Macho Mengi (M2) – Interferometric Telescope Program NSBE STS-2013 Conference Project Report

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Abstract – *Members of the National Society of Black Engineers (NSBE) gathered for a conference at the Colorado School of Mines (January 2013) to complete the learning phase towards developing the test bed for an interferometric telescope system called Macho Mengi (means "Many Eyes" in Swahili). This test bed was built for the purpose of educating young engineers and promoting STEM career fields for students. It will facilitate ongoing research and development to build a full ground and space based observatory system. The educational benefit given to the project team will be exposure to "systems oriented" thinking, which is a critical skill needed in today's technological culture. An interferometric telescope is more of a system than it is a piece of hardware. Therefore, the design, development and testing of Macho Mengi will require a higher level of "integrated" thinking and collaboration than designing a single telescope.*

Keywords: Interferometry, Fourier transform, fringes, test bed, phase difference, systemic

1 Introduction

The pursuit of gazing deeper into space has resulted in the construction of telescopes of increasing size and complexity. Typically the aperture (diameter) of the primary optical collector (lens or mirror) determines the maximum power of that telescope. However, building increasingly larger single aperture telescopes presents challenges due to the physical and logistical limits of their design and placement. Starting with radio astronomy and later optical, scientists have continued to peer deeper into space by synthesizing larger aperture telescopes with the aid of interferometric telescopes. This technology is successfully demonstrated on the ground through several observatories (VLTI, COAST, CHARA Array).

2 Basics on Optics and Interferometry

Most of us are familiar with one of the main attributes of a telescope where the larger the diameter of the lens, the more detail is revealed about the object being observed. This is a fundamental characteristics of any optical telescope; the more light that is collected from the object, the more detail is revealed. There is a finite amount of light, or packets of photons, being emitted from the source. Collecting as much light as possible over the area of interest leads to more detailed images. The collecting area is typically limited by the diameter of the collecting mirror or aperture. In optics, the resolution of a telescope image is expressed as follows:

$$R = \frac{\lambda}{D} \tag{1}$$

Resolution is the wavelength of the object over the diameter of collecting area D.

Interferometry describes a process where waves are overlaid with the intention of extracting additional information about the waves. For an interferometer, the equation reduces to the wavelength of B, where B is the distance between the collecting devices also referred to as baseline.

$$R = \frac{\lambda}{B} \tag{2}$$

Interferometry is a method that has become widely used for the measurement of minor shifts, refractive variations and anomalies on surfaces. In analytical science, interferometry is currently being utilized in continuous wave Fourier transform spectroscopy to analyze light comprising of features of absorption or emission linked with certain material or mixture of materials. This information assists in distinguishing the features of the object(s) imaged. Astronomical interferometry involves two or more separate telescopes and merging of their signals resulting in a resolution equivalent to that of a telescope of diameter equal to the largest separation between the two individual telescopes.

Interferometry employs the principle of superposition to interface waves in a method where the combination produces a more meaningful property diagnostic than would have resulted from the original capacity of the waves. When two waves, possessing the same frequency, conjoin the culminating pattern will be determined by the phase variance between them. The waves that are in phase will experience constructive interference, while those waves that are not in phase will experience destructive interference [1].

One other means to collect more light from an object is to observe the object from a stationary position and simply collect more photons over a longer period of time. This is period of time is commonly referred to as exposure or integration time. With increased exposure time requires that the image remain stationary else a distorted image will be the results. One can observed from peering through a telescope, whether at the moon or a nearby object, that the image will be in motion. To counteract the distortion from an image in motion requires an imaging platform with active precision pointing accuracy. The conventional measure for pointing accuracy is Arc Second:

$$Arc\ Second = \frac{1}{3600}\ Degrees \tag{3}$$

Roughly, 1 Arc Second projected to the surface of the moon (~240,000 miles from Earth) would result in an arc-length of approximately 6 Feet. This level of precision pointing accuracy is achievable on stationary surfaces such as the earth but more difficult on a flying platform in space, and even more difficult as the flying platform decreases in mass.

