Extremely Bright Orbital Guide Beacons for Extremely Large Telescopes

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ABSTRACT

Directly imaging Earth-sized exoplanets from the ground poses a considerable challenge for adaptive optics systems. For this endeavor, natural and laser guide stars are either too dim, or are outside of the science band. To overcome these limitations, a satellite carrying a bright light source could be placed into orbit to act as a guide beacon and photometric calibrator. Tomographic reconstruction of the atmosphere could be enabled using a small constellation of beacons flying in formation around the target. Eccentric orbits are found that would keep guide beacons near their target for one to three hours every 3-10 nights. These orbital parameters, the brightness of the beacons, and other considerations for high contrast imaging are discussed.

Keywords: Adaptive Optics, Wavefront Sensing, Guide Stars, Coronagraphy, Exoplanets

1. INTRODUCTION

Ground-based direct imaging of rocky exoplanets in reflected light will require unprecedented adaptive optics (AO) performance and near sky background limited sensitivity. An ideal AO solution would mitigate lag, very high order aberrations, and chromatic effects between guiding and science wavelengths. In the most extreme cases, we would like to correct wavefront errors before even a single aberrated photon arrives at the science camera so we are no longer limited by light from the star. For this scenario, natural guide stars are too dim to measure wavefront errors with sufficient speed and accuracy. Laser guide "stars" that excite the sodium layer of our atmosphere, on the other hand, only sense a single out-of-band wavelength and suffer from spot elongation, the cone effect, and are still relatively dim.

We propose that for high value targets like α-Cent, a constellation of artificial guide beacons could be launched into orbit to act as reference sources for an extreme adaptive optics system. Satellite based light sources have been used for photometric calibration [1] and have previously been proposed for guiding adaptive optics systems [2] [3]. More recently, satellite laser guide stars have been proposed as a way of reducing the stability requirements of segmented space telescopes [4]. Here we discuss the possibilities and considerations of orbiting guide beacons for high contrast imaging of exoplanets from the ground.

Such guide beacons could be very bright, allowing for extremely fast, high order corrections. They could be operated at any convenient wavelength, including in the science band. By using multiple wavelengths simultaneously it would in be possible in theory to perform tomographic reconstruction of the atmosphere, telescope, and optics; measure chromatic effects; and perform predictive control. Finally, such guide beacons could in addition serve as photometric calibration sources for detecting variability in the light from companions unaffected by stellar variability.

We outline two basic concepts for the orbital guide beacons themselves, describe a range of eccentric orbits that could periodically place the beacons near a target for a sufficient period to undertake observations, and give basic calculations on their brightness seen from the Earth.

2. GUIDE BEACONS

The primary purpose of a guide beacon is to act as a bright point source at a high altitude. This could be accomplished in two ways: either the beacon could be actively powered and shine light towards an observatory on the ground, or it could be a passive optical device that reflects light emitted from a ground source back down to the observatory.

Beginning with an active guide beacon, a small-sat could be equipped with a laser, 10cm launch telescope, and fine pointing capabilities. The small-sat would actively orient the launch telescope back towards the observatory using commercially available fine pointing solutions, perhaps with a low power laser uplink from the ground. The satellite could additionally be equipped with basic maneuvering capability for station-keeping, but we emphasize that it would not need to expend propellant during observations as in some occulting star-shade concepts. It would most likely not be feasible for photovoltaic panels to power the laser directly (see the brightness section for a discussion on laser power), so battery storage sufficient for 1-2 hours of observing time every few days would be necessary.

Passive guide beacons, on the other hand, could be constructed to act as retroreflectors. A retroreflector is a simple optical device that returns light in the incident direction. Small retroreflectors are present on many satellites in low Earth orbit where they are used for laser-ranging. Using a retroreflector, the passive guide beacon would return light emitted from a co-located launch telescope on the ground back towards the observatory. By placing the retroreflectors on multiple sides of the beacon, no active stabilization or electronics would be necessary reducing mass and cost. In this case, a larger constellation could be launched to overcome the lack of station keeping capabilities.

3. ORBITAL PARAMETERS

For this concept to be practical, an orbit for the guide beacon must be chosen to meet three requirements. First, the guide beacon must remain near the line of sight between a target and an observatory for long enough for observations to be carried out. Second, the beacon must return to that same line of sight at some regular period so there are multiple chances to observe the target. Finally, for the sake of reducing cost and complexity, the guide beacon should not have to actively expend propellant to maintain alignment during observations. Beginning with the conjunction period and desire not to expend propellants to extend observations, these requirements largely rule out low Earth orbits due to their very low conjunction durations on the order of seconds. Instead, the beacons could be placed into highly eccentric orbits with an apogee directly on the line of sight between the observatory and target. A high eccentricity orbit would minimize the orbital velocity at the apogee. To carry out multiple nights of observations of the same target, the beacon should be placed into an orbit with a period that is close to an integer multiple of one sidereal day. This will bring the guide beacon back in front of the target periodically. Observing times would be adjusted by approximately four minutes per night to account for the Earth orbiting the Sun.

