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Daytime Adaptive Optics for Deep Space Optical Communication

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ABSTRACT

Future deep space missions will tax the ability of existing radio frequency systems to return all the data. In addition, these missions must be able to communicate around the clock, including when the spacecraft is near the Sun. This is especially true for crewed missions. Optical communication can solve these problems, and also offers the promise of being more compact and using less power and mass. Traditional deep space optical communication concepts require large diameter telescopes (>8m) to collect enough photons to provide adequate signal-to-noise ratio. Systems operating during the day will experience strong turbulence which results in large point spread functions. This necessitates photon counting detectors with a large field-of-view which are difficult to build. The large field-of-view also lets in excessive sky background which degrades the communication performance. Adaptive optics (AO) can mitigate this degradation by concentrating the light and thus not needing a large field of view. We present an AO system architecture capable of operating in the daytime and requiring only moderate performance. We present the architecture along with performance predictions of the system for different size telescopes. Finally we include a technology gap list, which will guide future development of the component technologies.

Keywords: Laser Communication, Adaptive Optics

1. INTRODUCTION

NASA and other space agencies are currently planning multiple missions beyond the orbit of the Moon, also known as deep space. These missions will be sending back evermore data and the desire is to do so at even higher speeds than allowed by the conventional radio-frequency methods of the Deep Space Network (DSN). Laser communication can solve this problem and NASA is funding the development of the Deep Space Optical Communication (DSOC) demonstration that will send data back to Earth as the spacecraft cruises out to the asteroid belt.[1]

Ideally, deep space missions are be able to communicate around the clock, including when the spacecraft is near the Sun. This will become even more urgent with crewed missions to deep space such as the journey to Mars. Being able to communicate while close to the Sun is important to increase the duration of communication. The DSOC mission with a Sun-Earth-Probe (SEP) angle limit of 10° translates to 65 day outage per Mars synodic cycle.[1] The outage will shrink with decreasing SEP limit. Unfortunately, the detected sky background increases with decreasing SEP. This increased background quickly degrades the link margin and prevents communication. (Reduced SEP also puts more thermal stress on the telescope and communication system, but this can be dealt with more conventional means –e.g. solar telescopes – and is not discussed in this paper.)

Traditional deep space optical communication concepts require large diameter telescopes (>8m) to collect enough photons to provide adequate signal-to-noise ratio. Systems operating during the day will experience strong turbulence which results in large point spread functions. This necessitates photon counting detectors with a large field-of-view. The large field-of-view lets in excessive sky background which degrades the communication performance. Narrow band filters can help reduce the background light, but are not sufficient especially at small SEPs.

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Adaptive optics (AO) can dramatically reduce the detected sky background by concentrating the light and allowing the use of a smaller field of view. For the rest of this paper we give a short overview of AO and then discuss how AO could be used with laser communication to missions in deep space. Then we present an AO system architecture capable of operating in the daytime and requiring only moderate performance. Finally we include a technology gap list, which will guide future development of the component technologies.

2. INTRODUCTION TO ADAPTIVE OPTICS

Adaptive optics is most commonly used to improve image performance through ground based telescopes used for astronomy. With AO, telescopes are able create images with close to diffraction limited performance. AO has been used for laser communication with LEO satellites[2] and is planned to be used with the NASA's Laser Communication Relay Demonstration (LCRD) to GEO satellites.[3]

AO is a technique where a deformable mirror is used to correct aberrations in the wavefront of an incoming beam of light. These aberrations are sensed by a wavefront sensor (WFS). There are multiple types of wavefront sensors, each with its own advantages and disadvantages. We have chosen to analyze a Shack-Hartmann sensor as it is one of the most common sensors. It is not the most light efficient system, but if we can show that it works, then we are assured that more complicated systems (and light efficient) such as a curvature sensor or a pyramid sensor will work. Currently pyramid sensors are one of the most light efficient systems and are being developed for a number of astronomical AO systems.

