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DEVELOPMENT OF INFRARED PHASE CLOSURE
CAPABILITY IN THE
INFRARED-OPTICAL TELESCOPE ARRAY (IOTA)

Grant NAG 5-4900

Final Report

For the period 1 May 1997 through 31 December 2001

Principal Investigator

Dr. Wesley A. Traub

February 2002

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NASA Headquarters

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FINAL REPORT AND ANNUAL REPORT No. 5
For the period 1 May 2001 through 31 December 2001

Principal Investigator: Wesley A. Traub

February 9, 2002

Abstract

Background NASA awarded grant NAG 5-4900 to the Smithsonian Astrophysical Observatory (SAO) in 1997, to support the implementation of a third telescope and phase-closure capability at the Infrared-Optical Telescope Array (IOTA). Funds were requested only for equipment. The SAO agreed to provide a comparable level of support in the form of additional equipment, personnel, travel, transportation, and other on-site infrastructure costs. The total value of the grant award was \$297K; the third installment of \$110K was received in July 1999, thereby fully funding the grant. We have now successfully completed work on this grant. The first four annual reports covered our progress from 1997 to early 2001, including the commissioning of the third telescope itself. In this final report we cover only the remaining period from early 2001 through the end of 2001. Interim annual reports are attached as Appendices 1-4. A photo of the exterior of the IOTA array is shown in Appendix 2.

1 Progress during 2000-2001

We completed all major fabrication and testing for the third telescope and phase-closure operation at IOTA during this period. In particular we successfully tested the phase-closure operation, using a laboratory light source illuminating the full delay-line optical paths, and using an integrated-optic beam combiner coupled to our Picnic-detector camera. This demonstration is an important and near-final milestone achievement. As of this writing, however, several tasks yet remain, owing to development snags and weather, so the final proof of success, phase-closure observation of a star, is now expected to occur in early 2002, soon after this report has been submitted.

For detailed reports on individual aspects of the third-telescope project, the reader should also consult the list of 32 non-refereed papers and presentations at the end of this report, as well as the list of 11 refereed publications during this approximate reporting period.

People working on IOTA, and contributing directly or indirectly to this report, include Angela Ahearn, Jean-Philippe Berger, Michael Brewer, Nathaniel Carleton, Marc Lacasse, Rafael Millan-Gabet, John Monnier, Costas Papaliolios, Michael Pearlman, Ettore Pedretti, Sam Ragland, and Wesley Traub.

2 Control System

Integration and checkout of the new control system has been a major activity during the period. Since all aspects of the system - interface hardware, computer hardware, and software - are new to IOTA, a great deal of work has been necessary. The system is now capable of governing all of the elements of IOTA, including telescopes, delay lines, star trackers, mirrors in the relay path, and detectors. The operations controlled are star acquisition and subsequent tracking, delay acquisition and subsequent tracking of the zero-path-difference points, fringe scanning (by piezo-driven mirrors), detector readout, and data handling, including quick-look display and storage. Overall logistical functions include setting up a target list and observing program, providing for appropriate calibration observations, generating an observing log, and setting up complete header information for data files, with proper archiving. These functions are operating fairly reliably now, though there is still an ongoing effort to fix such bugs as continue to be revealed in the software, and to improve convenience as may seem necessary.

3 Beam Combination

We have employed four new beam-combination set-ups at IOTA during this period, as well as maintaining the FLUOR system for two-beam interference measurements in the K (2.2-micron) band, using fluorite single-mode fibers.

3.1 Two-beam Integrated Optics Combiner

The first new trial was of a two-beam integrated-optics (IO) beam combiner, fed by single-mode optical fibers, operating in the H band at 1.65 micron.

In collaboration with the Laboratoire d'Astrophysique de l'Observatoire de Grenoble we installed and successfully used an IO beam combiner at IOTA in November 2000. IO technologies, very similar to micro-electronics lithography, allow us to integrate single-mode waveguides in or on a substrate. It is therefore possible to integrate in a single chip complex instruments such as beam combiners. This work is an important step towards more complex combinations schemes aimed at combining up to eight beams.

The beam combiner was made of two single-mode fibers feeding an IO chip with two inputs and four outputs, two interferometric channels and two photometric channels. It was operated mainly in the H band (1.65 microns) but also successfully tested in the K band (2.2 micron). The optical interface allowed us to acquire the two beams coming from the interferometer and to send them to the IO beam combiner. A scanning mirror temporally encoded the fringe pattern and the IO beam combiner output was imaged onto the NICMOS detector.

Two different beam combiners using two different IO technologies were tested (called LEMO and LETI). The experiment was very successful. We recorded high quality interferometric fringes and we could observe several Mira stars. We demonstrated that visibility measurement was much more accurate than with a classical beam combination scheme.

3.2 Asymmetric Fiber Combiner

Second was again a two-beam trial of a single-mode-fiber beam combiner, operating at a shorter wavelength (0.8 micron), using commercially available fiber coupler components. The idea here is to use a 90% - 10% (reflecting - transmitting) fiber coupler as a beam combiner, after the light from each telescope has been injected into the single-mode fiber. The asymmetry of combination allows one to estimate the time-varying coupling efficiency into each fiber, caused by residual atmospheric tilt variations, and therefore permits a first-order correction for this variation. The technique only works with couplers that are not 50% - 50%.

The experiment was successful on a bright Cepheid, using a 50-50 coupler to start, and leading to the first sky fringes on a Cepheid in the visible. We now wish to observe fainter Cepheids. To do this, we need to replace our current optics which send a fraction of each input beam to the star tracker. The new optics will have a high transmission in the band around 0.8 micron, and will therefore feed all of this light to the asymmetric coupler and thence the science detector, with the balance of the spectrum going to the star tracker.

3.3 Three-beam Integrated Optics Combiner

Third was a trial of a complete three-beam integrated-optics combiner with single-mode fiber feed and read-out, again operating in the H band. We extended the previous IO combining concept to 3-beam correlation.

We tested a three-way pairwise beam combiner. This beam combiner (operating in the H band) was made with 3 single-mode fibers feeding a LETI chip with 3 inputs (one per telescope) and 6 outputs (each containing an interferogram from a pair of telescopes). The photometric channels were not included based on the consideration that photometric unbalance correction could be achieved with simple algebraic manipulations of the interferometric signals.

The optical interface feeding the chip is a much-improved version of the 2-beam experiment. It includes better focusing optics and the ability to dynamically center the fiber position to improve starlight coupling into the combiner. Two new piezo-driven scaning mirrors allow us to temporally encode the fringes on a non-redundant scheme in order to record simultaneously three fringe pairs. The scanning was synchronized with the fringe acquisition. Eventually the coupling optimization will be totally controlled by the system making the observation more automatic.

We successfully recorded simultaneous internal laser diode fringes on three baselines. The closure phases extracted from that experiment showed the good stability of the combiner. We then successfully recorded starlight fringes between telescope North (A) and South (B). We are very close to measuring phase closure with starlight, using telescopes A, B, and West (C). It is now just a question of getting some good weather and looking for them.

3.4 Free-space Combiner

Fourth was a free-space, Michelson-type combination scheme wherein the beam from each telescope is split and the resulting six beams are interfered pairwise. As output, then, we have three beams from one side of the beam combiner, AB, BC, and CA, and their complements BA, CB, and AC, from the other side. We considered relaying these beams to individual elements on the PICNIC detector by simple mirror reflections, and designed a viable scheme for so doing, but this seemed cumbersome. We therefore decided to focus each output beam onto a fiber, using off-axis paraboloids, and then to bring the other ends of the fibers into a tight linear array which could be imaged onto the detector by a suitable lens, as is done with the integrated-optics combiner output. These fibers can be single-mode, offering post-combination spatial filtering, or multi-mode, which is schematically the same as a relay by mirrors. The latter is less critical, and offers the best potential to get something from sources at the faint limit, but is more difficult to calibrate.

Since the combined beams here fall on different detector elements, we may place the three beam-combining elements on a common scanning mount, so that all the fringe systems are generated at the same frequency, which may then be chosen to be optimum for ambient atmospheric conditions. This option is not available for the IO beam combiners, where the path modulation must be done on the individual telescope beams. The main advantages of the free-space combination scheme, though, are the possibility of squeezing out a fainter limit, and a greater ease in shifting between wavelength bands.

4 Detectors

Our principal detector is now an engineering-grade PICNIC array from Rockwell. Since we use only a few pixels, an array with some bad spots, but otherwise with good sensitivity and noise figures, serves us very well. The earlier, similar, NICMOS3 array, though having slightly poorer characteristics than the newer PICNIC array, remains available for us to use as the star-tracker array, in place of the silicon CCD. This will furnish us much better tracking capability for highly reddened sources, which may have little flux below 1 micron. A different set of dichroic splitters is of course needed, separating the J band for guiding, and reflecting H or K for interference detection.

The data-acquisition hardware for the former system, the NICMOS3 detector, was a PC, programmed to clock the detector pixels, and to pass along the digitized detector output voltages. We have replaced this system with one based on field-programmable gate-array (FPGA) technology, using programming aids provided by Altera, the FPGA manufacturer, at no cost to us as an academic institution. The task of coordinating the timing pulses and collecting the data is now all resident in a single chip, which can have a different readout program installed essentially on the spot. The gains of such a system are its great flexibility, its readout stability, and its speed of operation.

