Satellite Laser Guide Stars for Large Aperture Segmented Ground Telescopes

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ABSTRACT

In this work we consider using satellite laser guide stars to enable high contrast imaging with extremely large telescopes (ELTs). In 2010, Traub and Oppenheimer calculated that a natural or artificial guide star of magnitude -4.2 +/- 0.2 (in BV, RI, J, H, and/or K band) is required to enable a 30-m ground-based telescope to image exoplanet systems with contrast ratios better than 10^{-10}. Telescopes with 100-m diameters require guide stars of magnitude -1.4 +/- 0.2. Typical sodium laser guide stars are much dimmer, magnitude 9 or 10. The angular size of a natural guide star modeled after a sun-like star at 10 pc is 0.9 mas (4.5 nrad), much smaller than a 10 m spot at the 80 km sodium layer, which is about 25 arcsec (125 μrad). Satellite laser guide stars were introduced by Greenaway and Clark in the early 1990s but were not considered cost-effective at the time. With recent advances in both satellite laser communication and the miniaturization and reduced-cost access to space of nanosatellites, we revisit the impact and value of a satellite laser guide star system. A satellite laser guide star with a 4 cm diameter spot at geostationary altitude (35,786 km) has an angular size of 0.2 mas (1 nrad), which is comparable to a natural guide star, but the satellite laser guide star has the potential to be several magnitudes brighter. For example, the 1064 nm GEO laser communications terminal Technology Demonstration Payload 1 (TDP1) that flew on Alphasat has a nominal 0.1 W transmit power and 1.5 arcsec (7.1 μrad) half-angle beam divergence with a magnitude brighter than -2. At maximum power of 5 W, the Alphasat terminal has magnitude brighter than -6. In the past year, flight and in-development nanosatellites have demonstrated laser communications downlinks as well as interplanetary operations. Leveraging nanosatellite technological advancements and electric propulsion systems, several cost-competitive satellite laser guide stars can be developed for specific targets of interest. The satellite laser guide stars can fly in coordination with ELT observational campaigns and enable high contrast ground-based imaging.

Keywords: AO systems design and modelling

1. INTRODUCTION

Since 1992, thousands of exoplanets have been discovered by astronomers, with many thousands more awaiting confirmation. The next giant leap in exoplanet science is the detection and characterization of Earth-like exoplanets orbiting Sun-like stars. This will require coronagraph measurements with adaptive optics (AO) to achieve contrasts at or exceeding 10^{-10}. In 2010, Traub and Oppenheimer[1] calculated that a natural or artificial guide star of magnitude -4.2 +/- 0.2 (in BV, RI, J, H, and/or K band) is required to enable a 30-m ground-based telescope to image exoplanet systems with such a contrast ratio. Telescopes with 100-m diameters require guide stars of magnitude -1.4 +/- 0.2. However, typical sodium laser guide stars are magnitude 9 or 10. (Keck's are somewhat brighter, for example, up to magnitude 7[2]). Laser guide stars are broader targets on the sky than natural stars; the angular size of a sun-like star at 10 pc is 0.9 mas (4.5 nrad), while a 10 m spot at the 80 km sodium layer is about 25 arcsec (125 μrad). Ground-based laser guide stars also cannot provide tip-tilt feedback; Keck's AO system relies on background stars of magnitude 15 or brighter for tip-tilt information.[2]

Satellite laser guide stars were introduced by Greenaway and Clark[3] in the early 1990s but were not considered cost-effective at the time. With the advances in both satellite laser communication and the miniaturization and

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reduced-cost access to space of nanosatellites, we revisit the impact and value of a satellite laser guide star system. A satellite laser guide star with a 4 cm diameter spot at geostationary altitude (35,786 km) has an angular size of 0.2 mas (1 nrad), which is comparable to a natural guide star. These angles are illustrated graphically in Figure 1.