As the target gets fainter, the wavefront sensor measurements will degrade and the performance of the AO system will in turn degrade. One way of dealing with this is to use a laser guidestar system (LGS). In this case, a laser is projected from the receiving telescope. This laser creates an artificial star that emits light that the WFS detects and analyzes. There are two mechanisms for generating the laser guidestar. The first is Rayleigh scattering, where the laser is focused at an altitude of between 8-15 kms. The guidestar is created by light scattering of the atmosphere via Rayleigh scattering. Since Rayleigh scattering is inversely proportional to the wavelength of the light to the fourth power, the efficiency of guidestar creation is improved when shorter wavelength lasers are used. For instance, the Robo-AO system uses UV lasers at 355 nm.[4]

The WFS can only measure aberrations between the guidestar and the telescope, so the higher the altitude the more aberrations can be measured. The second laser guidestar technique aims to use guidestars with an altitude of $\tilde{9}0$km by focusing a laser centered at the wavelength of 589 nm at the mesospheric layer of sodium (this is deposited by meteors entering the Earth's atmosphere.) The sodium atoms are excited by the laser and reemit the light, which is then sensed by the WFS.

One of the limitations of laser guidestars is that the WFS can not measure the jitter of the image on a detector, which is usually called tip/tilt, because the laser experiences the same tip/tilt on the uplink as it does on the downlink. Most laser guidestar AO systems use a separate WFS that looks at a natural star in the field of view to derive the tip/tilt information. This is doable, because a tip/tilt WFS only needs a few pixels and can operate on much fainter targets than higher order WFS.

3. AO AND OPTICAL COMMUNICATION FROM DEEP SPACE

When it comes to analyzing AO systems performance, we need to have baseline missions to compute the received signal. We have identified three scenarios of interest. The first is for a DSOC-like mission at the Mars with Mars being on the opposite side of the solar system from the Earth. This is the maximum Earth-Mars distance. DSOC itself will not go to Mars, but the most concrete mission design for any deep space mission and it is possible that the DSOC designed space terminal would be used on other future missions. The second scenario is again for a DSOC-like mission, but this time near Venus, when Venus is at maximum range from the Earth. The final scenario is for a hypothetical human crewed mission to Mars. The parameters for each of the scenarios are shown in Table 1. Ideally, we would operate at elevation angles as low as 20° but conversations with other users of sodium guidestar lasers have indicated that the U.S. Federal Aviation Administration prohibits the use of laser guidestars below 30° elevation.

As mentioned before, the normal paradigm for laser communication AO is to divert a sizable portion of the incoming communication light to the WFS. Unfortunately, due to the extreme ranges of deep space optical

Table 1. **Mission Scenario Parameters**

Parameter	DSOC-like Mars	DSOC-like Venus	Crewed Mars
Space Terminal Avg. Laser Power	4 W	4W	20-40W
Wavelength	1550.12 nm	1550.12 nm	1550nm
Space Terminal Aperture Size	0.22m	0.22m	0.5m
Range from Space Terminal to Earth	2.62 AU	1.66 AU	2.62 AU
Background solar flux (W/cm^2/sr/μm)	2e-4	7e-4-4e-3	7e-4-4e-3
Background planetary flux (W/cm^2/sr/μm)	0	0	8.3E-4
r_0 (@500 nm @ zenith)	3cm	3cm	3cm
Max. Point ahead angle	350 μrad	350 μrad	390 μrad
Range of Elevation Angles	30-80°	30-80°	30-80°
Photon Flux at ground station (photons/m^2/s)	1.6e6-1.6e8	1.6e6-1.6e8	3.0-3.8e7

communication, light is in very short supply and communication engineers are loathe to lose any of the light to drive an AO system. To operate an AO system, we will need to turn to a laser guide star system.

We considered both Rayleigh beacons and sodium beacons. During the day, the short wavelength lasers used for Rayleigh beacons have a very low signal to noise ratio over the blue sky. We studied the possibility of using near-infrared lasers as Rayleigh beacons. They are less efficient due to the strong inverse dependency of Rayleigh scattering, but do benefit from improved atmospheric transmission. That helps on both the uplink and the downlink. In the end we found to make sufficiently bright guide stars, we would need to have lasers 10 to 100 times more powerful than the conventional UV lasers, which is impractical.