5 Star Tracking

To simplify hardware, we have changed from our two-telescope scheme, where each guiding beam (selected by a dichroic filter) was focused on its own small CCD detector, and its centroid determined from the readout of that detector. Now all three images are focused onto three quadrants of a single CCD, and the three centroids all determined from the one readout. This requires a somewhat more complicated acquisition routine, to recognize the presence of each image sequentially and get each established in its place, but it has been successfully accomplished.

The FPGA technique, discussed above, is also used to read out data from the star tracker CCD detector, with similar advantages.

For the initial (two-telescope) experiment at shorter wavelength we had two silicon avalanche photodiodes as detectors, which worked well. If we pursue shorter-wavelength observations with three telescopes, we must expand this detector capability.

6 Summary

We have made enormous progress in converting the 2-telescope IOTA to a 3-telescope, phase-closure-capable interferometer. Key innovations include (1) a new real-time control system with shared memory for fast communication between all elements of the interferometer, (2) FPGA-based control of detector timing and readout, (3) a new Picnic detector system, (4) integrated-optics beam combination with initially a 2-beam and later a 3-beam combiner (unique to IOTA), and (5) a free-space 3-beam combiner with fiber-coupled output. We have tested all major elements of the system, and have demonstrated phase-closure on a laboratory source. The demonstration of phase-closure on a star is expected to occur early in 2002, probably soon after this report is submitted.

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9 Figures

Figure 1. A sub-section of the Picnic detector array is shown in a 3-D plot to illustrate the 6 well-focussed star images which are the outputs of the 6 combined beams from the integrated-optic beam-combiner. The images are focussed onto a single row of the detector, spaced with a period of 5 columns. In each case note that roughly 90% of the intensity falls within the target pixel, which is 40 micron on a side, indicating very good focussing.

Figure 2. Simultaneous modulated output from the 6 pixels as shown in the previous figure, with a laboratory short-coherence-length laser illuminating the system, as discussed in the text. The optical paths for this demonstration went from the lab, through the delay-line mirrors, out to retroreflectors located in the telescope shelters, and back through the optics to the integrated-optic combiner just in front of the Picnic camera.

Figure 3 and 4. Fringe phases and closure phase from 49 such scans as shown in the previous figure, using a laboratory laser as a light source. Data from all 6 outputs is shown, 3 per figure. The closure phases show a very small scatter, about 0.5 degree rms in both cases. This conclusively demonstrates that essentially the entire interferometer and beam-combination system is working quite well, and suggests that on a star our only limitation should be the photon and seeing fluctuations from the star itself.

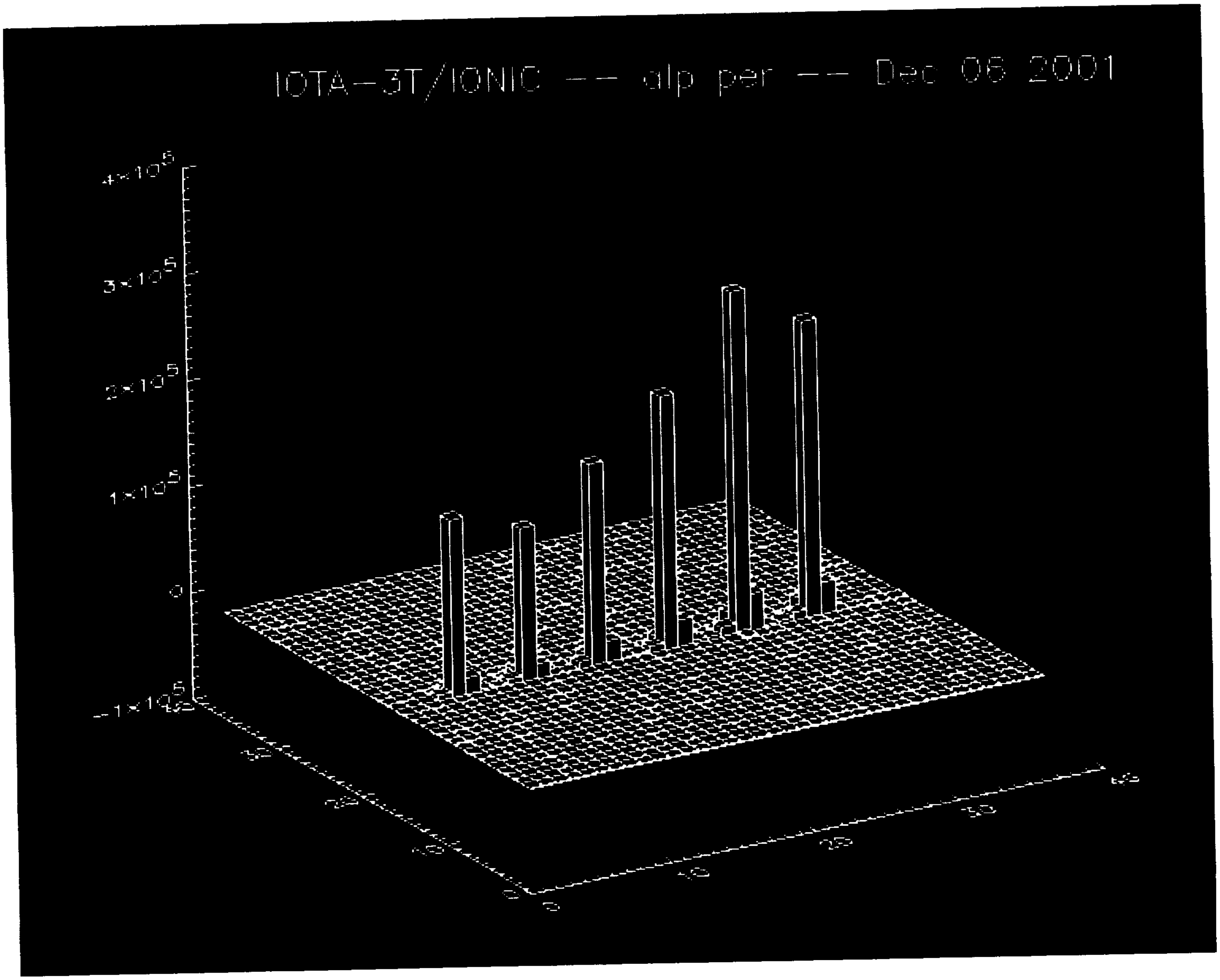


Fig. 1.

