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CCD TV FOCAL PLANE GUIDER DEVELOPMENT

and

COMPARISON TO SIRTF APPLICATIONS

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1) Introduction:

It is expected that the SIRTF payload will use a CCD TV focal plane fine guidance sensor to provide acquisition of sources and tracking stability of the telescope. Initial tests of CCD TV cameras for SIRTF by JPL some years ago were encouraging yet somewhat inconclusive since limited on-telescope testing was carried out and the range of stellar magnitudes used in the tests fell short of the 14th to 16th range for Mv which is expected to be required of the SIRTF fine guidance sensor.

We have been working to develop CCD TV cameras and guiders at Lick Observatory for several years and have produced state of the the art CCD TV systems for our internal use. NASA decided to provide additional support to this development effort so that the limits of this technology could be established and a comparison between SIRTF requirements and practical systems could be put on a more quantitative basis.

This report represents the results of work carried out at LIck observatory which was designed to characterize present CCD autoguiding technology and relate it to SIRTF applications. Two different design types of CCD camera were constructed using virtual phase and burred channel CCD sensors. A simple autoguider has been built and used on the KAO, Mt. Lemon and Mt. Hamilton telescopes. A video image processing system was also constructed inorder to characterize the the performance of the auto guider and CCD cameras. These systems are described in section 3.

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2) SIRTF Guiding Requirements:

The SIRTF concept has been through a number of design studies and scientific reviews. The present requirements for the facilities fine guidance sensor are defined in the PD1010 document (1988). As currently conceived the SIRTF will require stabilization of slow (.2 -1 sec) drifts of the telescope and also need image adjustments in the focal plane to compensate for mechanical or optical changes induced in the telescope structure by solar heating. The IRAC and MIPS instruments will use moderate integration times of (10-50 sec) and require .15 arc second stability in both tracking and pointing as per the PD1010.

The present design of the SIRTF uses a Fine Guidance Sensor (FGS) to control both the stability and pointing of the telesecope in order to meet the specifications set out in PD1010. The error budget for the FGS is not yet allocated however .05 to .1 arcsecond performance of the FGS will certainly be needed if the telescope is to meet the requirements laid down in the PD1010. Presently the FGS is baselined as a low light level CCD TV camera. An additional requirement placed on the FGS is that it must have a FOV which will allow a 90% chance of finding suitable guide stars anywhere on the celestial sphere. This requirement places a limit on the minimum FOV of the FGS which is in the neighborhood of 10'. Of course the required FOV is a function of the sensitivity of the CCD camera and the accuracy and speed with which pointing errors must be controlled. The requirements of the SIRTF FGS are about 10x more stringent in pointing precision and comparable in FOV and speed to our present KAO guiders performance. Section 5 of this report discusses the comparison of the proposed SIRTF FGS and present performance of the Lick KAO guider in detail.

3) Description of Lick Observatory Hardware:

Autoguider:

