Cislunar SSA/SDA from the Lunar Surface:

COTS Imagers on Commercial Landers

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ABSTRACT

In the coming years, renewed lunar exploration by the U.S., our allies, and our adversaries will transform the cislunar regime into a new strategic operations domain – one that is no longer uncontested. Surveillance of this domain is challenging; the radars and global telescope networks that maintain our current space domain awareness (SDA) are not designed to cover this enlarged volume, and at present, self-reported mission telemetry is the primary source of object data. This situation is fraught even for assets of allied and friendly nations, let alone from geopolitical adversaries.

Large, ground-based instruments can cover much of the cislunar volume, which extends from geostationary orbit to beyond the Earth-Moon L2 Lagrange point, 10 times farther away than geostationary orbit. Systems like this are multi-million-dollar facilities, subject to all the issues faced by ground-based telescopes, including nighttime operations, geographic coverage, weather, and especially scattered moonlight. Sky brightness near the Moon makes detecting faint objects close to the Moon exceedingly difficult, even for the largest ground-based systems. No one sensor or system of sensors will be sufficient, and a multilayered approach is necessary for robust SDA.

From the lunar surface, these regions are much easier to surveil, especially Low Lunar Orbit (LLO) and orbits on the far side of the Moon around L2. The challenge instead is deploying and operating a telescope there. Fortunately, the new activity in cislunar space also offers new opportunities. NASA's Commercial Lander Payload Service (CLPS) program is developing standardized platforms for instruments on the lunar surface, paralleling the cubesat revolution currently transforming near-Earth space. This means specialized billion-dollar, decade-spanning missions are no longer required.

The CLPS program presents a tremendous opportunity for deploying small, wide-field optics on the lunar surface. The first versions of these will have to be based on optics, detectors, and processing systems that already have a heritage in space. The right combination of these could be deployed rapidly and inexpensively on early CLPS missions – so far, the selected instruments for CLPS only look down at the lunar surface. A small optical telescope, appropriately optimized, could demonstrate the immense value of cislunar SDA from the lunar surface, while at the same time contributing to several other scientific missions.

1. INTRODUCTION

The first NASA SLS launch, currently scheduled for January 2022, will launch thirteen cubesats into cislunar space along with the first Orion capsule, Artemis-1, and three of these cubesats will enter lunar orbit. These 6U cubesats, along with several others in the coming years, represent the opening salvo of renewed activity on and around the Moon. Recent lunar missions by Israel, India, and especially China show the growing interest in this regime, and with that interest comes the complexities of contested and competitive space. The current set of sensors deployed around the world are not capable of routine monitoring of this much-enlarged volume of space that extends from beyond the geostationary (GEO) regime out to the orbit of the Moon and beyond to the Earth-Moon Lagrange points. The region will not, at least in the plannable future, be nearly as busy as low Earth orbit or GEO, but objects in this space are much more difficult to detect, measure, track, and predict. And the potential for accidental and intentional interference is still significant.

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The subtle multibody physics of cislunar orbits and large distances involved make SDA in this domain considerably more challenging than for traditional Earth-adjacent SSA. These effects are considered in detail in a primer by Holzinger, Chow, and Garretson (2021) and the interested reader is directed there [1]. Figure 1 shows a schematic depiction of cislunar space. Three major issues make monitoring cislunar space difficult. The first is that the objects can be up to 10 times farther away from the Earth than GEO and thus appear up to 100 times fainter. All else being equal, that means that optical monitoring of objects in cislunar space will require telescopes 10 times larger than is needed for GEO monitoring, which puts the system requirements in the realm of large telescopes – facilities that cost many millions or tens of millions of dollars.

The second is that over much of the high-interest regions of cislunar space, such as that around the Lagrange points, the gravitational potential well is very shallow and closed orbits are not the norm. While this means that the apparent angular rates of cislunar objects are small, making them easier to detect and monitor, it also means that small errors in measurement grow very large when propagated forward. The situation is somewhat better for objects in lunar orbit, but the lunar gravitational potential is much more irregular than that of the Earth and third-body perturbations are fractionally larger as well. Therefore, frequent observations from multiple locations are critical to establishing and maintaining custody.