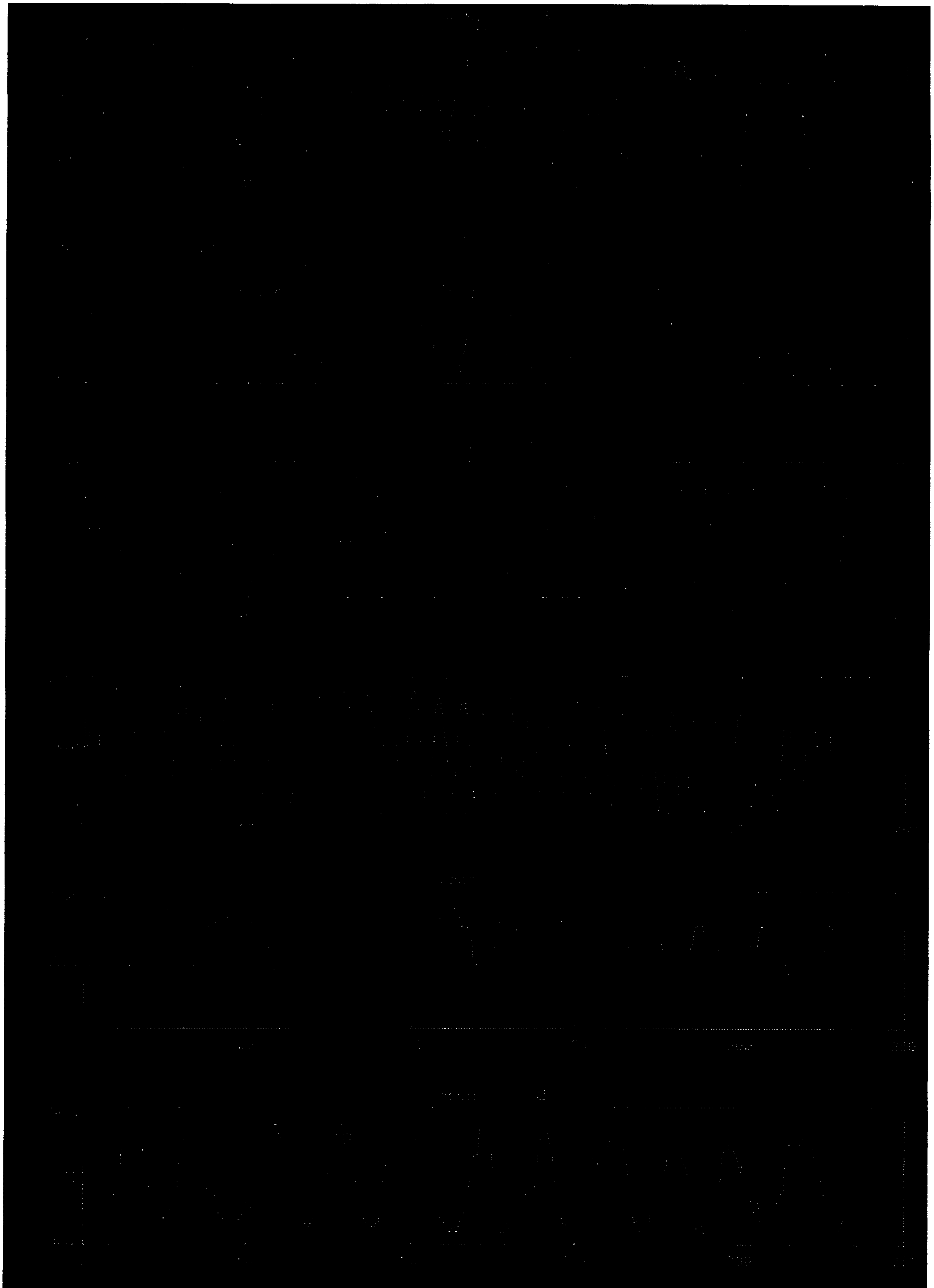
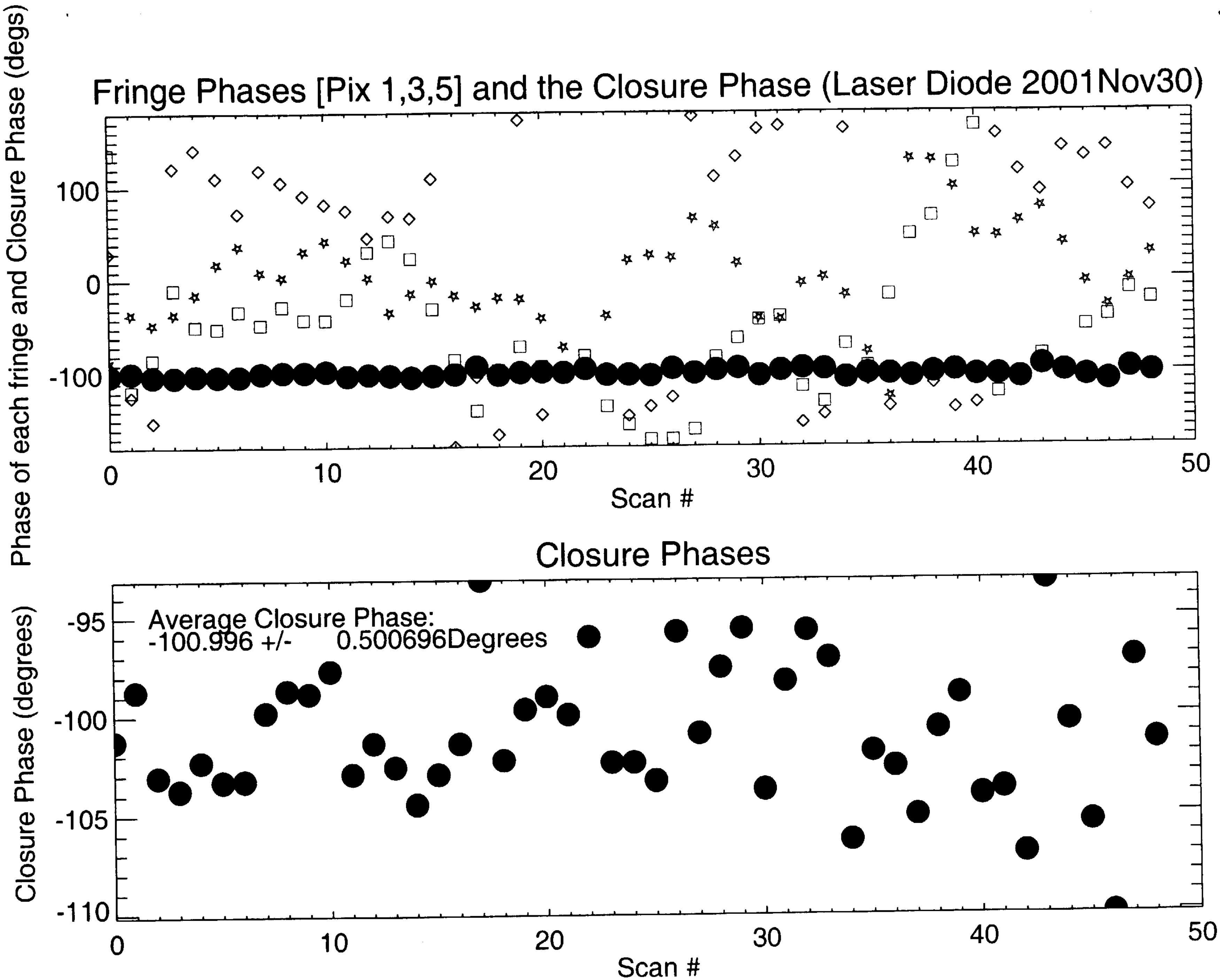
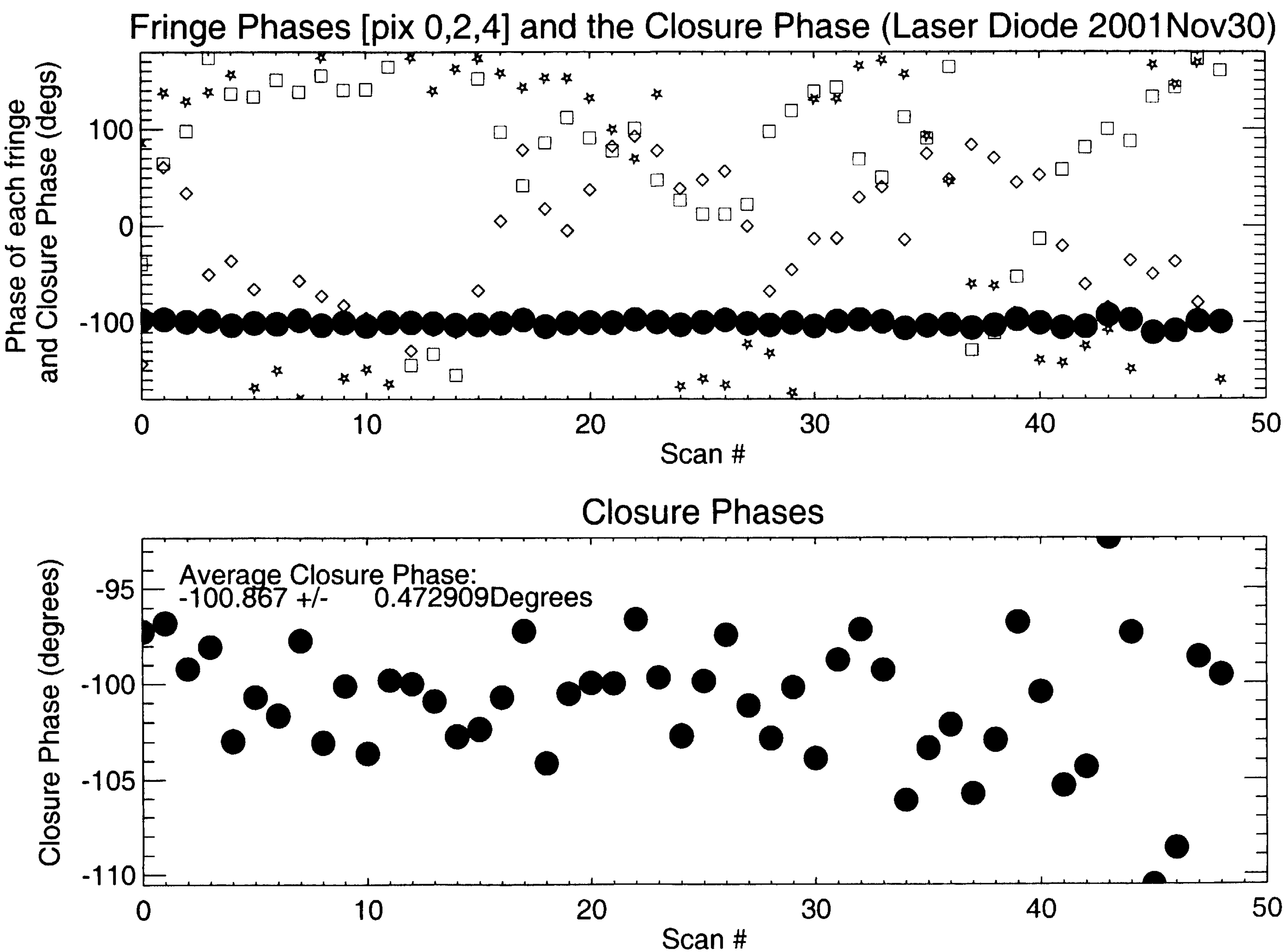


Fig. 2.



Fringe Phases [Pix 1,3,5] and the Closure Phase (Laser Diode 2001Nov30)
Phase of each fringe and Closure Phase (degs)
100
0
-100
0
10
20
30
40
50
Scan #
Closure Phases
Closure Phase (degrees)
Average Closure Phase:
-100.996 +/- 0.500696Degrees
-95
-100
-105
-110
0
10
20
30
40
50
Scan #

Fig. 3.



Fringe Phases [pix 0,2,4] and the Closure Phase (Laser Diode 2001Nov30)
Phase of each fringe and Closure Phase (degs)
100
0
-100
0
10
20
30
40
50
Scan #
Closure Phases
Average Closure Phase:
-100.867 +/- 0.472909Degrees
Closure Phase (degrees)
-95
-100
-105
-110
0
10
20
30
40
50
Scan #

Fig. 4.

ANNUAL REPORT

Grant NAS5- 4900

May 1, 1997 – April 30, 1998

Principal Investigator: Dr. Wesley Traub

Background

Grant NAS5-4900 was awarded to the Smithsonian Astrophysical Observatory (SAO) to support the implementation of a third telescope and phase-closure capability at the Infrared-Optical Telescope Array (IOTA). Funds were requested only for equipment; the Smithsonian Astrophysical Observatory agreed to provide a comparable level of support in the form of additional equipment, personnel, travel, transportation, and other on-site infrastructure costs.

