AFRL-DE-PS-
TR-2004-1020

# MAUI SPACE SURVEILLANCE SYSTEM PHASED ARRAY

**Lewis C. Roberts, Jr.**

**Boeing**
**535 Lipoa Parkway**
**Kihei, HI 96753**

**February 2004**

**Final Report**

**APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.**

**AIR FORCE RESEARCH LABORATORY**
**Directed Energy Directorate**
**3550 Aberdeen Ave SE**
**AIR FORCE MATERIEL COMMAND**
**KIRTLAND AIR FORCE BASE, NM 87117-5776**

DTIC COPY



This report has been approved for publication.

//signed//
CHARLES MATSON, DR-3
Project Manager

//signed//
DAVID L. DINWIDDIE, DR-IV, DAF
Chief, Advanced Optics and Imaging Division

//signed//
L. BRUCE SIMPSON, SES
Director, Directed Energy

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
01-02-2004

**2. REPORT TYPE**
Final

**3. DATES COVERED** *(From - To)*
30 Nov 00 – 15 Oct 02

**4. TITLE AND SUBTITLE**
Maui Space Surveillance System

Phased Array

**5a. CONTRACT NUMBER**
F29601-00-D-0204/0009

**5b. GRANT NUMBER**
N/A

**5c. PROGRAM ELEMENT NUMBER**
63444F

**5d. PROJECT NUMBER**
4868/4983

**5e. TASK NUMBER**
B3

**5f. WORK UNIT NUMBER**
BH

**6. AUTHOR(S)**

Lewis C. Roberts, Jr.

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Boeing
535 Lipoa Parkway
Kihei, HI 96753

**8. PERFORMING ORGANIZATION REPORT**

AFRL/DE 23-618

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
AFRL/DEBI (Det 15)
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
AFRL-DE-PS-TR-2004-1020

**12. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release; distribution is unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

Long baseline Interferometry is a technique where light from two or more telescopes is combined, creating interference fringes. Analysis of the interference fringes allows information to be extracted that has the angular resolution of a telescope with the diameter of the separation of the two telescopes. Since it is currently unfeasible to build telescopes with diameters of hundreds of meters, this is the only method to achieve resolutions on the order of micro arcseconds. If interferometry could be applied to space surveillance it would offer the potential for sub-centimeter resolution of low-Earth objects. This report investigates the feasibility of constructing an instrument to observe satellites and of placing that instrument at the Maui Space Surveillance System.

**15. SUBJECT TERMS**
MSSS, Phased array, optical long baseline interferometery, angular resolution

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| | | | | | Charles L. Matson |
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | Unlimited | 28 | **19b. TELEPHONE NUMBER** *(include area code)* |
| Unclassified | Unclassified | Unclassified | | | 505- 846-2049 |

**Standard Form 298 (Rev. 8-98)**
**Prescribed by ANSI Std. 239.18**

[This page intentionally left blank]

# TABLE OF CONTENTS

## LIST OF FIGURES

# 1. Summary

Long baseline Interferometry is a technique where light from two or more telescopes is combined, creating interference fringes. Analysis of the interference fringes allows information to be extracted that has the angular resolution of a telescope with the diameter of the separation of the two telescopes. Since it is currently unfeasible to build telescopes with diameters of hundreds of meters, this is the only method to achieve resolutions on the order of micro arcseconds.

If interferometry could be applied to space surveillance it would offer the potential for sub-centimeter resolution of low-Earth objects. This report investigates the feasibility of constructing an instrument to observe satellites and of placing that instrument at the Maui Space Surveillance System.

Simulations conducted as part of this paper demonstrate that it will require over 20 telescopes to create a detailed image of a satellite with an interferometer. Placing this many telescopes at the MSSS will be very difficult due to the limited available space. In addition to the 20 telescopes an interferometer requires an optical path length equalization building which for 20 telescopes with a maximum baseline of 100 meters requires a building ~100 meters by 60 meters. This will also be difficult to place at the MSSS.

If an interferometer was built at a site with more room, there is still the question whether it would be a good idea. Interferometers are very complicated optical systems and require a large number of optical elements. These optical elements reduce the throughput of light. Since only a few percent of the incoming light makes it through the interferometer, only bright objects can be observed. An interferometer does not provide a good method of imaging faint satellites such as geo-synchronous objects. The bright objects that the interferometer can image are the same objects that the AEOS adaptive optics system can image, though the interferometer would create images with much higher resolution.

Since satellites only emit at thermal wavelengths, an interferometer in the visible or near-infrared will detect reflected sunlight. This can only be done during terminator periods or during the day. Interferometery during daylight periods is possible, though it has not been extensively studied. The high background levels will pose a problem, and will further restrict the number of available targets. Interferometry at thermal infrared wavelengths is possible, and would allow for observations during the entire nighttime period, though at reduced resolution compared to observing in the visible.

The conclusion of the report is that building an interferometer at MSSS is unfeasible due to the large amounts of hardware that would required and the limited space available. Building an interferometer at another site with more room is feasible, but the instrument will only be able to observe a limited number of targets.

# 2. Introduction

Optical long baseline interferometery offers unprecedented angular resolution, unmatched by any other optical technique. If an interferometer could be used to observe satellites it would provide extremely detailed images with resolutions on the order of centimeter or sub-centimeter depending on the range of the satellite. This report studies the feasibility of using an interferometer to observe satellites and the feasibility of building an interferometer at the Maui Space Surveillance System.