Sodium guidestars are widely used for astronomy at night and have been used in the daytime.[5] One issue with sodium guidestars is that since they form at altitudes of 90km above the Earth's surface, when used at low elevation angles the range to sodium layer is increased which results in decreased returns.

The determination to use a sodium or a Rayleigh is still open, but we lean towards using a Sodium guidestar. Some of the determination will come down to mission requirements, such as how much of the time will would the system be operating at low elevations angles. The final determination will be decided in the implementation phase. For the rest of this paper we have assumed a sodium guidestar, but nothing is invalidated for the use of a Rayleigh beacon.

The DSOC mission is using a Superconducting Nanowire Single Photon Detector (SNSPD) for its communication detector.[1,6] The entire active area of the detector is photosensitive, and is divided into four quadrants for measuring tip/tilt. Each quadrant consists of 16 co-wound nanowires meandering to fill the active area, in order to maximize the uniformity of illumination. The nanowires are 160 nm wide and 5 nm thick, on a 400 nm pitch, and are patterned using electron-beam lithography. The design targets for the SNSPD array are a system detection efficiency > 70% (including all coupling losses and losses from windows and filters in the cryostat), maximum count rates approaching 109 counts per second, 1-sigma timing jitter below 150 ps, and false count rates below 2000 counts per pixel, including ambient 300 K blackbody radiation.

The fact that the DSOC SNSPD detector is divided into quadrants to detect tip/tilt is a key design feature as it allows us to measure tip/tilt on the downlink signal.[7] This eliminates one of the largest problems we envisioned when starting this design study. Laser guidestar AO systems are unable to measure tip/tilt of the atmosphere. For astronomical LGS AO systems, tip/tilt is normally measured on a nearby star, but there is not always a usable star available. In that case, AO is impossible. The use of stars will not work for a communicating with a spacecraft in deep space because the spacecraft will be moving across the sky at a different rate than a star. The tip/tilt system would need to switch between stars.

To determine if the SNSPD measurements would be sufficient, we carried out a analysis of the tip/tilt measurement accuracy for the crewed mission to Mars in Table 1. Since this is for a tip/tilt system in conjunction with a LGS AO system, the PSF on the tip/tilt system detector will be compensated resulting in improved performance.[8] Figure 1 shows the measured single axis tip/tilt angular measurement error as a function of the number of subapertures across the primary. We studied using more than one subaperture to determine if we could use the downlink signal to drive a full AO system (performance is not good enough to do that). As image quality improves, the tip/tilt performance improves, we did this analysis for an AO system producing images with a Strehl ratio of 10%. The Strehl ratio is a measure of image quality that corresponds to AO performance. It ranges from less than 1% for uncompensated light to 100% for a perfect image. We assumed that the system would have either a natural guidestar or LGS AO system. For the case where we are using only a two subapertures across the primary, the performance is quite good, because of the number of photons captured by such large subapertures.