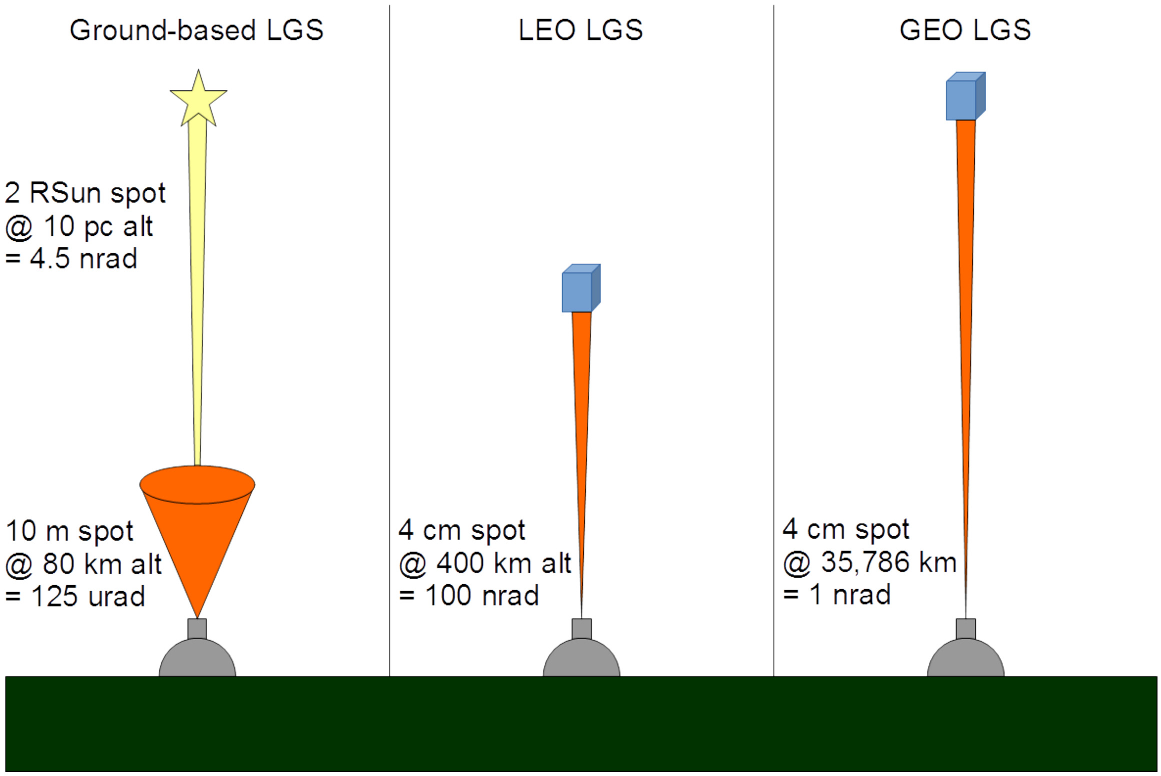

Figure 1. Space-based laser guide stars will produce tighter, more star-like beams than ground-based laser guide stars, which will improve AO system performance.

Additionally, the satellite laser guide star has the potential to be several magnitudes brighter than ground-based laser guide stars, and because they provide tip-tilt feedback, they can be used to service observations anywhere on the sky. The 1064 nm GEO laser communications terminal TDP1 that flew on Alphasat[4] at nominal 0.1 W transmit power and 1.5 arcsec (7.1 μrad) half-angle beam divergence has a magnitude brighter than -2 when observed at a range of 35,768 km (the altitude of geostationary orbit). At its maximum power of 5 W, the Alphasat terminal would have a magnitude brighter than -6. In the past year, flight and in-development nanosatellites have demonstrated laser communications downlinks as well as interplanetary operations. Leveraging these technological advancements as well as electric propulsion systems for nanosatellites, several cost-competitive satellite laser guide stars could be developed for specific targets of interest. The satellite laser guide stars would fly in coordination with ELT observational campaigns and enable high contrast ground-based imaging.

