Comparison of optical observational capabilities for the coming decades: ground versus space

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ABSTRACT

Ground-based adaptive optics (AO) in the infrared has made exceptional advances in approaching space-like image quality at higher collecting area. Optical-wavelength applications are now also growing in scope. We therefore provide here a comparison of the pros and cons of observational capabilities from the ground and from space at optical wavelengths. With an eye towards the future, we focus on the comparison of a $\sim$ 30m ground-based telescope with an 8–16m space-based telescope. The parameters relevant for such a comparison include collecting area, diffraction limit, accessible wavelength range, background emission, atmospheric absorption and extinction, Strehl ratio, field of view, temporal and spatial PSF stability, and target accessibility in time and on the sky. We review the current state-of-the-art in AO, and summarize the expected future improvements in image quality, field of view, contrast, and low-wavelength cut-off. We compare the depth that can be reached for imaging and spectroscopy from the ground and from space in the V and J bands. We discuss the exciting advances in extreme AO for exoplanet studies and explore what the theoretical limitations in achievable contrast might be. Our analysis shows that extreme AO techniques face both fundamental and technological hurdles to reach the contrast of 10^{-10} necessary to study an Earth-twin at 10 pc. Based on our assessment of the current state-of-the-art, the future technology developments, and the inherent difficulty of observing through a turbulent atmosphere, we conclude that there will continue to be a strong complementarity between observations from the ground and from space at optical wavelengths in the coming decades. There will continue to be subjects that can *only* be studied from space, including imaging and (medium-resolution) spectroscopy at the deepest magnitudes, and the exceptional-contrast observations needed to characterize terrestrial exoplanets and search for biomarkers.

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1. Introduction

The future of optical observational astronomy looks bright, with excellent prospects for the advent of larger aperture telescopes both on the ground and in space. As the telescope size increases, so does the cost and complexity of a project. The 2010 Decadal Survey will therefore face difficult choices for ground- and space-based astronomy investments in the coming decade. To facilitate these choices, it is important to understand the relative advantages of ground- and space-based facilities for observational astronomy. In particular, the ever increasing capabilities of adaptive optics (AO) from the ground motivate a critical side-by-side comparison of the observational parameter space accessible to either type of facility.

We focus here mostly on comparison of the capabilities of a $\sim$ 30m ground-based telescope with an 8–16m space-based telescope. Examples of the former are the Thirty Meter Telescope (TMT; Stone et al. 2009) and the Giant Magellan Telescope (GMT; McCarthy et al. 2009). Examples of the latter are the Advanced-Technology Large-Aperture Space Telescope (ATLAST; Postman et al. 2009) and the Terrestrial Planet Finder Coronagraph (TPF-C; Levine et al. 2009). We compare only briefly the capabilities of current ground-based 8–10m class telescopes to smaller space-based telescopes such as the 2.4m Hubble Space Telescope (HST), the 6.5m James Webb Space Telescope (JDEM), or the proposed Joint Dark Energy Mission (JDEM/IDECS; Gehrels et al. 2009).

We restrict attention to the regime below $\sim 1\mu$m, for two reasons. First, this is where future large space-based proposals are likely to focus their attention; JWST will already provide an important new large aperture facility for science longward of $\sim 1\mu$m. Second, below $\sim 1\mu$m is where the future capabilities of AO from the ground are most uncertain and least documented. AO corrections in the infrared (IR) are typically more capable and less technically challenging than in the optical (see Section 3). However, in comparing performance of space versus ground in the IR, careful consideration must be given to the role of background emission in achieving a given signal-to-noise ratio S/N (see Section 4).

We will not discuss here the relative cost for new optical observing facilities on the ground or in space. Observational facilities in space are generally more expensive to build and operate than those on the ground. So they are usually pursued only if they open up parts of parameter space that are not accessible from the ground. We highlight which parts of observational parameter space are uniquely accessible only from space. Scientific motivations for access to this parameter space are briefly mentioned where relevant. Costs and science drivers are discussed in detail in other submissions to the Decadal Survey.

2. Characteristics of Observational Parameter Space

2.1. Telescope Size

One of the main advantages for ground-based facilities is that they can generally be constructed with larger telescope diameters D than what is possible in space, which impacts two important characteristics: the collecting area and the diffraction limit.

2.1.1. Collecting Area The collecting area of a telescope scales as D^2. This implies that large-aperture ground-based telescopes are generally able to collect more photons than space-based telescopes, which is one of the factors that determines the achievable depth and signal-to-noise ratio (S/N; see Section 4).

