Space-Based Laser Guide Star Mission to Enable Ground and Space Telescope Observations of Faint Objects

Kerri Cahoy, James Clark, Gregory Allan, Yinzi Xin
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
77 Massachusetts Ave., Cambridge, MA 02139; (617) 253-8541
kcahoy@mit.edu, jimclark@mit.edu

Ewan Douglas, Jennifer Lumbres, Jared Males
University of Arizona
douglase@email.arizona.edu

ABSTRACT

We present the detailed design of a Laser Guide Star small satellite that would formation fly with a large space observatory or fly with respect to a ground telescope that use adaptive optics (AO) for wavefront sensing and control. Using the CubeSat form factor for the Laser Guide Star small satellite, we develop a 12U system to accommodate a propulsion system. The propulsion system enables the LGS satellite to formation fly near the targets in the telescope boresight and to meet mission requirements on number of targets and duration. We simulate the formation flight at L2 to assess the precision required to enable the wavefront sensing and control during observation. We describe a design reference mission (DRM) for deploying 18 Laser Guide Stars to L2 to assist the Large Ultraviolet, Optical, Infrared Surveyor (LUVOIR). The L2 LGS DRM covers over 250 exoplanet target systems with 5 or more revisits to each system over a 5-year mission using eighteen 12U CubeSats. We present a design reference mission for a laser guide star satellite to geostationary orbit for use with 6.5+ meter ground telescopes with AO to look at HD 50281, HD 180617, and other near-equatorial targets. We assess simulations on the maximum level of thruster noise permitted during the observations to maintain precision formation flying with the observatories.

INTRODUCTION

As presented in Douglas et al. 2019[1], the primary mirror segment stability requirements of a large segmented-aperture space telescope, such as LUVOIR, can be relaxed by more than a factor of ten by using wavefront control on a guide star of visible magnitude -1 or brighter. There are no natural stars of that brightness, so a spacecraft must carry a laser guide star payload to support the adaptive optics system to enable the segment stability relaxation. To minimize optical path difference errors between the LGS and target star, the LGS spacecraft must fly at a range of at least 40,000 km from the telescope.[1]

To fly in formation with the telescope at L2, the LGS spacecraft must carry an onboard propulsion system, and its performance should not negatively impact the pace or quality of observations. In this paper, we derive LGS mission requirements, present and evaluate options for its propulsion system, and present a preliminary CubeSat-based spacecraft design.

SCIENCE MISSION REQUIREMENTS

From personal communication with Chris Stark, we have obtained a list of targets of study for LUVOIR's design reference mission described in Stark et al., 2015[2]. A map of these stars is shown in Figure 1.

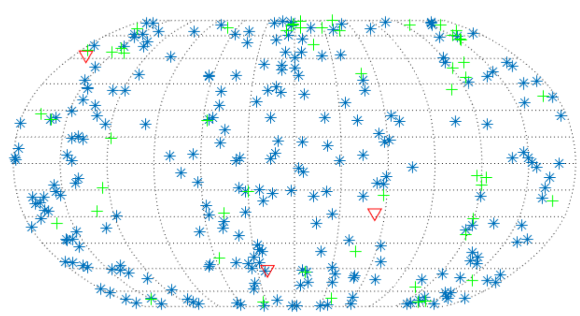

Figure 1: Map of exoplanet survey targets from Stark et al. 2015[2] (blue stars), Hubble and Chandra deep fields (red triangles), and stars brighter than V mag 2 (green crosses).

There are 259 stars in the list, and each is imaged five or six times over the course of five years. A total of 1,539 observations are made during the mission, at an average pace of 1.2 days per observation (with between 0.2 and 0.75 days of integration time). The requirement for the LGS spacecraft is to support this pace of observation.

Because the laser will be so much brighter than the target star under observation and any planets around it, it is necessary to make sure that its light does not affect active science bands. A high-optical-density filter will be required to divert the laser's light away from the science sensors. While a detailed trade study on laser wavelengths needs to be conducted depending on the science bands, in this work we assume the LGS spacecraft carries at least two different wavelength lasers that can be switched on and off.

The mission profiles that will be studied in this paper are summarized in Table 1. We include a case with an LGS-telescope range of 10,000 km to inform an ongoing trade comparing the reduction of LGS spacecraft against the addition of defocus correction optics into the wavefront control system.

Table 1: LGS Design Reference Mission cases.