With the basic Michelson Interferometer, the optical path from an object to a sensor is varied over a distance of a few wavelengths to create an interference pattern, which is evident at intervals of 1 wavelength of the light source. The wavelength of light in the optical spectrum ranges from 0.3 to 0.7 microns (μm), which would require varying the distance in the optical path (by mechanical means) to make the fringing pattern evident. Viewing an object through an interferometer, determining the number of fringing patterns on the image, and knowing the distance to the object, an accurate estimate of its diameter can be obtained. Other attributes of the image can be obtained from the fringing pattern through measurements of fringing contrast and position. However, the key characteristic of the interferometer is its ability to estimate the size of an object or features within the object.

2.1.1 Pre – Laboratory Lecture

Figure 1 illustrates the well-known Michelson configuration. A single beam of clear light is split into two identical beams by a beam splitter. Each beam travels a different route or path and is then recombined before arriving at a detector. The variance in path and distance traveled creates a phase difference between them. “It is this introduced phase difference that creates the interference pattern between the initially identical waves” [2]. If a single beam is split along two paths, then the phase difference is diagnostic of anything that changes the phase along the paths. This variation might be a physical change in the length of the path or difference in the refractive index along the path [1].

In Figure 2, there is a direct view of mirror M1 seen through the beam splitter, and the reflected image M'2 of mirror M2 is observed. Fringes are interpreted as the product of the interference between the beam emanating from the two virtual images S'1 and S'2 of the original source S. The features of the interference pattern depend on the nature of the light source and the exact positioning of the mirrors and beam splitter. In Figure 2a, optical elements are oriented so that S'1 and S'2 are aligned with the observer, and the consequential interference pattern consists of circles centered on the normal to M1 and M'2. If, as in Figure 2b, M1 and M'2 are tilted towards each other, the interference fringes will typically take the shape of conic sections (hyperbolas), but if M1 and M'2 overlap, the fringes near the axis will be straight, parallel, and equally spaced. If S is an extended source rather than a point source as illustrated, the fringes of Figure 2a must be observed with a telescope set at infinity, while the fringes of Figure 2b will be localized on the mirrors [1].

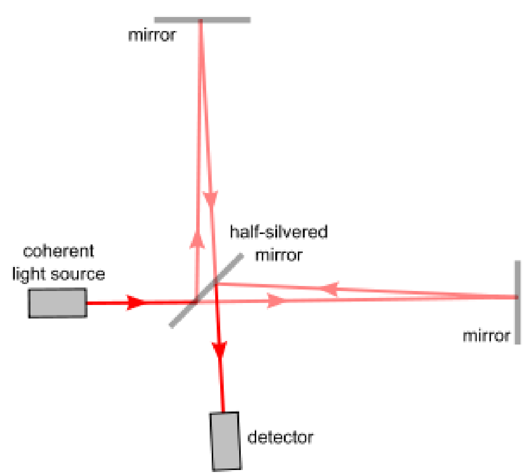

Figure 1: The light path through a Michelson interferometer [2]

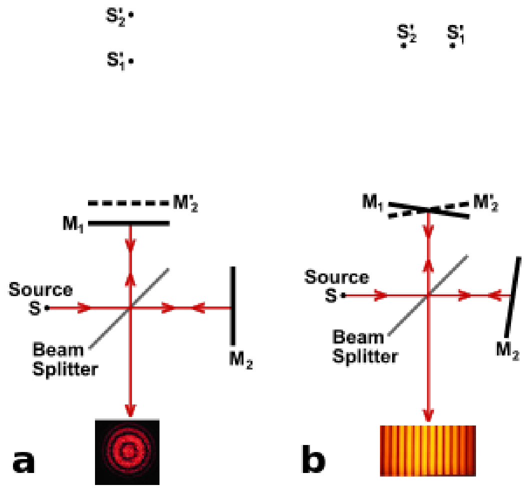

Figure 2: Formation of fringes in a Michelson interferometer [3]

Astronomical interferometry uses several telescopes or mirror segments interacting to probe structures with higher resolution by means of interferometry. This will result in the angular resolution of the instrument being close to that of a telescope with the same aperture as a single large instrument including all of the individual photon-collecting sub-components. The drawback is that it does not collect as many photons as a large instrument of that size, creating pixelated (i.e., fuzzy) images. (see Figure 3) Thus it is mainly useful for fine resolution of the more luminous astronomical objects, such as close binary stars.