The title of the report was taken from the name of the subtask, but the report does not actually talk about phased arrays. That term is normally used in the radio regime, and is usually applied to systems that are transmitting data.

# 3. Interferometery Basics

## 3.1 Interferometer Components

In the last 20 years, a number of optical interferometers have been built for astronomical observations. These instruments share many common features. First the light must be collected and then transported to the central laboratory. Once it is at the central laboratory the optical path length must be equalized and then finally the beams are interfered. The interference fringes are then analyzed. The exact analysis method depends on the goals of the observation. Images can be constructed if there are enough data points, or the morphology of the object can be studied if there are not.

Individual separated apertures collect the light from the object; this is normally done with siderealstats rather than focusing telescopes for reasons of cost. In the rest of the document, the light gathering devices will be referred to as telescopes for ease of use. After the light is collected, it is transmitted to a central laboratory. The central laboratory must first equalize the optical path length of all the beams. The light from the object arrives at the telescopes at slightly different times, and after traveling through slightly different amounts of space. This path length difference is almost always greater than the wavelength of light, so the optical path length difference must be equalized. The usual way of doing this has been to send the collimated beam from each telescope along an optical rail. A mirror moves along this optical rail, and reflects the light back. The mirror's position is adjusted so that the beams from all telescopes travel the same optical path length.

For instance, imagine a two-telescope array with an East-West baseline of 10 meters with both telescopes pointing at a star rising on the eastern horizon. The starlight will reach the eastern telescope before the western telescope, so the mirror on the eastern telescope's optical rail will have to be moved five meters, while the western telescope's mirror is put at zero meters. The mirror is placed at five meters, because the light travels to the mirror and is reflected back, making for a total travel distance of 10 meters. As the star rises, the eastern mirror will be moved to shorter distances while the western mirror is moved out. At the star crosses the zenith, the mirrors will be set at equal distances. Finally as the star sets in the West, the western mirror will be set at five meters, while the eastern mirror is set to zero meters.

Once the beams have had their path length equalized, they must be combined. This is where the actual interferometery happens. In contrast to the other aspects of interferometery, there are several different ways to accomplish this. The main driver behind these different designs is the number of telescopes in the array. Regardless of the individual design, there has to be a way of differentiating the fringes created by one set of baselines from another set of fringes.

## 3.2 Synthesis Imaging

A Fourier transform of an image consists of the phase and its modulus. If both are known, then the image can be reconstructed from a simple inverse Fourier transform, but interferometry does not sample the entire Fourier plane, which is also called the uv-plane. Instead, interferometry measures data at certain baselines. Each baseline involves the light from two apertures of the interferometer. For N apertures the number of baselines will be,

1. $$\frac{N(N-1)}{2}.$$

If there are a large number of apertures, then a high quality image can be generated from one “snapshot" observation of the source. This is only the case with the largest radio interferometers, such as the Very Large Array. More often, observations take advantage of the Earth's rotation. As the night progresses, the object will be at different positions in the sky. At each position the interferometer sees different orientations of the object, and the baselines will sample a different portion of the image during each observation. This process is called rotational synthesis.

After all the data are collected, the inverse Fourier transform is taken, but due to incomplete Fourier plane coverage there will be aliasing in the resulting image, which is often called the “dirty" image. The next step is to deconvolve the true image from the “dirty" image. There are several popular deconvolution algorithms, including CLEAN (HÖgbom 1974) and the Maximum Entropy Method (MEM) (Burg 1967, which was reprinted in Childers 1978). These techniques are fairly well developed, as the radio interferometry community has developed and used them for decades.

### 3.3 Phase Closure

Phase information is needed to create an image with synthesis imaging, but in optical interferometry measurements of phase for a given baseline are corrupted by atmospheric turbulence. It is possible to measure the closure phase for each independent triangle of baselines, $b_{12}$, $b_{23}$ and $b_{31}$ formed by three apertures, $A_1$, $A_2$ and $A_3$ (Jennison 1958). The observed phase from each baseline will be $J_{12}$, $J_{23}$ and $J_{31}$, while the true phases will be $j_{12}$, $j_{23}$ and $j_{31}$. The phase errors for each aperture will be $\Delta_1$, $\Delta_2$, and $\Delta_3$.

Thus,

$$
\begin{aligned}
&J_{12} = j_{12} + \Delta_1 - \Delta_2 \\
2.\quad &J_{23} = j_{23} + \Delta_2 - \Delta_3 \;. \\
&J_{31} = j_{32} + \Delta_3 - \Delta_1
\end{aligned}
$$

The closure phase, $\Psi_{123}$, is the sum of the observed phases,

3. $\Psi_{123} = J_1 + J_2 + J_3$ .

If Equations 2 are substituted into Equation 3, then the phase error terms cancel out resulting in,

4. $\Psi_{123} = j_{12} + j_{23} + j_{31}$ .

For an array with N elements, there are,

5. $\frac{N}{2}(N-1)-(N-1)$,

independent closure phases. This is compared to the number of baselines given in Equation 1. There is not a one-to-one relationship, which makes reconstruction more difficult. The National Radio Astronomy Observatory software package, AIPS++ *(http://aips2.nrao.edu/docs/aips++.html*), has been configured to deal with this problem, and it is widely used both on radio and optical data.