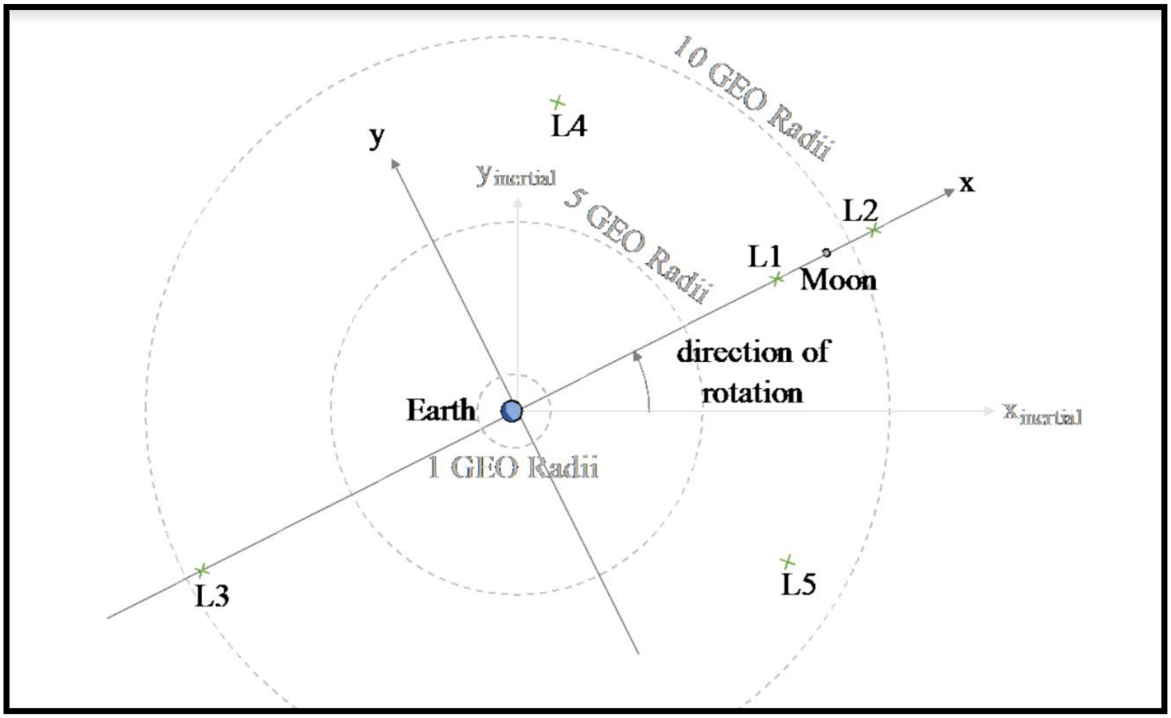

Figure 1 – (from Holzinger et al., 2021 [1]): This schematic of cislunar space shows the radical increase in distance compared to GEO SDA.

Lastly, as even non-astronomers know, the Moon is really bright. Much of the cislunar operations regime, such as the L4 and L5 Lagrange points, are sufficiently separated on the sky from the Moon that one- and two-meter class telescopes from the ground will likely be effective at surveying and monitoring these regions. However, close to the Moon, light scattered by Earth's atmosphere and within the telescope optics makes observing faint objects nigh impossible. Ground-based optical systems, along with upgraded passive radio frequency systems, will play a significant role, but cannot provide complete coverage, especially over the most valuable and contested portions, i.e., those in close proximity to the Moon itself.

In the past, contemplating a lunar telescope meant designing the entire mission, payload, lander, communications, launch and transit. This new effort resembles that of the cubesat revolution in low Earth orbit, where hardware standardization opened these missions to organizations that otherwise were prevented by the high cost and steep

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learning curve of one-off, custom everything. With commercial landers available, one only need design an optical system to the size, weight, and power (SWaP) specifications of the platform.

The first phase of the commercial lunar lander program already put out solicitations and chose the instruments for the first two landers. These were picked from existing or otherwise low-risk, high-technological readiness level (TRL) instruments to further lunar surface science. None of them included optical systems pointing up.