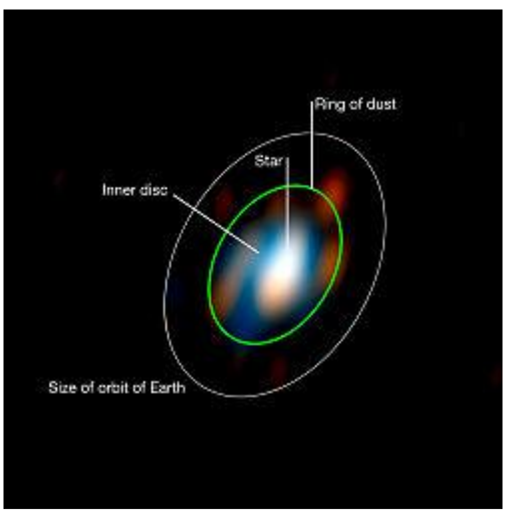

Figure 3: ESO's Very Large Telescope (VLT) takes the first detailed image of a disc around a young star [4].

3 Systems Integration

The Macho Mengi system will be used as an integrated test bed to test multiple scenarios of system configurations in an effort to select, understand, and optimize the ideal configuration for a space-based system. The final version of the test bed (i.e. Phase 4) will be a mobile platform capable of being taken outdoors for astronomy viewing as a real world test of the system's capabilities. Required sub-systems and entities include:

Optical system: The test bed must be reconfigurable to allow testing of various telescope formation arrays including testing using various types and sizes of telescopes.

Star Tracking System: To test the concepts of the guidance mechanism for the satellites, the ground units will use the same system. Star tracking systems are commonly used as pointing devices for the telescopes and satellites. Because we are dealing with an array of telescopes (satellites) each must be fixed to the same target (on command) even though their own locations (and even visibility) are vastly different. The actuating mechanism that points the telescope is a part of this complete system and must be tested with respect to using a space-based tracking mechanism.

Computing, Data, and Networking Infrastructure: Regardless of the interferometry method used, the process is data intensive. The computing network infrastructure will need to support high data transfer rates within a secure, user and maintenance friendly environment. Data storage must be robust enough to handle the quantity and integrity of data. Systems performance bottlenecks must be minimized or eliminated to provide fast response times when controlling the array and viewing images.

Stationary and Mobile Platform: The stationary platform in its basic form is an optical table useful for lab based research. The mobile platform will be designed to transport multiple telescope units together to an outdoor location, or separate telescope units to be spread out when conducting tests of extended interferometry formations.

Operations: The system will be maintained and controlled through the mission control computer(s). Each telescope can be controlled as a single unit or controlled as part of a larger array. The system screen will allow the operator to select particular arrays or individual telescopes for operations. The images formed by the system can also be displayed through the mission control center. Client logins on computers may access data or images, could possibly have control over a single ground telescope, but will not control the full telescope array.

Education and Partnerships: Students will be introduced to Intelligent Fast Failure (IFF) where they will learn the importance of failure during the design, development, and testing of systems because during operations failure is unacceptable. They will learn to work things in parallel finding out what "works" and what "does not work" as quickly as possible by climbing to the knowledge acquisition curve as quickly as possible. As a result, they will come up with an optimal design. By working things in parallel, students will learn the importance of "systemic thinking" and "systems integration" as they learn that the various components must function as an "integrated" system.

Project Management: The Macho Mengi test bed project is divided into four phases.

1. Build a simple Michelson Interferometer to learn about optics and interferometry.

2. Produce an imaging interferometer using two separate collecting mirrors (lab optics).

3. Add additional collecting mirrors to imaging interferometer.

4. Make the test bed a mobile unit. Replace collecting mirrors with telescopes and view a real target such as a galaxy or planet.