## 4. Telescopes

Siderealstats have been used by most early interferometers, because they are inexpensive and easy to manufacture. One reason for their inexpensiveness is that they are normally small, usually less than half a meter in diameter. The reason for the small size is that an interferometer can only successfully combine a beam that has a diameter on the order of the Fried's parameter. In the visible this is usually only 10-20 cm. Newer arrays such as the Keck Inteferometer or the Very Large Telescope Interferometer are using 8-10 m diameter telescopes. They can do this because they plan on using adaptive optics to make the effective Fried's parameter larger. They are also observing in the infrared where the Fried's parameters are on the order of meters.

Telescopes used in interferometry need to be of very high optical quality to preserve the incoming wavefront. The telescope mounts need to be very rigid to minimize any transmitted vibrations. Also to remove vibrations, they are normally put on large inertial slabs, usually made of concrete. Vibrations will disrupt the interferometric fringes, and prevent observations of the intended target.

The driver behind the choice of siderealstats or telescopes is the diameter of the mirrors. This depends on the objects to be looked at and the observation wavelength. There is no fundamental problem with using either. Since interferometer optics are mounted on inertial slaps to reduce vibrations; this would preclude positioning telescopes on existing buildings as was done with the Raven telescope.

## 5. Beam Transport

To date, interferometers have used beam tubes to transport the incoming light from the telescope to the central laboratory. Light from the telescope is collimated and reflected down a long pipe. The pipe minimizes air turbulence by preventing wind from disturbing the beam. Also for visible the tube needs to be evacuated, otherwise the air will add so much dispersion that it will make it impossible to successfully interfere the various beams. For infrared light, the beam tube may or may not need to be evacuated depending on the length of the beam tube.

This method will not work at MSSS because these tubes would have to run through existing buildings. An alternative method is to use fiber optic cables. While this has not been implemented at any working observatory, it is being used in several beam combiners and is being examined for use in the OHANA instrument on Mauna Kea on the island of Hawaii. The fiber optics would need to be single mode fibers which preserve polarization and only transmit a narrow waveband. Multimode fibers disrupt the beam too much, preventing proper beam combination. Single mode fibers have very small cores, on the order of several microns. This small size requires very precise optics to couple the incoming beam to the fiber. Even with the best optics, normally about 50% of the incoming light is lost.

## 6. Optical Path Length Equalization

The first component of the central laboratory is an optical path length equalization (OPLE) system. The standard method of this is to have motorized carts with reflective optics move along optical rails as the science object moves across the sky. This is used in almost all of the optical interferometers operational today.

These carts are typically several feet across and there has to be one for each telescope. There also needs to be space between the carts for personnel to maintain and align them. If horizon-to-horizon observations are going to be made the length of the building needs to be at least half the size of the longest baseline. If the instrument will only observe objects near zenith, then the building can be made shorter. Additionally, some room for optics and equipment will be needed. The building needs to be as close to the telescopes as possible to minimize light loss in the transport fiber optics. Traditionally it has been located at the center of the array.

The OPLE from the CHARA Array on Mt. Wilson, California is shown in Figure 1. The figure is from the CHARA web site (*http://www.chara.gsu.edu/CHARA/*) . This building is big enough for eight telescopes. Great care has been taken to reduce vibration. The sleeper rails, which support the optical rails, weigh over 80 lbs and the concrete piers that they rest on are mounted on concrete pads several feet thick. You can see the details of the sleeper rails on the rightmost delay line, which has been left empty until more telescopes are built.

The beam goes through air, and suffers dispersion, on a long baseline like the CHARA array ; this can be extensive. This is removed through longitudinal dispersion correctors. Alternatively the delay lines can be done in a vacuum, which eliminates dispersion, though this is costly and add complications.

The building housing the CHARA OPLE is constructed to eliminate thermal drifts. It is actually two buildings inside of one another with an air gap of several feet. The air gap is conditioned to maintain a set temperature. During normal operations, the lights are turned off and personnel do not enter the inner building for long stretches at a time.

Placing a beam combining facility on the MSSS is extremely difficult. An array of 25 telescopes with a maximum baseline of 100 m requires a building ~100m wide and ~60m long. This would require demolishing existing buildings or building underground. Also the construction of such a large building, could easily affect the seeing conditions of the site.


**Figure 1 11** The inside of the OPLE building of the CHARA Array. On the left are six sets of optical delay lines. The inset shows one of the delay line carts. The right most pier has been left empty, until additional telescopes are built.

## 7. Observational Wavelength

The choice of which wavelengths to use is an important one. As with much of high angular resolution astronomy, interferometry is easier at longer wavelengths. The tolerances in interferometry are based on the wavelength of the light, so longer wavelengths result in lower tolerances, which reduces costs. Additionally, at longer wavelengths the atmospheric turbulence has less of an effect.

Still, there are valid reasons to use visible wavelengths. The minimum resolved angle is proportional to wavelength, so visible observations have a higher angular resolution than infrared observations. Additionally optical coatings are usually easier to make for the visible. Some instruments actually observe simultaneously in optical and the infrared. If the object is assumed to be the same in both wavelengths, they can use the additional data to help fill in the uv-plane. If the object appears different in various wavelengths, then simultaneous images can be produced.

Observations of satellites bring up issues that astronomical instruments do not have. Earth orbiting satellites are usually seen in reflected sunlight, which peaks in intensity in the visible. These objects can only be imaged while illuminated by the Sun. During nighttime, this is only a few hours before sunrise and after sunset. Very little long baseline interferometry has been done in daylight. It should be possible, but it will have to look at brighter targets than at night due to the high background levels.