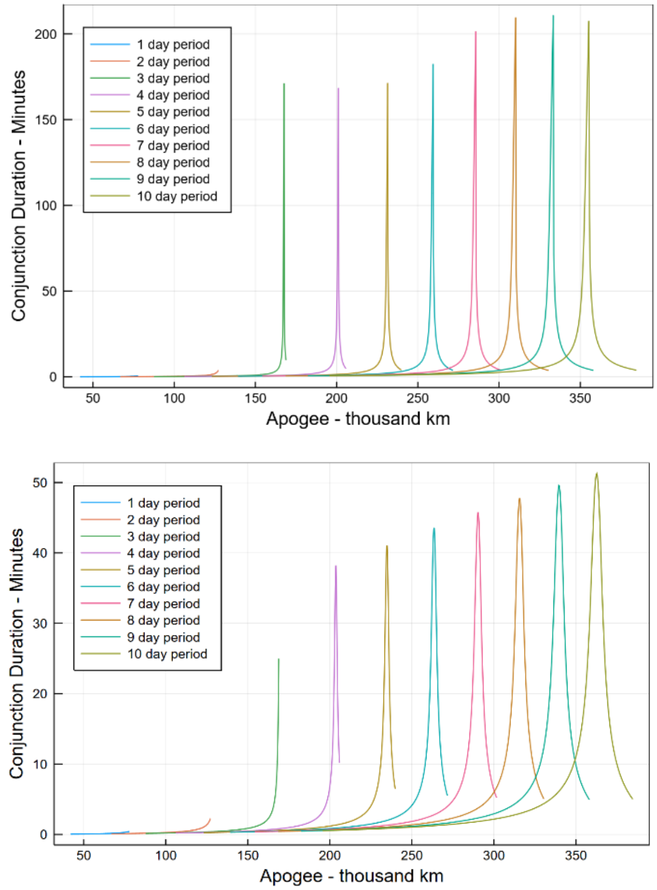

Figure 1. These curves show the duration a guide beacon could remain within 35 arseconds of the target. The different lines are given for different possible orbital periods which are multiples of one sidereal day and will therefore allow for repeat observations of the target. **Top**: a zero declination target seen from an observatory at the equator. **Bottom**: α-Cent seen from Gemini South.

We ran basic orbital simulations to find the orbital parameters that maximize the duration a guide beacon would stay in view. We consider both an observatory located at the equator with a target declination of zero degrees, and Gemini South with a declination of α-Cen, a high value target for high-contrast imaging. We calculate the duration in view assuming a 35 arcsecond diameter field of view consistent with the NFIRAOS laser guide stars. The actual tolerance requirements will be studied in a later analysis. The gravitational influence of the moon will in the very least cause the orbit to precess, but for this analysis we consider only the gravity of the Earth. Finally, we only consider orbits with periods that are integer multiples of one sidereal day to allow for multiple nights of observations during a semester.

The results presented in figure 1 show that the duration in which the beacon would remain close to the target depends on the observatory location, target declination, and of course, the orbital parameters of the guide beacon. For any given period (and corresponding semi-major axis) there is an optimal eccentricity that maximizes the conjunction duration which can be seen as peaks in figure 1. The main challenge is to find an orbit that has sufficiently low velocity compared to the observatory's motion around the Earth. This improved with either a wider orbit, or with an observatory closer to the equator. The conjunction duration also depends on the declination of the target, with targets closer to the celestial equator allowing for longer conjunctions.