CCD offset-auto guiders have been in use at Lick observatory for past few years. A block diagram of the Lick KAO guider is shown in figure 1. The basic elements of the guider are: an integrating CCD TV camera, a CCD controller, a frame buffer memory, a video interface board and a C-64 microcomputer. The principle of operation of the autoguider requires that the the CCD video output from the frame buffer sync to the C-64's video display. The position of a stars image on the CCD is then determined by using a video comparitor on the CCD video to trigger the light pen input of the computer. The C-64 computer provides a gate signal to the comparator so that only a small portion of each scan line is isolated and able to trigger the light pen. On successive scans of the video raster the C-64 uses the gate to define a box (typically 20 arc seconds in size) which is examined for the presence of an image which is above a preset threshold. The video comparator thus provides one level of grey scale resolution for the image of a star on the CCD and allows the computer to recognize the position of the stars image as referenced to the scan lines of the video display. Typically a stars image occupies several scan lines and a centroid is calculated from 6 to 8 points as measured by the comparator/lightpen. Offset guiding on two stars is used to compensate for field rotation of the telescope. Two communication ports are also used for input and output from the computer. An RS232 serial port for communications with other computers and an 8 bit parallel port for telescope control.
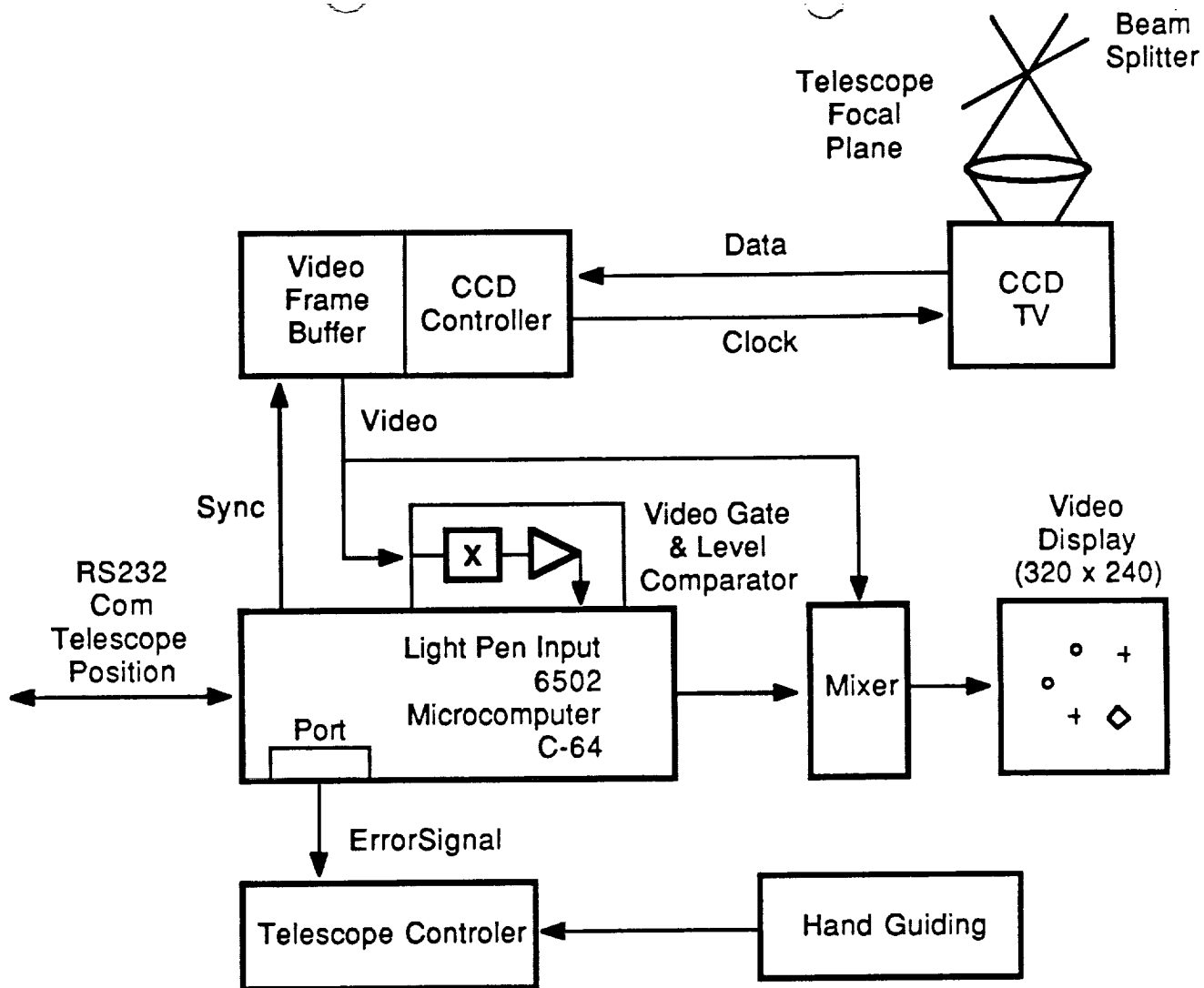
figure 1

(4)

At a telescope scale of 13 arc seconds/mm the single CCD TV pixel has a size of 1.2 an 1.8 arc seconds in two orthogonal axes. Thus the precision of guiding and offseting can be a few tenths of an arc second depending on the signal to noise and relative positions of the guide stars. The field of view of the camera consists of a square 256 x 256 pixels in size. The FOV size is presently limited by the display memory to be about 8 arc minutes along a diagonal section of the chip. A somewhat larger FOV (11') can be obtained from the guider by bining four pixels together electronically on the chip before they are digitized and put into the display memory. Ofcourse the TV resolution is degraded to about 3 arcseconds per pixel in the bining mode of operation.