A tabulation by year of the proposed equipment cost for this three year program is included in Schedule 1. The first year installment was proposed to fund as follows:

1. primary and secondary mirrors for the beam compressor;
2. siderostat mechanism;
3. siderostat mirror;
4. beam compressor structure.

Status of the Two Telescope Array

The two-telescope IOTA configuration has had a fully subscribed observing schedule since April 1995. Scientific work by the IOTA collaborators has focussed on three areas: (1) infrared (1.2-2.2 micron) observations of stellar diameters in continuum and absorption features; (2) infrared and visible (0.5 - 1.0 micron) observations of binary systems; (3) infrared observations of dust around late-type stars. As a result of an IOTA science planning meeting held in April 1996 at CfA, long term experiment plans were developed for five major scientific areas of study: (1) stellar surface features, (2) limb darkening, (3) stellar diameters and effective temperatures, (4) Mira variables, and (5) binary stars.

The addition of a remote control provision for some of the steering mirrors inside the vacuum chamber has greatly eased alignment procedures, and new guide cameras have been added to expedite star acquisition. The new IR NICMOS3 detector system has been added to improve measurement sensitivity and beam combination optics have been reworked to focus the full beam on the detectors. The mechanics, optics, dewar, and the NICMOS3 chip were provided by SAO; the electronics were built by UMass. Under good atmospheric conditions, stellar images can be focussed on a single 40 micron pixel.

Work on the optical system and the software continues for proper signal processing and for improvement of the star tracker system. A new image superposition system has been added to improve overlap star images on the detector surfaces.

A rapid scanning piezo-electric driven modulator has been added to increase data recording efficiency by a factor of about 20. Our colleagues from the Observatoire de Paris continue to improve the single-mode-fiber 2.2 micron IR beam combiner which is working routinely at IOTA.

Three Ph.D. theses were awarded for work done at IOTA during the past two years. Four papers were published, and three conference papers were delivered. See bibliography.

Eight graduate students worked on Ph.D. theses centered on IOTA: two at the University of Wyoming (Robert Thompson, through mid-1997; Gerard van Belle, Ph.D. awarded fall 1996, now at JPL); one at the University of Massachusetts, now working at SAO (Rafael Millan-Gabet); one at Harvard University (Chip Coldwell); two from the Observatory of Paris, Meudon, as guest investigators via KPNO (Bertrand Mennesson, current; Cyril Ruilier, current; Guy Perrin, Ph.D. awarded December (1996); and one at SAO, as an SAO pre-doctoral fellow, from University of Padova, Italy (Irene Porro, Ph.D. awarded 1997). Much of the scientific effort at IOTA is focussed on ensuring that these students obtain the data they need for their thesis topics.

In addition, through our French colleagues, a graduate student in astrophysics at Meudon (Damien Segransan) started a one year assignment at Mt. Hopkins with IOTA in June 1997 as part of his National Service.

First Year Progress Report

The first installment of funding was received by SAO in July 1997. Since that date the following has been done:

Siderostat

The contact for the machining of major items and weldments was awarded to Framingham Welding and Engineering Co in August. These parts will be completed by 15 May and ready for trial assembly at the contractor's facility. All of the smaller machined parts required for trial assembly have been fabricated at the University of Massachusetts. All of the bearings and fixtures required have been ordered. Delivery is scheduled for late April.

Once the trial assembly has been completed, the siderostat will be disassembled and shipped to the Whipple Observatory in Arizona for full assembly in the July-August timeframe. Space has been allocated at the Base Camp to support the assembly.

The harmonic drive units, the microsteppers, the controllers, and the remaining hardware parts will be ordered in May. The covers and other exterior pieces will be completed at the University of Massachusetts once the structure is assembled.

Siderostat Mirror

During the last year, the Instituto Nacional de Astrofisica Optica y Electronica in Puebla, Mexico joined the IOTA consortium. The Instituto purchased the siderostat blank and rough figured the flat at its optics shop in preparation for finishing, coating and testing at Zygo this summer.

Primary and Secondary Optics

SAO purchased the blank for the primary. The Instituto is now rough figuring the primary and secondary in preparation for finishing by Fair Optical and coating this summer.

Air Bearing Carriage

Although the fabrication of the beam compressor structure was scheduled for the first year and the upgrading of the air bearing carriage with a second track was scheduled for the second year, we were presented with an opportunity for some cost savings if we proceeded with the air bearing carriage first.

The upgrade of the air bearing carriage involves the addition of another track for the second delay-line. The original manufacturer, Anorad Corp., had a setup in place that would allow them to align and test the second track without the return of the entire air bearing table from the Whipple Observatory. There was also some concern that key personnel who were readily available now, might not be available next year. The second track will be ready for testing in May. The second track will be installed in the fall.

The next generation rate card to drive the siderostats and the delay line table is being designed at SAO for fabrication this summer. Design is also underway on the second generation electronics for the air-bearing table.

Beam Compressor Structure

The fabrication of parts for the beam compressor will await second year funding

Other Progress on Third Telescope

SAO has already completed the pedestal ($32K) and the piers and fittings ($8K). The shelter/transporter ($40K) is near completion.

Plan for the Second Year

In the second year of this grant, we will purchase the (4) beam compressor structure, (5) piezo-driven fast tip-tilt mirror for image stabilization, (6) the beam relay mirrors with mountings, (7) the beam combining optics with mountings, (8) the coupling optics and mountings for the detectors, (9) the laser metrology system, (10) one piezo mirror mount with tip-tilt capability for fringe scanning, (11) the motorized 5-axis stages for the secondary-alignment control, (13) components for the fiber-optic beam combining system, and (14) the computer facility, a UNIX workstation with the necessary I/O interface cards.

Schedule 1. Equipment Cost

		FY 1997	FY 1998	FY 1999	Total
1.	Primary and secondary mirrors for the beam compressor	$17,500			$17,500
2.	Siderostat mirror	25,000			25,000
3.	Siderostat mechanism	70,000			70,000
4.	Beam compressor structure	32,000			32,000
5.	Piezo-driven fast tip-tilt mirror for image stabilization with controller		9,500		9,500
6.	Beam relay mirrors with mountings		9,500		9,500
7.	Beam combining optics with mountings		6,000		6,000
8.	Coupling optics and mounting for detectors		5,000		5,000
9.	H/P laser metrology components		12,700	7,300	20,000
10.	Piezo mirror mounts with tip-tilt capability for fringe scanning (3 units)		16,000	32,000	48,000
11.	Motorized 5-axis stages for secondary-alignment control (3 units)		11,100		11,100
12.	Air-bearing carriage for fine-delay motion with controller		58,000		58,000
13.	Components for the fiber-optic beam combiner		9,000	4,000	13,000
14.	Computer facility		10,000		10,000
15.	Star tracking detection system			43,500	43,500
16.	Spare components			18,000	18,000
	Total Direct Cost for Equipment	$144,500	$146,800	$104,800	$396,100

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IOTA: INFRARED-OPTICAL TELESCOPE ARRAY

RECENT REFEREED PUBLICATIONS

(1) A search technique for planets in nearby binary stars using a ground-based interferometer (W.A. Traub, N.P. Carleton, and I.L. Porro) *Journal of Geophysical Research*, **101**, pp. 9291–9295, (1996)

(2) Radii and effective temperatures for K and M giants and supergiants (H.M. Dyck, J.A. Benson, G.T. van Belle, and S.T. Ridgway). *Astron. Jour.* **111**, pp. 1705–1712, (1996).

(3) Angular diameters and effective temperatures of carbon stars (H.M. Dyck, G.T. van Belle, and J.A. Benson). *Astron. Jour.* **112**, pp. 294–300, (1996).

(4) Angular size measurements of 18 Mira variable stars at 2.2 μm (G.T. van Belle, H.M. Dyck, J.A. Benson, and M.G. Lacasse). *Astron. Jour.* **112**, p. 2147, (1996).

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(2) On the detection of exo-zodiacal light by nulling interferometry with the Magellan telescopes (W.A. Traub, N.P. Carleton, and J.R.P. Angel) *Science with the VLTI Interferometer*, F. Paresce, ed., Springer-Verlag, Berlin, pp. 80–85, (1997).

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(5) Extension of the effective temperature scale of giants to types later than M6 (G. Perrin, V. Coude du Foresto, S.T. Ridgway, J.-M. Mariotti, W.A. Traub, N.P. Carleton, and M.G. Lacasse). *Cool Stars 10 proceedings*, to appear, (1997).

(6) A NICMOS3 fringe detector for the Infrared-Optical Telescope Array (R. Millan-Gabet, F.P. Schloerb, W.A. Traub, and N.P. Carleton). *Cool Stars 10 proceedings*, to appear, (1997).

(7) High dynamics infrared imaging of evolved stars with FLUOR/IOTA (G. Perrin, V. Coude du Foresto, J.-M. Mariotti, S.T. Ridgway, W.A. Traub, N.P. Carleton, and M.G. Lacasse). *Cool Stars 10 proceedings*, to appear, (1997).

(8) An Interferometry Primer (W.A. Traub) *Proc. of Conference on Exo-Zodiacal Dust*, to appear, (1997).

(9) Recent results from the IOTA interferometer (W.A. Traub) *SPIE Astronomical Interferometry*, to appear, (1998).

