Exploring Exoplanets from Near Space

Exoplanet Detection and Characterization from Balloons

Technology Whitepaper Submitted to the Discipline Panel on Electromagnetic Observations from Space (EOS)

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ABSTRACT

A cost effective and often overlooked approach to the direct detection and characterization of exosolar terrestrial planets is high altitude long duration balloon flights. Balloons can carry payloads of mass > 2000 kg aloft for > 3 weeks at altitudes of ~120,000 feet. At those altitudes the atmosphere is sufficiently benign to allow for control of the system to realize contrasts approaching 10^{10} necessary for terrestrial planets. In addition, balloons are a staged incremental approach since multiple launches would be possible, with each launch leveraging lessons learned from the aggregate set of prior launches – and could be realized for a fraction of the cost of a large space mission. While we believe a space flight mission will ultimately realize the best and most comprehensive exoplanet science – in the short term an alternative strategy would be to pursue the balloons as one option.

1.0 Introduction

The proposed, and well studied, flagship NASA mission for terrestrial planets was the Terrestrial Planet Finder – Coronagraph (TPF-C). It was acknowledged that this would have been a difficult and costly (> $5B) space mission requiring the launch of an 8 x 3.5 meter telescope with beyond state of the art thermal, structural and optical tolerances. If TPF-C were developed, launched and subsequently found and characterized 40 terrestrial planets then costs would have been ~ $125M per planet. However, if the probability of an Earthlike planet were low ($\eta_{Earth} << 1$), in any given star system, then likely only a few, or none, would have been found. Balloons can circumvent this problem by detecting and characterizing at least some of the easier TPF-C targets and advancing the science in the nearer term for a fraction of the cost.

The balloon environment is not well understood with regards to the parameters that need to be known for exoplanets. These comprise the atmospheric dynamics in terms of temporal variability, scintillation, coherence cell diameter, transmission and stray or scattered light. Thus to realize a long duration balloon exoplanet mission requires a smaller atmospheric characterization balloon mission. Such a mission could be realized as a smaller short-term balloon flight to the same elevation and carry as instruments both an imaging and nulling interferometer. The imaging interferometer would measure the atmospheric profiles needed to determine the turbulent cell size and atmospheric dynamics. The nulling interferometer would assess how deep, in contrast, the upper atmosphere limits the contrast. The Balloon Exoplanet Nulling Interferometer (BENI) mission has been studied for this task (Fig-1). BENI would be launched on a short term balloon and could be realized for < $4M [Lyon, et. al. 2009]. BENI would fly an existing Fizeau imaging interferometer [Lyon, et.al. 2004] comprising three 10-cm aperture telescopes on a 1.5 meter boom. Coherent interference of the telescopes on a bright target star gives the fringe visibility as a function of baseline at high bandwidth (800 Hz). The Fizeau interferometer already exists and is available for this effort and would be used to deduce the turbulent cell size and the atmospheric correlation time at various look angles and elevations. Additionally BENI would carry a visible nulling interferometer [Lyon, et. al. 2005] enabling direct starlight nulling in visible to NIR spectral bands placing a bound on the performance of larger scale exosolar planet balloon missions.

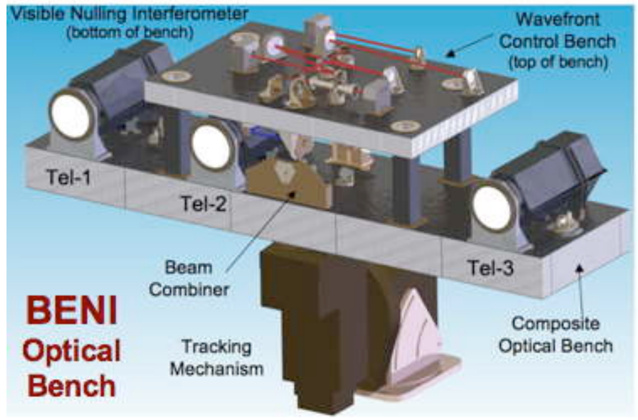

Figure – 1: *Balloon Exoplanet Nulling Interferometer* Uses an existing imaging interferometer coupled to a nulling interferometer. Proposed to fly on a short duration balloon to characterize 1-science target (ε-Eri), characterize the balloon environment and atmosphere, and advance technology. BENI could be realized in 3 years for <$4M.