2. OPTICAL ARCHITECTURE

During an observation, the satellite will transmit a laser beam to the telescope, which will be picked off to a high-rate wavefront control system. The high photon rate from the LGS beam will allow the WFSC to detect high-rate vibrations in mirror segments, complementing onboard laser metrology and edge sensors. One architecture depicted in Figure 2 shows the LGS using a wavelength which is outside of the science band, to avoid contaminating the measurement; this is one of several options under consideration.

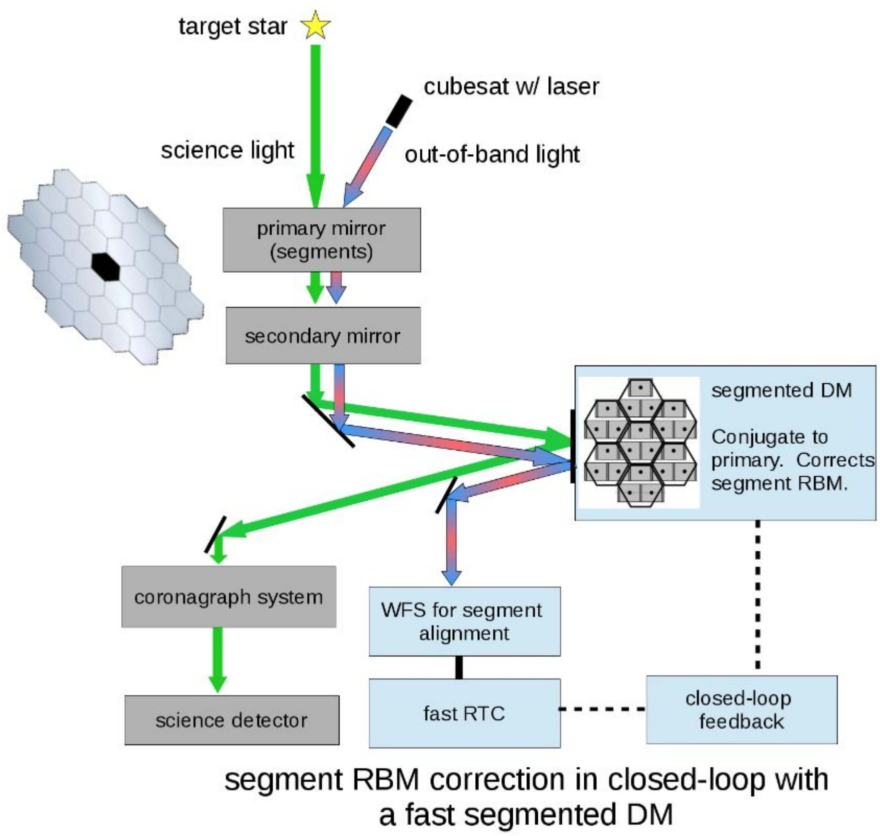

Figure 2. The out-of-band laser light is picked off to drive a high-rate wavefront control loop. Figure by Jared Males.

2.1 Optical Testbed

An optical testbed has been constructed at the University of Arizona to evaluate the telescope's side of the optical system, such as the effects of mirror segment controller bandwidth on the final wavefront stability. The layout is shown in Figure 3. Laser beams of different wavelengths, representing the target star and LGS, are combined with a beam combiner and reflected onto a segmented deformable mirror (SegDM). The SegDM is an IrisAO PTT111-L with 37 segments and an inscribed aperture of 7 mm. Off-axis parabolic (OAP) mirrors are used where multiple wavelengths are present to reduce chromatic aberration. A dichroic beam splitter is placed after the SegDM to separate the target star and zernike wavefront sensor (ZWFS) light onto different system paths. The target star's light leads to a focal plane detector, to evaluate the star's PSF (point spread function) off the segDM. The LGS light is sent to a ZWFS focal plane mask and through an imaging lens to form a pupil image at the detector. The ZWFS focal plane mask is sensitive to and can detect optical path length discrepancies, particularly for segment piston.

Preliminary images from alignment testing are shown in Figure 4, where each of the seven test segments have 0.2 μm of piston applied. The change in the star's PSF corresponds with the SegDM's adjustments. We can see in the ZWFS pupil plane that the LGS does provide information on the state of the segmented deformable mirror. The highlighted sections are where piston has been applied, which can bee compared with the flat DM setting that initially shows no light. Additional work in characterizing the dynamic range and linearity performance of the ZWFS are in progress.

