Advanced Technology Large-Aperture Space Telescope (ATLAST): Characterizing Habitable Worlds

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Abstract. The Advanced Technology Large Aperture Space Telescope (ATLAST) is a set of mission concepts for the next generation UV-Optical-Near Infrared space telescope with an aperture size of 8 to 16 meters. ATLAST, using an internal coronagraph or an external occulter, can characterize the atmosphere and surface of an Earth-sized exoplanet in the Habitable Zone of long-lived stars at distances up to \(\sim 45\) pc, including its rotation rate, climate, and habitability. ATLAST will also allow us to glean information on the nature of the dominant surface features, changes in cloud cover and climate, and, potentially, seasonal variations in surface vegetation. ATLAST will be able to visit up to 200 stars in 5 years, at least three times each, depending on the technique used for starlight suppression and the telescope aperture. More frequent visits can be made for interesting systems.

1. Overview of the ATLAST Concept

We are at the brink of answering two paradigm-changing questions: Do Earth-sized planets exist in the Habitable Zones of their host stars? Do any of them harbor life? The tools for answering the first question already exist (e.g., Kepler, CoRoT); those that can address the second can be developed within the next 10-20 years (Kasting, Traub et al. 2009). ATLAST is our best option for an extrasolar life-finding facility and is consistent with the long-range strategy for space-based initiatives recommended by the AAAC Exoplanet Task Force (Lunine et al. 2008). ATLAST is a NASA Astrophysics Strategic Mission Concept for the next generation flagship UVOIR space observatory (wavelength coverage: 110 nm – 2400 nm), designed to answer some of the most compelling astronomical questions, including “Is there life elsewhere in the Galaxy?” The ATLAST team investigated two different observatory architectures: a telescope with an 8-m monolithic primary mirror and two variations of a telescope with a large segmented primary mirror (9.2-m and 16.8-m). The two architectures span the range in viable technologies: e.g., monolithic vs. segmented apertures, Ares V launch vehicle vs. EELV, and passive vs. fully active wavefront control. This approach provides several pathways to realize the mission that would
be narrowed to one as the needed technology development progresses and the availability of launch vehicles is clarified.

While ATLAST requires some technology development, all the observatory concepts take full advantage of heritage from previous NASA missions, as well as technologies available for missions in development. The 8 m monolith architecture is similar to the Hubble Space Telescope (HST), although the optical design is different. The 8 m mirror has an areal density exceeding that of the HST mirror, providing superb stiffness and thermal inertia. The use of such a massive mirror provides excellent wavefront quality and is made possible given a launch vehicle with the capabilities of the proposed Ares V. The 9.2 m and 16.8 m segmented mirror concepts rely heavily on design heritage from the James Webb Space Telescope (JWST), in development of lightweight segmented optics, the OTA deployment mechanics, and wavefront sensing and control. The 9.2 m segmented concept can be launched on a Delta IV Heavy launch vehicle with a modified 6.5 m fairing; the 16.8 m concept requires an Ares V. The non-cryogenic nature of ATLAST makes the construction and testing of the observatory much simpler than for JWST. We have also identified departures from existing NASA mission designs to capitalize on newer technologies, minimize complexity, and enable the required improvements in performance.

Four significant drivers dictate the need for a large space-based telescope if one wishes to conduct a successful search for biosignatures on exoplanets. First, and foremost, Earth-mass planets are faint – an Earth twin at 10 pc, seen at maximum elongation around a G-dwarf solar star, will have \( V \sim 29.8 \) AB mag. Detecting a biosignature, such as the presence of molecular oxygen in the exoplanet’s atmosphere, will require the ability to obtain direct low-resolution spectroscopy of such extremely faint sources. Second, the average projected angular radius of the Habitable Zone (HZ) around nearby F,G,K stars is less than 100 milli-arcseconds (mas). One thus needs an imaging system capable of angular resolutions of \( \sim 10 \) to 25 mas to adequately sample the HZ and isolate the exoplanet point source in the presence of an exo-zodiacal background. Third, direct detection of an Earth-sized planet in the HZ requires high contrast imaging, typically requiring starlight suppression factors of \( 10^{-9} \) to \( 10^{-10} \). Several techniques (cf. Levine et al. 2009) are, in principle, capable of delivering such high contrast levels but all require levels of wavefront stability not possible with ground-based telescopes because the timescale of wavefront variations induced by the Earth’s atmosphere is shorter than the time to measure the wavefront error to the required precision. A space-based platform is required to achieve the wavefront stability that is needed for such high contrast imaging. Lastly, biosignature-bearing planets may well be rare, requiring one to search tens or even several hundred stars to find even a handful with compelling signs of life. The number of stars for which one can obtain an exoplanet’s spectrum at a given SNR and in less than a given exposure time scales approximately as \( D^3 \), where \( D \) is the telescope aperture diameter. This is demonstrated in Figure 1 where we have averaged over different simulations done using various starlight suppression options (internal coronagraphs of various kinds as well as an external occulter).