2.1.2. Diffraction Limit The diffraction limit of a telescope scales as λ/D. This implies that large-aperture ground-based telescopes generally have a smaller diffraction limit than

space-based telescopes. However, due to atmospheric turbulence it is more difficult for ground-based telescopes to achieve image quality near the diffraction limit than it is for space-based telescopes, especially at optical wavelengths (see Sections 2.3, 3 and 5).

2.2. Atmospheric Emission and Absorption

One of the most fundamental advantages of space-based over ground-based observations is the fact that light can be observed unaffected by the atmosphere. This impacts several important characteristics of the observational parameter space.

2.2.1. Accessible Wavelength Range and Absorption Ultra-Violet observations are not possible at all from the ground, due to atmospheric absorption. This blocks an entire wavelength range in which many astrophysical problems can be uniquely studied. Even in the optical there are spectroscopic absorption features (possibly time-variable) associated with telluric bands. These need to be corrected using observations of standard stars, which themselves are only characterized to finite accuracy.

2.2.2. Background The atmosphere creates a background in ground-based observations that needs to be subtracted. Figure 1 compares the background at Mauna Kea and L2. The shot noise from the background affects the the achievable depth and S/N (see Section 4). In addition, background variations can lead to systematic errors due to imperfect subtraction.

2.2.3. Line Emission In addition to a continuum background, ground-based observations accumulate photons from atmospheric emission in well-defined bands with many narrow emission lines (see Figure 1). The presence of these emission lines increases towards the IR, and their strengths vary with time. This limits the ability to study spectral features in astronomical objects at particular wavelengths.

2.2.4. Atmospheric Extinction Atmospheric extinction must be corrected on the basis of airmass estimates and standard star observations, to obtain absolute photometry. The accuracy with which these corrections can be done are critical for certain areas of science.

2.3. Image Quality

The image quality depends both on the diffraction limit of the telescope (Section 2.1.2) and the ability of the telescope to reach this diffraction limit.

2.3.1. Strehl Ratio (SR) The SR is the ratio of the peak flux in the normalized point-spread function (PSF) to that for a diffraction limited system. It (and other measures of image quality) describe the extent to which the light is concentrated in the PSF core as opposed to the wings. A space-based telescope is typically designed to be diffraction limited (commonly defined as SR $> 80\%$), at some target wavelength driven by the science. By contrast, large ground-based telescopes need an AO system that aims to optimize a combination of the complimentary goals of high SR and large field of view (see Sections 3 and 5). Even when an AO system achieves a diffraction-limed core, a low SR can severely limit the science. For example, in a crowded field the PSF wings of bright stars create an elevated background that drowns out the light of fainter stars.

2.3.2. Field of View (FOV) The FOV sizes for space- and ground-based telescopes are both limited by technological, design, and cost constraints related to their optics and detectors. However, for ground-based observations the FOV is further limited by the area

over which AO correction is possible (see Section 3). This limits the ability to do certain kinds of science, e.g, wide area surveys at high-resolution.

2.3.3. Stability Another advantage of space observations is the long-term stability of the environment, with no gravity, no seismic disturbances, no weather, and generally smaller thermal fluctuations. As a result, the PSF and optical geometric distortions are extremely stable. This makes the space-environment uniquely suited for science that requires high photometric or geometric precision. Absolute photometry is possible from space to levels around 0.01 mag, and relative differential photometry to levels of order 0.0001 mag. The latter is critical for photometric variation studies such as for planet transits (as in the Kepler mission). The photometric quality for ground-based AO is limited by temporal and spatial (field-dependent) PSF variations, which become more significant for decreasing wavelength and increasing field size. In the near-IR, current accuracies of ~ 0.05 mag (e.g., Davidge et al. 2003; Vacca et al. 2007) can likely be reduced to near space quality with the advent of, e.g., MCAO systems (see Section 3). Ground-based AO observations (e.g., for the Galactic Center) and space-based observations (e.g., for globular cluster stars) have both produced superb proper motions results, with the former benefitting from the small diffraction-limited core, and the latter from the exquisite geometric stability over large time baselines.

2.4. Target Accessibility

2.4.1. Time Sampling One other obvious advantage of space, and in particular the L2 Sun-Earth Lagrange point, is that there is no day-night cycle (this does not apply to low-earth orbit satellites such as HST). From L2 it is possible to continuously follow time-variable phenomena and to take continuous deep exposures, without the need to compare or co-add data from different nights during which observing conditions may have been different.

