

Near-infrared guiding and tip-tilt correction for the UC Berkeley Infrared Spatial Interferometer

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ABSTRACT

The UC Berkeley Infrared Spatial Interferometer (ISI) is a heterodyne stellar interferometer which operates in the mid-infrared between 9 and 12 microns. This wavelength range makes the ISI particularly well-suited to high resolution study of late-type stars and other objects surrounded by relatively cool dust, the emission from which peaks in the mid-infrared. Unfortunately, this same dust tends to reduce the amount of visible light available from the sources, making many interesting infrared objects too faint for the original telescope guiding system, which used a silicon CCD camera. This system has been replaced by a guiding and tip-tilt correction system based on an InSb infrared camera and a fast, controllable tilting mount for one of the mirrors in the signal path. The new system has improved the quality of ISI fringe visibility data on bright sources and allowed the study of previously inaccessible objects.

Keywords: Tip-Tilt Correction, Telescope Guiding, InSb FPA, Mid-Infrared, Interferometry

1. INTRODUCTION

The Infrared Spatial Interferometer (ISI) consists of two 1.65 m aperture telescopes, located at Mt. Wilson observatory. The ISI has been described¹ previously, and is the subject of a paper² in this volume. Each ISI telescope is equipped with a single-element HgCdTe infrared detector.³ The radiation from the source being observed is combined with that from a grating-tuned ¹³CO₂ laser, which during the course of the work described in this paper was operated at a wavelength $\lambda = 11.15 \mu\text{m}$. The combined beams, which have been arranged to have the same focal ratio, are then focused onto the detector (Fig. 1).

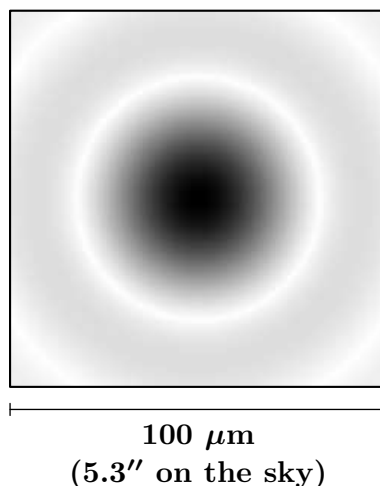


Figure 1. ISI signal detector with $\lambda = 11.15 \mu\text{m}$ beam. The detector is a square, approximately 100 μm on a side, corresponding to 5.3'' in the telescope field of view. The beam shown here, with the Airy disc and most of the first diffraction ring on the detector, would result from a point source at the center of the field.

The beams in both telescopes must be on the signal detectors simultaneously in order for the interferometer to detect fringes. Deviations in the beam position corresponding to as little as $1''$ on the sky can result in a significant loss of fringe signal. In addition, some structure, such as that in the dust shells around evolved stars, is present more than $1''$ from the center of the field of view, and is therefore imaged onto the edge of the detector. Information about this structure will be lost if the beam does not remain centered. There are two major obstacles which must be overcome in order to keep the telescope beams centered. Small errors in the telescope star tracking occur over the course of a few seconds, while on a time scale ranging from tens to hundreds of milliseconds, atmospheric distortion of the wavefront from the source displaces the beam.

When the ISI was first built, guiding of the telescopes was carried out with a manual control, used by the operator to send corrections to the telescope servo system. The first autoguiding system used an inexpensive surveillance camera, which was later replaced with an astronomical grade silicon CCD-based camera. For sources with adequate visible flux, this system was able to correct errors in the telescope guiding, but the maximum frame rate of 10 Hz was not sufficient for fully correcting atmospheric fluctuations. In addition, the need for high flux in the visible presented a problem. The ISI is used to observe sources with substantial mid-infrared flux, and objects with high flux in this wavelength range tend to be surrounded by dust, which reduces the amount of visible radiation available to the guider camera. Table 1 gives photon fluxes from some typical ISI targets.

Table 1. Photon fluxes⁴ from a sample of ISI observing targets. Values shown for variable stars are averages.