Satellites do self-emit at thermal infrared wavelengths. An interferometer could image at 10 µm, which would allow operations during the entire nighttime period. Currently single mode fiber optics for use at thermal wavelengths are just starting to be developed by the telecommunication industry, so the beams would need to be transported via optical tubes, which are incompatible with the existing MSSS buildings.

## 8. Magnitude Limit

It is hard to determine the exact magnitude limit of a potential interferometer with out knowing the exact design. The limiting magnitude depends on the size of the telescope apertures, the observational wavelength and the exact optical design of the instrument. Existing visible instruments have magnitude limits about seventh magnitude in the V-band (Turner private communication). The major problem with interferometers is the large number of reflections required; typical throughput is a few percent.

Using bigger apertures can extend the magnitude limit, but interferometry needs apertures on the order of the Fried's parameter, otherwise the visibility is reduced. Adaptive optics (AO) can increase the effective Fried's parameter by correcting aberrations in the incoming wavefront. It does this by directing a portion of the incoming light to a wavefront sensor, which measures the aberrations. These measurements are fed into a deformable mirror, which corrects the aberrations.

No AO system perfectly corrects the incoming light. A measure of how close a system comes is the Strehl ratio, which is 1.0 for a perfect system, and usually below 0.01 for uncorrected systems . Strehl ratio is related to the phase by,

6. $S \cong \exp(-s)^2$,

where $s^2$ is the variance of the phase of the incoming beam. Low Strehl ratios produced by an inadequate AO compensation will lead to increased variance in the incoming phase and reduced image quality. To achieve high Strehl ratio requires either an extremely high order adaptive optics system for visible system or working in the infrared. The AEOS AO system currently produces a Strehl ratio of about 0.2 in at 0.8 µm with 941 actuators (Roberts & Neyman In Preparation). The Lick Observatory AO system mounted on the 3.0-m Shane telescope currently produces Strehl ratios about 0.5 at 2.2 µm with only 127 actuators (Oliver et al. 1995). The Keck Interferometer became the first interferometer to combine AO and interferometery when it recorded first fringe in March of 2001. The system was working in the near-IR bands of H and K.

## 9. Simulations

Simulations were run in order to determine the number of telescopes required to properly image a complex satellite. These simulations are somewhat crude. The simulations assumed all the telescopes of the MSSS are the same size and the incoming light was monochromatic. Optical interferometery is unable to measure absolute phase of the incoming light due to atmospheric distortion. Instead closure phase is measured. The simulations ignored this point. Also the simulations did not include noise. The main point behind the simulations was to determine an approximate number of telescopes that are required, not to simulate the results from an actual interferometer.

In the simulations the autocorrelation of the telescope pattern is applied as a filter to the fast Fourier transform (FFT) of the image. An inverse FFT is then applied to the sampled image. This produces the dirty image. The dirty image has a great deal of aliasing, due to the incomplete sampling of the Fourier plane. The CLEAN deconvolution algorithm was applied to the dirty image.

The CLEAN algorithm was created by Högbom (1974). The technique as summarized by Cornwell and Braun (1994) is:

1) Identify the maximum point in the dirty image. Record the value and location of this point in the clean image.
2) Subtract the dirty beam multiplied by the maximum value of the dirty image and a damping factor from the dirty image.
3) Repeat steps 1) and 2) until a user defined threshold is reached.
4) Convolve the accumulated point source model with an idealized clean beam. The clean beam is normally an elliptical Gaussian fitted to the central lobe of the dirty beam.

A simplistic version of CLEAN created by Bagnuolo (private communication) was used to deconvolve the dirty images.

The simulations assumed that the images had to be acquired in snapshot mode. Astronomers can image the same object at different positions on the sky, which helps fill in the uv-plane. Unfortunately, most satellites change their aspect as they move across the sky. So an interferometer intended to image satellites needs to work in snapshot mode.

The object used in the simulations is shown in Figure . Figures 3-7 show the results for different numbers of telescopes. Each figure consists of four sub-figures. The upper-left sub-figure is of the locations of the telescopes used in the simulation. The telescopes were placed in somewhat of a random fashion, but care was taken to avoid placing telescopes in the parking lot or in other buildings. The upper right sub-figure is the autocorrelation of the telescope locations. The lower left figure is the dirty image, while the lower right figure is the clean image.

The conclusion drawn from the simulations is that on the order of twenty telescopes are required to produce high quality images of satellites. The exact number would depend on where exactly the telescopes are placed and what type of objects the interferometer would be optimized to image.