2.4.2. Sky Coverage AO observations require bright guide stars to correct for atmospheric turbulence. With natural guide stars (NGSs), only $\sim 5-50\%$ of the sky is accessible depending on the galactic latitude, for K-band imaging at moderate Strehl Ratios ($\sim 20\%$; Frogel et al. 2008). This limitation has now been mostly overcome through the use of Laser Guide Stars (LGSs). However, even with an LGS system the sky coverage is not complete, since it still requires an NGS for the tip-tilt correction (although this NGS can be several magnitudes fainter than for a pure NGS system). In general, sky coverage drops with increasing SR and Galactic latitude. For example, NFIRAOS on TMT is expected to cover $\sim 50\%$ at the Galactic pole (Ellerbroek, priv. comm.) and up to 100% at low Galactic latitude. Projects and proposals exist to improve sky coverage further using various techniques, both on TMT and on smaller telescopes (e.g., Keck, CFHT).

3. AO: Current State-of-the-Art and Future Prospects

The limitations imposed by atmospheric turbulence can be characterized by the Fried diameter r_0, turbulence lifetime τ_0, and isoplanetic angle θ_0. All are proportional to $\lambda^{6/5}$. For example, typical magnitudes for a good groundbased site are $r_0 = 10$ cm, $\tau_0 = 6$ ms, and $\theta_0 = 1.8''$ at 5000Å and $r_0 = 160$ cm, $\tau_0 = 95$ ms, and $\theta_0 = 30''$ at 5μm.

For a given SR, the number of subapertures that must be corrected is proportional to $(D/r_0)^2$ in a time interval τ_0. Consequently the technology challenges of both applying a sufficiently high fidelity wavefront correction, and making a sufficiently accurate wavefront measurement within a turbulent cell of scale length r_0 in a time interval τ_0 are much more manageable for AO corrections in the near-IR than at optical wavelengths. The number of

photons required for a constant level of correction is roughly $\propto (r_0^2\tau_0\lambda)^{-1} = \lambda^{-23/5}$ (the $r_0^2\tau_0$ comes from the area of the subaperture and time scale over which a given number of photons are required; the λ comes from the need to achieve the same path error expressed in waves). Hence, lower wavelengths require much larger laser power for wavefront sensing.

Today, AO for near-IR observations is in routine operation on the Keck, VLT, Gemini and other telescopes. A detailed overview of current AO capabilities was provided by Frogel et al. (2008, 2009), together with a roadmap for future development. They found that both AO performance and the number of AO-enabled refereed science papers has grown steadily over the last five years. We discuss the various types of AO in turn below.

classical AO In classical AO, a single guide star, either natural (NGS) or laser (LGS), is used to measure the deformations of the incoming wavefront with a wavefront-sensor and to correct them with the help of a single Deformable Mirror (DM). In this case the FOV is limited to a few times the isoplanetic angle θ_0. Since $\theta_0 \lesssim 10''$ for $\lambda < 2\mu$m, this is an important limit for many scientific applications. One limitation of classical AO with an LGS is the so-called called "cone effect". This results from the incomplete sampling of the turbulence in front of the aperture due to the finite distance of the LGS. This becomes increasingly problematic for larger telescope diameters and shorter wavelengths.

LTAO In Laser Tomography Adaptive Optics (LTAO), multiple LGSs and wavefront sensors are used to measure the full volume of turbulence above the telescope in order to solve for the cone effect and operate a single conjugate deformable mirror, as in classical AO. This is what is planned for visible 10m-class AO systems, and for near-IR first light use on 30m-class ground-based telescopes such as the TMT. The SR will range from 0.3 at 1.0μm to 0.8 at 2.5μm over a FoV of about 30", with a technical FoV for guide star acquisition of 2′. The short wave cutoff for science will be $\sim 0.8\mu$m, where one might still expect a diffraction limited core at very low SR (Ellerbroek, priv. comm.).

MCAO An exciting recent advance has been the advent of Multi-Conjugate Adaptive Optics (MCAO), in which multiple DMs are optically conjugated at different altitudes. Multiple wavefront sensors use LGSs to tomographically measure and compensate for turbulence-induced phase aberrations in three dimensions. This new technique increases the compensated FOV, provides a more uniform PSF over the field, and also solves for the "cone effect". The solar community has been using MCAO to deliver arc-minute scale, fully corrected near-IR images of the solar granulation. A demonstrator at the ESO/VLT has delivered stable arc-minute scale images with $\lesssim 10\%$ PSF variations. The first MCAO on Gemini will deliver nearly-uniform performance over a 2′ FOV with SR ranging from 45% to 80% from 1–2.5μm.

GLAO Ground-Layer Adaptive Optics (GLAO) is a "lite" form of MCAO, in which only the ground-layer turbulence is corrected. This technique does not provide the same image quality improvement as MCAO. It is therefore sometimes referred to as "seeing enhancement", with FWHM improvements of a factor of a few. However, the technique offers the advantage of a large FOV (up to several arcmin). Moreover, it has the potential to be implemented on 30m-class ground-based telescopes at visible wavelengths.

