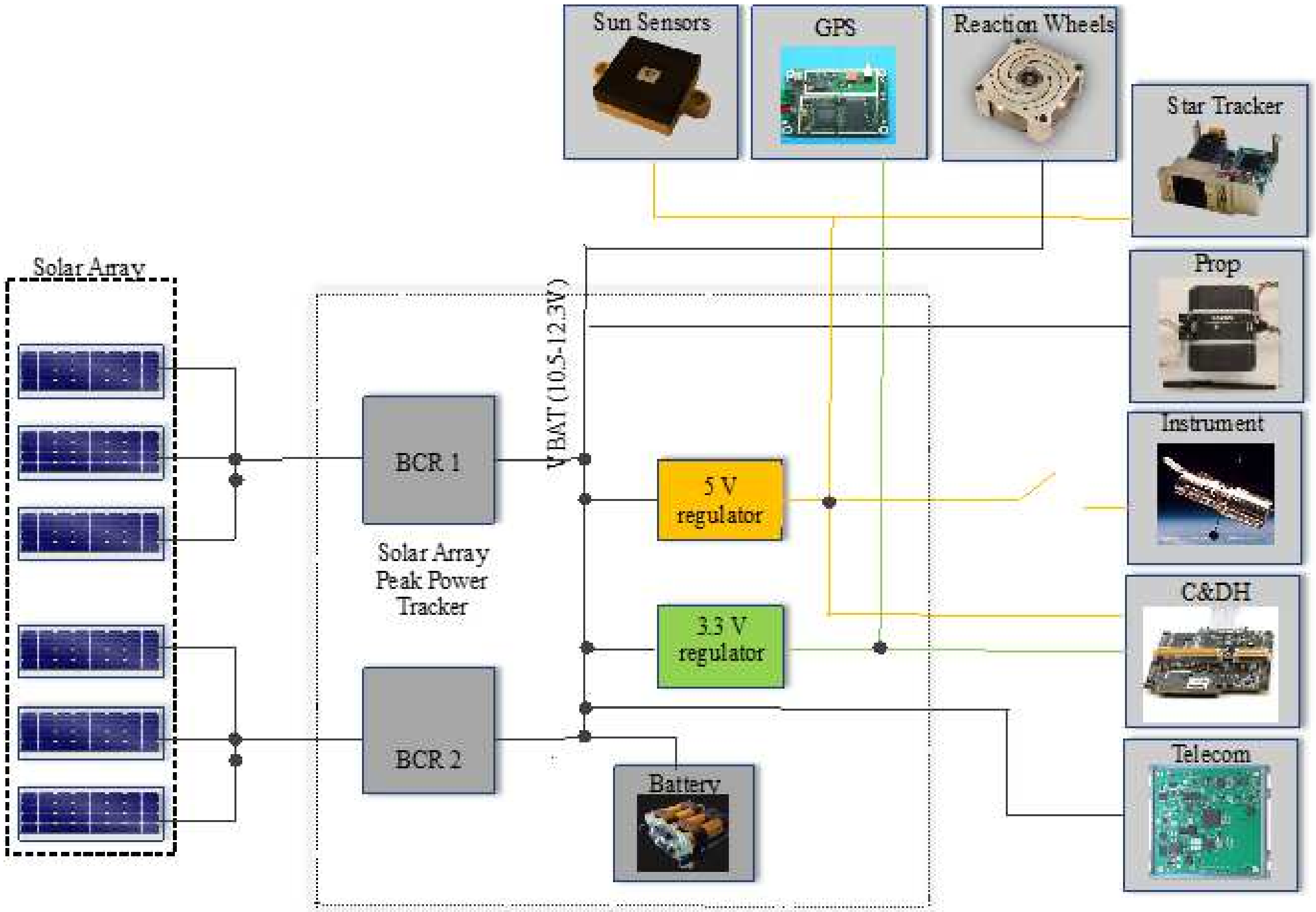

Figure 6. Electrical block diagram of mDOT A

Propulsion

The driving requirement imposed on the propulsion subsystem is to provide alignment between mDOT A and mDOT B during the science phase. During this period, mDOT A has to thrust quasi-continuously in order to keep alignment with mDOT B. In an ideal case, the mission would only require about 5 m/s for alignment keeping. The propulsion system also needs to have a margin to be able to lower its perigee at the end of its mission enough to re-enter atmosphere.