3. SPACECRAFT DESIGN

We have adapted a flexible 12U smallsat bus developed for another reesearch project at MIT into an LGS spacecraft. A cutaway view is depicted in Figure 5. The design includes 2U of volume allocated for a propulsion

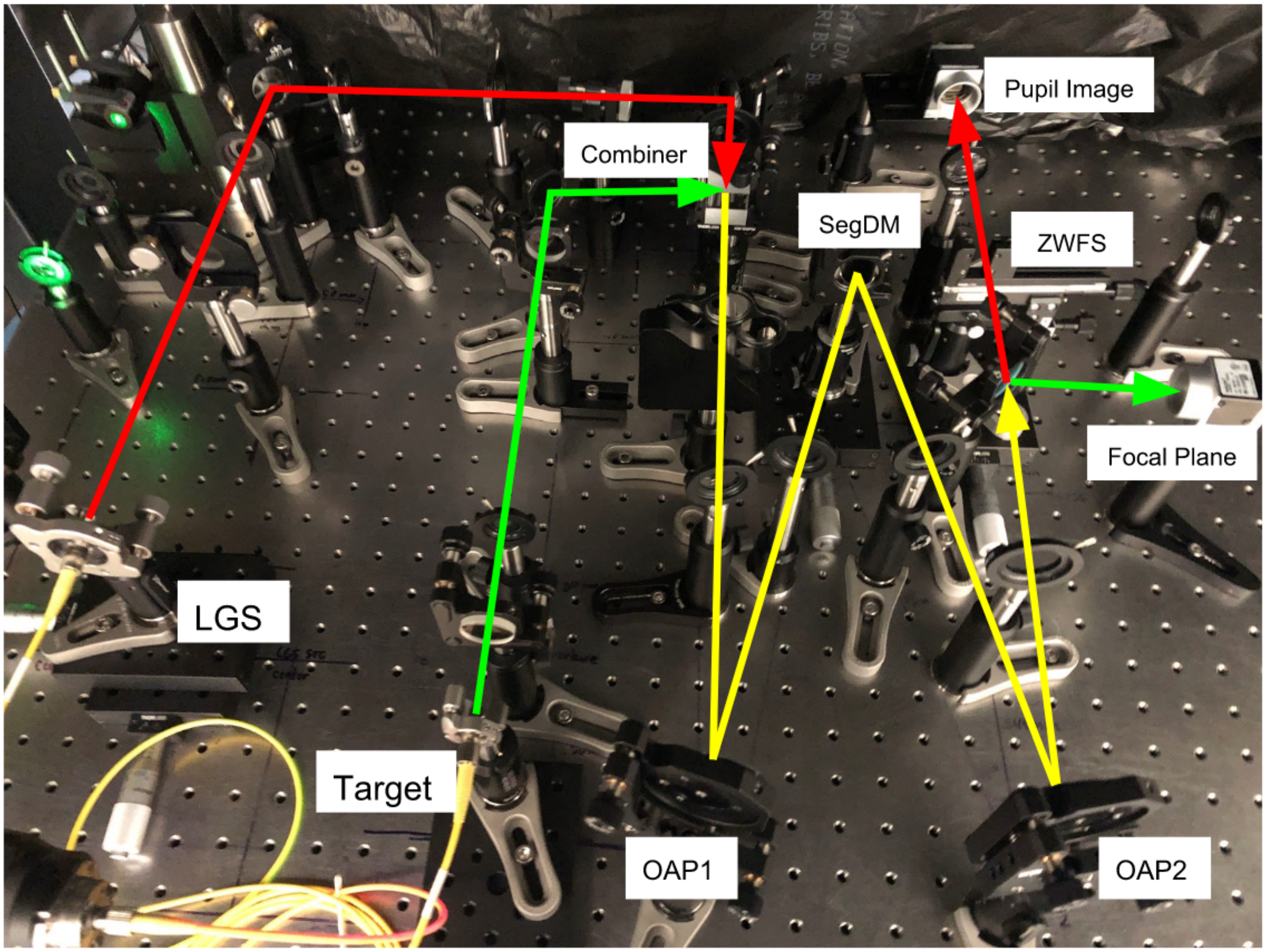

Figure 3. Optical test bed for simulating the satellite laser guide star mission (University of Arizona). The segmented deformable mirror ("SegDM") represents the primary mirror of the Large UV/Optical/IR Surveyor (LUVOIR), and further optical stages may be simulated after OAP2.

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.[5,6] Physically, all components including propulsion can be accommodated in a 12U form factor. Ongoing trade studies on the power and propulsion requirements for the mission may expand the platform to 16U for additional solar panel area and battery capacity.

The small satellite can be deployed into a geostationary orbit or highly elliptical orbit to minimize its movement across the telescope's field of view, and it is equipped with onboard propulsion to extend observation windows, adjust observation schedules, or