MOAO In Multi-Object Adaptive Optics (MOAO), a number of objects are selected in the field. Each object goes through it own AO system with one DM per object. The correction is based on tomographic knowledge and is open-loop. Like MCAO, MOAO provides the potential for significant FOV enhancement over the isoplanetic angle. Its concepts are well developed and have been run on a testbed, but remain to be demonstrated on large astronomical telescopes.

Visible-Light AO Even in the optical, improvements in technology have demonstrated correction around bright sources across a narrow (1–2″) FOV. These advances have so far been led by investments by the US Air Force on the 3.5m SOR telescope. In the next decade we should see these technologies (and others pursued on, e.g., CFHT/VASAO and Palomar/PALM3K) move to large ground-based telescopes, as the cost-effectiveness of high-density DMs and high-power lasers improve (e.g., Dekany et al. 2009). However, the delivered SRs will always decrease strongly towards lower wavelengths. Moreover, the technological challenges to extend the FOV remain enormous. Because the guide star brightness requirement scales with $\lambda^{-23/5}$, challenging amounts of laser power will be necessary for visible AO (independent of D). Solutions exist to mitigate these power requirements, for example using predictive control or uplink correction (Gavel et al. 2008). Laser power drives the cost of these systems. Routine visible-light AO operation with *both significant SR and FOV* on 30m-class ground-based telescopes is not foreseen in the coming decade(s).

ExAO In Extreme AO (ExAO), narrow field, high-SR systems are specifically designed to detect planets around nearby bright stars, as discussed in Section 5.

Wavefront Control in Space Although space has no turbulent atmosphere to correct for, figure control is definitely important. Following in the footsteps of JWST, future observatories are increasingly likely to use wavefront-sensing for optimum image quality. Although corrections can be done at much lower speeds that from the ground, the necessary technologies (e.g., MEMS) have strong overlap with those (being) developed from ground-based AO.

4. Signal-to-Noise Ratio and Limiting Magnitude for Deep/Faint Science

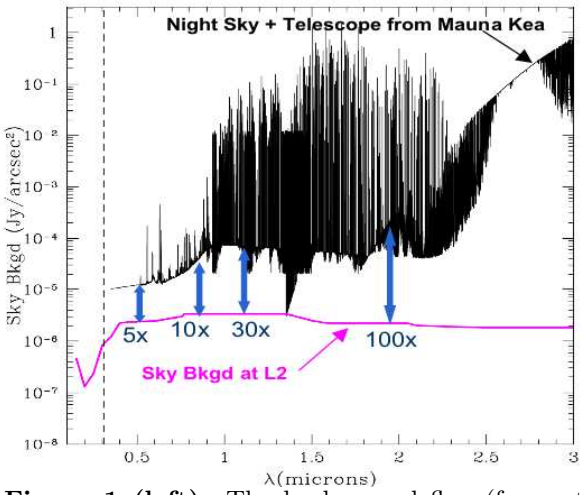
A crucial consideration in the comparison between ground-based and space-based observations is the atmospheric sky background emission B_λ (see Figure 1), which becomes particularly important in observations designed to reach the faintest possible limits. The noise contribution in imaging observations is determined by the photometric aperture size r. For seeing-limited observations $r \propto$ FWHM, independent of D, while for observations with a diffraction limited core $r \propto \lambda/D$. For given target flux and wavelength or passband, this yields for the limit in which background noise dominates other sources of noise that

$$S/N \propto (D/\mathrm{FWHM})\sqrt{\eta/B_\lambda} \qquad \text{or} \qquad S/N \propto D^2\,\mathrm{SR}\,\sqrt{\eta/B_\lambda}, \tag{1}$$

for seeing-limited or diffraction-limited observations, respectively. Here η is the product of the throughput and quantum efficiency of the system, which nowadays is close to unity for both ground- and space-based systems. These equations make it clear that the deepest science benefits are derived from larger telescopes, better image quality, and lower background.

4.1. Imaging Studies

For extremely faint sources (e.g., $V > 30$), the atmospheric sky background emission, even at the best ground-based sites, is at least 10^4–10^6 times brighter than the source. To illustrate what is feasible in this context, Table 1 shows the exposure times needed to reach a given S/N for a set of representative target magnitudes. The exposure times are given for the V and J-bands at $\lambda = 5000$Å and 1μm, respectively. This brackets the range of wavelengths on which we focus in the present paper. These values were obtained from the integration or exposure time calculators for 2.4m (HST), 8m and 16m space-based observatories, the latter two located at L2, as well as 8m and 30m ground-based observatories with AO capability.



