Macho Mengi – Ground-based Interferometric Telescope

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Abstract - *This paper presents a short background of astronomical interferometry and the current and future work of the National Society of Black Engineers (NSBE) Houston Space Chapter on the "Macho Mengi" Project. The goal of Macho Mengi (which is Swahili for 'Many Eyes') is to gain technical knowledge in the design and construction of interferometric telescopes. The objective of the project is to design and build a small ground-based interferometric telescope to be used as a prototype and training tool for NSBE members. Designs are explored for various types of interferometric telescopes and hypertelescopes, with Fizeau interferometry selected as the basis for the prototype design. Current plans and expectations for the project are described. Becoming experts in interferometric telescopes through this experience is necessary to fulfill a vision to build NSBE's first interferometric space telescope.*

Keywords: Macho Mengi, NSBESAT, aperture synthesis, interferometry, interferometric telescope.

1 Introduction

The goal for the NSBE-Alumni Extension Space Special Interest Group's small satellites projects is for NSBE members to gain first-hand experience at designing, building, and operating satellites. This will be accomplished by first designing a single space telescope, NSBESAT 1. The next phase will be to launch NSBESAT 2, an array of space telescopes that use interferometry to act as a large space telescope. Developing an interferometric telescope requires a higher degree of experience and expertise than designing a single telescope. Currently our membership has little to no experience with this type of technology. By building and operating an interferometric telescope, NSBE members will gain the necessary experience and contribute to the development of NSBESAT 2. Project leadership is comprised of working engineering professionals and scientists in the space industry.

1.1 Background

The telescope was one of the central instruments of what has been called the Scientific Revolution of the seventeenth century. The earliest evidence of working telescopes was the refracting telescopes that appeared in the Netherlands in 1608. In 1668, Isaac Newton built the first practical reflecting telescope that bears his name, the Newtonian reflector. The invention of the achromatic lens in 1733 partially corrected color aberrations present in the simple lens and enabled the construction of shorter, more functional refracting telescopes. Reflecting telescopes, though not limited by the color problems seen in refractors, were hampered by the use of fast tarnishing speculum metal mirrors employed during the 18th and early 19th century — a problem alleviated by the introduction of silver coated glass mirrors in 1857 [1], and aluminized mirrors in 1932 [2]. The maximum physical size limit for refracting telescopes is about 1 meter (40 inches), dictating that the vast majority of large optical researching telescopes built since the turn of the 20th century have been reflectors. The largest reflecting telescopes currently have objective lenses larger then 10 m (33 feet).

The 20th century also saw the development of telescopes that worked in a wide range of wavelengths from radio to gamma rays. The first purpose-built radio telescope went into operation in 1937. Since then, a tremendous variety of complex astronomical instruments have been developed. Building increasingly larger telescopes for deep space viewing has limited the size of single telescopes due to the physical and logistical challenges of their design and placement. Starting with radio astronomy and later optical astronomy, scientists have continued to peer deeper into space with larger telescopes with the aid of interferometric telescopes.

An interferometric telescope is a device that combines multiple telescopes to act as a single large telescope. Interferometry is the technique of combining two or more waves in such a way that interference occurs between them. If aligned properly the signal can become amplified or nullified. In the case of interferometric telescopes, the goal is to amplify the light signal coming from separate telescopes to create images similar to that of a large telescope that has a mirror diameter equal to the distance between the two separate telescopes. To understand how this works, imagine taking a large refractor telescope and masking out most of its main mirror leaving only a few small patches. These patches direct light to the focus where it can be recorded with a light detector. Next, repeat the procedure using different patches of the mirror that were previously covered. After repeating this process enough times, with different parts of the mirror each time, analysis is performed on all the separate recordings to produce a single picture with the same detail as though the whole mirror was used at once. This is also known to astronomers as "aperture synthesis," because a larger telescope is synthesized by using smaller pieces of it at a time [3].

Two challenges behind aperture synthesis are recombining the light from the separate pieces with minimal distortion, and moving the telescopes around on the ground, so as to trace out the larger mirror they are trying to synthesize.

2 Research Phases

The Houston Space Chapter plans to build a small interferometric telescope using four telescopes (a fifth as reference), here on Earth, as an engineering exercise to better understand how to build and operate such a system before developing a spacecraft and associated systems designed to perform a mission in space.

The research project is divided into three phases. The first phase (see Figure 1) is to build a tabletop-sized prototype that combines just two optical paths using only mirrors to view an artificial target. This will be accompanied by a paper reporting our planned work on interferometric telescope arrays. We are basing this simple prototype on a published paper and previous design by the University of Maryland [3]. This will be used as a demonstration to gather financial support, volunteers, and necessary facilities to continue further work on Macho Mengi – a working interferometric telescope. In phase two, two more optical paths will be added for a total of four optical paths. In phase three, telescopes will be attached at the beginning of each optical path and the setup modified for outdoor use to view the stars.