gain access to more of the sky. We have selected a handful of smallsat propulsion systems which meet LGS requirements and are either available or or nearing production as of 2019, and have summarized their properties in Table 1. We also include the delta-V capacity provided by each propulsion system for a 24-kg (12U) spacecraft, which shows that multiple options exist for providing a LGS spacecraft platform with between 1,000 and 1,500 m/s of delta-V.

3.1 Sky Access

The easiest location to deploy a satellite laser guide star to support a ground-based telescope is to place it in geosynchronous equatorial orbit (GEO). The satellite will remain fixed in the sky from the telescope's perspective, and the telescope's line-of-sight through the LGS will slowly rotate over the stars. However, this will only grant

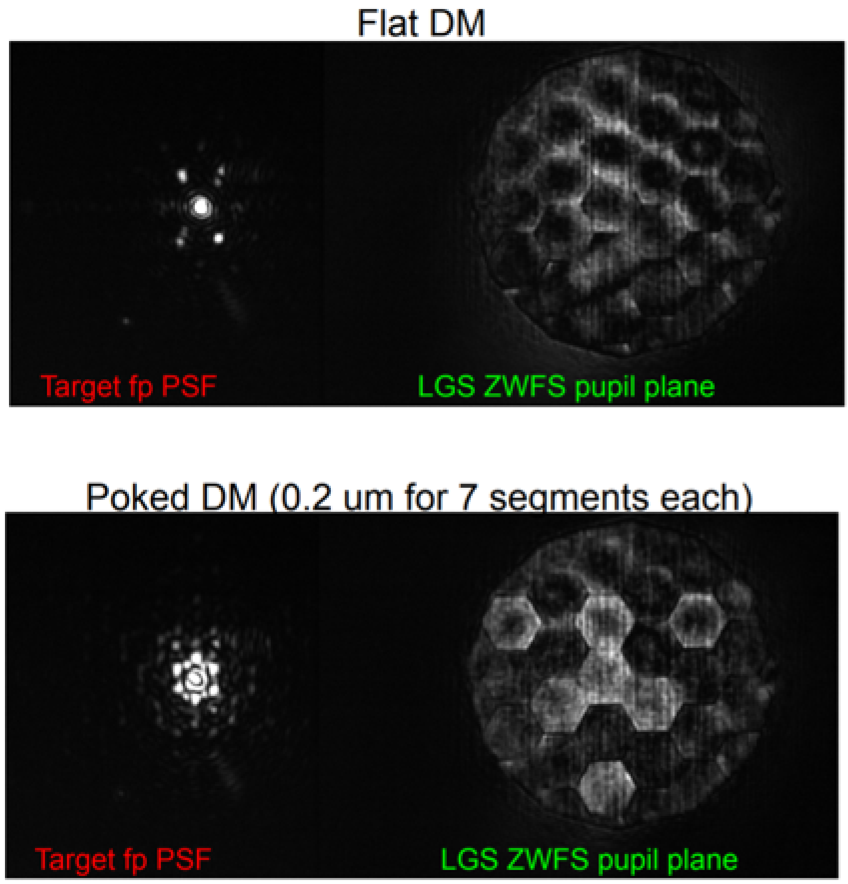

Figure 4. Views from the focal plane ("Target fp PSF", representing the green star-light path in Figure 3) and Zernike wavefront sensor ("LGS ZWFS pupil plane", representing the red LGS light path) with the segmented DM flat and with seven segments pistoned forward.