Imaging exposure time (hours) to reach S/N=10 for space and ground observatories

	Space-based			*Ground-based*		
	HST	**8m**	**16m**	**8m**	**30m**	**PSF assumed**
1 μm:						
J=25	0.16	0.015	0.001	16.4	0.005	Diffr.-lim.*
J=30	398	3.9	0.29		12.0	Diffr.-lim.*
J=31			1.5			
J=32			8.5			
~5000 Å:						
V=30	218	0.3	0.04	580	60.4	0.4"
V=31		1.3	0.14		23.8	0.1"
V=32		7.3	0.57		37.3	D-lim, Strehl=10%
V=33		43.5	3.0			
V=34			17.4			
V=35			97.4			

Notes: All magnitudes are in AB for a point source, using standard spectra.
*PSFs for J-band are diffraction-limited for 30m, and use current NIRI+Altair performance for Gemini 8m.
Ground-based 8m numbers are for Gemini GMOS(g') and NIRI(J), using current exposure time calculators.
Ground-based 8m numbers are for Gemini GMOS(g') and NIRI(J), using current exposure time calculators.
Conditions used for Gemini: seeing= best 20%-ile, optimum S/N aperture, other parameters set to defaults.
HST numbers are for ACS&WFC3/UVIS F555W, WFC3/IR F110W, using average background conditions.
Photometric aperture = 3 x PSF FWHM in all cases, exposure time is total on-source time.
For the future facilities, assume same detector properties (pixels, read-noise, dark current, etc).

Figure 1 (left): The background flux (from atmospheric molecular, ionic and continuum emission and telescope thermal emission) for a ground-based telescope on Mauna Kea as compared to a space-based telescope at L2.

Table 1 (right): Sensitivity comparison between space-based (L2) and ground-based observatories. The imaging *observing time in hours* is listed to reach $S/N = 10$ at the magnitude listed in the left column. See table notes and main text for details on the calculations. For the ground-based 30m, each line uses a different PSF, as listed in the last column. For the V-band, this spans the range of what may be achievable.

For the ground-based 8m we used existing capabilities, in particular Gemini/NIRI+Altair in the J-band and a Gaussian FWHM of $0.4''$ (good seeing) in the V-band (at present, there are no general-user optical AO systems available on 8m class telescopes). For the ground-based 30m telescope in the J-band we optimistically assumed diffraction-limited performance with the same SR as for the space-based systems. For the V-band we present a sampling of three potential PSFs that span the range of where we might be in a decade or two: (a) a Gaussian FWHM of $0.4''$ (good seeing); (b) a Gaussian FWHM of $0.1''$ (optimistic estimate with a successful advent of visible GLAO); or (c) a diffraction limited core with SR = 10% (optimistic estimate with a successful advent of visible LTAO, MCAO, or MOAO).

The results for the current generation of facilities show that in the J-band, HST (with the WFC3 camera) goes several magnitudes deeper than a ground-based 8m, with only a moderate difference in spatial resolution. In the V-band, both facilities can reach comparable depths, due to the smaller difference in background at ~ 5000Å (see Figure 1). However, HST provides the better spatial resolution. For future facilities, a 16m space-based observatory at L2 will be capable of reaching $J \sim 32.5$ and $V \sim 34$ in integrations shorter than 1 day. This is a completely unexplored parameter space. A 30m ground-based telescope will fall short of these limits by 2–4 mag. The difference is due to a combination of a higher sky emission and (in V) poorer image-quality on the ground. An 8m telescope in space at L2 still goes deeper in V than a 30m ground-based telescope by 1–3 mag. However, in J the depth is more similar and the ground-based telescope with diffraction-limited AO will have the better spatial resolution.

Figure 2 provides a graphical way to look at results of calculations of this nature as function of wavelength, with the spectrum of the earth as it would be seen at 20pc overplotted.

4.2. Spectroscopic Studies

Similar considerations apply to spectroscopic observations, since the spatial resolution determines the smallest slit width and spatial aperture dimension for producing a final