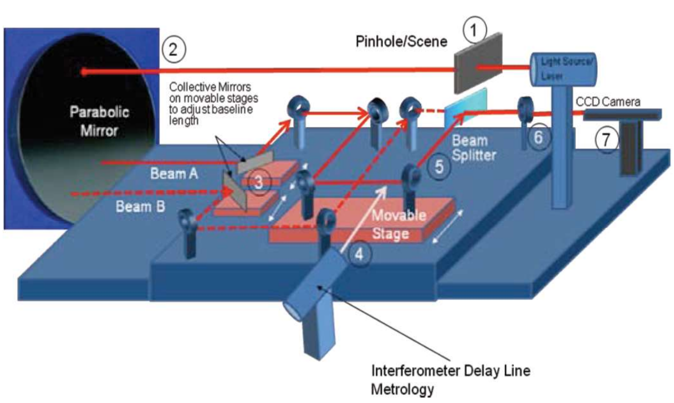

Figure 1. Phase 1 – Macho Mengi Interferometer prototype.

3 Astronomical Interferometers

3.1 Fizeau Interferometric Telescopes

Principles from Fizeau interferometry were assessed for incorporation into the design of the Macho Mengi telescope. Fizeau interferometry is an image-plane based interferometry that consists of two reflecting surfaces.

Figure 2 illustrates the layout of a basic Fizeau interferometric device for measuring wavefronts [1]. It shows the primary components of the interferometer, including a source of light, front and rear reflecting plates, a detector of the image, and a beam splitter. The beam splitter is used to bring the reference and test beams out for capture.

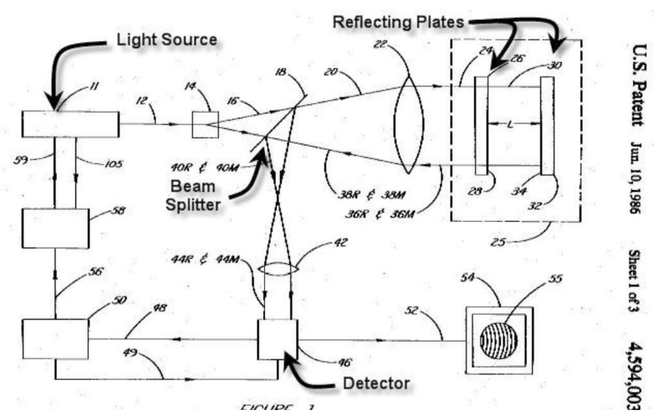

Figure 2. Fizeau interferometric device for measuring wavefronts [1].

Fizeau telescopes provide imaging with unprecedented angular resolution, sensitivity, and field of view at visible to near infrared wavelengths [5]. They are considered stable in design and are typically used to measure the shape of optical surfaces, or are used in fiber optic sensors to measure physical qualities such as strain, temperature, or pressure, amongst other parameters.

However, a common problem encountered with the Fizeau interferometer is the additional reflection from the rear surface reflecting plate. This results in unwanted parasitic intensity distribution, which alters the two-beam interferogram of the plate front surface creating an inefficient application of phase methods for automatic fringe pattern analysis [6].

3.2 Michelson Interferometer

In the world of astronomy, interferometry is an important investigative technique that diagnoses the properties of two or more waves by studying the pattern of interference created by their superposition. The angular resolution that a telescope can achieve is determined by its diffraction limit (which is proportional to its diameter). The larger the telescope, the better its resolution. However, the cost of building a telescope also scales with its size. The purpose of astronomical interferometry is to achieve high-resolution observations using a cost-effective cluster of comparatively small telescopes rather than a single very expensive monolithic telescope. The basic unit of an astronomical interferometer is a pair of telescopes. Each pair of telescopes is a basic interferometer.

The Michelson interferometer is the most common configuration for optical interferometry and was invented by Albert Abraham Michelson. An interference pattern is produced by splitting a beam of light into two paths, bouncing the beams back and recombining them. The different paths may be of different lengths or be composed of different materials to create alternating interference fringes on a back detector [7].

There are two paths from the (light) source to the detector. One path reflects off the semi-transparent mirror, to a flat mirror and then reflects back through the semi-transparent mirror, and to the detector. The second path first goes through the semi-transparent mirror, to a different flat mirror, reflects back to the semi-transparent mirror, and then reflects from the semi-transparent mirror into the detector.