Table 1. Propulsion systems for small satellites.

System	**Size (U)**	**Thrust (mN)**	I_{sp} **(sec)**	**Fuel cap. (g)**	ΔV **(m/s)**
2x Accion TILE 5000[7]	2x 1.25	2x 1.5	1500	2x 340	423
Apollo Constellation[8]	4+	33	1500	1000	626
Busek BIT-3[9]	2	1.2	2300	1500	1456
2x Enpulsion IFM Nano[10]	2x 1	2x 0.4	3500	2x 230	664
2x IFM Nano Max Isp[10]	2x 1	2x 0.3	6000	2x 230	1139
Phase Four Maxwell[11]	4+	4+	570+	2000+	660+
Vacco MarCO[12]	3	0.1	75	1030	32
Vacco MiPS[13]	3	0.4	169	2000	144

access to stars in a band of declinations approximately a half-degree wide near the equator (depending on the location of the LGS in GEO relative to the telescope).

The GEO LGS orbit is suitable for proof-of-concept observations, and does include some targets of interest identified by the LUVOIR (Large UV, Optical, Infrared Surveyor) science and technology definition team,[14] but it is desirable to access much more of the sky. One way to do this is to use onboard propulsion to change the

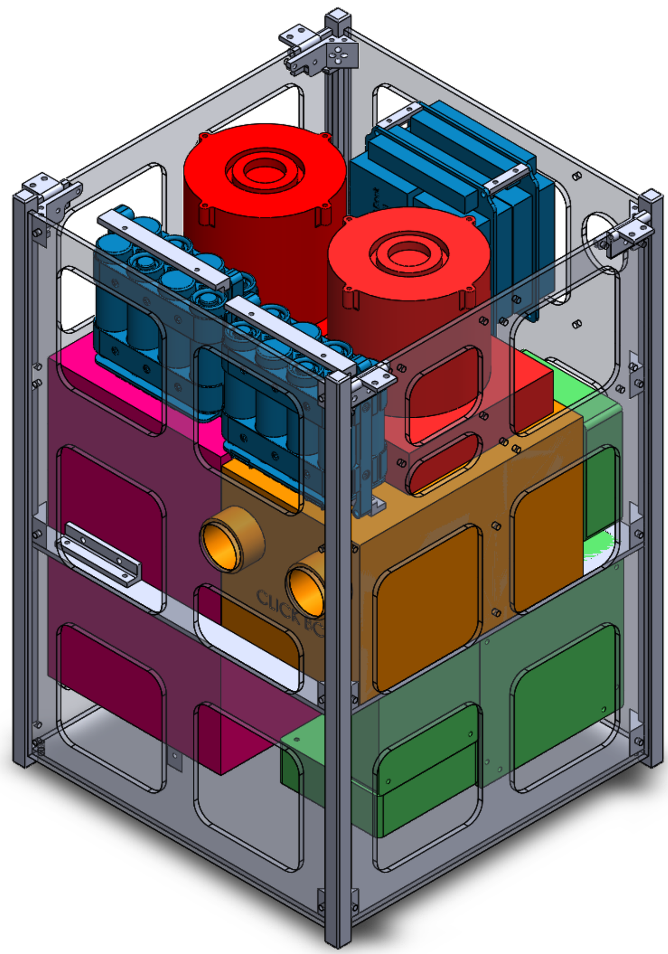

Figure 5. Cutaway view of LGS spacecraft design, by W. Kammerer and J. Clark. Deployable solar panels not shown. Subsystems shown: propulsion (red), avionics and RF communications (magenta), power (blue), lasers (gold), and attitude determination and control system (green).

inclination of the satellite's orbit. The telescope-LGS line of sight will oscillate north and south, which will grant access to larger and larger bands of stars around the Equator as the inclination increases. The delta-V cost to access stars seen from Keck is illustrated in Figure 6. We can see that the 1500 m/s band, which corresponds to the upper limit enabled by propulsion systems identified in Table 1, encompasses over 25% of the sky, including over 70 of LUVOIR's targets and the Chandra Deep Field South.