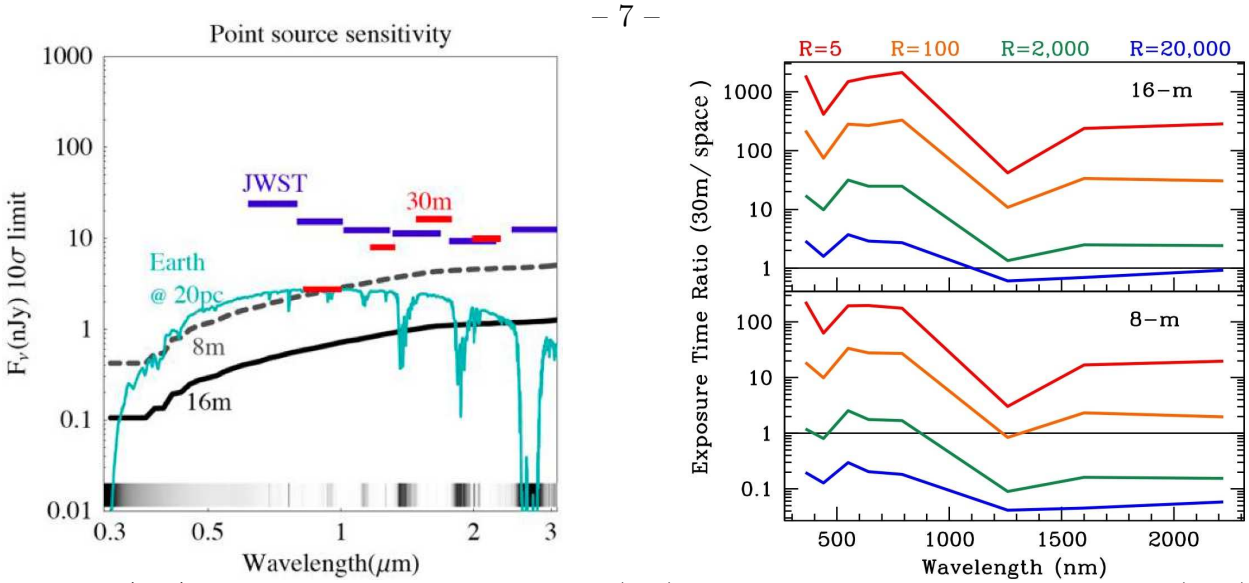


Figure 2 (left): 10-sigma point source sensitivities (nJy) for background-limited 1-hour broadband (R=5) imaging for: an 8-m and 16-m space telescope (black); a 30-m ground-based telescope with diffraction-limited AO (red); and JWST (dark blue). Sensitivities in this figure were calculated with the methodologies of Beckwith (2008). The superposed spectrum (light blue) shows for comparison a terrestrial exoplanet at a distance of 20 pc. To detect such a planet one also has to contend with additional backgrounds not shown here: (1) the exo-zodi light around the parent star (a factor ~ 2 larger than the L2 background itself); and (2) the PSF halo of the parent star (depends on achieved contrast; see Section 5). The band at the bottom of the plot shows the ground-based sky absorption (black = sky opaque to external radiation).
Figure 3 (right): Ratio of exposure times for reaching $S/N = 10$ as function of wavelength λ, with a ground-based 30m telescope or an L2 space-based telescope of size 16m (top) or 8m (bottom), respectively. Ratios are indicated for four different spectral resolutions $\mathcal{R}$, with the top curve in each panel being the lowest resolution.

summed spectrum. As an example, Figure 3 compares the time to reach $S/N = 10$ for a point source as a function of spectral resolution for a 30-m ground-based telescope, versus the time required for a space-based 8m and 16m observatory located at L2. As in Table 1, all are assumed to have the same instrument and detector performance. In these calculations we have assumed that the 30m ground-based telescope is diffraction-limited at wavelengths longer than $\sim 1\mu$m, and is seeing limited ($0.4''$ FWHM) at lower wavelengths. Some form of optical AO would decrease the advantage of the space-based observatory, as in Table 1.

Figure 3 shows that an 8m space-based telescope is 10 to 100 times faster than a ground-based 30m for all optical seeing-limited imaging ($R \sim 5$) and up to 40 times faster for most low-resolution ($R \sim 100$) spectroscopy. The space-based 8m is also more sensitive for medium-resolution optical spectroscopy ($R \sim 2000$). Similarly, a 16m space telescope is much faster for all spectroscopy in the visible compared to a seeing-limited 30m ground-based telescope. Wide-field optical imaging and moderate resolution spectroscopy at the depth allowed by a new large space-based telescope will allow important new studies of, e.g., planets (Kasting et al. 2009), distant and/or faint galaxies (Giavalisco et al. 2009), and resolved stars outside the Local Group (Brown et al. 2009).

At highest spectral resolutions, background noise ceases to be the dominant noise contribution, so that space observatories loose their edge. Also, another important metric is how many sources can be observed spectroscopically at any given time. Such multiplexing is possible in space (e.g., JWST/NIRSpec), but ground-based observatories may well have fewer constraints in pushing this to its limits.