The VACCO MiPS thruster [13] is the only available propulsion system that allows lateral translation, using cold gas and an adjustable configuration of eight valves. Because of delta-v requirements, the nominal 0.8U module would be scaled up to 2U, adding extra propellant. This propulsion system will be demonstrated on the upcoming CubeSat Proximity Operations Demonstration (CPOD) mission by Tyvak, which uses lateral translation thrusters for a docking demonstration [14].

Busek Electrospray thruster was also considered given its low thrust and high I_{SP}, but in present configuration, it only allows translation in one axis [13].

Table 4. VACCO MiPS CPOD 2U thruster properties

Power	5 W
Input voltage	9 – 12.6 VDC
System volume	2U
Thrust	25 mN
I_{SP}	40 s
Propellant	R134a cold gas
Wet mass	2.5 kg
ΔV	31 m/s

Electrical power system

After analysis of the power budget and survey of existing power systems, GomSpace EPS with batteries and MMA Design solar panels were selected to provide power generation, storage, and distribution. Six 8.4 W (on Sun nominal) 3U panels support power generation, a standalone battery provides 200 Wh of storage, and the NanoPower P-series system board handles power distribution to the spacecraft and payload. The current design charges the GomSpace BPX 200Wh Lithium-Ion battery pack at 8.2 V. Figure 6 shows the power system block diagram. Two regulators will provide 5 V and 3.3 V volts while the battery line will be operating at 10.5-12.3 V.

Command and data handling

The Tyvak Intrepid board will be used in the C&DH subsystem to provide processing power to the spacecraft bus and payload. This board uses the AT91SAM9G20 processor at 400 MHz with a 512 MB flash memory and 32 MB Phase Change memory. The C&DH subsystem will also feature a 1 GB micro SD card for purposes of backing up data. Intrepid comes with a real-time clock, 3-axis gyro, 3-axis magnetometer and accelerometer, 6 power sensors, and 3 temperature sensors. Intrepid also has a fault tolerance architecture providing latch-up protection and a recovery system coupled with a software watchdog. This feature is useful for the harsh environment beyond LEO. Similar to the XACT module, effects of GTO/HEO environment on the C&DH board needs to be addressed.

Ground segment

Data transfer can be ideally executed close to perigee. If the satellite does not pass above any available ground station during that period, data can be saved for multiple orbits and downlinked later thanks to its large memory capacity.

Communication

The L3 Cadet Radio and Astrodev Li-1 Radio will both be used with the Isispace deployable monopole antenna. mDOT A needs to directly communicate with ground as well as have a cross-link communication with mDOT B. The link budget from mDOT A to ground closes with a 6 dB link margin at 0.5 Mbps using the L3 Cadet Radio in UHF frequency. The cross-link from mDOT A to mDOT B also closes with a 7dB link margin at 9600 bps using the Astrodev Li-1 Radio in UHF frequency. The analysis was carried out using a custom model, taking into account noise and signal attenuation from various sources, such as atmospheric conditions. Table 5 summarizes the generated data during the orbit before science measurement begins and Table 6 summarizes the generated data during the science measurement. The entire data generated in one orbit can be downlinked in a total of 20 minutes at the 0.5 Mbps data rate.

Table 5. mDOT A Data Budget during reconfiguration phase

Parameter	Value
Engineering Data	4 Kb per second
Total data (per orbit)	353 Mb
Required Downlink (0.5Mbps capability)	11 minutes

Table 6. mDOT A Data Budget during science phase

Parameter	Value
Science Data	230 Mb per orbit
Engineering Data	4 Kb per second
Total Data	1880 Kb per orbit
Required Downlink (0.5Mbps capability)	8 minutes

Structure

In line with the requirement for miniaturization and cost reduction, the CubeSat standard was selected for mDOT A. The 6U configuration is the most promising, with commercially available structures, deployers and with enough space to fit all the components. The basic parameters of a 6U satellite are shown in Table 7.

Table 7. 6U CubeSat specifications [15]

Mass	12 kg
Width	238.0 mm
Length	360.9 mm
Depth	106.4 mm

The structure itself will be a 6U frame made of aluminum. A commercially available 6U structure such as the Pumpkin Supernova [16] or ISIS 6-Unit can be used.