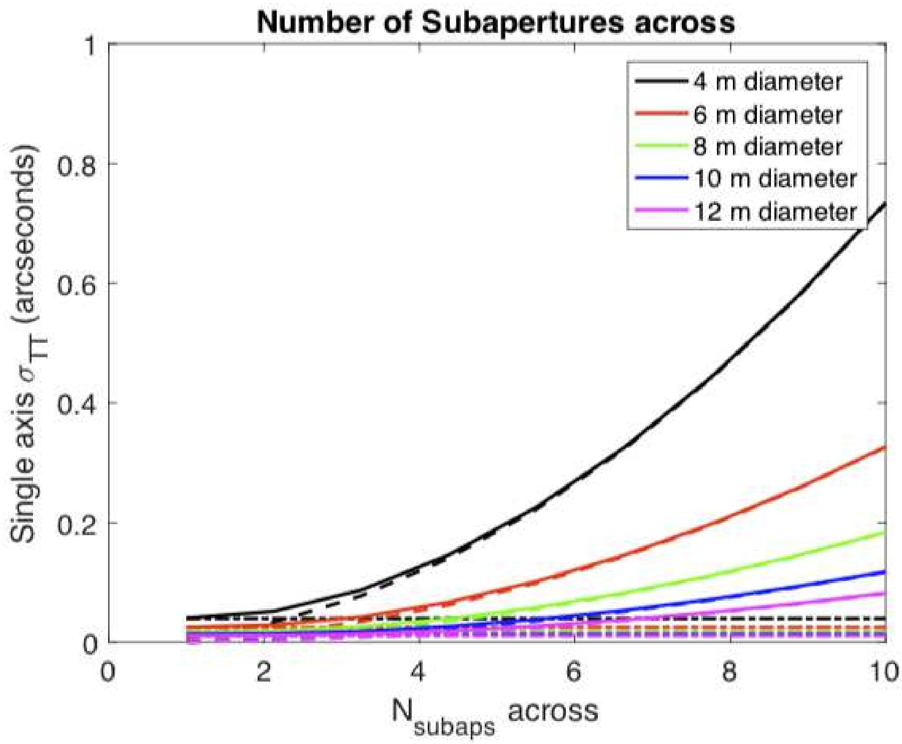

Figure 1. The tip/tilt measurement error in one axis as a function of the number of sub apertures across the primary aperture.

With tip/tilt measurements taken care of, we turned to the problem of higher order correction. There were two possibilities: divert some of the light from the communication system to drive the WFS, or to use a laser guide star system. Using the communication downlink photons would reduce the photon flux to the SNSPD, but the remaining photons would be concentrated in a small area on the detector, hopefully yielding improved link margin. We did an analysis and the cases were borderline. In the end, we decided to proceed with a laser guide star system. It is more complex, but it is more photon efficient.

We also realized a problem with either of these schemes. The SNSPD are photon counting detectors. When a photon hits one of the nanowires, it is no longer sensitive to second photon until the nanowire resets. Any photons that arrive before the nanowire resets are not sensed. Here concentrating the light into a smaller area would actually be detrimental to performance. What we really want to do is shrink the field of view of the detector to reduce sky background, but spread the light across the detector to avoid saturation. A variable zoom system can accomplish this. As the wavefront error decreases, the system will zoom in on the detector. This will maintain the linear size of the PSF on the detector so that the photon density does not increase. As the system zooms in, the field of view of the SNSPD detector will correspondingly shrink. This will decrease the amount of detected background yielding improved link margin. At night, when there is no background, it can unzoom to capture every available photon.

Our suggested architecture is this: the SNSPD communication sensor will measure tip/tilt and send those commands to the fast steering mirror (FSM). We will use a laser guidestar system to control the deformable mirror. The variable zoom system is controlled by the measured wavefront error. This control loop will be slow with a time constant of 10s of minutes. A cartoon of our system is shown in Figure 2.

4. CONCEPT

The next question is how good of an AO system do we need and how much does it benet optical communication. To understand this we simulated a link from Mars, from the largest distance 2.6 AU, during daytime. The downlink conditions are those described in the mission scenario in Table 1. The transmitter average power is 4W with PPM modulation and SCPPM coding.[9] The ground station elevation is 30°, while the SEP is 10°. This proximity to the Sun indicates that the sky background is one of the main source of noise to degrade the SNR of the receiver and therefore the achievable date rate (capacity).

At the same time, the astronomical seeing that a downlink experiences induces a broadening of the PSF at the receiver with an increase of the required receiver field of view and the consequential increase in the unwanted background radiation. Therefore, to evaluate the link performance we considered that the ground station experienced a large variation of astronomical seeing, which in turn correspond to a variation of the atmospheric coherence length (or r_0 parameter) varying from 3cm (bad seeing) to 2m (extremely good seeing, comparable to link in a presence of very efficient AO system) as indicated in Table 2. Notice that the r_0 values in Table 2 use the general convention and are referred to 500 nm and at zenith. At the same time the, Table 2, the ground aperture was varied from 4m to 12m diameter.