Source	V band flux	K band flux
	Photons per second into ISI telescope $\div 10^6$	
α Boo	21,000	72,000
α Tau	9,600	60,000
α Sco	8,300	160,000
α Ori	8,300	150,000
α Her	1,100	110,000
\circ Cet	80	72,000
R Leo	13	50,000
IRC +10420	8	290
CIT 3	5	720
IRC +10216	0.3	1,100
IK Tau	0.1	12,000

The CCD-based guiding system, in order to function effectively, had to acquire at least one frame per second with an adequate signal to noise ratio for the control computer to determine a star position. This condition resulted in a lower flux limit, after various losses in the optical system, sources of noise, and spreading of the star image on the CCD were taken into account, of about 5×10^7 photons per second incident on the primary mirror. This prevented the ISI from observing a number of interesting sources.

A significant gain in photon flux is available in the near-infrared, hence the new ISI guiding system is based on an InSb array detector which is sensitive to infrared light of between 1 and $5 \mu\text{m}$ wavelength. The camera is equipped with an astronomical K band filter (half-power points at 2.0 and $2.4 \mu\text{m}$) in order to reduce background noise. This camera allows the guiding system to follow the dim stars which were previously inaccessible, and for the brighter stars (at K band), it allows short enough exposures to do tip-tilt correction.

2. OPTICAL CONFIGURATION AND HARDWARE

After the light from the source is focused by the paraboloidal primary mirror in one of the ISI telescopes, it enters a Schwarzschild optical system, as shown in Fig. 2. This combination of two front-surface spherical mirrors collimates the beam with minimal aberration and without the use of transmissive optics. A virtual pupil lies approximately 30 mm behind the tip-tilt mirror, toward the paraboloid. Due to the large focal ratio of the outgoing beam ($f/89$), the displacement due to the offset of the tip-tilt mirror from this pupil is negligible.

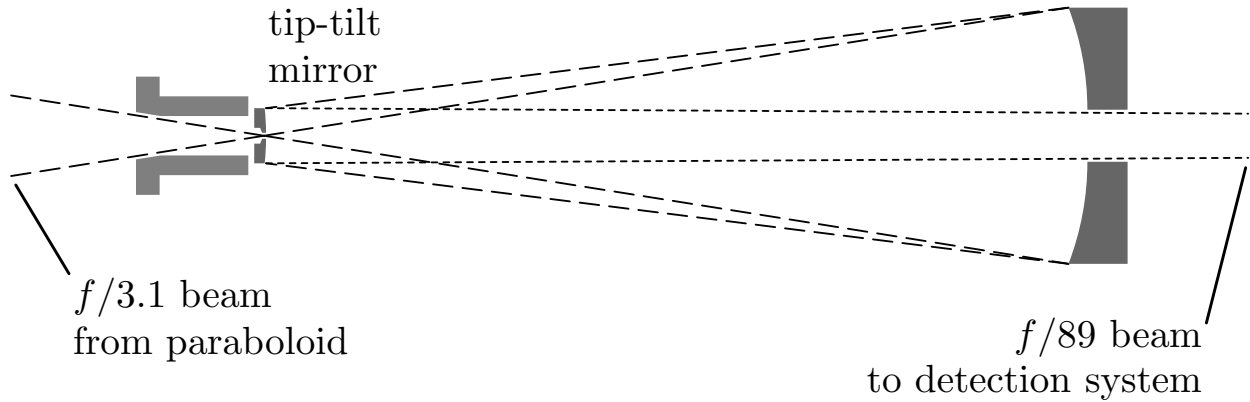


Figure 2. Schwarzschild optical system and telescope beam. The focus of the ISI telescope primary mirror lies at the center of the tip-tilt mirror.