4 Construction of the Michelson Interferometer as a Teaching Tool

The goal for Phase 1 was to learn the basics of optics and interferometry while gaining hands-on experience in the process. The first objective was to build a simple Michelson Interferometer as our first hands-on model. We successfully completed this objective using LEGOs for structural support, simple 2”x2” glass mirrors, a beam splitter, and a laser pen (Class III, 530nm (green)) for the light source (see Figure 4 through 9).

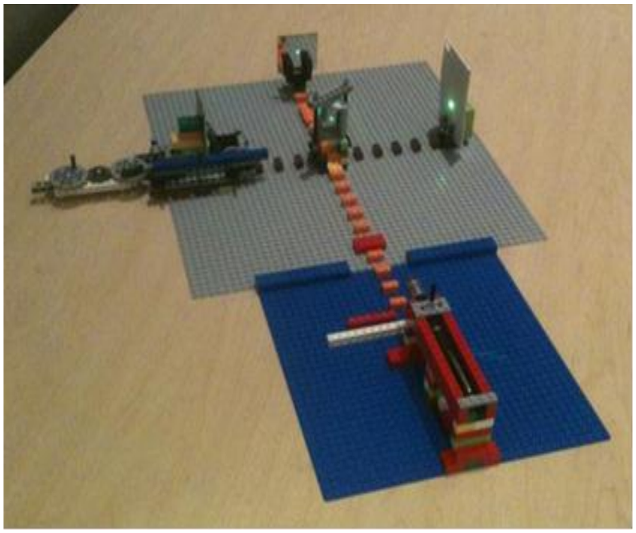

Figure 4: Michelson Interferometer Built at STS-2013

For this early stage of development the LEGOs provided a low cost means of mounting the optical components and aligning our structures in way that was easy without any tooling (see Figures 6 through 9). It took us a few hours to figure out the right combination of LEGO blocks to mount everything and achieve acceptable results. The Michelson Interferometer takes a single collimated beam of light (laser), splits the beam and uses mirrors to recombine the beam again to form a single image. This recombined image will show fringes which are interference patterns of light (see Figure 5).

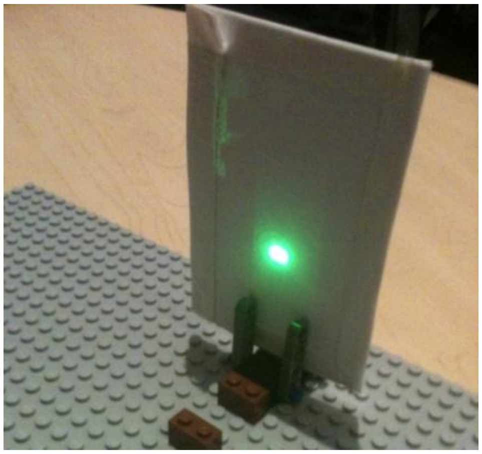

Figure 5: Fringe Patterns

Fringe patterns are used to take measurements and gather useful information related to the light source, including (for our case) reconstructing images of the original light source. With the success of building a Michelson Interferometer using LEGO’s we attempted to use the same components to build an imaging interferometer setup similar to one done at NASA Goddard Space Flight Center (GSFC). For the convenience of the reader the components are shown below (some have been rebuilt for simplicity) (see Figure 10).

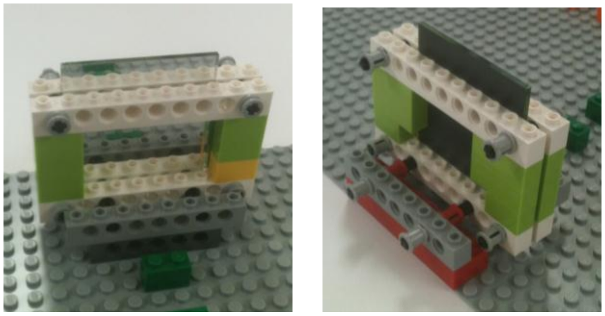

Figure 6: Front (right) and Back (left) of Sliding Mirror (modified from original build)