Case	Scope/LGS location	Scope D (m)	Tgts	Obs	LGS-Scope range (km)
Standard	L2/L2	9.2	259	1539	40,000
L2 Close	L2/L2	9.2	259	1539	10,000
Pathfinder	Ground/GEO	6-30	Opportunistic		~40,000

Segment Wavefront Control Architecture

Evaluation of how to implement the wavefront sensing and control system on the observing telescope is still in progress.

The simplest implementation is to apply feedback to the primary segment actuators directly. The advantages of this approach are that it does not require modifications to the existing optical design, and thus does not require additional components. However, the primary segments are large and heavy, and the relaxation of the stability requirements would be limited by the rate at which the actuators can control the segments.

An alternative approach is to use a deformable mirror (DM) to implement segment wavefront control in addition to the two DMs used for electric field conjugation (EFC). Actuating a small DM is very fast and would solve the issue of the limited actuator speed of the primary segments, but adding a DM would increase the optical complexity of the system and require modifications to current LUVOIR models. This architecture also suffers from additional sources of error depending on the specific DM implementation. For example, with a continuous facesheet DM such as the Boston Micromachines 2K DM, fitting errors from fitting DM influence functions to the wavefront error introduced by the segments prevents EFC from working with an input RMS segment error of just 100 pm. Using a hexagonal DM with segments conjugate to the primary is an alternative approach. However, the architecture of existing hexagonal DMs is still based on fitting individual actuator influence functions to segment motion (see Figure 2). Currently, the surface flatness figures of these DMs are limited to around 20 nm RMS (Iris AO PTT111)[3] and 40 nm RMS (BMC Hex Class)[4], much higher than the <10 pm error required for LUVOIR. Although fitting is the dominant source of error, the hexagonal DM architecture is also subject to a variety of other errors, including edge diffraction, fill mismatch, and nonconjugacy and distortion effects, all of which would need to be carefully characterized and mitigated.

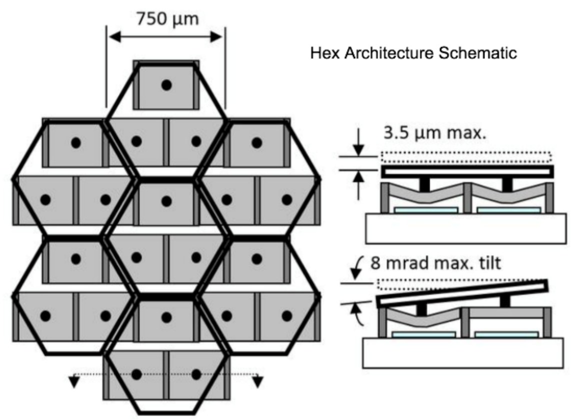

Figure 2: Layout of Boston Micromachines Hex DM actuators.[4]

PROPULSION NEEDS

The LGS spacecraft will use propulsion to fly in formation with the telescope during observations, and to transit from one target to another. This concept of operations is presented in Figure 3.

Orbits at L2 are unstable; this is good for the safety of the telescope, because an LGS spacecraft that loses functionality will drift away and most likely will not recontact the telescope, but it means that the LGS spacecraft will have to use its thruster during observations to stay on the line of sight from the telescope to the science target.

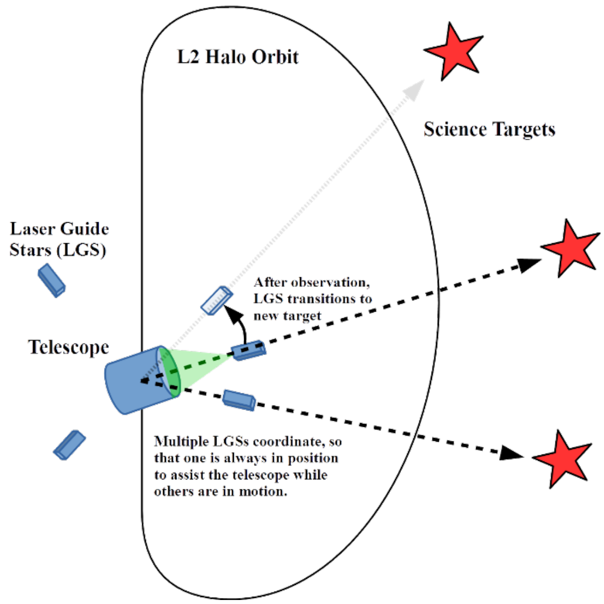

Figure 3: Telescope/LGS concept of operations at L2.