Table 2 indicates the results of the downlink calculation in terms of maximum information data rate for each configuration. The link budgets were calculated using the Deep Space Optical Link tool (DeSOL) software developed at the Jet Propulsion Laboratory.[10] In the calculation of the link budget we included a conventional margin of 3 dB. We also assumed that any improvement in link budget would be used for improved data rate, but it could be used for other purposes such as decreasing the size of the space transmitter or the spacecraft's laser power. Other ancillary outputs calculated (and not shown in Table 2) were the optimal receiver field of view and the PSFs Strehl ratio.

The results of the simulation data captured in Table 2 can be interpreted in a direct way when considering the implementation of an AO system on the ground station. The data rates indicated in the rows corresponding to a $r_0 = 3$cm are the achievable data rates when no AO compensation is used. The following rows show downlink data rate an AO system performance improves the system capacity. In other terms, the action of an AO system can be considered as an artificial way to improve the atmospheric seeing and to increase the effective r_0 form 3cm to 2m. To better visualize the content of Table 2, we also turned this table into Figure 4. The figure shows that the data rate makes rapid gains with just modest improvement in eective r_0. We also reported the improvement of the Strehl ratio with a larger effective r_0 as in in Figure 5. In Figure 5, for the larger telescope diameters, the data points are concentrated at the lower Strehl ratio values. This is due to the r_0 being a smaller fraction of the telescope diameter.

Table 2. **Data Rate (Mb/s)**

	D=4m	D=6m	D=8m	D=10m	D=12m
r_0=3cm	0.045	0.95	0.15	0.21	0.28
r_0=10cm	0.3	0.67	1.17	1.78	2.5
r_0=50cm	1.02	2.34	4.17	6.43	9.08
r_0=100cm	1.25	2.95	5.32	8.22	11.55
r_0=200cm	1.27	3.32	6.11	9.32	13.38

Figure 5 shows that the data rate plateaus after rather modest Strehl ratios. The reason for this is shown in Figure 3. On the left is a uncompensated PSF, while the image on the right is the image after the AO system was turned on. When the AO system is turned on the PSF shrinks dramatically, but it still leaves behind a core of uncompensated light. If we shrink the FOV of the SNSPD as the PSF shrinks, we eliminate the vast majority

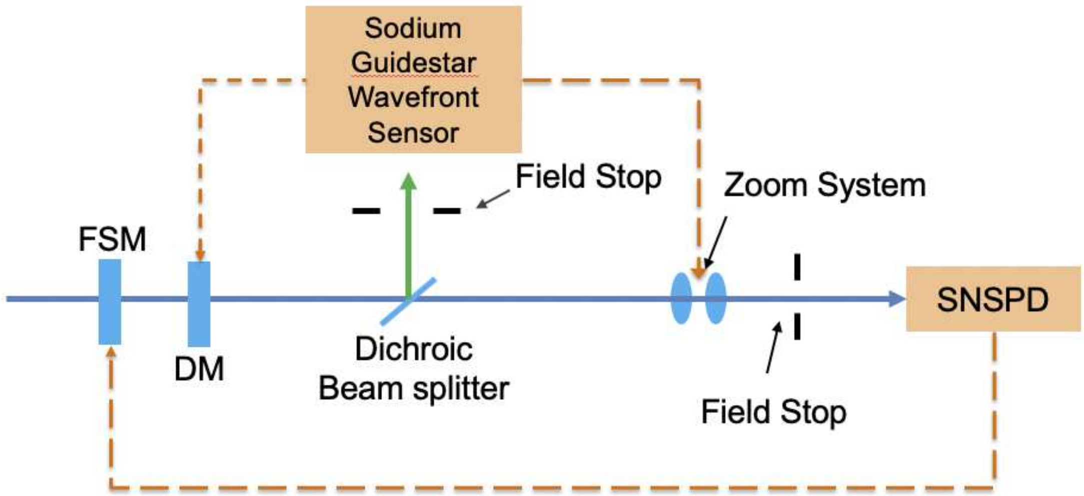

Figure 2. This is a block diagram of the proposed AO concept for communicating with spacecraft in Deep Space. The blue arrow is the light path of the system (with all the FSM and DM being depicted as transmissive to simplify the diagram.) The dashed lines are control signals from sensors to active elements.