4. SUMMARY

In summary, we show that satellite laser guide stars are technologically feasible thanks to advancements in small-satellite laser communication and electric propulsion technologies, and can be beneficial to upcoming extremely large telescope observations of high-contrast targets. We are continuing to refine the concept of operations and laboratory testbed, and are developing proof of concept plans that can use an already existing telescope and satellite-based laser system, as well as developing prototype purpose-built LGS spacecraft and ground telescope LGS systems.

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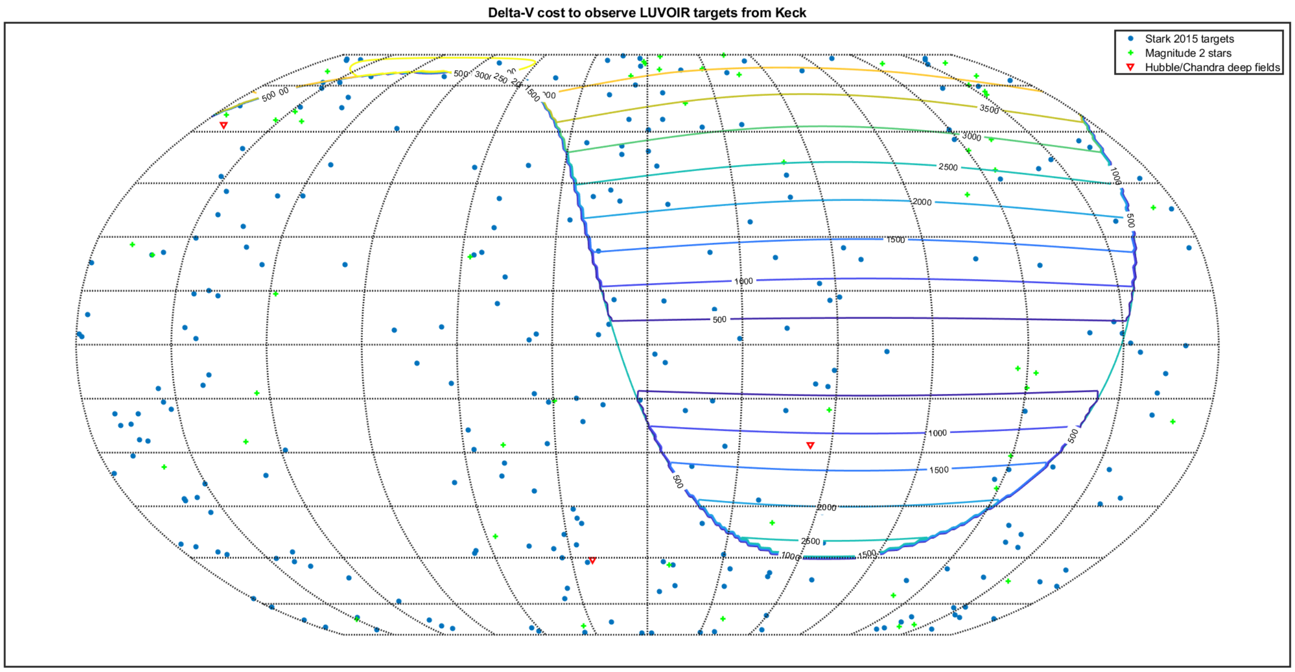

Figure 6. This chart shows the region of the sky visible to Keck at a particular time of day (large shape), and the delta-V (m/s) required to move an LGS spacecraft from GEO to get a line-of-sight to a particular point in the sky (numbered stripes). The figure rotates over the stars once per sidereal day.

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