Nautilus Deep Space Observatory: A Giant Segmented Space Telescope Array for a Galactic Biosignature Survey.
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Introduction: With over 4,000 exoplanets known – many of which may be similar to Earth – the systematic characterization of exo-earths and the search for atmospheric biosignatures is emerging as one of the highest-level science goals of modern astrophysics. With no prior knowledge on the probability of the emergence of life on other planets, the characterization of a very large number of potential earth-analogs is desirable to ensure statistically meaningful results.

As our baseline goal we identify an atmospheric compositional study of 1,000 earth-sized habitable zone planets. This survey will target a large enough sample to allow statistically significant conclusions on biosignatures occurrence rates, exo-earth diversity, climate stability, and atmospheric loss mechanisms.

Our survey requires a very large aperture space telescope.

The Deep Space Gateway, and specifically the infrastructure for the Gateway, offers a unique opportunity to (partially) fabricate and assemble a very large (50 m diameter equivalent) segmented space telescope that will be capable of carrying out the ambitious atmospheric biosignatures survey outlined above. Such a segmented giant space telescope will also transform observational astrophysics.

Key Science Requirement for Transmission Spectroscopic Biosignature Survey: We aim to determine the occurrence rate of life in the galaxy by measuring the atmospheric abundances of H_2O, O_2, O_3, and CO_2 in the atmospheres of 1,000 transiting habitable zone earth-like exoplanets around broadly sun-like stars. Studying a large number (~1,000) transiting earth-like planets will require observing relatively distant stars (G and K-type stars up to 200 pc, considering the number densities of G and K-type stars and geometric probabilities of habitable zone planet transits). The spectral feature depths for key absorbers in Earth twins are about 1 ppm ([1], Fig. 1). A confident (>10 $\boldsymbol{\sigma}$) detection of H_2O, O_2, and O_3 for a target 200 pc away will require a telescope with a collective area equivalent to that of a 50m telescope (assuming overall throughput of 0.25). This is 200 times greater area than that of the largest mirror flown in space.

Current telescope architectures cannot be scaled up so dramatically. Therefore, our science goal requires a revolutionary new telescope technology and design.

Baseline Telescope Design: We envision a giant segmented space telescope with the following design (see also Figure 1):

1) A segmented telescope with a combined light-collecting area equivalent to a that of a 50m diameter telescope.
2) Hexagonal segments with individual segment diameters between 1.5m to 3m. Each segment group (7 hexagons) phased coherently, but light from the segment groups combined incoherently (i.e., digitally co-added).
3) The segment groups are located in a large, lightweight hexagonal honeycomb-like grid system, providing individual two-axis pointing and tracking capability for each unit. The entire telescope will not need to coherently combine light, i.e., it will not provide diffraction-limited performance for its entire 50m diameter.
4) A modular design allows sub-units (segment groups) to be used as individual telescopes or to be used in a coordinated array mode (common target). The modular design will also enable step-wise construction of the telescope and operations with the partial telescope aperture.
5) We envision very lightweight and thin optical elements, preferably fabricated in space. The in-space fabrication reduces the structural strength that would be required if the optical elements would be fabricated on Earth.

Operations: The Nautilus Deep Space Observatory (NDSO) will operate in two modes:

1) Transit Search Mode: The unit telescopes will monitor sun-like stars independently of each other, and through their parallel operation carry out the most sensitive and most comprehensive exoplanet search yet.

2) Follow-up Transit Spectroscopy Mode: During known transit events all unit telescopes will obtain the transmission spectrum of the same planet; the signal will be combined non-coherently (by digitally coadding), enabling the confident detection (>10 sigma) of major atmospheric absorbers (O_2, O_3, H_2O) in Earth twins up to 200 pc distance (scaled from [1]).

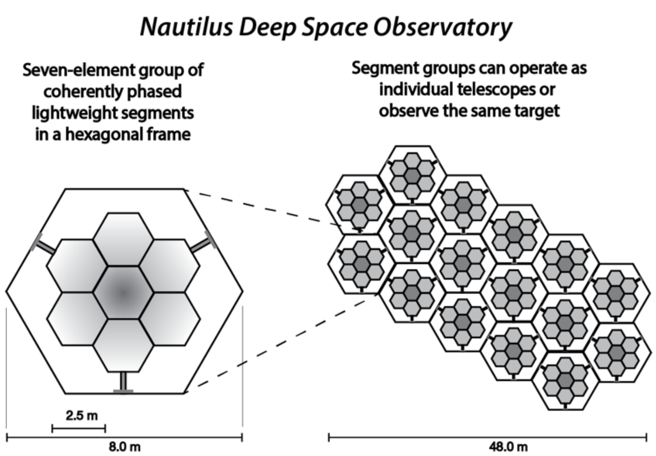
Assembly at or near the Deep Space Gateway: NDSO is a modular system assembled from identical telescope cells, which itself are constructed from a very small set of unique components. Only two different types of telescope segments are required: on-axis and off-axis segments.