2.0 Atmosphere at High Elevations

Modeling of the effects of atmospheric turbulence has been performed but is lacking in hard data to validate the models. A small balloon mission flying an interferometer would serve to characterize this environment. Fig-2 shows the results of atmospheric modeling. The absorption generally decreases with increasing elevation angle (Fig-2 upper left) while the atmospheric turbulent cell size (Fried's parameter) generally increases with elevation and ideally should be larger than the aperture of the telescope; this is realizable at elevations of > 100,000 ft and elevation angles > 0.0 degrees. The Rytov scintillation index (Fig-2 lower left) is a measure of multiple layers of Fresnel diffraction and is the variation in light intensity; scintillation indices of < 0.001 are desirable for terrestrial planet detections and is realized at > 5 degrees elevation above 100,000 ft. The Greenwood frequency (Fig-2 lower right) is a measure of the inverse of the atmospheric correlation time and set the frequency of wavefront sensing and control; frequencies < 1 Hz are realized above 100,000 ft for elevation angles greater than 0 degrees (horizon).

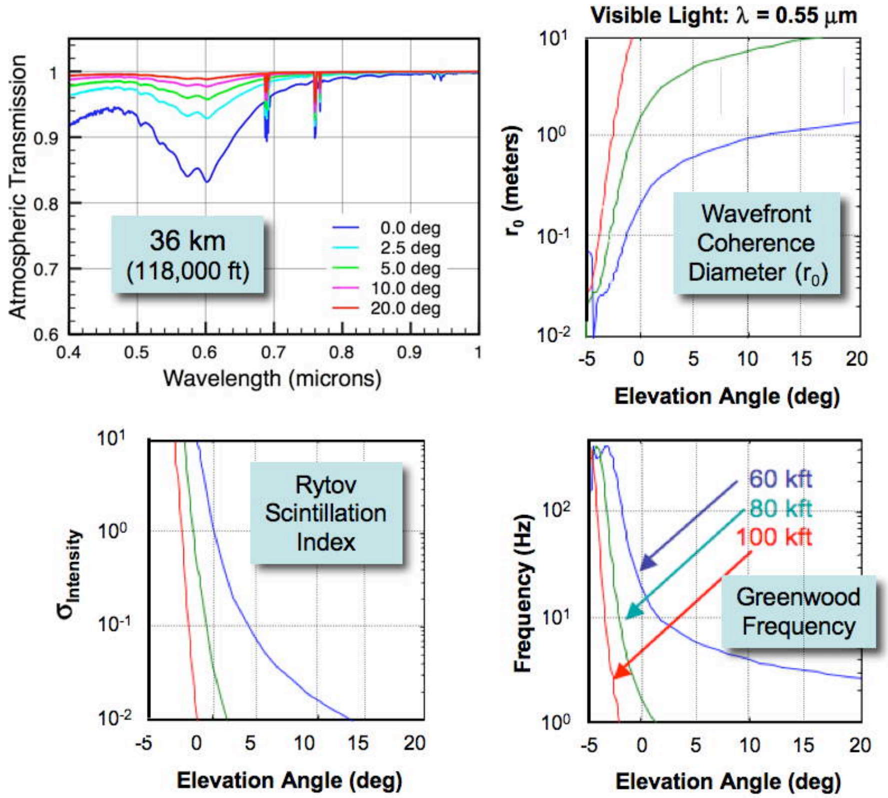

Figure – 12: *Atmospheric modeling at high Altitude*

This represents only a partial understanding, since straylight, solar scatter, ice crystals etc will all contribute and must be better understood prior to a long duration balloon flight.