2. CLPS LANDERS

NASA's CLPS program selected 14 companies as eligible to bid for lander contracts and six missions have been awarded to four companies so far with launches to begin in 2022. Ten CLPS missions are expected through 2025. Each of these landers has a total payload capacity up to 250 kg and will be carrying a dozen or more individual payloads, a combination of NASA instruments and other public and private sector instruments. The ultimate goal is to make lunar science and exploration more readily available. By creating standardized interfaces for mechanical mounting, thermal management, power, and data, a lunar payload will no longer require a decade or more of planning. The interface documents for the scheduled lander missions are publicly available – see for instance Astrobotic's Peregrine lander [2] and Firefly Aerospace Blue Ghost [3]. These are still a long way from a plug-and-play level of standardization.

The payload services are priced by the kilogram. NASA's goal is to make the cost \$1M/kg delivered to the surface, though the current estimates are in the range from \$1.2-1.3M/kg. Along with payload mass, each kg comes with an allocation of power and data, typically 1W and 10 kbps per kg of payload.

3. SUNLIGHT PROBLEM

In considering the utility of lunar lander-based optical systems for SDA, the Sun provides both lander power and the source of the reflected light signal that allows detection. For observation platforms that are at significant distance from the Moon, such as sensors on Earth, in orbit around the Earth, or in orbit around one of the Earth-Moon Lagrange points, the most favorable illumination conditions, that is low illumination phase angles, for targets around the Moon occurs when the Moon is also near its maximum illumination phase: full Moon. The Moon then is a source of scattered light and enhanced background.

In principle, optical systems on the surface of the Moon don't have this problem. However, at least for the planned missions, the CLPS landers will all be solar powered with little to no run time after the Sun sets. So, landers on the Earth-facing side, the ones that could see the cislunar highway between the Earth and Moon, could only operate when the Sun is above the horizon, which is detrimental both for both light perspective and illumination phase. Figure 2 shows the fall-off in apparent brightness with phase angle for a Lambertian sphere. Dayside illumination starts 1.5 magnitudes down from the peak and decreases rapidly.

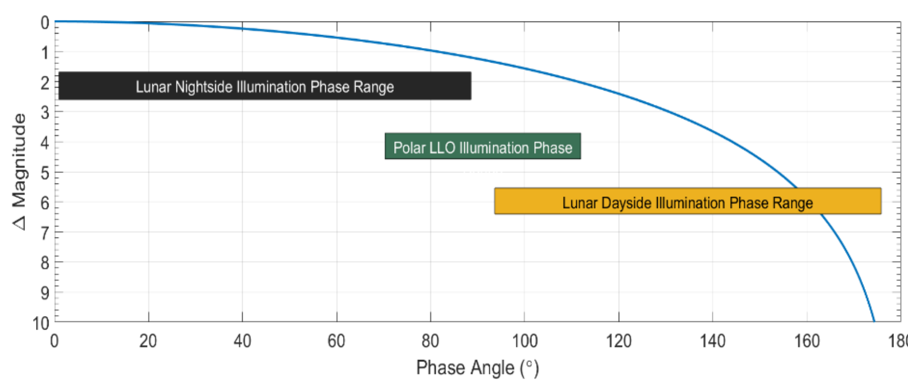

Figure 2 – This figure shows the falloff in apparent magnitude with illumination phase. When the Sun is up at a lunar observation site, the phase angle effect makes it significantly harder to detect objects, especially in the region between the Earth and the Moon.

However, for lander-based systems near the poles of the Moon, this is less of a problem. The illumination phase is more consistently close to 90 degrees and some sites will have sunlight for solar panels for very long durations, over

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200 days rather than 14, at most, for low latitude sites. Polar sites also have the advantage of offering sky coverage in exactly the places that will be most contentious, where most orbiters will be focusing their attention and most landers will be measuring and exploring. Moreover, these are the most difficult objects to measure with systems anywhere else. Thus. this work focuses on optical systems intended to find and monitor objects in polar low lunar orbit.

4. ZODIACAL LIGHT BACKGROUND

For cislunar SDA observations from the Moon, the primary limiting factor on SNR for objects moving in this space is sunlight scattered by dust grains in orbit around the Sun, called zodiacal light. This dust forms a thin disk in the plane of the solar system, the ecliptic plane, and the orbit of the Moon around the Earth is almost co-planar with the rest of the solar system. The sky background in regions close to the ecliptic on the sky is considerably brighter than in regions perpendicular to it – see Figure 3 adapted from Cox (2000) [4]. It is dramatically brighter in directions towards the Sun and slightly brighter when looking directly away from the Sun due to backscatter from the dust, called gegenschein. While cislunar space does technically encompass the entire spherical volume in proximity to the Earth-Moon system, most cislunar objects will be near the Earth-Moon plane.