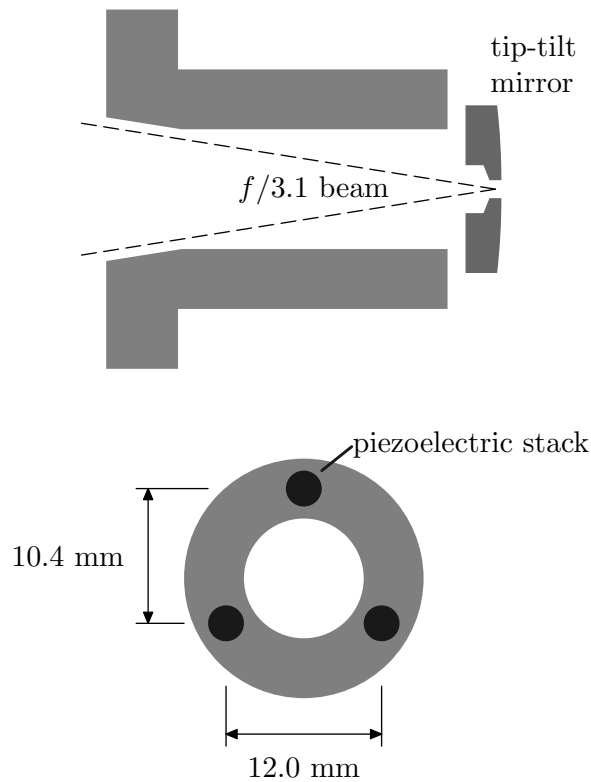


Figure 3. Tip-tilt actuator side and front views. Each stack has a throw of $12 \mu\text{m}$.

Figure 3 shows an enlarged view of the tip-tilt actuator. The actuator was manufactured by Physik Instrumente (model S-315.10, with the addition of a small conical bore at the end to accommodate the beam). The tip-tilt mirror is fastened to a thin movable platform (not shown in the figure) at the front end of the actuator. The actuator has three piezoelectric stacks, each with a $12 \mu\text{m}$ throw, positioned in an equilateral triangle. The spacing of the stacks and its placement in the optical system give the tip-tilt mirror a range of positions on the sky as shown in Fig. 4. In all but the very worst seeing conditions at Mt. Wilson observatory, the range of the tip-tilt mirror has been sufficient to correct for the atmospheric fluctuations. The remaining nights, during which the star image diameters vary from

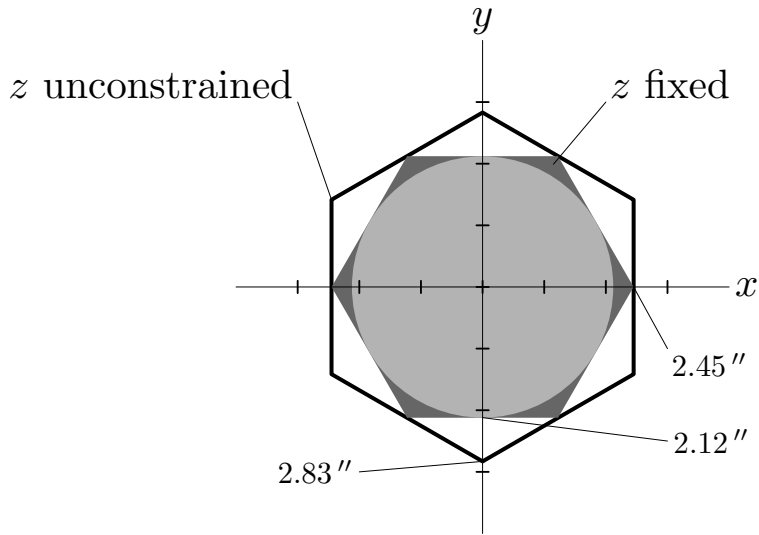


Figure 4. Tip-tilt range on the sky. The axis markings are spaced at $1''$. The outer hexagon encloses the region which is accessible if the mirror is unconstrained in the direction (z) along the optical axis. If the center of the mirror is fixed in position, the star can be moved anywhere within the inner hexagon. The central circle is the region in which all directions are available, and is the range over which the tip-tilt system can move to correct the apparent position of the star.

5–10'', do not allow the acquisition of useful fringe visibility data.

After being collimated by the Schwarzschild optical system, the beam is split into two parts by a dichroic beamsplitter (Fig. 5). The mid-infrared radiation is sent to the fringe detection system, while the near-infrared light is sent into the guider camera.