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PH.D. THESES USING IOTA

(1) Vincent Coude du Foresto, 1994

(2) Gerard T. Van Belle, 1996

(3) Guy Perrin, 1996

(4) Irene Porro, 1997

(5) (planned for 1998) Rafael Millan-Gabet

(6) (planned for 19xx) Charles Coldwell

(7) (planned for 1999) Bernard Mennesson

(8) (planned for 1999) Cyril Ruilier

(9) (planned for 19xx) Damien Segransan

ANNUAL REPORT

Grant NAS5- 4900

May 1, 1998 – April 30, 1999

Principal Investigator: Dr. Wesley Traub

Background

Grant NAS5-4900 was awarded to the Smithsonian Astrophysical Observatory (SAO) to support the implementation of a third telescope and phase-closure capability at the Infrared-Optical Telescope Array (IOTA). Funds were requested only for equipment; the Smithsonian Astrophysical Observatory agreed to provide a comparable level of support in the form of additional equipment, personnel, travel, transportation, and other on-site infrastructure costs. A tabulation by year of the proposed equipment cost for this three-year program is included in Schedule 1. Funding for the third year activities is anticipated on August 1, 1999.

Progress during FY 1999

Science

The IOTA interferometer (see Figure 1) had a fully subscribed observing schedule throughout FY 1999, with data being taken on an almost routine basis. Our principal scientific collaborators at IOTA are: F.P. Schloerb at the University of Massachusetts, V. Coude du Foresto at the Observatoire de Paris in Meudon, and J. Bregman at NASA Ames Research Laboratory. Major projects pursued during the year at IOTA are as follows:

(1) X-ray transient event.

We observed CI Cam (XTEJ0421+560) in October and November 1998, about 6 months after it produced a short (1-day) x-ray transient event with a peak luminosity of about 10**37 erg/s, suggestive of material infall onto a neutron star or black hole. (Radio observations initially claimed 0.9c jets, but this was later withdrawn.) CI Cam has long been known to have a thick dust envelope, which we suspected might have been perturbed by the transient event. We used IOTA and the classical Michelson beam combiner to measure the diameter of the cloud in the infrared (H and K bands), finding circular symmetry and no apparent change of diameter over a 1-month period.

(2) Dust around Herbig AeBe stars.

We used IOTA and the classical Michelson beam combiner to survey the angular sizes of 19 Herbig AeBe stars in the infrared (J, H, K), looking for signs of binarity or disks. HAeBe stars are intermediate mass analogs of T Tauri stars. We found most of these to be resolved, and discovered one to be a binary system. We focussed on the prototype AB Aur, finding clear evidence of a dust disk with a characteristic diameter larger than previous models, clearly ruling out both a binary system as well as an accretion disk (the heretofore favored model).

(3) SW Virginis.

IOTA was used with the single-mode fiber beam combiner to measure the diameter of the semi-regular variable SW Vir, thought to be a Mira-type precursor. The goal was to infer oscillation characteristics from precision diameter measurements at 2 epochs. We found evidence for a 5 percent departure from circular symmetry, and a mean diameter that corresponds to the fundamental mode of radial oscillation, both of which results are new.

(4) R Leonis.

The Mira-type star R Leo was observed with the single-mode fibers in K band at 2 epochs, and in both the main and first sidelobe of the visibility function (i.e., well past the nominal angular resolution limit of the array). The data are not well fit by a uniform disk, but are much better matched by an ad-hoc model which posits that the continuum photospheric radiation is strongly scattered by a CO or H2O molecular envelope. The resulting disk diameter agrees with that predicted by fundamental mode oscillation, and the effective temperature is in agreement with non-Mira temperatures of similar spectral types.

(5) Other Miras.

We used the classical Michelson beam combiner and infrared JHK bands to observe a list of Mira variables, as often as possible throughout the year, and at a variety of baseline orientations, with the goal of getting pulsation phase coverage and angular resolution at different orientations, to see if non-radial oscillations might explain the currently poor agreement between theory and observation. We have many observations, and we expect to interpret these during the coming year.

(6) Zeta Geminorum.

Zeta Gem is a Cepheid variable which was recently measured with the single-mode fiber technique at IOTA to have an angular diameter of about 2 milli-arcsec, and an amplitude of about 10 percent. The resulting distance estimate is accurate to about 10 percent, but this can be improved substantially by further measurements. The current measurement is remarkable because it was done in the infrared where the angular resolution of IOTA is nominally 6 times wider than the star's diameter, and is only possible because of the high accuracy of single-mode fibers.

(7) L and M bands.

The first attempts to do ground-based interferometry at wavelengths longer than K-band were recently done at IOTA using the single-mode fiber technique, with the result that the diameters of a few bright stars were measured at L (3.8 micron), but no detections were possible at M (5.0 micron). The main difficulty is the high thermal background from the instrument, and the associated fluctuations. This work paves the way for future interferometers operating in the thermal infrared at 3 to 13 microns.

(8) Low mass stars.

The binary system Gl570 was measured with IOTA to determine its components' angular separation and relative magnitudes. These results were combined with radial velocity data to give component masses (about 0.52, 0.35 suns) accurate to 1 percent, significantly contributing to the very sparse exiting data on the low-mass end of the mass-luminosity curve.

Seven refereed papers were published or submitted in the FY 1998-9 period; these are listed in the bibliography.

System Upgrades

The infrared NICMOS3 detector system and beam combination optics were installed at the end of FY 1998 and have continued to work beautifully; during FY 1999 almost all data at IOTA was recorded with this detector. In late FY 1999 we plan to improve this system by replacing the NICMOS3 detector (which is no longer being manufactured) with its lower read-noise successor, PICNIC. A similar system is being built to provide infrared star tracking so that we can observe T Tauri stars next year. A rapid scanning piezo-scanner with a 60 micron stroke, built and installed at the start of 1999 for use on the classical Michelson beam combination table, has increased our data recording efficiency by a factor of about 25. Recently Meudon provided a 180-micron stroke piezo-scanner for use with either narrow-band filters (such as a CO or H2O filter) or longer wavelengths (such as L and M bands).

An improved single-mode fiber beam combiner unit from Meudon was permanently installed at IOTA early in the year. The unit works optimally at K band, but is also useable at L band. This combiner was used to produce much of the single-mode science results mentioned above.

We have taken several steps toward further use of single-mode fibers at IOTA. We designed a special mount (which was then fabricated at Meudon) to allow the 4 separate beams from the single-mode fiber output to be focussed onto the SAO-UMass NICMOS camera; this allows the high-precision fibers to be used with the low-noise camera, a potent combination. We also purchased a dewar, which will be used to test fibers in the lab, and later used at IOTA. We remain in close contact with the Grenoble group who are working on the "interferometer on a chip" optics, in the hope that these will someday be useful to IOTA.

The image overlap system was improved with better software, so star images can now be more easily and reliably overlapped. NASA Ames Research Center continues to work with us to improve the response of the IOTA star tracker control system.

Avalanche photo-diodes were purchased, and electronics designed for their use as visible light detectors. We plan to test these APD's at IOTA during the coming year.

Second Year Progress Report

Funding for the second year of this program was received in two installments: $36.7K in May 1998 and $110.1 K in August 1998. During this reporting period, much new hardware was designed and built.

Pedestal

The pedestal structure has been installed on site.

Siderostat

Fabrication of the major siderostat components was completed by Framingham Welding and Engineering Co. After trial assembly at the contractor's facility, the parts were shipped to the Whipple Observatory Basecamp for full assembly with the harmonic drive units, the microsteppers, the controllers, and remaining small parts. The siderostat has now been installed on the pedestal.

Siderostat Mirror

Zygo completed the polishing, coating, and testing of the siderostat flat and delivered it to the Whipple Observatory in August.

Telescope

The parts for the third telescope were fabricated, and the telescope tube has been installed on the pedestal. Completion of the telescope assembly is scheduled for August when the primary and secondary mirror pair, now being polished at a shop near Tucson, are due for delivery. New secondary mirror mounts with controllable 5-axis motions are being fabricated and will be installed this summer. New primary mirror supports are also being added to reduce stress and improve mirror figure.

Delay Line

The second air-bearing carriage (short delay line) was delivered and will be installed this summer on the granite table. A second generation set of electronics to drive the carriage has been built and is undergoing testing on-site. A commercial rate-generating module has been found to replace the prototype rate cards that had been made in house, providing considerably more flexibility for the control of both the siderostats and the delay lines. A second long delay line is being installed, along with an improved control systems.

Hollow corner cube mirrors for the delay lines are being fabricated for installation this summer. These corner cubes will replace the dihedral mirrors to provide better bean steering stability. A low-roofed hut was built at the far northeast end of the facility to house the long-delay line laser system. During this summer we will install the HP laser, beamsplitters, interferometer components, detectors, a control computer, a long-delay driver motor control program, a tip-tilt adjustment mechanism to peak up the laser signal, and communications with the main control building. Most of the major items for this installation have been purchased.

Shelter

The third telescope shelter floor was installed on-site early in FY 1999. After the siderostat mechanism, pedestal structure, and telescope tube were bolted in place, the shelter wall and roof-structure were added. The installation of roof insulation, lights, roof pull-back chains, an intercom system, equipment support shelves, a hydraulic system (to lift the pedestal, and operate the roof flap), and other necessities are underway.

Control System

A plan was developed to collaborate with the University of Massachusetts for the design of a new operating system for the three-telescope configuration. The software will be based around VxWorks, a modern, commercially available, real-time control software that will provide an efficient observing environment at IOTA. Work is underway on the overall architecture and the first module for the long delay line is in process. We target the first level installation of this system for early FY 2000.