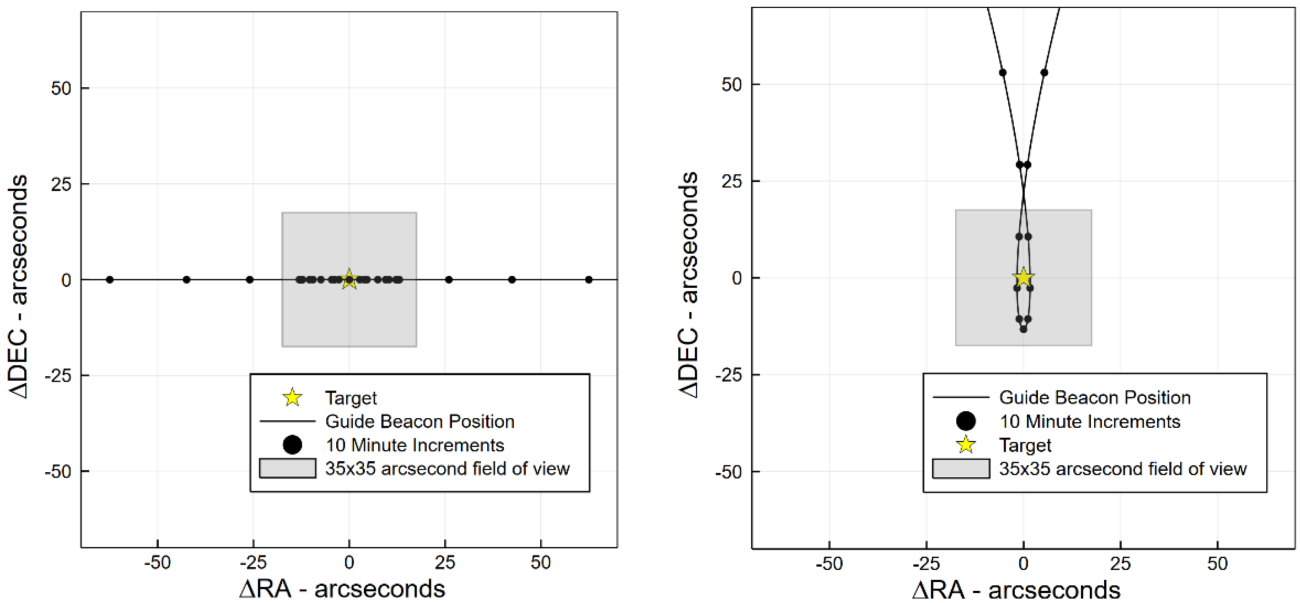

Figure 2. These plots show the projection across the sky that a guide beacon could take in front of the target for two example orbits with ten day periods. **Left**: a zero declination target seen from an observatory at the equator. **Right**: α-Cent seen from Gemini South.

Figure 2 shows the paths across the sky a guide beacon could take for two scenarios. For low declination targets, the limiting effect is the relative horizontal motion between the observatory and the guide beacon, whereas for high declination targets, the limiting effect is the vertical motion from the inclined orbit necessary to place the beacon in front of the target. Note that for some targets further away from the celestial equator, there are orbits that exhibit retrograde motion.

There are many options for constellation formations, one example of which is presented in figure 3. These best paths of the formations will depend on the observatory, target, and adaptive optics system, so we leave a full study for a later analysis.

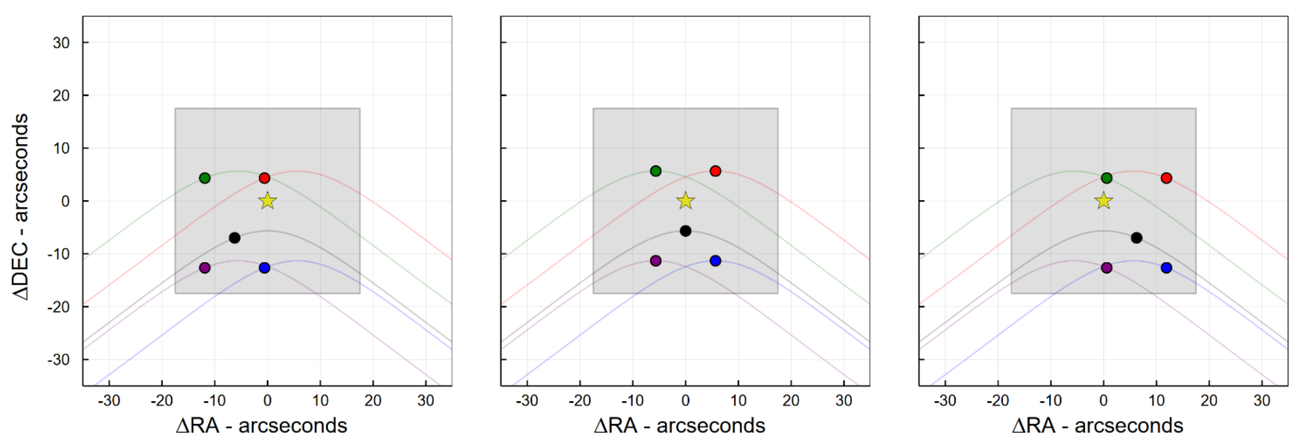

Figure 3. These plots show the motion of a constellation of five beacons moving past a target over 30 minutes calculated for a target with a declination of 10 degrees seen from Maunakea. **Left:** -15 mins **Center:** 0 mins **Right:** +15 mins.