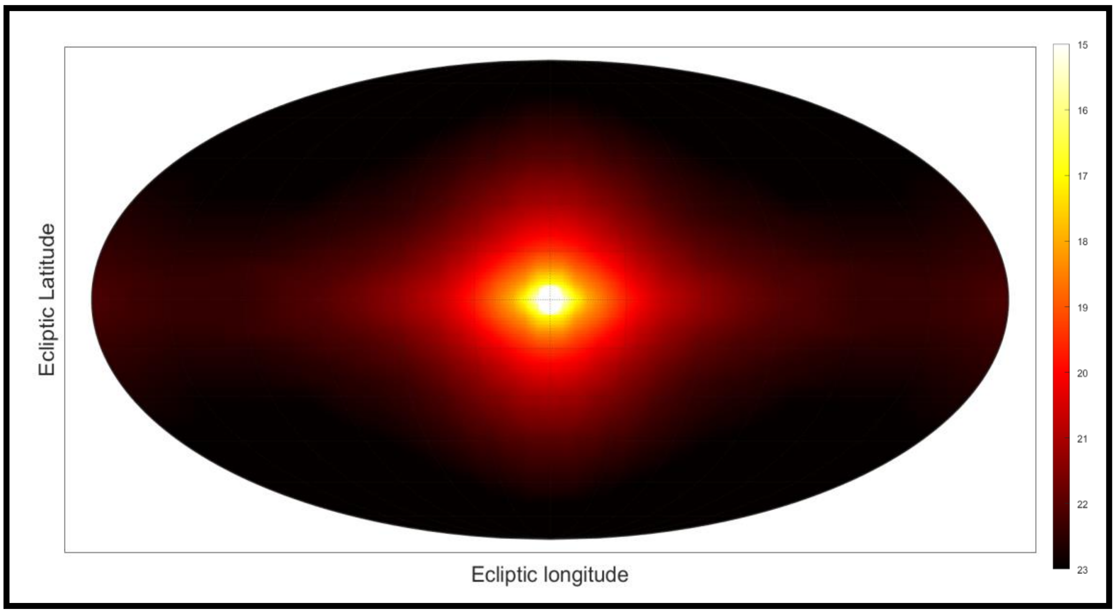

Figure 3 –In addition to the solar power and illumination problem, viewing objects in directions toward the Sun experience a much-elevated sky background caused by zodiacal light, sunlight reflected from dust in the plane of the solar system, including the gegenschein opposite the Sun. The most favorable sky backgrounds are away from the Sun and out of the ecliptic plane—toward the ecliptic poles. Regions near the ecliptic plane have comparable (or brighter) sky background to dark terrestrial sites. Values in this figure are adapted from Cox (2000) [2].

For the polar observing configuration, the zodiacal light contribution is near the minimum possible. The mean value is fainter than 23 magnitudes per square arcsecond and only increases substantially above that when the sensor is tilted towards the Sun. This will happen for a few solar days per lunation when the lower elevations observed will see sky as bright as 21 magnitudes per square arcsecond.

5. PROPOSED LANDER-BASED LLO SENSOR

We evaluated many potential sensors, selected from those with a spaceflight history or are space-qualified, and have the required radiation tolerance for operating on the lunar surface. The LLO detection task places a premium on sensor size, read noise, and dark current. One candidate sensor stood far above the others in this combination: the 12MP Space Camera Head from 3D Plus. This CMOS sensor has 4096 x 3000 3.45 µm pixels with 2 e^- RMS read noise, and 11,000 e^- full well depth. The camera head also embeds radiation hardened FGPA-based controller with 1 GB of processing RAM and 6 GB of flash storage. A picture of the camera head is shown in Figure 4. The entire package is

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40 x 40 x 30 mm and weighs 125 g. Average power required is 2.5 W with a peak of 5 W for the module. This power requirement places the greatest constraint on the system and will be a major focus of continued development work.