The modular design and identical elements provide greatly reduced fabrication costs. The honeycomb structure provides an excellent structural strength / mass ratio. The support structure of the NDSO telescope array could be launched as a folded structure as a compact payload, which would be deployed by the DSG crew in orbit. The individual segment groups would be inserted and connected to the honeycomb support structure. As the units primarily function as independent telescopes, no precise alignment is necessary between the segment groups.

Reflective or Diffractive-Transmissive Optics: With an overall design similar to the James Webb Space Telescope the Nautilus Deep Space Observatory will provide a viable framework for reflective segmented telescopes. However, our team is also working on developing the capability to design and injection mold large-scale on- and off-axis transmissive-diffractive (multi-order) optical elements [e.g., 2,3,4]. Large-scale transmissive-diffractive optical elements have been explored in the LLNL and DARPA-funded Eyeglass [5] and MOIRE projects [6] aimed at constructing 25 meter diameter earth-observing space telescopes.

Our team has designed, fabricated, and replicated (via injection molding) two generations of small-scale multi-order diffractive engineered material lenses (MOD-EML). As part of our technology maturation process we are currently carrying out on-sky and laboratory tests with a MOD-EML-equipped astronomical telescope. Equipping NDSO with lightweight MOD-EMLs instead of mirrors would provide a significant reduction in launch weight.

In-orbit Fabrication: If the molding of large MOD-EMLs can be successfully demonstrated, the extension of this process may also provide a natural opportunity for the Nautilus Deep Space Observatory and the Deep Space Gateway. By launching the two *molds* (one on-axis and one off-axis segment) and unmolded glass, the injection molding process could conceivably be carried out in orbit. This step would allow for even lighter optical elements, as the elements would not need to survive the launch stresses.



Scientific Impact: The NDSO array will provide a light-gathering capability that exceeds current state-of-the-art (Hubble Space Telescope, 2.4m mirror diameter) by about 400 times. The NDSO system will be capable of carrying out the first large-scale assessment of atmospheric biosignatures in the galaxy, leading to profound breakthroughs in science. Furthermore, the powerful light-gathering capability combined with the flexibility to observe the same target with all unit telescopes or to survey large fields simultaneously will transform multiple modern observational astrophysics, cosmology, and planetary science.

Estimated Requirements: NDSO is a preliminary concept that builds on a similarly ambitious space mission concept (Nautilus Array) under development by our team. Here we provide preliminary, baseline estimates for the fundamental requirements and will provide more comprehensive assessment at the workshop.

Mass: Approx. 500-700 kg per unit. A 40 unit telescope array would be between 20,000 to 28,000 kg.

Power: None. Power will be supplied from NDSO's own solar panels.

Cost: We do not yet have a reliable cost estimate. Nevertheless, assuming the first unit cost to be between \$0.5B and \$0.7B and an exponential cost scaling law with a coefficient between 0.4 and 0.7, the 40 unit array cost would be between \$2.5B and \$9B.

Volume: No volume within DSG.

Amount of Crew Interaction: The NDSO deployment and installation would require crew interactions (multiple EVAs). Once deployed, the NDSO will require additional crew interactions only during expansion and servicing.

Desired Orbit: An orbit similar or identical to DSG is desired; our desired orbit is Near Rectilinear (NRO).

Nautilus website: http://nautilus-array.space/

References: [1] Ehrenreich et al. (2006) *Astron. Astroph., 448,* 379. [2] Fakli, Morris (1995) *Applied Optics, 34(14),* 2462. [3] Hansen (2013) *Transmissive Diffractive Optics,* 20-23. [4] Lo, Arenberg (2006) *SPIE Astron. Telescopes,* pp. 626522. [5] Hyde (2002), Astron. Telescopes and Instr. (pp. 28-39). [6] Atcheson et al. (2014) *SPIE Astron. Telescopes* pp. 41431.

Figure 1 The Nautilus Deep Space Observatory comprises of an array of individual, segmented telescopes. The entire array is build using only two distinct type of optical elements: on-axis and off-axis hexagons. The modular construction that minimizes unique elements allows for low construction and assembly costs, flexible operations, and increased serviceability.