If these two paths differ by a whole number (including 0) of wavelengths, there is constructive interference and a strong signal at the detector. If they differ by a whole number and a half wavelengths (e.g., 0.5, 1.5, 2.5, etc) there is destructive interference and a weak signal at the detector. This might at first appear to violate the principle of conservation of energy. However, energy is conserved because there is a redistribution of energy at the detector in which the energy at the destructive sites is re-distributed to the constructive sites [8]. The effect of the interference is to alter the share of the reflected light which heads for the detector and the remainder of which heads back in the direction of the source.

In the late 1800s, the interference pattern was obtained by using a gas discharge lamp, a filter, and a thin slot or pinhole. In one version of the Michelson-Morley experiment, the interferometer used starlight as the source of light. Starlight is temporally incoherent light, but since it is a point source of light it has spatial coherence and will produce an interference pattern [9].

3.3 Interferometry Without Delay Lines

One of the challenges to interferometry is combining light beams into matching phases using delay lines. The difficulty in this sensitive process is amplified by the costs of precision equipment used to make the necessary adjustments to the delay line. A hypertelescope (invented by Antonie Lardière, Collège de France in Paris) is an interferometer that uses no delay lines and allows for direct imaging. It is created by "densifying" the entrance aperture in order to concentrate the light, spread in secondary peaks of the diffraction pattern, in the central peak. Two hypertelescope concepts are the Carlina and OVLA (Optical Very Large Array) [3].

The Carlina concept (Figure 3) uses fixed mirrors placed on a hemispherical surface. Light coming from a star is reflected by the primary mirrors, on the sphere, and goes through a Mertz corrector (compensates for the spherical shape of the diluted primary mirror) and a densifier to enlarge the beams and increase the sub-pupil diameter. Finally, the lens focuses the beams on a single CCD camera. A simplified prototype was successfully built and tested in 2004 (by a team from the College de France) using a balloon to suspend the housing carrying the Mertz corrector, densifier, and CCD camera over two mirrors on the ground. The next step will be to use three or more mirrors arranged to fill a spherical pattern on the ground. Very large baselines can be achieved with this concept up to a few hundred meters [3].

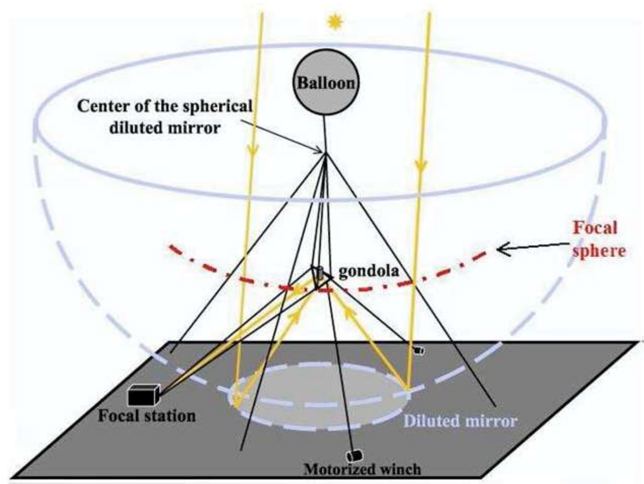

Figure 3. Optical Design of Carlina hypertelescope.

The OVLA concept (Figure 4) uses movable telescopes on a flat ground along an elliptical formation. The combiner is located on a focus within the ellipse. The movement of the telescopes during observation allows the stars to be tracked and imaged without delay lines. The important advantage is that the telescope positions can be optimized to obtain a filled output pupil which improves the dynamic range of imaging. To increase the size of the OVLA each combiner can be positioned in an elliptical formation around a central combiner as though each was a single telescope. The innovator behind this concept expects kilometric baselines to be achieved for viewing exoplanet surfaces when used in space [3].

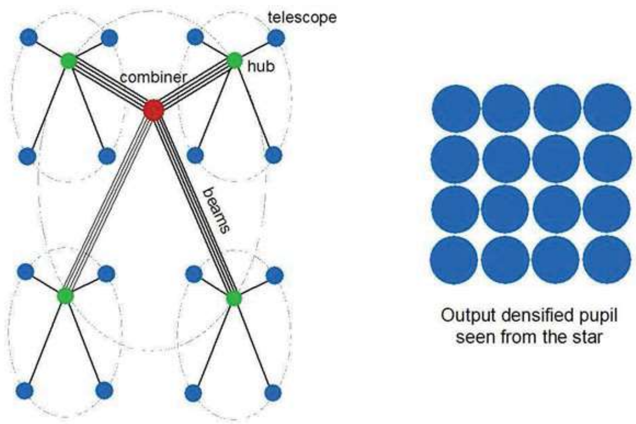

Figure 4. OVLA hypertelescope with 4 rings of 4 telescopes each.