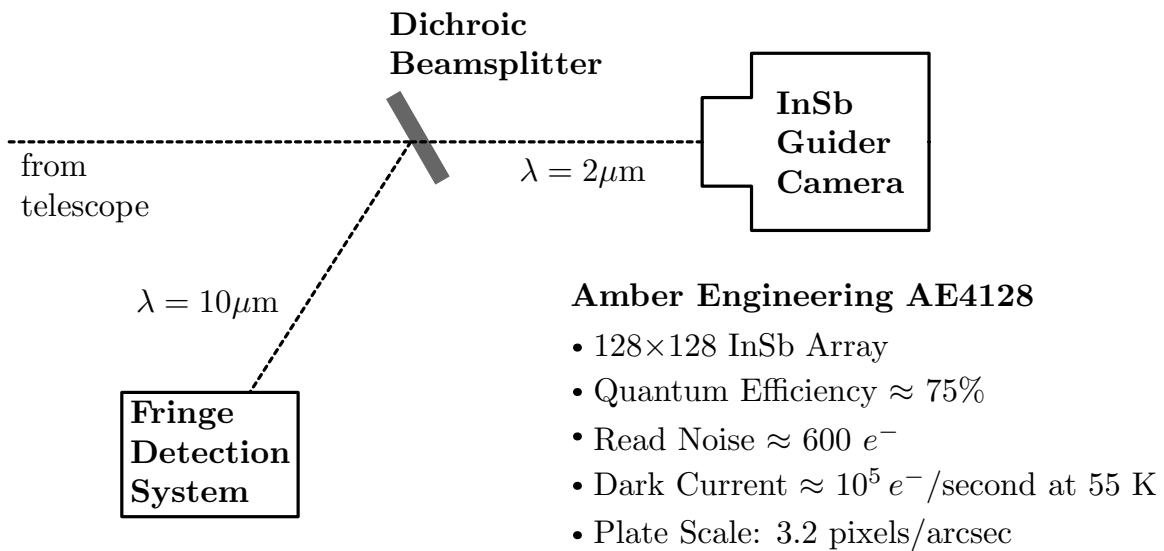


Figure 5. Guider camera and dichroic beam splitter.

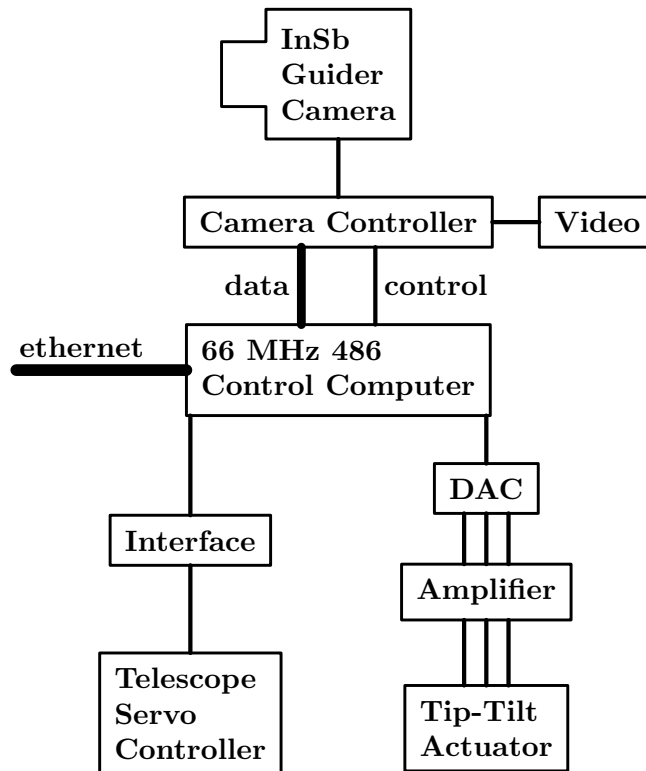


Figure 6. Guiding system configuration.

3. SYSTEM OPERATION AND CONTROL

A block diagram of the ISI guiding and tip-tilt correction system is shown in Fig. 6. The system is controlled by an Intel 486-based PC running MS-DOS. The PC receives instructions and control information over the ethernet, which is connected to the ISI real-time control system and the Sun workstation on which the user interface runs. The networking software used by the PC is Sun Microsystems PC-NFS, which is no longer available.