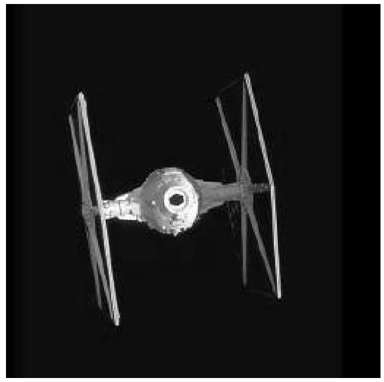

**Figure 2** This is the object that the simulations are based on.

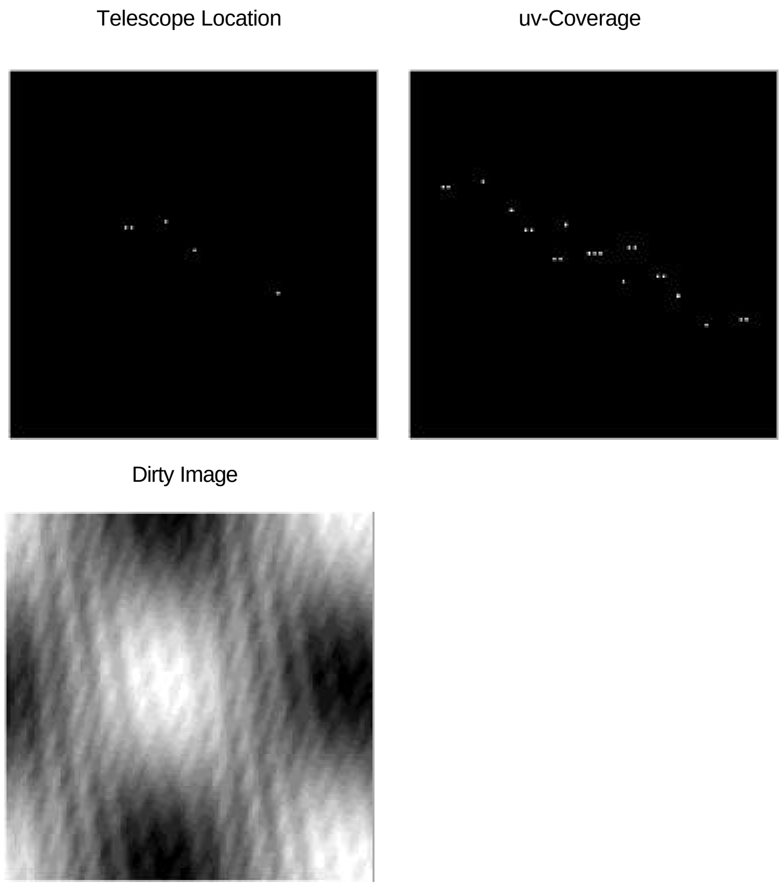


**Figure 3** These figures show the results for the existing MSSS telescopes: AEOS, 1.6-m, 1.2-m and BDT. The 1.2-m has two telescopes. There is no CLEAN image, because the dirty image is so poor.

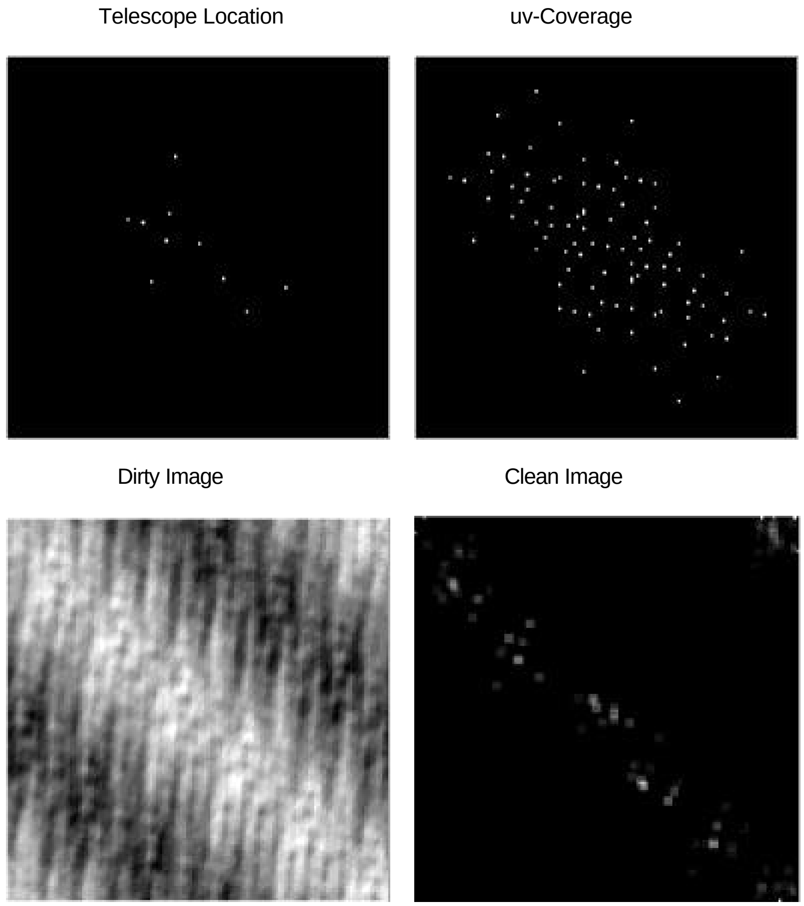


**Figure 4** These figures show the results for the existing MSSS telescopes: AEOS, 1.6-m, 1.2-m, and BDT and four other telescopes placed around MSSS.