4 Macho Mengi CAD Model

A computer-aided design (CAD) model of the Macho Mengi interferometric telescope will be created to provide a computerized two-dimensional (2D) design that will be useful for prototyping, modeling, and fabrication. The configuration of the optical and structural components will be optimized for the space environment and for successful functionality by using CAD modeling. Subsequent to the completion of the 2D model, a three-dimensional model will be rendered from it to include depth and a range of views.

CAD models allow for reproduction of early conceptual designs and rapid prototyping. They can also be used for functional analyses, including stress and thermal. Such analyses would provide useful information on the environmental effects and impacts on the telescope. Another aspect of the stress and thermal analyses would assist with proper material selection for the telescope parts.

Two- and three-dimensional CAD models provide the Macho Mengi engineers with design experience that allows them to build original models, correct flaws and perfect the design prior to the actual fabrication of the ground-based interferometric telescope. The use of CAD modeling for designing space telescopes has proven to yield significant time savings [2].

5 Expectations

After a review of the various methods of interferometry we expect to use a Fizeau type design – although interferometry without delay lines deserves further investigation. We expect to produce a device that will produce an image of its celestial target to 60% of the clarity when compared to a single telescope with a diameter the same size as the length of baseline used by Macho Mengi. Further improvements required to achieve over 80% comparable clarity will involve advanced systems such as adaptive optics systems that may inflate the costs beyond the scope of this project. It is important to note that no ground-based interferometric telescopes work "perfectly" – this is primarily due to unavoidable Earth-based conditions such as vibrations, weather, humidity, temperature, etc. This is why the vacuum and weightlessness of space is such a prized environment.

No amount of classes, books, or discussion can adequately substitute for the knowledge, understanding, and experience that Macho Mengi engineers will gain by working through the challenges of building their own ground-based interferometric telescope. Without the prototype building experience, the team will not be adequately prepared for the challenges of building a space-based version in NSBESAT 2.

This paper and all subsequent efforts derived from it, can grow into new developments for satellite use. Currently, satellites are used in a variety of ways, including Weather Satellites, Space Stations, Communication and Navigational Satellites. The future for the Macho Mengi project and modular satellites in general is ultimately giving others more access to space and beyond [10].

6 Summary and Conclusions

This paper presents a short background of astronomical interferometry and the current and future work of the NSBE Houston Space Chapter based on the original multi-satellite telescope constellation proposal by McCullar [11]. The proposal was submitted in response to a Request For Proposals released by the NSBE Space Special Interest Group in 2006 for small satellite concepts. As noted earlier, an interferometric telescope is a device that combines the light from multiple telescopes in such a way that constructive interference occurs between them causing them to act as a single large telescope. Project status and plans toward achieving the objective to build a ground-based testbed for an interferometric telescope are discussed. Members are currently working on designing phase one of the project – the table-top prototype. This phase is expected to last two to three years (starting in 2010) to develop the design, determine adequate funding amounts, fabricate and acquire components, and for final assembly and troubleshooting. The remaining phases may be completed within an additional two years. With full funding and consistent team effort the project could be finished by 2015 to 2017. This work contributes to the goal of developing the proposed Multi-Satellite Interferometric Telescope for eventual use in space.

Several types of interferometric telescopes designs were explored. The Fizeau interferometer is an image-plane based interferometer that consists of two (or more) reflecting surfaces and uses a beam splitter to bring the reference and test beams out for capture. The Michelson interferometer combines two (or more) paths from a light source directly to the detector. Two concepts of hypertelescopes were explored – a Carlina concept, which uses fixed mirrors placed on a hemispherical surface, and an OVLA concept, which uses movable telescopes on a flat ground along an elliptical formation. The Macho Mengi prototype testbed will be built based on the Fizeau type design, which provides imaging with high angular resolution, sensitivity, and field of view at visible to near infrared wavelengths and is considered stable in design. The Fizeau type was chosen due to the availability of a considerable amount of background research information including a completed design built by the NASA Goddard Space Flight Center and the University of Maryland [4]. Although the final Macho Mengi design will be very different, this detailed example will facilitate the early stages of the project.

The Houston Space Chapter is looking for volunteers, subject matter experts, funding, and research facilities. Please address any inquiries, questions, or suggestions to the NSBE HSC Chief Engineer or Macho Mengi representative at the following electronic mail address: Michael.McCullar1@gmail.com.

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