The average difference in the acceleration of gravity between the telescope on an L2 halo orbit and a "nearby" LGS at 40,000 km range is 5.5 µm/s^2. For a 24 kg smallsat, combating this acceleration requires 0.13 mN of thrust on average (which may actually be sustained by duty-cycling a more powerful thruster). We have selected a handful of smallsat propulsion systems which meet this requirement and are in or nearing production as of 2019, and have summarized their properties in Table 2. We also include the delta-V capacity provided by each propulsion system for a 24-kg (12U) spacecraft.

Table 2: Propulsion systems for small satellites

System	Size (U)	Thrust (mN)	Isp (sec)	Fuel cap. (g)	DV (m/s)
2x Accion TILE 5000[5]	2x 1.25	2x 1.5	1500	2x 340	423
Apollo Constellation[6]	4+	33	1500	1000	626
Busek BIT-3[7]	2	1.2	2300	1500	1456
2x Enpulsion IFM Nano[8]	2x 1	2x 0.4	3500	2x 230	664
2x IFM Nano Max Isp[8]	2x 1	2x 0.3	6000	2x 230	1139
Phase Four Maxwell[9]	4+	4+	570+	2000+	660+
Vacco MarCO[10]	3	0.1	75?	1030	32
Vacco MiPS[11]	3	0.4	169	2000	144

Transiting between targets

The maximum thrusts of the candidates are all much greater than the differential acceleration at L2; therefore, to a first-order approximation, we can disregard the effect of L2 during transits and regard only the LGS spacecraft's acceleration.

To transit between two targets that are separated by angular distance θ while flying at a range R from the telescope, the LGS must travel a distance $\approx R\theta$. The small-angle approximation is justified here, as the mean nearest-neighbor separation of 259 uniformly-distributed targets over the sphere is 11 degrees, which we will use as a 'standard' maneuver for comparison.

For low-thrust electric propulsion, with high delta-V capabilities, the most time-efficient way to make this maneuver is to accelerate towards the new target line of sight until the half-way point is reached, then turn around and decelerate to a stop. For spacecraft acceleration $a = T/m$ (for spacecraft mass m, approximately constant for low fuel-mass fractions, and propulsion system thrust T), the time t required to execute the maneuver is given in Equation 1, and the delta-V cost at is expanded in Equation 2. The minimum time that a 24 kg satellite can complete one of these maneuvers, and the number of maneuvers that each propulsion system can support, are given in Table 3. Note that all of these systems require more than 1.2 days to make a transit maneuver.

$$t = 2\sqrt{R\theta/a} \quad (1)$$

$$\Delta v = at = 2\sqrt{R\theta a} \quad (2)$$

Table 3: Transit capabilities for different propulsion systems.

System	Min. maneuver time (days)	Maneuver count
2x Accion TILE 5000	5.7	6
Apollo Constellation	1.7	3
Busek BIT-3	8.9	36
2x Enpulsion IFM Nano	11.9	19
2x IFM Nano Max Isp	14.0	45
Phase Four Maxwell	7.0	7
Vacco MarCO	31.4	2
Vacco MiPS	15.7	6

From Equation 2, we can see that, regardless of our choice of propulsion system, we can always reduce thrust to increase the number of transits that an LGS spacecraft can execute with its fuel capacity, at the cost of requiring proportionally more time for each transit.

So, to enable the mission to proceed at the desired pace, we will deploy multiple LGS spacecraft at the same time, each servicing a different domain of the sky at the same time. They can stagger their maneuvers so that, even though each one will take more than 1.2 days to transit from one target to another, one will always be in position to support an observation when the telescope is ready. The optimum number of LGS spacecraft turns out to be the number such that each domain is exactly serviced by one LGS (i.e. the number of stars in each domain is $1/6^{th}$ the number of maneuvers the LGS can sustain). A chart of the number of LGS spacecraft required, as a function of the propulsion system used, is presented in Figure 4. We can see that the Busek BIT-3 allows the mission to be executed with the least number of LGS spacecraft.

The variable to which this analysis is most sensitive is the range to the telescope. If the LGS spacecraft are permitted to fly at 10,000 km away from the telescope, then only half as many are required to support the mission, although at that range, the LGS's wavefronts are detectably curved compared to the wavefronts from the target system, which may require additional optical elements in the wavefront control system.