The image taken by the guider camera is digitized by the camera controller, which does a gain and offset correction before passing the image to the PC via a digital image acquisition card (Dipix P360F). The PC can change the operating parameters of the camera, such as the frame rate, integration time, and gain settings by sending commands over a serial line to the controller. Once the image is in the PC memory, a centroid is computed for a small region which includes the star image, and the positional error of the image is calculated using the centroid.

Although it has been pointed out^{5,6} that for imaging tip-tilt systems, tracking the brightest pixel can give better results than tracking the centroid, for the ISI, centroid tracking gives more consistent results over a wide range of seeing conditions. The problem of tip-tilt tracking for the ISI, with its single-element detectors, differs from that for an imaging system. A large fraction of the uncertainty in the ISI fringe visibility measurement is due to fluctuations in the infrared power measured by each telescope. Centroiding allows the maximum amount of energy from the star to be consistently available on the detector.

The positional error is used by the PC to correct the position of the star by adjusting both the tip-tilt actuator and the telescope servo controller. The sequence of image capture, error computation, and correction is carried out by the PC in two nested feedback loops. The tip-tilt loop, which runs at rates up to 73 Hz[†], operates continually, with an update of the actuator position each time an image is taken. Every few seconds (with the exact interval depending on the tip-tilt loop rate), the average offset of the tip-tilt actuator from its center position is computed, and the telescope servo is adjusted to remove this offset.

[†]At a closed-loop rate of 73 Hz, a full image capture, error computation, and correction cycle occurs every 13.7 ms.

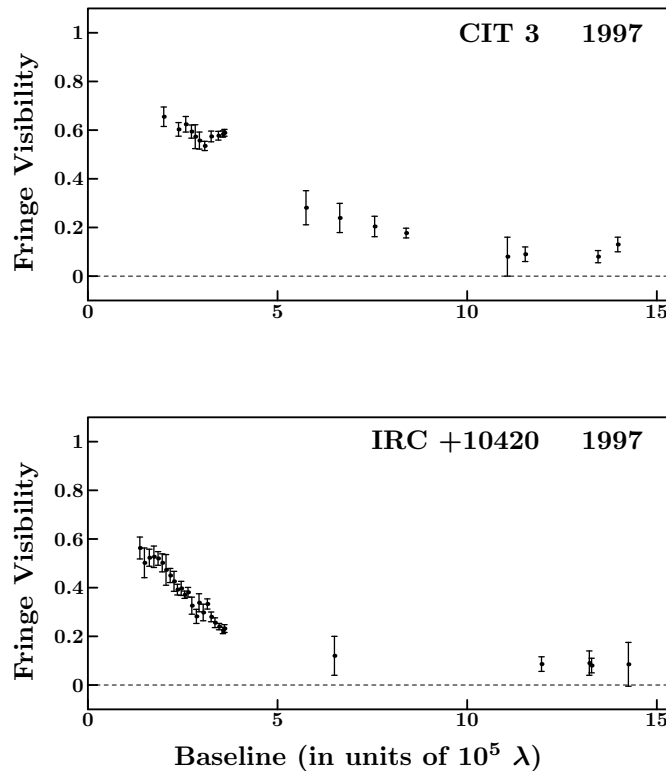


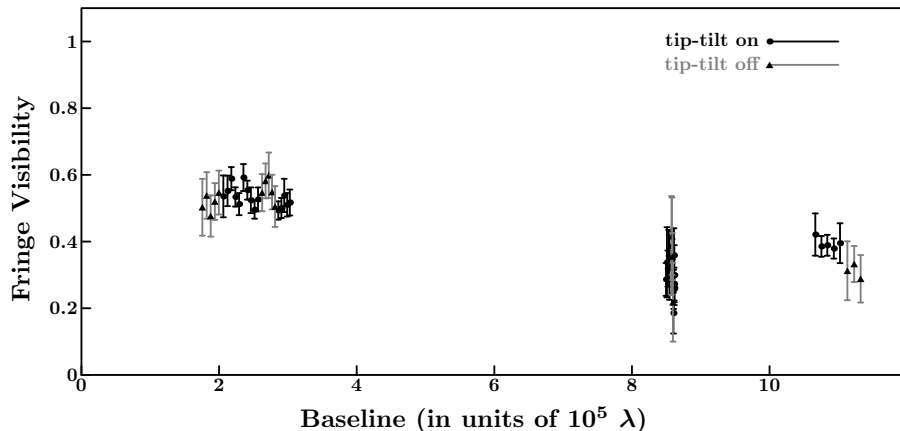
Figure 7. Preliminary fringe visibility data on two previously inaccessible sources. Some uncertainty remains about the accuracy of the data shown here at baselines shorter than $2 \times 10^5 \lambda$. Revised data will appear in a future publication.