Proposed Work for FY 2000

Science

The observing program in the coming year will continue most of the current science projects. These will expand to include new types of observations as our technical ability increases, particularly in the areas of better precision in visibilities. Three-beam combination and phase-closure measurements will begin late in the coming year.

(1) Measure the dust distribution around young, hot stars to learn more about where the dust is located, radially and azimuthly; in particular we will focus on continued studies of the dust around Herbig AeBe stars, and around CI Cam. Our initial work on these objects has provided the first-ever angular measurement constraints on their

geometry, but has also shown that further selected observations (other baselines and position angles) are needed to better understand these systems.

(2) Measure the diameters of giant stars at infrared wavelengths (JHK) to provide a body of observational data on diameters comparable to that which exists for main sequence stars (based largely on eclipsing binaries), and also to test stellar model atmospheres, especially in the infrared, where opacity calculations are only recently beginning to include most of the important molecular absorption lines; in particular we will focus on measuring effective temperatures in late type stars.

(3) Observe suitable stars over a range of baselines to determine the visibility function out into the secondary lobes and thus measure limb darkening (or limb extension) and further constrain atmospheric models; this program is best suited for the fiber beam combiner and new PICNIC detector combination.

(4) Measure dust shells around late-type stars, where at 2.2 microns, we are sensitive to the hotter dust nearer the star; this will complement existing 11-micron interferometric measurements of this class of stars, which are sensitive to the cooler dust farther from the central star; this includes Miras and other slow variables.

(5) Attempt to measure binary stars in the Taurus and Ophiuchus star forming regions in order to determine the frequency of binary systems in the unexplored range of separations from 1 to 15 AU, and to thereby further constrain models of the star-formation process; this is a new program.

(6) Study stars that have some photometric or spectrometric evidence of surface features in order to resolve these features; in particular we will study Betelgeuse with the fiber beam combiner.

Third Telescope Plan for the Third Year

With the third installment of funding on this grant, we will undertake the third (and final) year of our third telescope upgrade project. Items that are scheduled to be purchased include (1) beam-combining optics with mountings, (2) coupling optics and mounting for detectors, (3) piezo mirror mounts for fringe scanning, (4) some test single-mode fiber-optic beam-combining components, (5) a star tracking detection system, (6) computer components for the control system, and (7) spare components.

Three Beam Combination System

The beam combination system is the heart of the three-telescope configuration. Since IOTA is a prototype interferometer, the new optical layout must accommodate several different possible data-taking arrangements, potentially including both a visible and infrared classical Michelson-type beam combiner section, a visible and infrared single-mode fiber beam-combining section, star tracking capability in the visible and infrared, and adaptive optics capabilities in the visible and infrared. At present we have facilities for four out of these eight possible functions.

We anticipate developing the three beam combination plan this summer, taking into account all of the functions just mentioned, and the physical constraints of the beam-combining area at the facility.

Fringe Tracking System

The fringe-tracking system on IOTA will be required to measure the instantaneous differential phase shift between the beams from pairs of telescopes and to apply a piston correction to one of the corresponding beams. Our goal is to correct the phase to within about one wavelength, not the more stringent limit of less than one radian. We expect that this will be sufficient for phase closure measurements. Dr. Sebastien Morel, a visiting Post-doctoral fellow from France, and Dr. Jesse Bregman from NASA Ames Research Center are currently working with us on a one-beam prototype version, which we have been testing this spring, and which we expect to have operating at the site in late FY 1999. This would then be expanded to the full three-beam system in FY 2000.

Control System

The complexity of adding a third telescope and the need to simultaneously increase system operating efficiency, requires the development of a new control system. This work began in FY 1999, through our collaboration with the University of Massachusetts. The new system will be designed primarily at the University of Massachusetts, in parallel with a similar system being developed for their Large Millimeter Telescope in Mexico. We hope to derive benefits of cost and experience from this parallel development. Using VxWorks, a modern, commercially available, real-time control software package, we will complete the basic control system (telescopes, delay lines, star tracker, and data acquisition) for installation in early 2000. Enhancements, including scheduling and planning algorithms, as well as phase tracking and phase closure algorithms, will be developed subsequently. We anticipate that the new control system will be state-of-the-art for ground-based interferometers, and that it will be a candidate for transference to other existing or future interferometers in which we might have an interest.

Adaptive Optics

We recently completed a study (Porro et.al., 1999) of the contributions of the various subsystems at IOTA to the overall instrumental and atmospheric visibility functions. We found that the major sources of visibility loss are the wavefront curvature from atmospheric turbulence, the tip-tilt servo system time constant, and the flatness of the relay optics. The relative contributions vary with wavelength. This study showed that the addition of faster tip-tilt corrections plus adaptive corrections to wavefront curvature components would significantly improve the median fringe visibility at IOTA, and one can expect that it would likewise dramatically reduce the variance of visibilities, perhaps an even more critical improvement.

Adaptive optics had not been previously considered for IOTA because of the expected high cost of such systems, but recent developments suggest that we might be able to include adaptive optics at affordable levels during the coming year. Adaptive optics would be highly desirable at IOTA (and at any ground-based interferometer with collecting optics larger than the Fried coherence length) because a flatter wavefront implies higher, more stable fringe visibilities, using either a classical or a single-mode fiber beam combiner. One development is a membrane mirror that can be driven with roughly 36 independent elements to compensate for wavefront deformations, given an appropriate set of drive signals. Another development is the wavefront curvature sensor and matching piezo-deformable curvature mirror system, which is increasingly being used at large telescopes. IOTA personnel are currently involved in activities to seek funds for adaptive-optic systems.

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Ph.D Theses Using IOTA

1. Vincent Coude du Foresto, 1994
2. Gerard T. van Belle, 1996
3. Guy Perrin, 1996
4. Irene Porro, 1997
5. Rafael Millan-Gabet, planned 1999
6. Bernard Mennesson, planned 1999
7. Cyril Ruilier, planned 1999
8. Damien Segransan, planned 2000

Figure 1. Present View of the IOTA Site

Schedule 1. Equipment Cost

		FY 1997	FY 1998	FY 1999	Total
1.	Primary and secondary mirrors for the beam compressor	$17,500			$17,500
2.	Siderostat mirror	25,000			25,000
3.	Siderostat mechanism	70,000			70,000
4.	Beam compressor structure	32,000			32,000
5.	Piezo-driven fast tip-tilt mirror for image stabilization with controller		9,500		9,500
6.	Beam relay mirrors with mountings		9,500		9,500
7.	Beam combining optics with mountings		6,000		6,000
8.	Coupling optics and mounting for detectors		5,000		5,000
9.	H/P laser metrology components		12,700	7,300	20,000
10.	Piezo mirror mounts with tip-tilt capability for fringe scanning (3 units)		16,000	32,000	48,000
11.	Motorized 5-axis stages for secondary-alignment control (3 units)		11,100		11,100
12.	Air-bearing carriage for fine-delay motion with controller		58,000		58,000
13.	Components for the fiber-optic beam combiner		9,000	4,000	13,000
14.	Computer facility		10,000		10,000
15.	Star tracking detection system			43,500	43,500
16.	Spare components			18,000	18,000
	Total Direct Cost for Equipment	$144,500	$146,800	$104,800	$396,100

ANNUAL REPORT

Grant NAG5- 4900

May 1, 1999 – April 30, 2000

Principal Investigator: Dr. Wesley Traub

Background

In 1997 NASA awarded to the Smithsonian Astrophysical Observatory (SAO) Grant NAG 5-4900 to support the implementation of a third telescope and phase-closure capability at the Infrared-Optical Telescope Array (IOTA). Funds were requested only for equipment; SAO agreed to provide a comparable level of support in the form of additional equipment, personnel, travel, transportation, and other on-site infrastructure costs. The total value of the grant award is $447,659; the final installment of $150,376 was awarded in March 2000, thereby fully funding the grant. We anticipate that the funded work will be completed by mid-2001. We report here our progress during the past year.

Progress during the Past Year

We made major progress toward installing the third telescope and light relay path hardware, up to the beam-combining area at IOTA. We also began work on two related areas, fiber optics and integrated optics. Finally, we maintained a full observing schedule throughout the year.

Shelter

The third shelter-transporter unit was completed. All mechanisms for lifting and transporting the telescope and for roof operation are installed and functional. Weather stripping and precipitation guards are in place.

Siderostat

The siderostat has been aligned in its position on the third pedestal, with respect to the telescope structure that it feeds. Its drives, motors, and controls are all operational. Tests have been carried out with an aluminum dummy mirror in place of the actual mirror, so as to keep the latter (which is coated and ready for use) protected as long as possible.

Telescope

The primary and secondary mirrors were accepted from D. A. Loomis Custom Optics in Tucson after careful testing (and some re-work) to verify that this system met our stringent requirements. The mirrors were subsequently silver coated at Denton Vacuum, and were installed in their mountings and aligned to preliminary tolerances. They were left in place, being well protected. Final alignment will be done when all components of the beam path are in place.

The primary-support configuration was improved by reducing friction in the edge supports, so that the pull-back springs that hold the mirror against its axial defining points can act reliably against temperature change and against any mechanical vibrations during station changes. This improvement was retrofitted to the first two primaries, as well.