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1Such stability is achievable regardless of the space telescope’s aperture (within reasonable limits) – so this driver is primarily for the space locale of the telescope rather than its aperture.
To estimate the number of potentially habitable worlds detected, one must multiply the numbers in Figure 1 by the fraction of the stars that have an exoplanet with detectable biosignatures in their HZ ($\eta_\oplus$). The value of $\eta_\oplus$ is currently not constrained but it is not likely to be close to unity. One must conclude that to maximize the chance for a successful search for life in the solar neighborhood requires a space telescope with an aperture size of at least 8 meters.

All ATLAST concepts require many of the same key technologies. We believe these designs compose a robust set of options for achieving the next generation of UVOIR space observatory in the 2020 era. There are several fundamental features common to all our designs. All ATLAST concepts are designed to operate in a halo orbit at the Sun-Earth L2 point. The optical designs are diffraction limited at 500 nm (36 nm RMS WFE) and the optical telescope assembly (OTA) operates near room temperature (280 K – 290 K). All OTAs employ two, simultaneously usable foci: a three-mirror anastigmat channel for multiple, wide field of view instruments, and a Cassegrain channel for high-throughput UV instruments and instruments for imaging and spectroscopy of exoplanets (all designs have an RMS WFE of < 5 nm at < 2 arcsec radial offset from Cass optical axis). The ATLAST concept study is available online and on the astro-ph archives (Postman 2009a; Postman 2009b).

2. Simulated Data and Exoplanet Characterization Performance

Estimates of the SNR of habitability and biosignature features in an Earth-twin spectrum, achievable with ATLAST, are shown in Table 1. For these calculations we use a fully validated model of the Earth’s spectrum (Marais et al. 2002; Woof et al. 2002), in combination with the observed visible reflection spectrum of the present Earth. We assume that the exoplanet is at maximum elongation and that the planet is observed for a length of time sufficient to achieve an SNR of 10, at a spectral resolution $R = 70$, in the red continuum. The vegetation signal is the enhanced albedo of the Earth from land plants, for wavelengths longer than 720 nm (Seager et al. 2005), with a modest SNR. Column 3 gives the width of the spectral feature. All of these SNR values can easily be improved with re-visits. In addition, ATLAST will allow us to glean substantial information about an exo-Earth from temporal variations in its features. Such variations
inform us about the nature of the dominant surface features, changes in climate, changes in cloud cover, and, potentially, seasonal variations in surface vegetation (Ford et al. 2003). Constraints on variability require multiple visits to each target. The 8-m ATLAST (with internal coronagraph) will be able to observe \( \sim 100 \) different star systems 3 times each in a 5-year interval and not exceed 20% of the total observing time available to the community. The 16-m version (with internal coronagraph) could visit up to \( \sim 250 \) stars three times each in a five-year period. The 8-m or 16-m ATLAST (with a single external occulter) can observe \( \sim 85 \) stars 3 times each in a 5-year period, limited by the transit times of the occulter. Use of two occulters would remove this limitation.

Table 1. Habitability and Bio-Signature Characteristics

| Feature                        | \( \lambda \) (nm) | \( \Delta \lambda \) (nm) | SNR | Significance                               |
|--------------------------------|-------------------|---------------------------|-----|-------------------------------------------|
| Reference Continuum            | 750               | 11                        | 10  |                                           |
| Rayleigh Scattering            | <500              | 100                       | 4   | Protective atmosphere                      |
| Ozone (O\(_3\))                | 580               | 100                       | 5   | Source is O\(_2\); UV Shield              |
| Oxygen (O\(_2\))              | 760               | 11                        | 5   | Plants emit; Animals inhale                |
| Cloud/Surface reflection       | 750               | 100                       | 30  | Rotation indicator                         |
| Land Plant reflection          | 770               | 100                       | 2   | Vegetated land area                        |
| Water vapor (H\(_2\)O)         | 940               | 60                        | 16  | Needed for life                            |