Thermal protection system

The telescope CCD will need cooling to about -40 to -100 °C to reduce detector noise. Moreover, it is desirable that the entire mDOT A structure is kept at a constant temperature to prevent distortions in the optical payload. This is a challenge, especially because observation starts when the spacecraft enters Earth's umbra, which produces large temperature differences. Assuming a constant heat dissipation of 25 W due to waste heat of various subsystems, the surface temperature of the spacecraft was modeled. The temperature drops suddenly from 220 K (-53 °C) to 160 K (-113 °C) when entering Earth's umbra and then recovers. Naturally, the temperatures and temperature differences inside the spacecraft will be less extreme, but for their estimation a more accurate model needs to be developed.

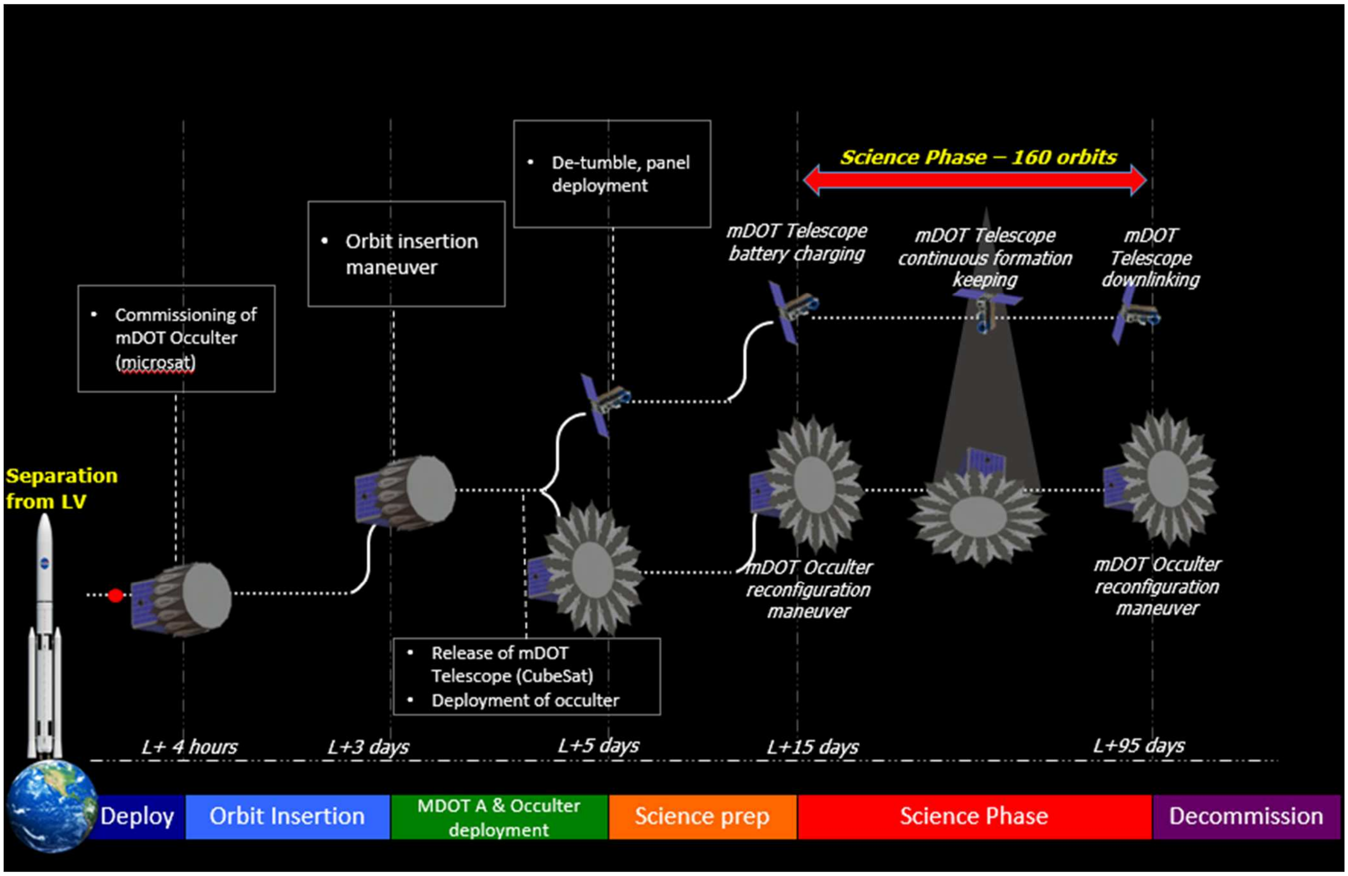

Figure 7. Concept of operations

Given the linear thermal expansion coefficient of aluminum, which forms the spacecraft structure, of 2.2 $\times 10^{-6}$ K^{-1}, the strain of the structure will be 0.00013 (0.013%), which could be a problem. Two possible solutions to this problem are to select an optical device which does not lose performance under strain (such as a mirror coated glass block), or to minimize the thermal strain. This could be achieved by dissipating more heat and insulating the spacecraft with low emissivity coatings. A bigger problem than thermal strain is the low surface temperature. The spacecraft will have to be well insulated and heated inside to protect the electronics and propellant from freezing during eclipse. The low temperatures, however, are favorable to the telescope CCD detector.