3.0 Overview of the Approach

Long duration balloons with a telescope with > 3 meter aperture would allow a staged approach consisting first of a small balloon payload to image one science target where a confirmed planet is known, advance technology development, and to characterize the atmosphere at elevation, in the manner needed for exoplanet detection. Following this a larger scale long duration balloon mission would be designed and developed. Table-1 delineates the top-level system mission and payload parameters for such a mission; all of which are within

Table – 1: Strawman Balloon Mission

Balloon Mission	
Launch Location	Antartica (night)
Elevation	> 100,000 ft
Duration	> 3 weeks
Payload Mass	> 2000 lbs
Payload Power	300 - 600 Watts
Location	Redundant GPS
Data Rates	Omni/TDRS 2kbps/6 kbps
Payload	
Tracking platform	Reactionless target tracking
Telescope	> 3 meter
Coronagraph	Contrast > 10^{10}
Science imager	R ~ 3 (spectral filters)
Integration Time (3σ detection)	~ 10 hours
Spectrometer	R = 3 - 50 (dispersing)
Integration times (spect)	7 - 14 days
Pointing Control	
Balloon	> 10 arcmin
Tracking platform	<5 arcsec
Fine steering mirror	<5 milli-arcseconds

reason for existing and/or future balloons and technology. This would uses a telescope coupled to a coronagraphic, an approach that could be realized for ~$125M. This mission would fly for ~3 weeks and survey targets. Follow-up balloon missions could subsequently be realized for << $125M since the telescope would already exist and the majority of the new costs would be for the balloon (< $20M) and its operations, launch and recovery. Multiple missions could be flown in this manner, advancing simultaneously balloon environmental knowledge and coronagraph technology culminating in a near optimal approach. The staged incremental approach would lead to imaging and spectroscopy of detected planets, better understanding of η_{Earth} in our local neighborhood. It would advance technologies needed for the future space flight mission in the near term without incurring the risk inherent in launching a single complex and costly space telescope that must work correctly the first time, and, cannot be easily changed if an alternative approach becomes more viable.

4.0 Required Technologies and their Status

Balloon borne missions typically cost less than 10% of an equivalent satellite mission but with much shorter timescales for operations. It also allows upgrades to instruments and re-flights not possible with satellite missions. Development of super-pressure long duration (15 to 100-day flights) balloons that can operate at any latitude is underway. In February 2009, a test flight of 54 days was demonstrated. NASA aims to fly an operational system with a payload capability of 1000 kg at an altitude of 33.5 km for a 100-day flight duration. [Fairbrother et. al., 2009]

Pointing and stabilization systems: –Balloon pointing and tracking systems need advancement for exoplanet detections. Reactionless three degree-of-freedom platforms are essential for allowing multiple payloads to co-operate. Reactionless systems have been built for satellite applications but must be tailored for balloon applications to allow operations both on ground as well at altitude. Pointing stabilization system would be sensed and controlled using two star trackers, gyros and motor encoders to provide pointing stability on the order of 0.5 arcsecs. The star trackers would use frame-transfer CCDs such as ones from backthinned E2V CCD47-20; algorithms, the readout and star catalog architecture can be adapted from the Spitzer program. A single star fast stabilization mode would be added to allow pointing stabilization at 40 Hz or greater. The fast pointing mode is augmented by low noise fiber optic gyros. Internal payload/instrument fine pointing would be achieved by fast steering mirror technology with feedback from the science camera. Command and data handling will require continuous communications to handle science data flow and command and control and for monitoring instrument safety.

Coronagraphic and Nulling Technology: Multiple approaches for suppressing the starlight are available for the initial mission. NASA has developed both visible nulling coronagraph and focal plane mask based technology and has shown laboratory results at the level needed for flight to detect and characterize Jupiter like planets and surround dust disks of nearby stars. Incremental advancement is occurring that will, in the next two years, likely lead to suppression depths capable of detecting Earthlike planets. These approaches are readily adapted to a balloon-borne mission.

5.0 Summary

Nearly all the technologies are complete or are on track for development of long duration balloon missions and to realize exoplanet detection and characterization from near space. Balloon missions could be realized at relatively low cost, in the near term (3 – 5 years), and represent a viable and cost-effective path forward for both imaging and spectroscopic characterization of exoplanets in the coming decade.

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