4. EXPERIMENTAL RESULTS

As expected, the InSb guider camera has enabled observations on stars which were impossible to detect with the silicon CCD camera. Fringe visibility curves for CIT 3 and IRC +10420 are shown in Fig. 7. Visibility data⁷ have also been measured for IK Tauri, on which the operator was previously forced to guide by hand, since the CCD image was too dim for autoguiding. Some preliminary work has been done on CIT 6 and R Cancri, and more data will be taken on these sources in the upcoming observing season. Although the Amber camera (see details in Fig. 5) is designed for high-background applications, and has higher than desirable dark current and read noise, the guiding system has proved capable of tracking reliably on stars down to magnitude 3 in K band (equivalent to 2.9×10^8 photons per second incident on the ISI primary mirror).

The tip-tilt system has provided a substantial improvement in the quality of data taken on bright targets. The system can be used on sources brighter than magnitude 0 in K band (4.5×10^9 photons per second incident on the primary mirror). Figure 8 shows the results for three nights when the tip-tilt system was turned off for short periods of time during observations of α Orionis. The fringe visibility values shown for each night are raw data, and were taken consecutively, with no delay between the “on” points and the “off” points. These measurements, taken on a total of 5 nights with varying seeing conditions, showed that the tip-tilt system provides an average increase of 40% in the mid-infrared power received by the signal detectors. As can be seen from the error bars and table in Fig. 8, the RMS fluctuations in the fringe visibility measurement drop by about 40% when the tip-tilt system is on. Although improvement was always seen when the system was in use, the magnitude of that improvement varied widely (e.g. increase of IR power between 12% and 96%) depending on the seeing conditions.

The data at the longest baseline in Fig. 8 show a marked increase in fringe visibility when the tip-tilt system is on. This is most likely due to the fact that at the longer baseline, there are more atmospheric fluctuations which are



	IR Power		RMS Visibility Fluctuation
	T1	T2	
12Aug97	35.9	77.0	0.037
	27.5	53.2	0.063
13Oct97	25.0	85.0	0.043
	20.2	65.4	0.071
09Dec97	25.2	165.5	0.070
	13.5	93.5	0.113
Avg on/off	1.41	1.54	0.607

Figure 8. Tip-tilt results on α Orionis. Observations with the tip-tilt system off are shown in gray. Infrared power measurements are taken independently with the signal detectors in Telescope 1 and Telescope 2.

not correlated between the two telescopes. The tip-tilt system compensates for some of these fluctuations, keeping the star images centered on both detectors. This results in a more accurate visibility measurement.

During these tests, the tip-tilt system was run at a closed-loop rate of 73 Hz. No significant difference was seen when the system was run at 55 Hz, and the results at rates lower than this varied depending on seeing conditions.

5. SUMMARY

The ISI telescopes have been equipped with a new guiding and tip-tilt correction system based on a 128×128 InSb focal plane array. This system has enabled the instrument to gather data on a number of sources which were not previously accessible, such as CIT 3, IRC +10420, and CIT 6. The tip-tilt system has significantly improved the data quality on brighter sources. In tests on α Orionis, the average infrared power received by the signal detectors was increased by about 40%, and the fluctuations in the final fringe visibility measurements were reduced, also by about 40%. In addition, the fringe visibility value obtained in some cases was more accurate due to stabilization of the star images on the signal detectors. This new system will allow the ISI to gather more data in less time and on a wider range of sources in the future.

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