of the background light. This improves the detection of the communication signal. As the AO system improves performance, light is moved from the halo into the core. To get most of the light into the core only requires a moderate amount of AO correction. This is different for AO systems working with coherent detection schemes such as DPSK that work with single mode fibers, in those cases, the light coupled into the is proportional to the Strehl ratio and work best with very high Strehl ratios.[3] The images in Figure 3 were taken at night and the uncompensated image had a full width half-maximum (FWHM) of 2.6 μradians. Images taken during the data at low elevation would have FWHM 10 to 20 larger and will make the improvement even more dramatic.

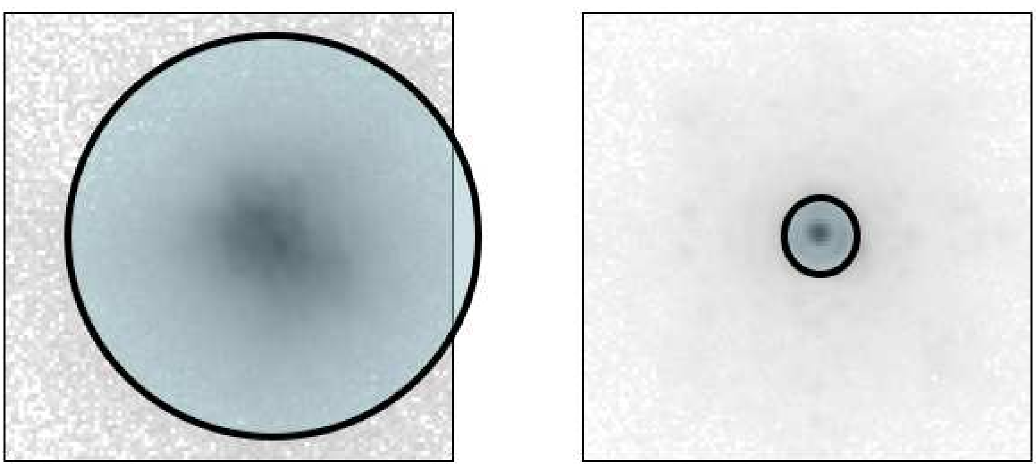

Figure 3. This figure shows the PSF for an uncorrected image on the left and an AO corrected image on the right. The black circles show the size of an aperture that would encompass most of the light of the PSF. AO enables the user to use a smaller aperture to capture the same amount of light with a dramatically reduced amount of background signal.

The data also shows that a 4-m telescope with a modestly performing AO system can achieve equivalent performance to a 12-m telescope. Telescope costs increase is proportional to telescope diameter to the 2.5

power.[11] With this relationship, a 12-m telescope would cost roughly 15 times that of a 4-m telescope. Of course, the 4-m telescope requires a modest AO system which would need to be costed, but the total cost will still be less than for a 12-m telescope. In addition, a 4-m telescope has a much smaller physical footprint and would be easier to insert into existing facilities.