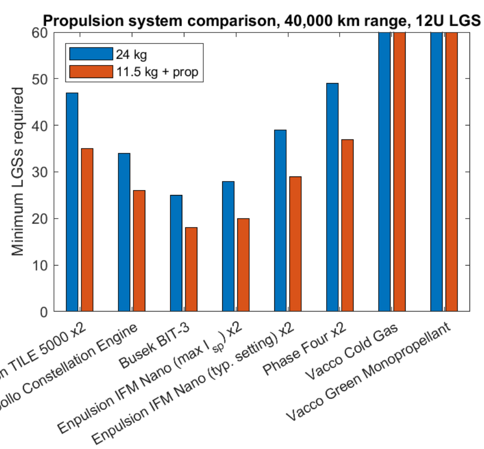

Figure 4: Number of LGS spacecraft required to support L2 DRM at 40,000 km range to telescope for several propulsion options. Blue bars: LGS mass 24 kg exactly; red bars: LGS mass is 11.5 kg plus the mass of the propulsion system.

After telescope-LGS range, these results are most sensitive to the propellant mass fraction of the LGS spacecraft. Figure 4 shows the result for using 24-kg LGS spacecraft, which is the maximum mass permitted in the 12U form factor, in blue bars, and uses red bars to show the result for a lighter estimated mass based on an MIT 12U spacecraft design effort (which will be used for the remainder of this analysis). If the thrusters can be ordered with greater fuel capacities than their stock configurations, the number required could be reduced still further.

Formation flight during observations

Having evaluated the ability of different thruster systems for transiting between targets, we can now begin simulating the formation flight at L2 and develop requirements for how the thruster must perform during observations. Propulsion system requirements will have direct implications for the electrical power system, as noise in the thrust of electrical thrusters is directly correlated to noise in the power supply.

We have performed simulations of the telescope-LGS formation flight activity at L2 using the circular restricted three-body problem. The LGS is initialized on the line of sight from the telescope to the target star, and then is commanded to remain on that line of sight. Its thrust vector is constrained to be perpendicular to the line of sight due to the spacecraft's construction (see Figure 7). Thruster noise is simulated by multiplying the commanded thrust at each time step by a normally-distributed random number with mean 1 and standard deviation of e.g. 1%. Simulations are run for one day of elapsed time, representing one of the longer observations from Chris Stark's LUVOIR DRM, and for ten days, representing a deep field observation. The LGS is required to remain within 500 nrad of the line of sight, to keep its wavefronts flat against each primary mirror segment. This is comparable in magnitude to 200 nrad, the $4\lambda/D$ inner working angle of the LUVOIR coronagraph.[5] Angular error is plotted as a function of the magnitude of thruster noise (as a fraction of commanded thrust) in Figure 5, and we can see that the current implementation of the controller can acceptably control the spacecraft with noise up to 1% for 1-day observations and 0.01% for 10-day observations.

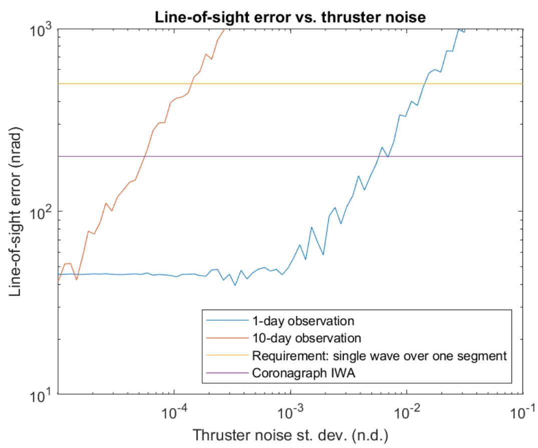

Figure 5: Line-of-sight error after 1 and 10 days of observation vs. thruster noise.

Pathfinder with ground-based telescope

As an early pathfinder mission, we are proposing to launch an LGS spacecraft to geostationary orbit, to work with ground-based telescopes. This will demonstrate the adaptive optics system across ranges similar to those in the L2 mission, without the expense of launching a space telescope to L2.