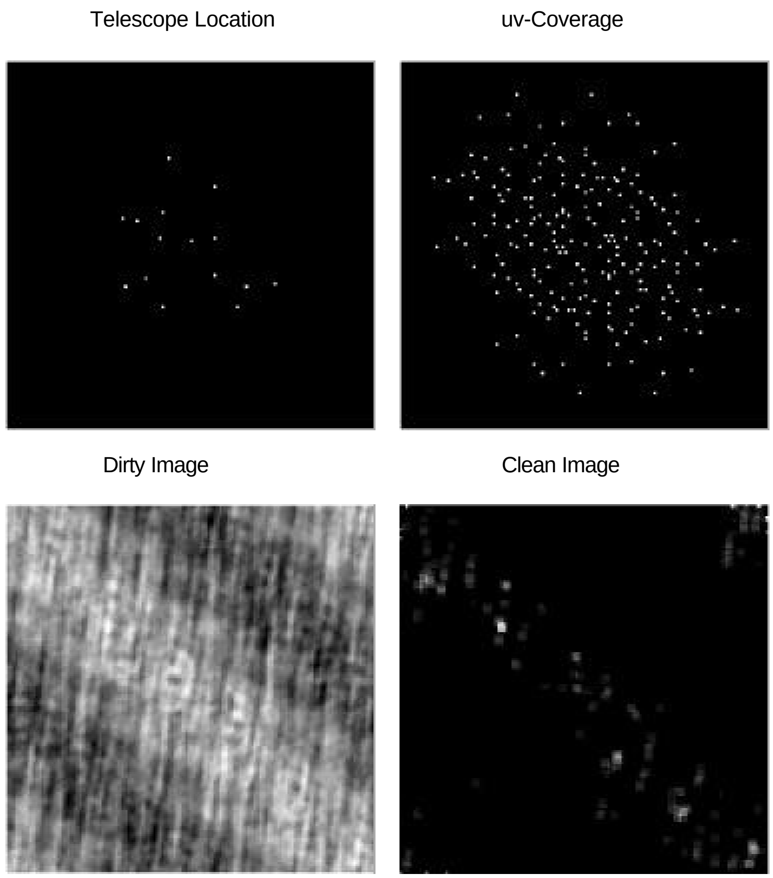


**Figure 5** These figures show the results for the existing MSSS telescopes: AEOS, 1.6-m, 1.2-m, and BDT and ten other telescopes placed around MSSS.

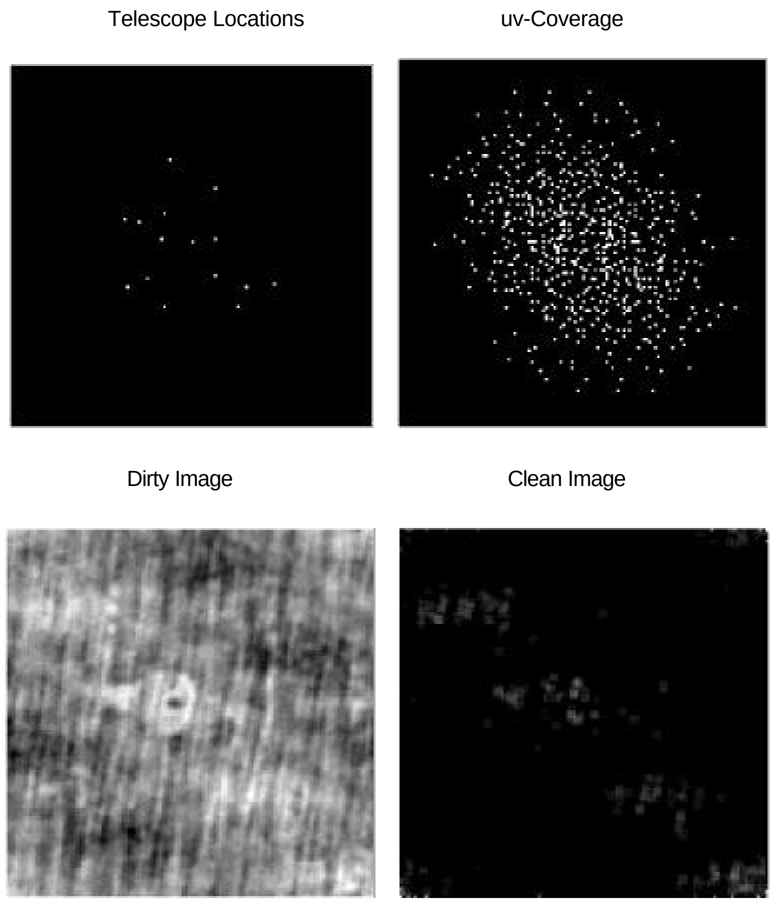


**Figure 6** These figures show the results for the existing MSSS telescopes: AEOS, 1.6-m, 1.2-m, and BDT and 15 other telescopes placed around MSSS.

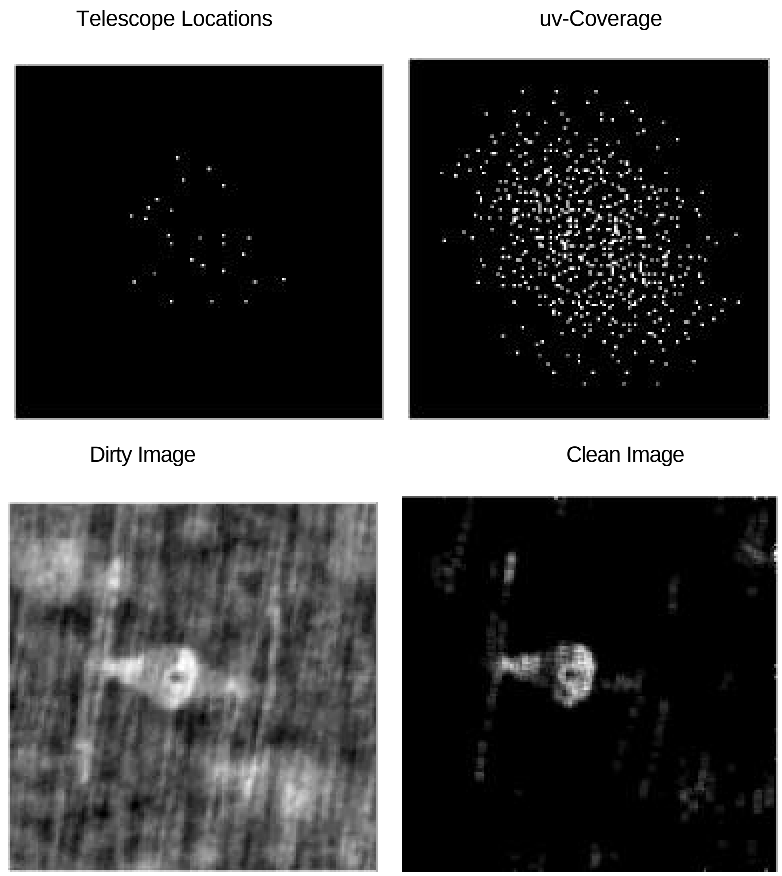


**Figure 7** These figure show the results for the existing MSSS telescopes: AEOS, 1.6-m, 1.2-m, and BDT and 21 other telescopes placed around MSSS.