5. High-contrast science

5.1. Extreme AO with Coronagraphs

ExAO Extreme Adaptive Optics pushes high-contrast observations, geared in particular towards study of exoplanets. It gives a very high correction ($SR > 90\%$) within a small FOV (a few arcsec, corresponding to a few AUs to a few tens of AUs around nearby stars). The target star itself is used for wavefront sensing, therefore eliminating any anisoplanetic errors. ExAO requires large numbers of corrected modes, and fast correction rates in order to achieve the very high image quality. Currently, ExAO systems are designed and built for the near infrared where the correction is easier than in the visible (see Section 3).

Coronagraphs and high-contrast calibration In order to produce high-contrast images, ExAO needs to be combined with coronagraphs and additional calibration schemes (active calibration, speckle nulling, differential imaging, etc.). Many coronagraphs have been developed and proven in the laboratory. The best laboratory experiments have reached $\sim 5 \times 10^{-10}$ contrast in medium bands (10%), which proves the feasibility of the concept for the detection of Earth analogs. Coronagraphs work best for perfect non-obstructed apertures. Although some schemes exist to mitigate the effects of a central obstruction or segmentation, the performance is severely affected by the diffraction of these geometrical features, especially with the typically large central obstruction and wide support structures required on future 30m-class ground-based telescopes (hereafter referred to as Extremely Large Telescopes, ELTs). It is not clear whether internal coronagraphs can be designed to deliver 10^{-10} contrast with large on-axis segmented telescopes, but the task is facilitated by the increased angular resolution of ELTs. The coronagraphs need only reach this contrast level at 10–20 resolution elements (λ/D) for the detection of an Earth-twin, as opposed to a few for smaller telescope. After coronagraphy, space-observations and ground+ExAO-observations require similar levels of calibration, in order to improve the performance and remove residual starlight propagation artifacts (speckles). This task is made easier in space because of the greater thermal and mechanical stability of a space-based telescope.

State of the Art On the ground, new instruments are being built for current 8m-class telescopes and will start operating in 2011. These instruments (e.g., GPI, SPHERE, Subaru, Palomar) involve ExAO, advanced coronagraphy, spectrographs and polarimeters. These projects will focus on observations of young (< 2 Gyr) giant planets in the near-IR (0.9–2.5μm). ELTs also envision high-contrast instruments, but very little funding has been invested so far. Their AO is more challenging, and mirror segmentation increases the difficulty for coronagraphic efficiency and stability. The science goals for high-contrast ground-based ELTs are very exciting and mostly include the study of young planets in star forming regions, mature reflected light giant planets, known radial velocity (RV) planets, Neptunes for nearby stars, and high-resolution images of protoplanetary disks.

5.2. The Limits for Ground-Based High-Contrast Science

Science Drivers Imaging and spectroscopic characterization of exoplanets or disks is the principal science motivation for high-contrast observations. The most exciting goal is arguably the direct detection of habitable terrestrial planets and the search for spectroscopic biomarkers. Strong motivations exist for doing these observations at short wavelengths ($\lesssim 1\mu$m), as discussed in, e.g., Kasting et al. (2009) and Lawson et al. (2009). This is because of the strong oxygen band at 760nm, as well as other potential biomarkers (ozone, vegetation red edge, Rayleigh scattering). This prompts the question whether such a science

program could be achieved with a ground-based 30m class telescope. We use the Sun-Earth system at 10 pc as a template for addressing this discussion.

Idealized Analysis Adaptive optics is fundamentally limited by the capacity to analyze the wavefront because of the finite number of photons available for wavefront sensing. Based on the analysis by Guyon (2005) this allows one to derive fundamental limits for high-contrast imaging in the visible for a 30m class telescope. We consider a perfect telescope with a perfect AO system and perfect coronagraphic instrumentation. We consider an ideal wavefront sensor making theoretically optimal use of all incoming photons (a few existing WFS concepts do offer this level of sensitivity, but have not yet been deployed on telescopes). We only consider errors due to photon noise in the wavefront sensor, and assume that the AO system has no other source of error (perfect DM, no calibration error). We assume that WFS is performed with the science detector, therefore removing any chromatic or non-common path issues. We also assume correction of both phase aberrations and amplitude (scintillation) by means of two perfect DMs. For each spatial frequency, an optimal exposure time (and therefore optimal control loop rate) exists which optimizes the time lag effect on the corrected phase and the photon noise. Better control, including for example predictive methods would improve these fundamental limits by a factor of a few but would not change the main conclusions. With these ideal assumptions, the residual aberrations from the atmosphere create a halo in the final raw image with the raw contrast given by

$$C(\alpha) = 2.348 \frac{v^{2/3} \Psi(\alpha/\lambda) \lambda_0^{2/3}}{D^2 F^{2/3} r_0^{5/9} \alpha^{5/9} \lambda^{1/9}}. \quad (2)$$

Here v is the wind speed, F the star flux, α the angular separation, Ψ is a term resulting from Fresnel propagation between the turbulent layers, and the Fried r_0 is defined at $\lambda_0 = 0.5\mu$m (see Guyon 2005 for derivation and details).