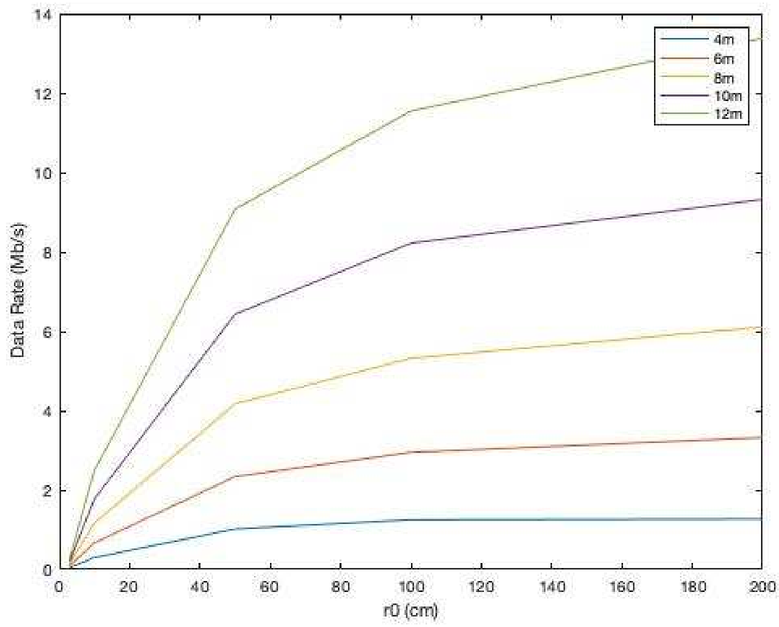

Figure 4. The achievable data rate for different effective r_0 values. The lines correspond to a variety of telescope diameters.

5. TECHNOLOGICAL GAP LIST

The system described here consists of several parts. There is a laser guide star system, SNSPD detector, fast steering mirrors, and a deformable mirror. Laser guide star systems are fairly well known and are operational on a range of telescope diameters from 4-10m for night time observations. The modest performance that is required for deep space optical communication poses little concern. These system have not been used as much during the day and one area of concern is filters to block the sky background from the WFS detector. Hart et al.[5] used a magneto-optical filters while[12] advocated that off the shelf filters would be sufficient. This seems like an area where some thought and study are needed, but seems achievable.

The SNSPD used in our system is no different than the one being developed for DSOC and poses little challenge. The detector will need narrow band filters which will reduce the background that is detected. The DSOC mission is developing ultra narrow filters with bandwidths as low as 0.2nm[13] and the proposed AO system would be able to take advantage of those.

Fast steering mirrors are well developed and our use is not a stressing case. The one are of concern is the deformable mirror (DM). DMs are critical to any AO system, as it is the element that corrects for the atmospheric aberrations. DMs are characterized by their stroke, which is the amount that they can bend the surface of the mirror at a given point. The stroke needed by an AO system is dependent on the strength of the turbulence and the size of the telescope. The two most common brands of DMs in the US are Boston Micromachines[14] and Xinetics. In Figure 6, we show the required stroke as a function of telescope diameter for r_0 of h 3 and 5 cm. The horizontal lines show the stroke of several models of DMs. Neither company's standard products can achieve the required stroke. Xinetics does have a surface parallel actuator DM that has 50 μm of stroke that would be provide sufficient stroke and ALPAO offer similar performance DMs. These DMs are not commonly

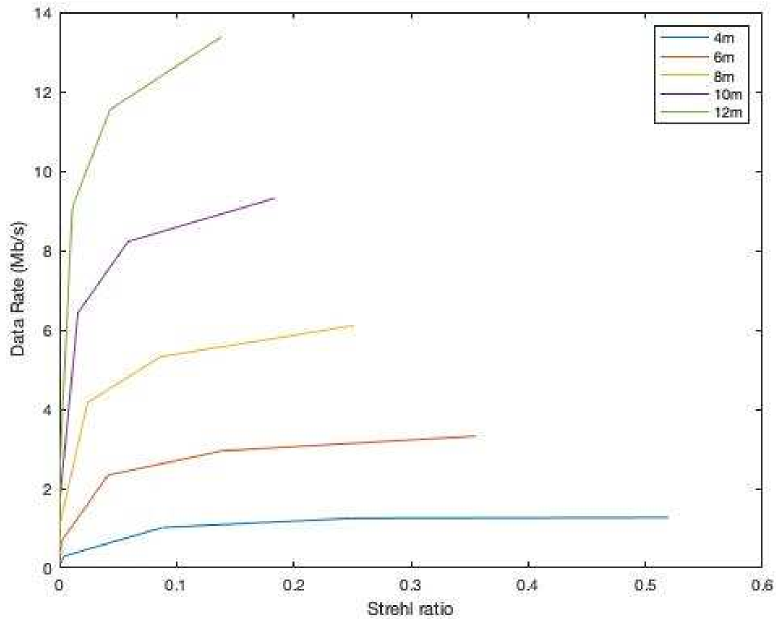

Figure 5. This is the same data as in Figure 4, but the effective r_0 was converted to Strehl ratio.