6. FLIGHT SYSTEM CHARACTERISTICS

mDOT design balances an infusion of new technology with flight proven commercial-off-the-shelf (COTS) components. By mass, the spacecraft is comprised of 33% COTS components, 46% components with minor modifications, and 21% new components. Table 8 shows the mass budget. With 19% average system contingency (based upon the maturity of the components/design), the spacecraft mass is about 10.7 kg. This level of margin is in-line with typical CubeSat designs that primarily utilize COTS components.

Table 8. mDOT A mass budget

Subsystem	CBE (kg)	CBE+Cont. (kg)
Structures	1.000	1.30
Power	2.10	2.31
C&DH	0.06	0.06
Thermal	0.05	0.07
ACS	0.992	1.01
Telecom	0.226	0.24
Payload	2.000	2.60
Propulsion	2.50	3.07
Cabling	0.040	0.05
Total	8.96	10.70
Margin	3.04	1.30

The mass, volume, power and data capability requirements and margins are presented in Table 9.

Table 9. mDOT A system margins

Design Parameter	Requirement	Capability	Margin
Mass	8.96 kg	12 kg	25 %
Volume	5.5 U	6U	8%
Power (per orbit)	500 Wh	1000 Wh	50%
Data Storage	31 MB	1 GB	>1000%

7. OCCULTER SPACECRAFT DESIGN

This section covers mDOT B, the spacecraft carrying the occulter payload. The occulter spacecraft design will depend on the concept of operations. Two viable options on how to carry mDOT A and mDOT B into the designated orbit were considered. Option 1 consists of a microsatellite (mDOT B) that carries mDOT A in a deployer within itself. Option 2 consists of two 6U CubeSats (mDOT A and mDOT B). In this scenario both mDOT A and mDOT B will get a ride from a dedicated carrier. Because mDOT B has to carry the precisely manufactured occulter and a relatively large impulsive propulsion system for formation reconfiguration, option 1 was selected.

In this scenario the microsatellite is capable of inserting itself into the required initial orbit before ejecting mDOT A. Once mDOT A is ejected [17], then the microsatellite will position itself at the desired distance from mDOT A and deploy the occulter.

8. MISSION OPERATIONS

Figure 7 shows the overall concept of operations for mDOT. As it can be seen, mDOT B will be separated from the launch vehicle and use impulsive maneuvers to insert itself into the desired orbit. After insertion mDOT B will release mDOT A and deploy the occulter. The mDOT A will drift to a safe distance from mDOT B before initiating its operations.

Similar to other CubeSat missions, mDOT A will establish communications with the ground within the first seven days after deployment, if not earlier. In the setup phase, the spacecraft deploys the solar panels and the UHF antennas, autonomously stabilizes, and transmits beacon signal continuously until communications is established.

mDOT lifetime is designed for 80 days. mDOT A will be producing 1140 Wh per orbit (Depth of Discharge = 60%, recharge efficiency = 70%), which results in a power positive design.

9. SUMMARY

This paper outlines the preliminary system design for a miniaturized distributed occulter/telescope mission. The mDOT mission has the capability to directly image exozodiacal dust and large bright exoplanets, and at the same time prove that miniaturized space systems are capable of executing complex missions. mDOT can serve as a precursor, paving the way for larger missions with higher scientific return, which can capitalize on lessons learned from mDOT.

There is a number of unresolved issues raised in the process of creating this preliminary design that call for deeper analysis. First, the pointing accuracy of the spacecraft is not good enough for the telescope, so an alternative method has to be devised to stabilize the image. Possible solutions could be a piezoelectric mount for the telescope optics or the usage of electric propulsion for attitude control. Second, the proposed navigation and control methods need to be verified in realistic simulations, including sensors and actuators models as well as possible disturbances, such as reaction wheel vibrations and propellant sloshing. Third, the detrimental effects of the radiation environment on the CubeSat parts need to be analyzed.

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