4. BRIGHTNESS

Figure 4 shows the brightness of guide beacons calculated for both the active and passive reflector cases. In the first case, we consider a 10cm diameter launch telescope on the beacon and a laser with a 20W output. In the second case, we consider a laser with a 2kW output launched from a 10 meter telescope with adaptive optics on the ground and reflected off of a 10cm diameter retroreflector. These choices are all on the higher end of plausible to demonstrate the idea, but could be scaled down and still provide a bright reference source. In both cases, diffraction dictates that a guide beacon with a 10 cm diameter and an apogee near the orbit of the moon would have a spot size of approximately 2 km by the time its light reaches the Earth (for a wavelength of 800 nm). We find that the guide beacons could possess apparent magnitudes as bright as -5 to -10. With such a bright, in-band reference source, a wavefront sensor could be sensitive to high order aberrations even with very short exposure times. Though these sources would be very bright by astronomical standards, there is no risk to human eye safety since they would still appear dimmer than the full moon, and only active for short periods of time.

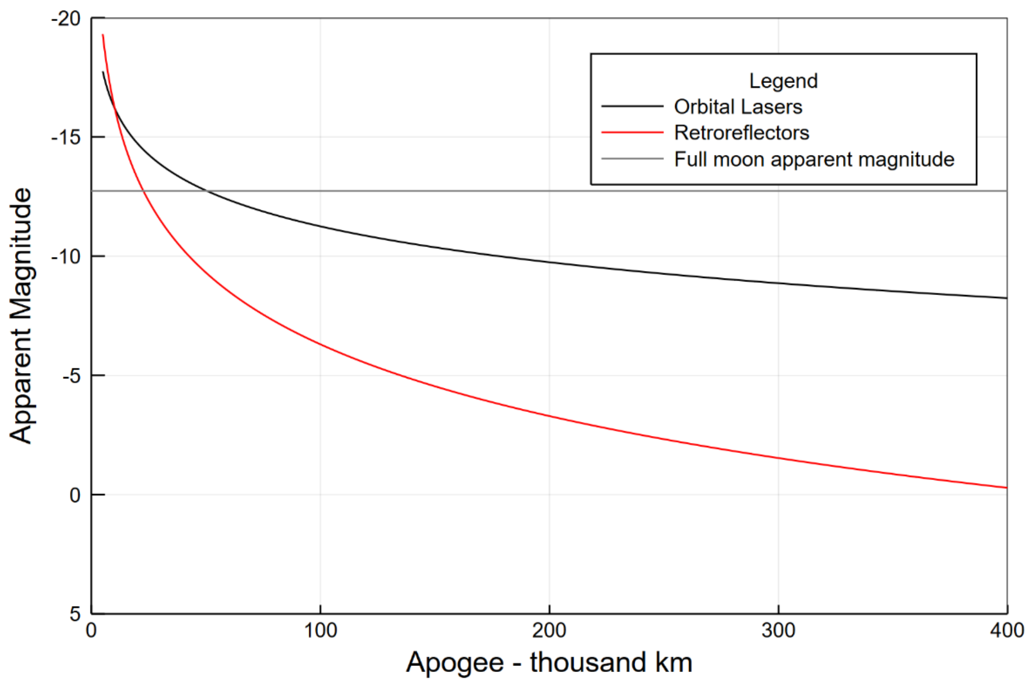

Figure 4. The I-band apparent magnitude of a beacon with the properties described above as a function of distance, for two cases: a 20W laser on an active guide beacon, and a 2kW laser launched from the ground at a passive retroreflector.

5. OUTLOOK

Though building and launching orbiting guide beacons would clearly require a significant development effort, they could consist mostly of commercially available components. In comparison to orbiting star-shade concepts, this effectively shifts the research effort from space to the ground. Taking full advantage of this concept from the ground will necessitate the development of very high frame rate detectors, high density deformable mirrors, high performance coronagraphs, and fast realtime controllers. Techniques will need to be developed for closing an AO loop and performing tomographic reconstruction on moving guide beacons. An opportunity for early testing could be to use existing satellites that carry retroreflectors in low Earth orbit. While this paper has focused on presenting the orbital guide beacon concept for high-contrast imaging, end-to-end simulations will be required to understand the limits of high-contrast coronagraphic adaptive optics systems that are not starved for light and evaluate the full potential of this concept.

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