If the LGS spacecraft remains exactly in GEO, any given telescope can only image targets in a narrow range of declinations, of less than half a degree. However, the same electric propulsion system to be used for the L2 mission can be used to incline the LGS's orbit to enable access to broader regions of the sky. Figure 6 shows a map of the sky accessible from Keck at a particular time of day (large outline) with the assistance of an LGS equipped with a particular amount of delta-V (labeled stripes). Note that the 1500 m/s outline, which is supported by electric propulsion, encompasses approximately 25% of the sky, including over 70 of Chris Stark's targets and the Chandra Deep Field South (and Hubble Ultra/Extreme Deep Field).

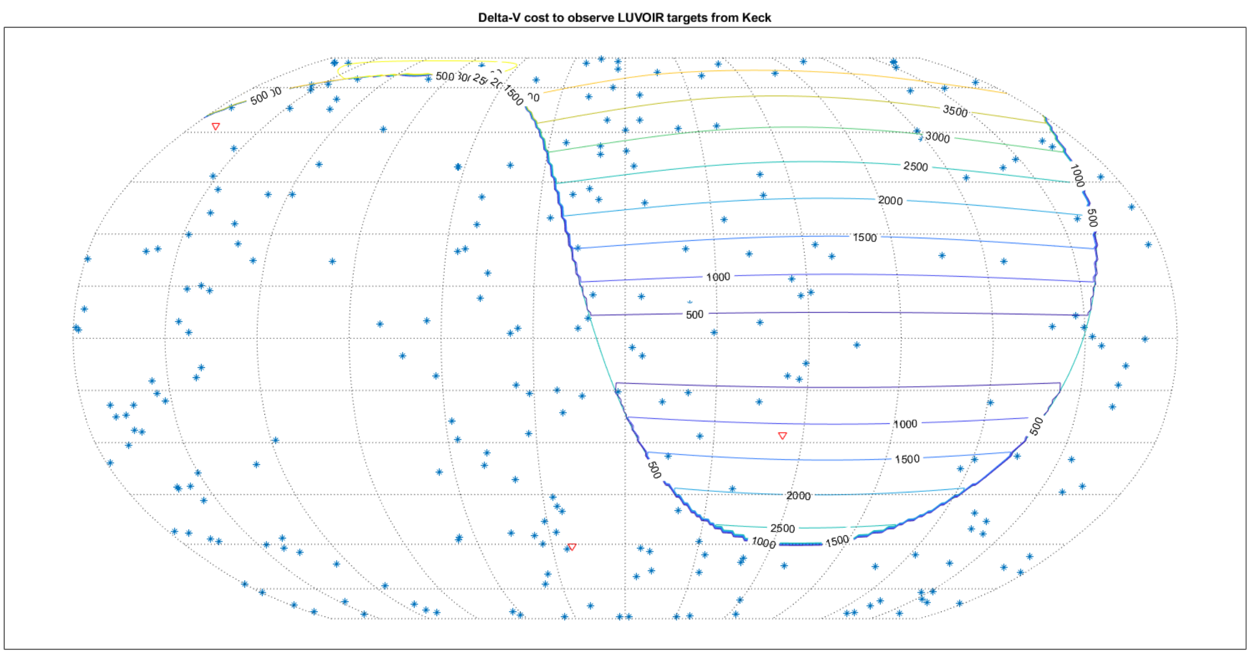

Figure 6: Map of delta-V cost to deploy an LGS spacecraft from GEO to have line-of-sight from Keck to astronomical targets (m/s), and map of Keck's view of the sky at a particular time of sidereal day. Blue asterisks are targets from Stark et al. 2015[2], red triangles are Hubble and Chandra deep fields.

SPACECRAFT DESIGN

We have adapted a flexible 12U smallsat bus developed by another design effort at MIT into an LGS spacecraft. A cutaway view is depicted in Figure 7.

The design includes 2U of volume allocated for a propulsion system (shown here as two Enpulsion IFM Nano thrusters) and 2U of volume for the laser guide star system, based on a laser communication system under development at MIT.[12,13] The thrust vector and laser axis are oriented at right-angles to each other, so that the spacecraft can combat drift across the telescope-LGS line of sight during observations.

Physically, all components can be accommodated in this form factor, but we are conducting trade studies on the power requirements for the mission and may expand to 16U for additional solar panel area and battery capacity.