## 10. Other Uses of Interferometry

Building an interferometer to image satellites appears to be a large, difficult, and expensive task. There are other possible uses for an interferometer that may interest the Air Force. Much like astronomers do not require images to perform science, it may be possible to extract valuable information on satellites, without doing a full image reconstruction. This would require fewer telescopes and be more affordable.

Visibility is a measure of the fringe contrast; as defined by Michelson (1891) it is,

$$7.\ V = \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})}.$$

The visibility is 1.0 at all baselines for a monochromatic point source; the visibility of an extended source decreases at longer baselines.

The visibility response of an interferometer at a baseline, $d$, to a single star, where the star has been assumed to be a uniform disk, is

$$8.\ V^2(d) = \left[\frac{2J_1(pJ_D d / l)}{(pJ_D d / l)}\right]^2,$$

where $J_1$ is the first order Bessel function, $J_D$ is the angular diameter of the star, and $l$ is wavelength. Visibility squared is often used rather than visibility because it is a positive quantity. The one-dimensional response to a binary star is the sum of two single stars.

$$9.\ V^2(d) = \frac{1}{1+R^2}\left[R^2V_1^2(d) + V_2^2(d) + 2RV_1(d)V_2(d)\cos\left(\frac{2pdJ_s\cos\Psi}{l}\right)\right],$$

where R is the intensity ratio of the two stars, $V_1^2$ and $V_2^2$ are the responses for each star as given in Equation 7, $J_s$ is the angular separation of the two stars and $\Psi$ is the angle between the line joining the two components and the baselines.

Equation 8 is only useful for linear arrays such as the Intensity Interferometer (Hanbury Brown 1974) or the Sydney University Stellar Interferometer (Davis 1994). For non-linear arrays the equation most be modified by allowing the projected baseline, $\Psi$, to become a variable,

$$10.\ V^2(d,\Psi) = \frac{1}{1+R^2}\left[R^2V_1^2(d) + V_2^2(d) + 2RV_1(d)V_2(d)\cos\left(\frac{2pdJ_s\cos\Psi}{l}\right)\right].$$

The derivation of the visibility functions for other shapes is fairly simple. In an analogous way, we could build visibility functions for various objects that represent satellites, for instance squares or combinations of squares. Of course the more complicated the model, the more baselines that will be required to determine one model from another. The measurement of stellar diameters is also helped in that the object is circularly symmetric, so it doesn't matter what the orientation of the object is to the interferometer.

An example of visibility fitting is shown in Figure . The figure combines data from the CHARA Array and the FLUOR instrument (ten Brummelaar et.al. 2001). FLUOR is the Fiber Linked Unit for Optical Recombination, that is located at the Infrared Optical Telescope Array (IOTA). The curves are different models for the appearance of the star, RS Cancri. One model is a uniform disk, while the other model shows limb darkening due to the spherical nature of the star. By observing at different baselines, they are able to determine that the star is best modeled by a limb-darkened model. If there were additional data beyond the first null, then the exact amount of limb darkening could be determined. These observations assume the star is circularly symmetric, which is a fairly good assumption for most stars.

It is also necessary to properly design the interferometer to observe the desired targets. The FLOUR instrument with its shorter baselines was unable to differentiate between the two models. Also if the baselines were too long, the object would be over resolved. The data points would at baselines where the visibility is very small, and the scatter of the data is bigger than the difference between the two models.

A problem with doing this technique at the MSSS is that if an object is bright enough to observe with an interferometer, than it is probably bright enough that another technique such as adaptive optics or speckle interferometery could image the satellite. Objects that those techniques cannot resolve tend to be faint also.

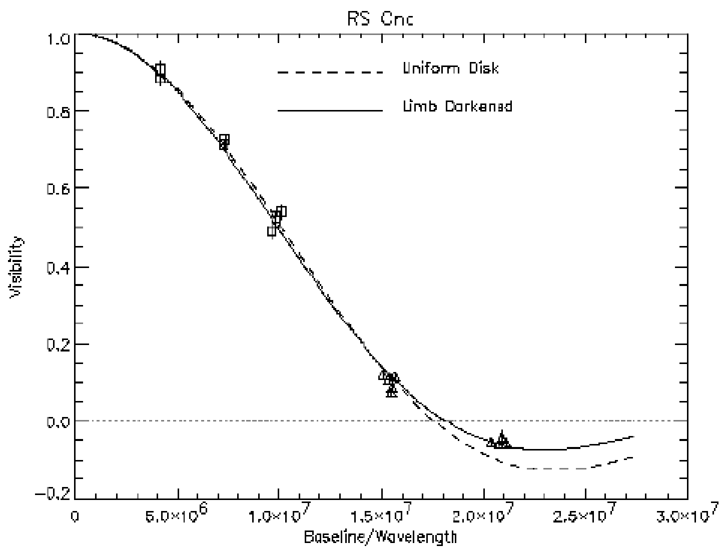


**Figure 8** This plot is a combination of data from the FLUOR instrument (Squares) and the CHARA data (Triangles). The points in the first lobe show evidence for limb darkening (ten Brummelaar et al. 2001).