The secondary-mirror mounting was improved by incorporating, into an in-house designed and fabricated secondary hub and spider, adjustments for the five parameters involved in alignment: tip and tilt, x and y translation, and focus. All adjustments are made with piezo-driven fine screw mechanisms (so called picomotors from New Focus, Inc.). These mechanisms provide very precise adjustment with remote control. This improved mounting has been retrofitted to the first two telescopes.

A new platform has been designed and built, to allow the mounting of a laser interferometer on the telescope-support pedestal for aligning the telescope primary and secondary to each other to high precision, in autocollimation with the siderostat.

Guide Mirror Assembly

Our image stabilization is accomplished by a piezo-driven tip-tilt mirror, immediately behind the telescope. The best supplier for this mirror mount is still Physik Instrument, from whom we obtained the units for the first two telescopes. They no longer make the model we have, however, having replaced it with a more sophisticated push-pull unit, which requires different driver circuitry and a different mounting geometry. We have designed and made a new mount and new circuitry, and will again retrofit the first two telescopes with these improved assemblies. Together with ongoing improvements in our image-position sampling and control algorithm, this should result in increased effective bandwidth for image stabilization.

Beam-Relay Path

All windows and turning mirrors in the beam path have been procured and installed. We are providing remote tip-tilt control on all mirrors in the evacuated beam path with the above-described picomotors. New mounts were designed and fabricated to provide this control, and again retrofitted to the mirrors in the first two beam paths.

Delay Lines

We have a second long-delay carriage operating, like the first, in a slew and clamp mode. The metrology for these carriages is now derived from a laser mounted in a hut built for the purpose at the far end of the delay path. Steering mirrors for these laser beams are again remotely controllable through picomotor mounts. The position measurements are derived from the laser signals by Hewlett-Packard circuitry housed in a dedicated PC in the hut, which communicates them to our central computer.

A second air-bearing carriage on the existing granite track provides precision tracking for the second beam. This carriage, together with motor-driving circuitry, was obtained from the Anorad Corp., who made the track and first carriage. We have designed and built new control circuitry, which now can operate both carriages. The second carriage has had a brief test, but has not yet been in full operation.

We have not yet been able to assemble to sufficient accuracy cube-corner components for the long-delay carriages, as we had intended. While we continue to look into refining this assembly process, we will make up dihedral mirror units for the second delay path, like those we have been using. These require a remote yaw adjustment on the long-delay carriage, every time it is slewed, since it runs on a low-precision track (which offered us a large cost saving).

Control System

Our new control system, running on a VxWorks-equipped computer, has been nearly completed by our colleagues at the University of Massachusetts. In the first on-site trial, scheduled for June 2000, we will test control of the siderostats and the delay lines.

Beam Combination and Detection

We have a design effort under way for three-beam combination in a straightforward Michelson-type geometry. We also have experiments planned in single-mode-fiber combination, extending what our colleagues have done in a two-beam combination from Observatoire de Meudon. We are exploring the potential of using commercially-available components from the communication industry for wavelengths out to the atmospheric H-band, at 1.65 microns.

Rapid Scanning

As part of our collaboration with NASA Ames, we have purchased and constructed a Rapid Scan Platform for the IOTA delay path. This platform was tested and improved by the addition of stiffening plates which eliminated a very small but noticeable bending of the metal platform at the micrometer level. The platform has since seen heavy usage on a nearly daily basis, and has performed extremely well on our classical Michelson beam-combination infrared table.

Star Tracking

In a related area, Drs. J. Bregman and F. Witteborn from NASA Ames Research Center (ARC) continued their study of the IOTA CCD-based star tracker system, by constructing a device to simulate star motion having a specified frequency and amplitude of motion, and by examining the response of the tracker to this simulated star input. A key result of this research is that the system gain was found to be optimally set at a value well below that which we originally considered to be correct (roughly a factor of two lower). We now believe that this result can be readily explained by the effect of the finite time delay involved in the read-out cycle of the CCD, and the subsequent computation cycle, all prior to the application of a correction signal to the piezo-mirror which is used to compensate for the atmospherically-induced instantaneous tilt of the incoming star-light beam. This new understanding of the system has led us to propose that a second-generation star tracker should be built, based on the more rapidly-responding avalanche photo diode (APD) technology, the only impediment to implementation being that APDs are significantly more expensive than our current CCD detectors.

Fringe Tracking

In collaboration with NASA Ames, and in particular with Dr. Robert Mah, we developed a fringe-packet-tracking algorithm, based on data obtained at IOTA by Bregman and Witteborn. The algorithm was tested in the lab at ARC, and found to work well for both strong and weak fringes. The next step in this program occurred when Dr. Sebastien Morel came to work at IOTA as a post-doctoral fellow, under a one-year French government sponsorship. Morel's first task at IOTA was to travel to ARC and meet with Traub, Bregman, and Mah, to discuss the possibility of transferring this algorithm from the laboratory to a real-time application at the IOTA interferometer. Morel was successful in adapting a simplified version of the algorithm to a laptop computer at IOTA. This in turn was connected to a control computer which was able to command the Rapid Scan Platform such that the previously measured fringe-packet centroid deviation from a predetermined target position was compensated within one-tenth of a second. A number of computer interconnect problems slowed the full application of this research, but the basic principle was demonstrated successfully.

Subsequently, Morel was able to spend a second year at IOTA (January 2000 to January 2001), this time under NASA sponsorship, with the goal of completing the application of the control algorithm. Since a major activity at IOTA this year is the installation of a new, real-time, control system, which will include within its structure the entire fringe-tracking measurement and command algorithm, Morel has also become an active player in the coding of the control system software. The new system will be a huge improvement over the current system, from the point of view of the fringe-tracking algorithm, in that all computations and commands will take place in a single real-time computer, thus obviating the need for communications between different computers with the associated time delays. The new system will be capable of controlling three telescopes at once, thus allowing us to make phase-closure measurements with IOTA, and for this purpose the fringe packet tracking capability is an absolute requirement.

We recently reported results from this program at the Munich meeting of the SPIE in March 2000. Preprints of two relevant papers from this meeting are attached as appendices to this report. The papers are "The Third Telescope Project at the IOTA Interferometer" by Traub, Carleton, Bregman, et al., and "Fringe-tracking Experiments at the IOTA Interferometer" by Morel, Traub, Bregman, Mah, and Wilson.

Proposed Work During 2000-2001

Major activities scheduled for the final segment of this research are all natural continuations of the above topics. Briefly, these are as follows.

Three-Beam Combination

We are currently planning a classical Michelson beam-combiner system for three beams, based either:

1. an "all-in-one" approach, with all 3 beams modulated at different speeds and combined on a single detector, with subsequent extraction of the visibilities and phases on the three baselines via a fourier-transform of the time sequence data; or

2. a "pairwise" approach, with the beams combined in pairs and the same modulation frequency imposed on each pair.

There are advantages and disadvantages to each, and we will decide which path to follow based on expected signal-to-noise, and on the practicality of construction and operation. Sorting out through the various possibilities has been one of the tasks pursued this past year by Dr. Irene Porro, a Bunting Postdoctoral Fellow (through Radcliff College) at SAO.

Integrated Optics

An alternative approach for beam-combination is to use integrated optics to combine the beams, using technology developed at Grenoble Observatory, and brought to IOTA by Dr. Jean-Philippe Berger, who begins his NASA Michelson postdoctoral appointment at SAO in September 2000. We will first test a 2-beam unit in November 2000, and hope to have available a 3-beam unit in spring 2001.

Fiber Optics

We have recently started a small laboratory effort to evaluate the use of commercial single-mode fibers for interferometry. We are focussing on the visible wavelength region, where we expect that this work will pay off initially in the future measurement of Cepheid star diameters at IOTA, likely using 2 telescopes. Two postdoctoral fellows are taking a strong role in this work, Dr. John Monnier, a CfA Postdoctoral Fellow, and Dr. Rafael Millan-Gabet, a NASA Michelson Postdoctoral Fellow, both now starting their second years here at SAO.

Detectors

We are currently upgrading our very reliable and low noise NICMOS3 detector to an even lower noise PICNIC detector. Key people are Dr. Rafael Millan-Gabet and Mr. Ettore Pedretti, an SAO Predoctoral Fellow.

Control System

In the fall 2000 we expect that the control program operating under the VxWorks operating system will be complete, thanks to a major effort by Dr. F. Peter Schloerb, M. Brewer, and K. Souccar, all at the University of Massachusetts, plus extensive contributions by SAO personnel, especially Dr. S. Morel. This system will control the telescopes, delay lines, star tracker, fringe tracker, and data acquisition tasks.

We plan to install this system permanently at IOTA in November 2000, followed by an extensive shakedown in December, all leading to a first operation of the 3-beam system shortly thereafter. Our goal is to have the entire system operational for first scientific observing tests in early 2001. Mr. Ettore Pedretti will have a major responsibility for carrying out work with the new 3-beam system. We plan to continue testing throughout at least the first half of 2001, as part of our regularly scheduled observing program. The 2-beam operations will not be affected, and in particular we will maintain the ability to use IOTA in the FLUOR mode (single-mode fiber beam combiner at K-band), and in the visible 2-beam mode, with APD detectors.

Recent Non-refereed Bibliography: (http://cfa-www.harvard.edu/cfa/oir/IOTA/)
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2. Fringe-tracking experiments at the IOTA interferometer, S. Morel, W. A. Traub, J. D. Bregman, R. W. Mah, E. Wilson, SPIE, 4006, (2000)

3. Cepheid observations by long-baseline interferometry with FLUOR/IOTA, P. Kervella, V. Coudé du Foresto, W. A. Traub, M. G. Lacasse, SPIE, 4006, (2000).