Mission costs

The 12U smallsat bus design is estimated to cost approximately $12 million to complete the design, integrate, test, and launch a single vehicle. Further units are estimated to cost $5 million each. Figure 4 shows that the minimum number of LGS spacecraft required to support the mission is 18, which would have a total cost less than $100 million. The James Webb Space Telescope is anticipated to cost nearly $10 billion[14], and LUVOIR is expected to be twice as large and be orders of magnitude more sensitive. Companion LGS spacecraft may more than pay for themselves by reducing primary mirror segment stability requirements.

Negative impacts on the observatory

Before placing a spacecraft directly in the line of sight of an observatory, we have a responsibility to understand and mitigate the spacecraft's negative impacts during observation. Besides filtering the laser's light when in use, as described before, we have made preliminary studies of the LGS spacecraft's thruster plumes and sunlight glinting from its body.

Because the top thruster candidates are electric propulsion systems with exhaust velocities in excess of 15 km/s, if the thruster is shut off, the plume will leave the outer working angle of the coronagraph (1.3 μrad = $24\,\lambda/D$)[5] in 4 ms. It will be straightforward for the LGS to pulse its thrusters and coordinate with the telescope to integrate between impulses.

During an observation, the sides of the vehicle will either be facing the telescope aperture directly, or at right angles to it. As shown in Figure 8, there will be no direct reflections from the Sun into the telescope. This still leaves the question of scattered light from the LGS spacecraft's edges. Steeves et al. 2018[15] have measured the light glinting from sharp aluminum edges and found that the total glinting from the Starshade will be between 22nd and 26th magnitude, depending on the angle to the Sun. Scaling from the perimeter of Starshade (~400 m of edges) down to a 12U bus (up to 5 m of edges, with dual-deployed solar panels), and moving from 48,800 km inwards to 40,000 km, LGS would have a glint between 26th and 30th magnitude (23rd-27th magnitude at 10,000 km). This is comparable in brightness to an Earth-like planet around a 5th-magnitude star, but as shown in Figure 5, if thruster noise is controlled to less than 0.5%, the LGS will remain within the inner working angle of the coronagraph for a single-day observation (5×10^{-5} for a 10-day observation) and it will not disturb the observation.

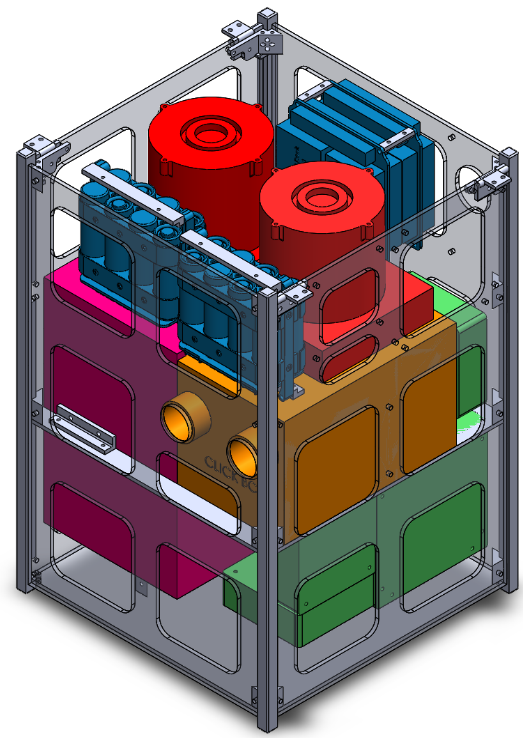

Figure 7: Cutaway view of LGS spacecraft design, by W. Kammerer and J. Clark. Deployable solar panels not shown. Subsystems shown: propulsion (red), avionics and RF communications (magenta), power (blue), lasers (gold), and attitude determination and control system (green).

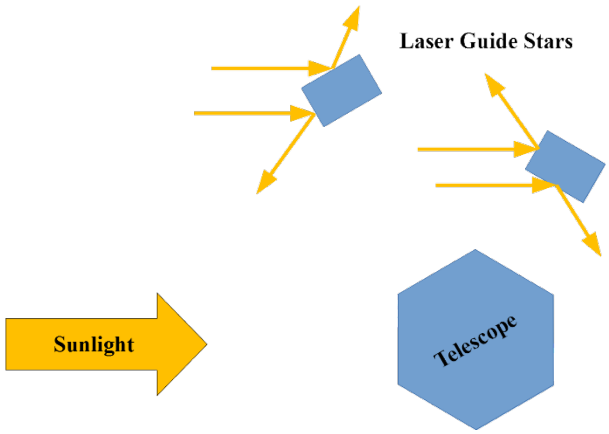

Figure 8: As long as the telescope-LGS line of sight is not facing directly towards or away from the Sun, there will be no direct reflections from the Sun into the telescope from any of the LGS's faces.