## 11. Radio Interferometry

This report has focused on optical interferometry because that is the wavelength that the MSSS has traditionally observed at, but there are other forms of interferometry. While the first interferometric experiments observed at optical wavelengths (Michelson 1890), the first practical long baseline interferometers observed in the radio regime. Many of the details of interferometry are much simpler at radio wavelengths.

The Very Large Array (VLA) in Soccoro New Mexico is a 27-element array that has been operational since 1980. On the other hand, optical interferometry is still in its infancy. The Infrared-Optical Telescope Array (Dyck et al. 1995) and the Cambridge Optical Aperture Synthesis Telescope (Baldwin et al. 1996) are the only two arrays with three telescopes operational. The Naval Prototype Optical Interferometer (Benson et al. 1997) and the CHARA Array (ten Brummelaar et al. 2001) are both partially completed and will have six telescopes when complete. It is a long way from these facilities to a 25 element optical array.

A radio interferometer could operate 24 hours a day and is much less likely to be affected by weather. Radio waves are also much less affected by the atmosphere, although this gets worse at the shorter wavelengths. The instrument would need to have the target illuminated by radar to provide enough signal to the interferometer. This seems fairly reasonable, since radar is commonly used to track satellites, though the required power level is unknown. It would probably require one tracking radar, and one illuminator radar. Also the entire beam transport and beam combination systems can be done with electronics, which are fairly compact.

One of the disadvantages of radio interferometry, is that radio waves have much longer wavelengths, which produces a lower resolution. Using a one-millimeter wavelength would require a 50 km baseline to produce a resolution of one centimeter at 1000 km range. To achieve the same resolution with 900 nm light only a 45 m baseline is required. A radio interferometer is not feasible on Haleakala, both due to the topographical constraints and the high levels of radio emissions from the nearby radio transmitters. It is something that could be built in the deserts of New Mexico or in another large flat area. Such large baselines are not very difficult for radio interferometry. The Very Long Baseline Array has baselines that run from the U.S. Virgin Islands to Hawaii. In recent years orbiting radio telescopes have been tied into ground based telescopes to make an interferometer that has baselines larger than the Earth.

Radio telescopes can also be moved with little difficulty, so the array configuration could be modified to image different classes of satellites. More compact arrays are useful for imaging large satellites. Another advantage is that there is a large pool of people trained in building radio interferometers. Currently there is a great deal of research in optical interferometry, which makes for a competitive job market.

## 12. * MERGEFORMAT Conclusion

Constructing a long baseline interferometer at the site of the MSSS is unfeasible. The main problem is that an interferometer will take up a great deal of room, and there is little free space available. An interferometer could be built at another less developed site. A prospective site should have excellent seeing and be fairly flat. The observable number of targets will depend on the design of the instrument and may be too small to make the instrument cost effective.

There are no immediately apparent technical problems that would prevent an interferometric array from being built with twenty or more telescopes. While the current state-of-the-art interferometers are only using a handful of telescopes, large arrays are under consideration (Ridgway private communication). An idea that was discussed, but not studied is the idea of mounting several optical telescopes on a large steerable mount such as a radar dish. The mount would be pointed at an object, and the individual telescopes would all have the same optical path length. This would eliminate the need to have a large optical path length equalization facility. A small amount of path length equalization would still be necessary, as a large mount would have considerable flexure and vibration.

## Referenced Documents


Baldwin, J. et al. 1996, A&A, 306, L13

Benson, J.A. et al. 1997, AJ, 114, 1221

Brown, H.R., Davis, J., & Allen, L.R. 1967, MNRAS, 137, 375

ten Brummelaar, T.A. et.al. 2001, 198$^{th}$ AAS Meeting

Burg, J.P. 1967, Proc. Of the 37$^{th}$ Meeting of Society of Exploration Geophysics

Childers, D.G. 1978, Modern Spectrum Analysis, IEEE Press, 34

Cornwell, T., & Braun, R. 1994, Astronomical Society of Pacific Conference Series, 6, 167

Dyck, M.B. 1995, AJ, 109, 378-382

Jennison R.C. 1958, MNRAS, 118, 276

HÖgbom, J. 1974, ApJS, 15, 417

Michelson, A. A. 1891, Nature, 45, 160

Oliver S.S. et al. 1995, Proc. SPIE, 2534, 26

DISTRIBUTION LIST

| | |
|---|---|
| DTIC/OCP<br>8725 John J. Kingman Rd, Suite 0944<br>Ft Belvoir, VA 22060-6218 | 1 cy |
| AFRL/ VSIL<br>Kirtland AFB, NM 87117-5776 | 1 cy |
| AFRL/ VSIH<br>Kirtland AFB, NM 87117-5776 | 1 cy |
| Official Record Copy<br>AFRL/DEBI/Charles Matson | 1 cy |
| AFRL/DES/Bob Fugate<br>Kirtland AFB, NM 87117-5776 | 1 cy |
| AFRL/DEBS/ Victor Gamiz<br>Kirtland AFB, NM 87117-5776 | 1 cy |

[This page intentionally left blank]