used in the US, but have been used in multiple AO systems from European observatories. Additional study of these DMs will need to be made before a down select can happen. It does appear that there are several suitable possibilities.

6. SUMMARY

Optical communication with spacecraft in deep space benefits from even middling adaptive optics performance. This can be used to achieve similar data rates with smaller/cheaper ground telescopes or to increase the achievable data rate. While some study of the different components are needed, we have not identified any show stoppers in the necessary technology.

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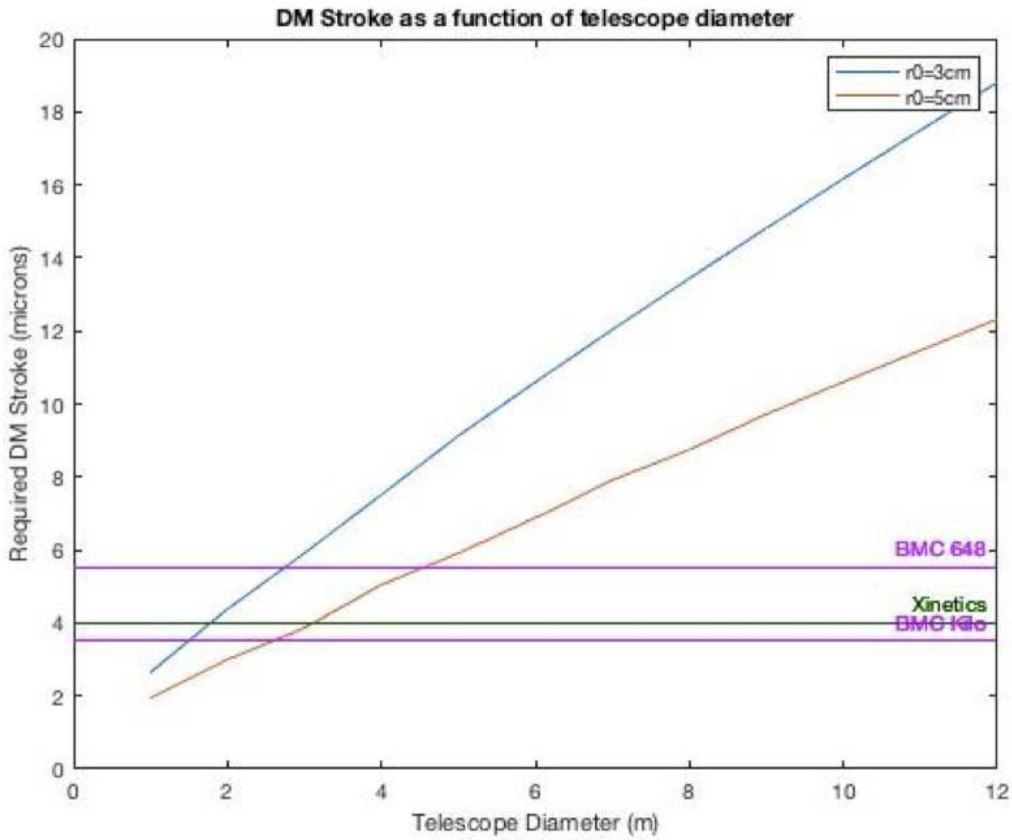

Figure 6. The required DM stroke required as a function of telescope diameter for multiple r_0 values. The horizontal lines are the achievable stroke for three different DMs. All Xinetics surface normal DMs achieve the same stroke.

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