SUMMARY

In summary, we have presented a laser guide star spacecraft in the 12U form factor that can support a large segmented-aperture space telescope at L2. Eighteen of these vehicles can support a campaign of over 1500 observations of over 250 stars in less than five years, and one (or more) could be used from geostationary orbit in a pathfinder mission supporting large ground-based telescopes.

Future work

In a planned future publication, we will address this spacecraft's power budget and develop mitigation strategies for radiated heat. Subsequently, we will study the impacts of flying the LGS spacecraft closer to the telescope, trading the complexity impact on the wavefront control system against the reduction of the number of LGS spacecraft required. We are also conducting more detailed studies of the pathfinder mission assisting ground-based telescopes, with particular attention to access windows and revisit times for specific targets.

Acknowledgements

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REFERENCES

[1] Douglas, E. S., Males, J. R., Clark, J., Guyon, O., Lumbres, J., Marlow, W., and Cahoy, K. L., "Laser Guide Star for Large Segmented-aperture Space Telescopes. I. Implications for Terrestrial Exoplanet Detection and Observatory Stability," *The Astronomical Journal*, vol. 157, Jan. 2019, p. 36.

[2] Stark, C. C., Roberge, A., Mandell, A., Clampin, M., Domagal-Goldman, S. D., McElwain, M. W., and Stapelfeldt, K. R., "LOWER LIMITS ON APERTURE SIZE FOR AN EXOEARTH DETECTING CORONAGRAPHIC MISSION," *The Astrophysical Journal*, vol. 808, Jul. 2015, p. 149.

[3] Iris AO, Inc., "PTT111 DM System" Available: http://www.irisao.com/product.ptt111.html.

[4] Boston Micromachines Corporation, "Hexagonal Deformable Mirrors," *Boston Micromachines Corporation* Available: http://bostonmicromachines.com/hex-mirrors.html.

[5] Accion Systems Inc., "TILE," *Accion Systems — A New Ion Engine* Available: https://www.accion-systems.com/tile/.

[6] Apollo Fusion, Inc, "Apollo Constellation Engine (ACE)" Available: https://apollofusion.com/ace.html.

[7] Busek Co. Inc., "BIT-3 RF Ion Thruster" Available: http://www.busek.com/index_htm_files/70010819D.pdf.

[8] Enpulsion GmbH, "IFM Nano Thruster" Available: https://www.enpulsion.com/wp-content/uploads/2019/03/ENP_-_IFM_Nano_Thruster_-_Product_Overview.pdf.

[9] Phase Four, Inc, "Phase Four Radio Frequency Thruster" Available: http://phasefour.io/wp-content/uploads/2017/06/SPEC.pdf.

[10] VACCO Industries, "JPL MarCO Micro CubeSat Propulsion System," *VACCO Industries* Available: https://www.cubesat-propulsion.com/jpl-marco-micro-propulsion-system/.

[11] Vacco Industries, "Standard Micro CubeSat Propulsion System," *VACCO Industries* Available: http://www.cubesat-propulsion.com/standard-micro-propulsion-system/.

[12] Clements, E., Aniceto, R., Barnes, D., Caplan, D., Clark, J., Portillo, I. del, Haughwout, C., Khatsenko, M., Kingsbury, R., Lee, M., Morgan, R., Twichell, J. C., Riesing, K., Yoon, H., Ziegler, C., and Cahoy, K., "Nanosatellite optical downlink experiment: design, simulation, and prototyping," *Optical Engineering*, vol. 55, Sep. 2016, p. 111610.

[13] Čierny, O., and Cahoy, K. L., "On-orbit beam pointing calibration for nanosatellite laser communications," *Optical Engineering*, vol. 58, Nov. 2018, p. 041605.

[14] Overbye, D., "NASA Again Delays Launch of Troubled Webb Telescope; Cost Estimate Rises to $9.7 Billion," *The New York Times*, Jun. 2018.

[15] Steeves, J., Lee, H. J., Hilgemann, E., McKeithen, D., Bradley, C., Webb, D., Shaklan, S., Martin, S., and Lisman, D., "Development of low-scatter optical edges for starshades," *Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III*, International Society for Optics and Photonics, 2018, p. 107065K.