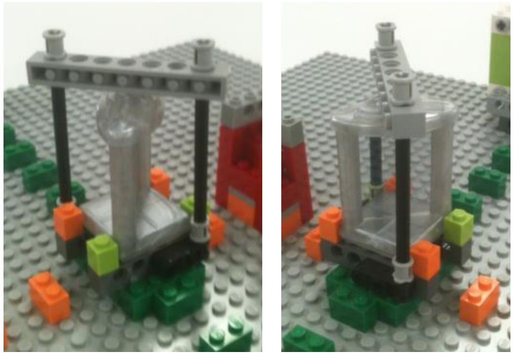

Figure 7: Beam Splitter Mount

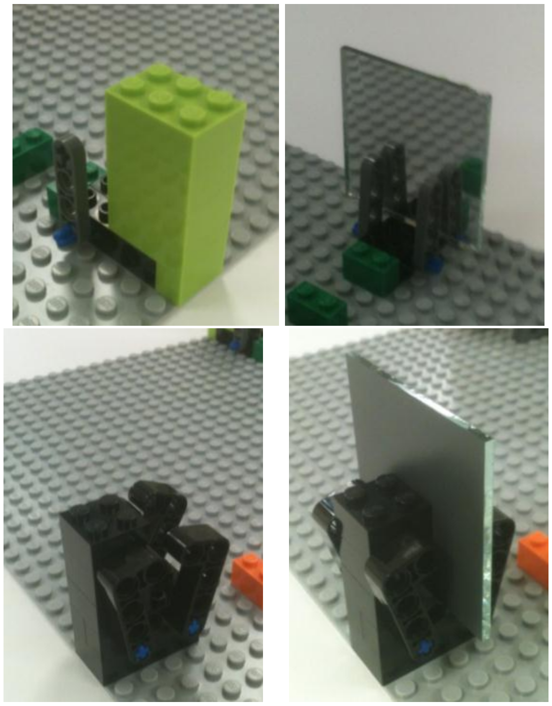

Figure 8: Simple Mirror Holder #1 (top) and #2 (bottom)

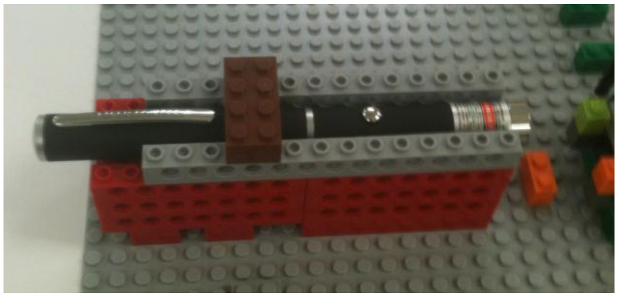

Figure 9: Laser Pen Holder

4.1 Imaging Interferometer

4.1.1 Background

Wide field mosaic imaging for optical/IR interferometry (Imaging Interferometry) is designed to expand on single-detector interferometers to see as the name implies a wider field of view. The technique makes use of the mosaic method employed in millimeter and radio astronomy, but is applicable to Michelson interferometers. As a basic principle, the technique allows the recording of fringe patterns from many contiguous telescope fields to effectively multiply the resultant field size by Image/2. There is extensive experimental work going on in this area.

4.1.2 Imaging Interferometer Test Bed

In January of 2013 at the Colorado School of Mines, the Macho Mengi project team set out to gain a better understanding of interferometry by studying the imaging experiments conducted using a Wide Field Imaging Interferometer test bed used by D. Leisawitz [5]. A diagram of the Imaging Interferometer is shown below.