4. The circumstellar environment of Herbig Ae/Be stars as seen by the IOTA, R. Millan-Gabet, F. P. Schloerb, W. A. Traub, SPIE, 4006, (2000)

5. Observations of Mira stars with the IOTA interferometer, K. H. Hofmann, T. Bloecker, V. Coudé du Foresto, M. G. Lacasse, S. Morel, B. Pras, D. Schertl, M. Scholz, W. A. Traub, G. Weigelt, M. Wittkowski, SPIE, 4006, (2000)

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7. Third telescope project at the IOTA interferometer, W. A. Traub, N. P. Carleton, J. D. Bregman, M. K. Brewer, M. G. Lacasse, P. Maymounkov, R. Millan-Gabet, S. Morel, C. D. Papaliolios, M. R. Pearlman, I. L. Porro, F. P. Schloerb, SPIE, 4006, (2000)

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Recent Refereed Bibliography: (http://cfa-www.harvard.edu/cfa/oir/IOTA/)
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2. Effect of telescope alignment on a stellar interferometer, I.L. Porro, W. A. Traub, and N. P. Carleton, Applied Optics, 38, pp. 6055-6067, (1999).

3. Thermal infrared stellar interferometry using single-mode guided optics: first results in the L band with the TISIS experiment on IOTA, B. Mennesson, J. M. Mariotti, V. Coude du Foresto, G. Perrin, S. Ridgway, C. Ruilier, W. A. Traub, N. P. Carleton, M. G. Lacasse, and G. Maze, Astronomy and Astrophysics, 346, pp. 181-189, (1999).

4. Interferometric observations of R Leonis in the K band: First direct detection of the photospheric pulsation and study of the atmospheric intensity distribution, G. Perrin, V. Coude du Foresto, S. T. Ridgway, B. Mennesson, C. Ruilier, J.-M. Mariotti, W. A. Traub, and M. G. Lacasse, Astronomy and Astrophysics, 345, pp. 221-232, (1999).

5. Interferometric observations of the semi-regular variable star SW Virginis in the K band, G. Perrin, V. Coude du Foresto, S. T. Ridgway, C. Ruilier, B. Mennesson, W. A. Traub, and M. G. Lacasse, Astronomy and Astrophysics, submitted, (1999).

6. Sub-astronomical unit structure of the near-infrared emission from AB Aurigae, R. Millan-Gabet, F. P. Schloerb, W. A. Traub, F. Malbet, J.P. Berger, and J. D. Bregman, Astrophysical Journal Letters, 513, pp. L131-L134, (1999).

7. A NICMOS3 camera for fringe detection at the IOTA interferometer, R. Millan-Gabet, F.P. Schloerb, W. A. Traub, and N. P. Carleton, Pub. Astronomical Society of the Pacific, 111, pp. 238-245, (1999).

ANNUAL REPORT

Grant NAS5- 4900

May 1, 2000 – April 30, 2001

Principal Investigator: Dr. Wesley Traub

Background

In 1997 NASA awarded to the Smithsonian Astrophysical Observatory (SAO) Grant NAG 5-4900 to support the implementation of a third telescope and phase-closure capability at the Infrared-Optical Telescope Array (IOTA). Funds were requested only for equipment; SAO agreed to provide a comparable level of support in the form of additional equipment, personnel, travel, transportation, and other on-site infrastructure costs. The total value of the grant award is $447,659; the final installment of $150,376 was awarded in March 2000, thereby fully funding the grant. The work is proceeding briskly and nearly on schedule. We anticipate that the funded work will be completed by the end of 2001. We report here our progress during the past year.

Progress during the Past Year

The siderostat mirror was installed in the third telescope and the telescope optics were aligned. The new platform for the laser interferometer, to facilitate alignment, was installed. The new Physik piezo-driven tip-tilt mirror system to stabilize the star images has been installed in all three telescopes. Together with ongoing improvements in our image-position sampling and control algorithm, this should result in increased effective bandwidth for image stabilization.

The additional dihedral mirror units for the third telescope light path were fabricated. A remote yaw adjustment has been added on the long-delay carriage to facilitate alignment.

Design was completed for the straightforward Michelson-type geometry three-beam combiner. Experiments have also been underway on a single-mode-fiber combination system, an extension of work on a two-beam combiner developed by our colleagues at the Observatoire de Meudon.

Dr. Jean-Philippe Berger, who began his NASA Michelson postdoctoral appointment at SAO in September 2000, is working on a beam-combiner using integrated optics using technology developed at Grenoble Observatory. The 2-beam unit was successfully tested in December 2000.

Work continues in our fiber-optic laboratory, using commercial single-mode fibers for the visible wavelength region initially planned for Cepheid star diameter measurements at

IOTA, using 2 telescopes. Two postdoctoral fellows are taking a strong role in this work, Dr. John Monnier, a CfA Postdoctoral Fellow, and Dr. Rafael Millan-Gabet, a NASA Michelson Postdoctoral Fellow, both are presently completing their second year at SAO. Work also continues on commercially available components from the communication industry for wavelengths out to the atmospheric H-band, at 1.65 microns.

The rapid scan platform for the IOTA delay path, developed and installed as part of our collaboration with NASA Ames, continues to work well. The platform has seen heavy usage over the year, and has performed extremely well on our classical Michelson beam-combination infrared table.

Collaboration continued with NASA Ames, and in particular with Dr. Robert Mah. Earlier, Dr. Sebastien Morel, post-doctoral fellow at IOTA, was successful in using a simplified fringe-tracking algorithm on a laptop computer at IOTA. A number of computer interconnect problems slowed the full application of this research, but the basic principle was demonstrated successfully. Since a major activity at IOTA has been the installation of the new, real-time, control system, which will include the fringe-tracking measurement and command algorithm, Morel was also an active player in the control system development. Mid-year, Morel left IOTA to accept a position in France. In April a new full-time resident programmer, Angela Ahearn, started at IOTA. She has since proved to be a great asset to our program. Part of her work is the implementation and testing of the fringe tracking software under development with Ames.

Work also continues on the transition from our NICMOS detectors to the lower noise PICNIC detectors. This new camera has also been integrated with our new VxWorks architecture for control of all interferometer tasks. We implemented the readout electronics in FPGAs (field-programmable gate arrays), which will result in faster sampling times and therefore better immunity to atmospheric effects on the interferometer's fringes. Dr. Rafael Millan-Gabet and Mr. Ettore Pedretti, an SAO Predoctoral Fellow, are conducting this work.

In June and July 2000, we held the first of several full-scale engineering integration sessions at the IOTA site in Arizona. For this run we brought to the site the new Sun Ultra-10 instrument control workstation and the associated real-time Motorola computer and associated hardware hosting our VxWorks operating system. The hardware was purchased by SAO with funds from this grant. The programming was provided by Prof. F.P. Schloerb and colleagues at the University of Massachusetts (UMass), Amherst. This activity is part of their long-standing participation within the IOTA Consortium. The programming effort is part of the larger UMass program to build and operate a 50-m radio telescope in Mexico, so in effect, IOTA is the alpha test site for this programming.

This session was helpful in revealing a number of wiring and conceptual inconsistencies, but in spite of a number of surprises we were able to drive the two existing telescopes. We brought the computer system back to Amherst in early July for continued development of the control system.

We scheduled normal observing sessions for in the fall 2000, and capped that season at IOTA with the first successful test of an integrated optics beam combiner at any interferometer (Berger et al., 2001). Soon thereafter several other papers from IOTA were also published (Millan-Gabet et al., 2001; Kervella et al., 2001; Monnier, 2001).

In December 2000, immediately after the integrated-optics demonstration, we held our second full-scale engineering integration effort at IOTA. We reinstalled the VxWorks system, and were able to command the long delay line, the short delay line, and the third telescope as well. We were very pleased with this success, but we also realized that more programming work was needed. The computers were returned to UMass in early January 2000 for some software revisions and the next phase of upgrading.

In March 2001 we attempted to improve the flatness of our short delay line granite block, but the person we hired made an error, and gouged the surface, forcing us to send the block back to the original vendor in Vermont for repolishing, a task that we had never anticipated. Fortunately the vendor was able to respond immediately and block was returned quickly, in much better shape than before the accident. We reinstalled it in April. At the same time we focussed on the issue of our air pad flatness in the Anorad Table. We installed our best air pads and sent off several others for repolishing. This was very successful and gave us a short delay platform that was free of the occasional oscillations, which had plagued earlier operation. We subsequently had all air pads polished, and will install the remaining ones on our second short delay carriage in June 2001.

Work Remaining for the Near Future

As this report is being written, we are at Mt Hopkins working to install the two new 3-beam combination focal-plane instruments: the free-space beam combiner with classical half-reflecting beamsplitters and combiners, and the integrated optics combiner. Our plan is to test both and achieve our first phase-closure measurements by the end of June 2001. Several systems will be tested at the same time: the 3-beam star-tracker unit, the second short delay and second long delay lines, the full operation of the 3rd telescope, and the latest evolution of the computer control system. Even if we get this test accomplished successfully this month, we still have a number of programming tasks to complete before the project becomes operational. We are planning for a fall 2001 operational capability, and look forward to that occasion.

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"Interferometric observations of the semi-regular variable star SW Virginis in the K band", G. Perrin, V. Coude du Foresto, S.T. Ridgway, C. Ruilier, B. Mennesson, W.A. Traub, and M.G. Lacasse, Astronomy and Astrophysics, to be submitted, (2001).