The data transmission limit of 10 kbps per kg of payload is less of a concern. Within this limit, transmitting the RA, Dec, and measured magnitude of each star and any moving object in the frame would be feasible, but more likely to occur in a summary digest form with values averaged over multiple frames. Detections of moving objects would be relatively rare and could be transmitted with considerable metadata. Raw imagery for the full FOV however could only be transmitted on very rare occasions.

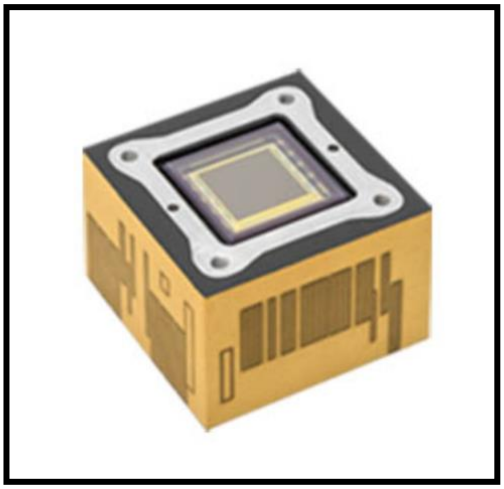

Figure 4 -- This commercial 12-megapixel CMOS sensor coupled to a 12mm f/2 radiation resistant lens, yields a 65 x 50-degree FOV.

The dark current for this radiation hardened CMOS sensors is two orders of magnitude higher than for typical commercial CMOS devices. At room temperature, the rates can be as high as 10 e^-/pixel/s, but like other silicon sensors, the dark current is a strong function of temperature, with doubling constant between 5-7 C degrees. In order to not substantially degrade the SDA detection performance, this sensor will need to be kept below 0 C when operating. With a conservative estimate of 7 C dark doubling temperature, the resulting dark signal per pixel will fall below 2 e^-/pixel/s, which is sufficiently less than the expected sky background to not contribute too detrimentally to the SNR. Temperatures at or lower than this are readily achievable with passive cooling techniques, especially for the polar observing configuration where this sensor will most effective.

Coupled to a 12 mm focal length f/2 radiation resistant lens, this sensor subtends a 65 x 50-degree FOV. This lens will add 40 mm to the overall length and 200 g to the mass including the mounting hardware.

We've modified our LEO SDA performance models used for ground-based observing to estimate the detectivity of LLO objects with lander-based optical systems. The major differences in model input are the sky background and the lack of atmospheric transmission losses. The analysis assumes an average solar phase angle of 90 degrees and a sky brightness of 23 magnitudes per square arcsecond, which is the bright level encountered in the polar mounted FOV.

In Figure 5, we show the estimated SNR for a 1 m^2 area Lambertian sphere in orbit around the Moon at various altitudes as it would appear streaking through the FOV of the sensor. In the results shown, the integration time is 15 seconds, so the results at altitudes below 40 km are overstated because the object crosses the entire FOV in less than the exposure time, though they would still be detected with SNR > 100. The FOV from the lunar surface would only cover a small volume at those low altitudes, so this is an acceptable trade-off to get higher SNR on slower objects. The per pixel SNR is high enough for all the modeled cases that detection in a single image is very likely, except for objects above 700 km at the largest look-angles above 60 degrees away form the zenith.