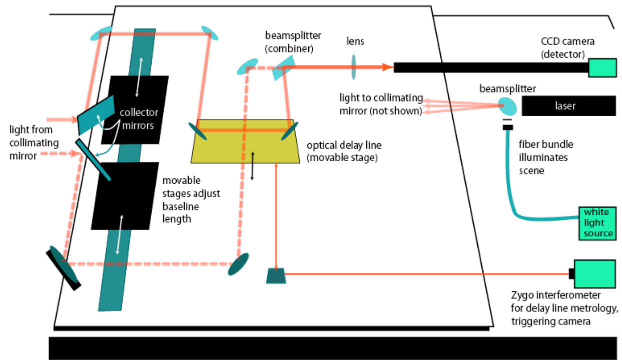

Figure 10: NASA GSFClo Wide-Field Interferometer [5]

The test bed consists of the following items: a laser that provides a light source to a collimating mirror (parabolic mirror), a beam splitter, white light source where applicable, a CCD camera detector, a lens to focus light for the CCD camera, a beam splitter (combiner), 7 optical mirrors, 2 collector mirrors to collect light from a collimating mirror, a movable stage for the collector mirrors and a movable stage for two optical mirrors to create an optical delay line [5].

The basic operation of the test bed starts with the laser light source (right of diagram) shining onto a 21-inch diameter parabolic mirror (2.4 m focal length) through a pinhole or a miniature scene. The collimated beam then returns to two collector mirrors on the opposite side of the light source. The collector mirrors are mounted on a stable rail and move on a cushion of air with very precise alignment. The baselines range from 1 mirror diameter (25 mm) to about 200 mm. The collector mirrors are of elliptical shape. The baseline rail must be perpendicular to the incident beam. The collector mirrors (flat) reflect two pieces of the wave front in opposite directions. One beam passes through and optical delay line (a pair of mirrors [flat] arranged in a rooftop configuration mounted on an air-bearing translation stage). The other beam bounces off two flat mirrors and both beams then combine through a half-reflective/half transmissive beam splitter. The beams arrive at 45 degree angles and exactly 90 degrees apart onto the half-reflective surface. The combined rays then enter a lens parallel to their optical axis and are focused on the CCD camera at 9 micrometer pitch. The scene at the focus of the collimating mirror appears on the CCD camera when either arm of the interferometer is blocked. The resolution of the image is that given by the diffraction limit of the 25 mm mirror diameter used in the interferometer. In subsequent experiments, parallel filter wheels were added between the beam splitter and the lens allowing a set of interference filters to vary bandwidth. To ultimately produce an image, there will be additional set-ups needed beyond the basic setup described here [5].

4.1.3 Macho Mengi Test Bed Set-up Results

The Macho Mengi project team attempted to replicate the set-up of the Imaging Interferometer test bed as described above. Through the set-up process, the team experienced several difficulties reproducing the basics of the set-up due to the equipment on-hand. The first difficulty came with producing light on a collimating mirror from the laser source. The team tried to construct a mirror from extra parts, but the mirror proved unsuccessful due to the fact it was undersized and did not have the proper focal length. As the team continued to set up other mirrors in the process, we noticed that the incident angle of light varied greatly from mirror to mirror. The mirrors were not of optical grade and would refract the light significantly to change the angle of light when going to the next mirror where it would miss the next mirror. The mirrors had the reflective surface behind ~2 mm of glass and led to the refracted light. Even placing the mirrors very close to one another in the set-up, was still unsuccessful. Ultimately, the Imaging Interferometer set-up replication was unsuccessful due to lack of proper equipment used in this first attempt.

In the future, the primary way to improve success at replicating the test bed set up is to acquire the proper equipment. The team has made a list of equipment items needed to work on the test bed set-up in the future. At a minimum, a collimating mirror and optical grade mirrors should give us a better chance to improve our test bed.

5 Conclusions

In the spirit of the National Society of Black Engineer's pursuit in increasing the number of minority youths that enter into STEM fields by exposing them to exciting new STEM projects and programs, the Macho Mengi team has developed a lesson plan that introduces the study of interferometry using the LEGO blocks as it relates to the imaging of very distant celestial objects. The team has since moved on to acquiring professional grade optical components to continue the project. One imaging technique that we will set out to explore is Intensity Correlation Interferometry. This technique uses multiple telescopes to image a single object to reveal features in the object that are not evident from a single telescope. The process involves capturing images from multiple telescopes, converting the images into digital form, converting each image to a spectrum of frequencies and applying intensity correlation and digital filtering techniques, fitting mathematical models to the data, and then reconstructing the image from the resulting modified spectrum of frequencies.

Acknowledgment

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