Figure 2 shows two simulated ATLAST spectra for an Earth-twin at 10 pc, one at \( R=100 \) and one at \( R=500 \), taken with sufficient exposure to reach SNR=10 at 750 nm in the continuum. A 3-zodi background was used (local plus exosolar). The \( R=100 \) exposure times are 46 ksec and 8 ksec, respectively, for an 8-m and 16-m space telescope. The corresponding exposure times for the \( R=500 \) spectrum are 500 ksec and 56 ksec, respectively, for the 8-m and 16-m telescopes. The reflected flux from an Earth-like rocky planet increases as \( M^2/3 \), where \( M \) is the exoplanet mass. Hence, the exposure times for a 5M\(_\oplus\) super-Earth would be \( \sim 3 \) times shorter. At both resolutions, the O\(_2\) features at 680 nm and 760 nm are detected, as are the H\(_2\)O features at 720, 820, 940, 1130, 1410, and 1880 nm. Rayleigh scattering is detected as an increase in reflectivity bluewards of 550 nm. The higher spectral resolutions enabled by large-aperture space telescopes enable the detection of molecular oxygen in exoplanets with lower abundances than those on Earth and provide constraints on the kinematics and thermal structure of the atmosphere that are not accessible at lower resolution.

For a 16-m class space telescope, time-resolved spectroscopy over intervals of a few hours may reveal surface composition variations, if the planet is not cloud dominated, as the exoplanet rotates. However, even broadband photometry can be used to detect short-term variations in albedo that can determine the rotation period and constrain the amount of cloud cover. Ford et al. (2003) generated model light curves for the Earth over 6 consecutive days using data from real satellite observations. Photometric variations of 20 – 30% on timescales of 6 hours were typical in the B,V,R,I passbands. Their models are shown in Figure 3. On top of these light curves we show grey bands whose height represents the \( \pm 5\% \) uncertainty for SNR=20 broadband (\( R=4 \)) photometry and whose length represents the time it would take to perform such an observation with a 4-m, 8-m, and 16-m space telescope. We show the results of such calculations for an
Figure 2. Simulated ATLAST spectrum of an Earth-twin at 10 pc, shown at R=100 in the upper plot and R=500 in the lower plot. The SNR=10 at 750 nm in both cases. Key O$_2$, O$_3$, and H$_2$O features are shown. The increased reflectance at the blue end of the spectrum is due to Rayleigh scattering. An 8-m ATLAST obtains the R=100 and R=500 spectra in 46 ksec and 500 ksec, respectively.

Figure 3. Model light curves of Earth for a six day interval (Ford et al. 2003). Superposed are grey bands whose length indicates the time required (in days) to achieve SNR=20 broadband photometry of an Earth twin at 10 pc (top bands) and 20 pc (bottom bands) for space telescopes with apertures of 4, 8, and 16 meters. The height of the grey bands corresponds to the ±5% photometric error.
Figure 4. Simulated ATLAST transit spectra for two super-Earth exoplanets around a K=6 mag M2 star. Instrumental effects are modeled assuming JWST NIRSpec performance. The transit period is \( \sim 22 \) days. The broad features are water absorption bands.

Earth twin at 10 pc and 20 pc. The 4-m has marginal capability to study such photometric variations at 10 pc but telescopes with apertures of 8-m or larger would be able to perform the measurements well as the integration time is less than the typical period between significant albedo changes. At 20 pc, even an 8-m telescope reaches its limits but a 16-m telescope is still able to acquire the needed accuracy in photometry in less than 4 hours.

Transit spectroscopy with ATLAST will permit characterization of super-Earth mass exoplanets. Figure 4 shows two simulated ATLAST transit spectra for planets around a 6th magnitude M2 star where the orbital period in the HZ is \( \sim 20 \) – 30 days. Such observations are time consuming but do not require the use of a coronagraph or occulter.

In summary, with ATLAST, we will be able to determine if HZ exoplanets are indeed habitable, and if they show signs of life as evidenced by the presence of oxygen, water, and ozone. ATLAST also will provide useful information on the column abundance of the atmosphere, the presence of continents and oceans, the rotation period, and the degree of daily large-scale weather variations.

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