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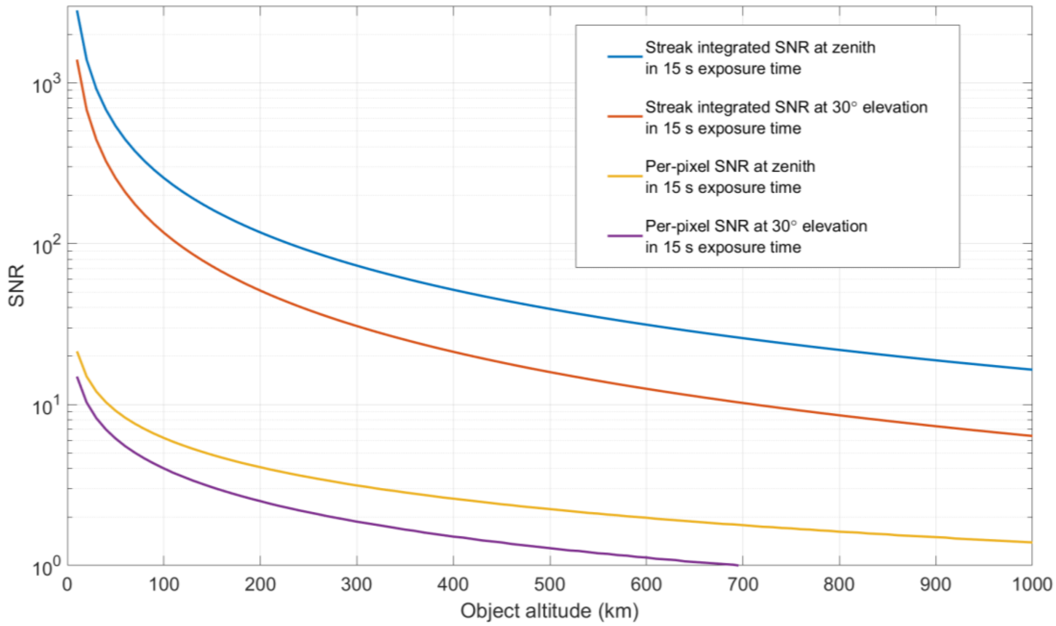

Figure 5 – We modeled the streak integrated and per-pixel SNR for a 1m^2 surface area Lambertian sphere at various altitudes in LLO using the proposed lander-based sensor.

Figure 6 shows one concept for polar surveillance of LLO using two landers, each with two 65 x 50-degree FOV optical systems and covering one the poles. The planned polar orbiters that have published their intended orbits tend to have high eccentricity, allowing them to remain over one of the poles for extended periods of time. This configuration would allow the observation and measurement of those objects and other more circular LLO missions.

The same analysis for 6U cubesats, which are a common bus size for planned LLO orbiters, show that detecting them above 250 km altitude will require larger optics, a larger sensor, or both. That includes the effects of their deployed solar arrays which typically increases their light scattering cross-section by a factor of 3 or more. In this case, a 25

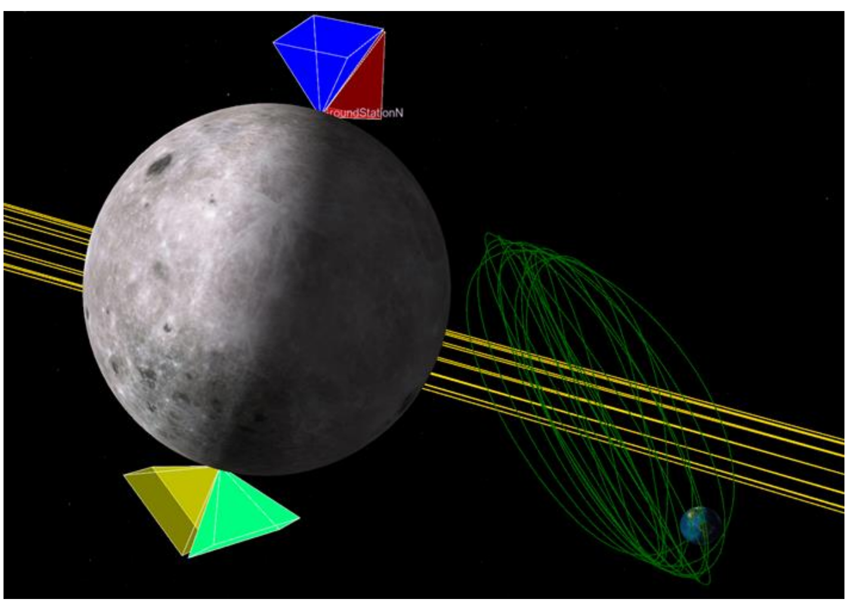

Figure 6 – Conceptual coverage with four sensors on two landers. Each cone is 65 x 50 degrees. These sites have good access to solar power with the minimum amount of sunlight or zodiacal light interference.

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mm focal length f/1.4 lens provides sufficient sensitivity but with a drastically reduced FOV of 16 x 12 degrees on the same 12-megapixel sensor. These would still have a small overall weight and size but many more would be required to provide good LLO coverage.

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