Theoretical Limit We assume a 30m telescope with such a perfect system operating at the wavelength of the oxygen A-band (760nm). The raw final image PSF consists of a residual halo as shown in Figure 4. This does not correspond to the actual contrast sensitivity, since this residual halo can be subtracted further using calibration and differential methods. The ultimate sensitivity limit is set by the photon noise in this halo. As a template, we consider the case of the Sun-Earth system at 10pc, with star magnitude m=4.1 (I band). We also assume 100% throughput and that a perfect noiseless halo can be subtracted. The required contrast for our template science case is 10^{-10} at 0.1 arcsec. We find that the exposure time required to reach $S/N = 5$ with a resolution R=70 is $\sim 10^6$s ($\gtrsim$ 10 days). Given the unrealistic set of assumptions adopted, we believe that this demonstrates that this observation is not feasible.

Technological limitations There are numerous technical difficulties that will make it impractical to get close to the theoretical limit on an ELT in visible light. This includes the required number of actuators, achievable loop rate, implementation of science camera wavefront sensing, coronagraph designs for segmented apertures, stability required for calibration and halo subtraction, etc. Even at longer wavelengths, the 10^{-10} contrast regime will be extremely challenging. A number of studies of ExAO instruments for 30m class telescopes found that in practice one might reach 10^{-8} contrast at $\sim$ 40 mas and 10^{-9} contrast at 100 mas in the near-IR (1.6μm) (e.g., Macintosh et al. 2006; Cavarroc et al. 2006; Kasper et al. 2008). Although this comes short of what is required for studying terrestrial planets, these instruments will have extremely interesting and exciting scientific capabilities for the broader study of exo-planetary systems.

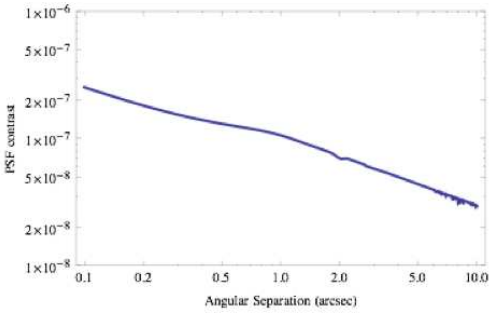


Figure 4: Raw PSF for a 30m telescope observing at 760nm with perfect telescope and ExAO. The PSF is shown *after* correction with a perfect coronagraph, and is normalized to be PSF = 1 at the center *without* coronagraph. It therefore shows the achieved contrast before application of any further differential methods. Ideal WFS is assumed to be performed with the science detector at the same wavelength to eliminate non-common path errors or chromatic propagation effects. The turbulence parameters are standard. As discussed in the text, even such an idealized setup would not be sufficient for low-resolution spectroscopy of an earth-twin at 10pc.

5.3. High-Contrast Science from Space

When combining fundamental limits and realistic technical capabilities for AO on the upcoming 30m class telescopes, it is clear that space observations will be necessary for very high-contrast science at wavelengths shorter than $\sim 1\mu$m, as required for the study of terrestrial planets in the habitable zone of nearby stars. Several space-based high-contrast projects are under study at this time (e.g., Cash et al. 2009a,b; Kasdin et al. 2009; Postman et al. 2009). The most exciting prospect is to address the habitability of terrestrial planets and search for life by identifying spectroscopic biomarkers (O_2, O_3, H_20, CH_4, etc.; Kasting et al. 2009).

6. Concluding Remarks

Adaptive optics has made exceptional advances in approaching space-like image quality at higher collecting area, although the exact prospects for optical-wavelength applications remain uncertain. This will provide exciting new access to scientific problems that were previously inaccessible. Nonetheless, there will continue to be subjects that can *only* be studied at optical wavelengths from space, including wide-field imaging and (medium-resolution) spectroscopy at the deepest magnitudes, and the exceptional-contrast observations needed to characterize terrestrial exoplanets and search for biomarkers. So we expect that there will continue to be a strong complementarity between observations from the ground and from space in the coming decades. This provides strong motivating for continued technology development and new facilities, both for ground- and space-based optical (and UV) applications.

7. References

[ASTRO 2010 abbreviations: NOI: Notice of Intent; SW: Science Frontiers White Paper; SP: State of the Profession Paper]

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