In practical operation the guider offset guiding accuracy is limited by our ability to determine the correct scale of the focal plane. We have found that the focal plane scale factor (arcseconds/mm) is usually determined no better than about one percent so that large, offsets 200 to 250 arc seconds, are typically in error by 2 to 3 arcseconds. It is also our experience that the formal statistical errors to the guiding based on the S/N ratio of the images are often much smaller than the actual performance of the guider using small offsets. We also find that for many fields which are of interest to IR astronomy are heavily obscured and contain only faint guide stars. Typically CCD integration times of 1 to 3 seconds are used for guiding and especially on the KAO we see a degradation of guiding accuracy due to high frequency mechanical jitter which is outside the control bandwidth of the of the autoguiding control loop.
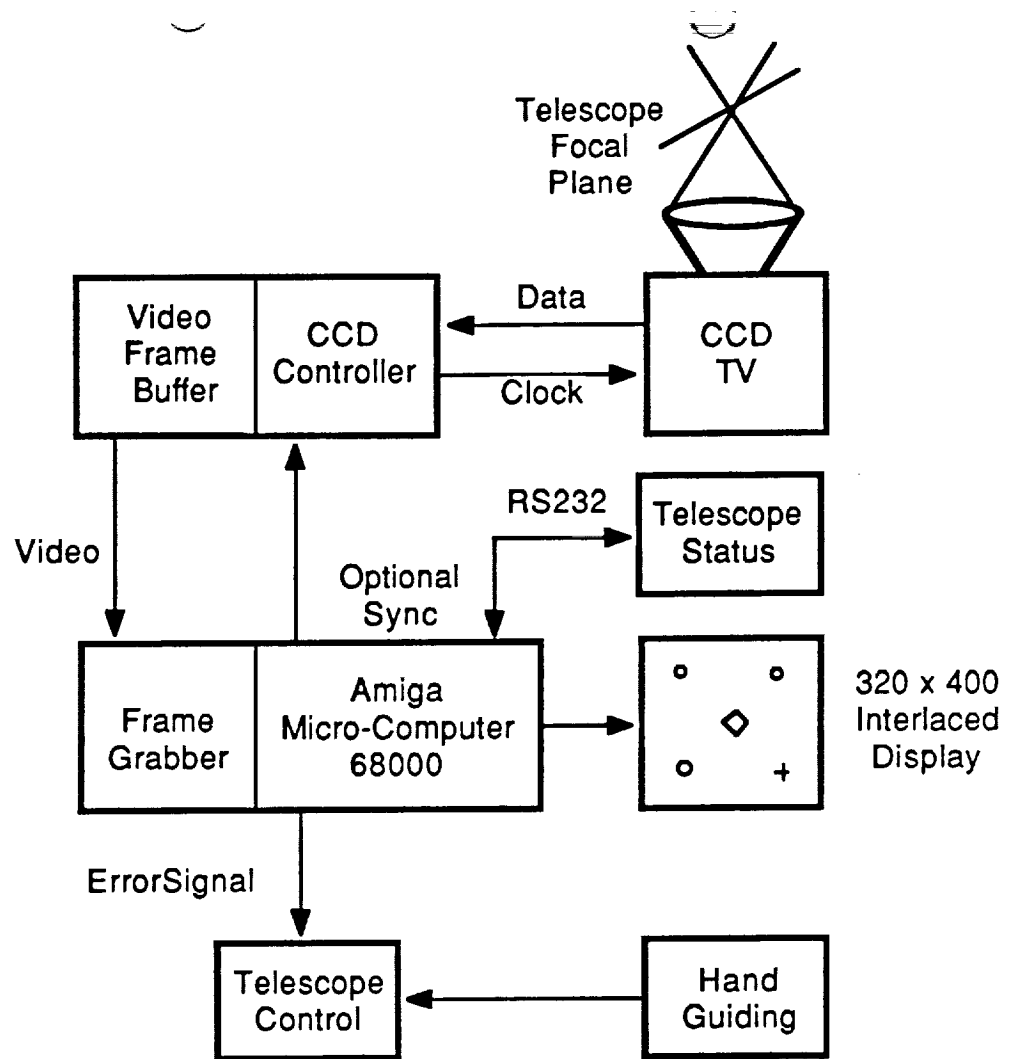
(5)

figure 2

Amiga image processor system:

An image processing system has been developed to determine the performance of the C-64 guider and evaluate the potential of CCD TV cameras for use as guide sensors. The block diagram of this system is shown in figure 2. The image processor uses an Amiga microcomputer and a commercial frame grabber to digitize the RS170 video produced by the CCD TV. The digitized CCD fame is stored in RAM memory and then analyzed by specially written software. At present the offset between of two stars, rms tracking jitter and the image full width at one half maximum are measured in real time. Digital images can also be recorded and processed at a later time. A Five bit flash A to D converter is used in the frame grabber hardware which limits the measurement precision of a single pixel to about 3%. The Amiga system has been used to analyze images from KAO and ground based observing runs, as well as perform laboratory tests with our CCD TV systems. Some of the results of the on telescope testing are shown in appendix D.

CCD TV Camears:

Two different types of CCD TV cameras have been developed at Lick observatory. The first to be constructed was a virtual phase camera based on the Texas Instruments Corp. 4849 chip. This camera is described in Appendices B and C. The second camera type uses a GEC Corp. P86 123 chip (see appendix E) with a modified controller and camera head taken over from the first design. The two cameras are quite similar in performance. The newer GEC chip offers a somewhat lower readout noise and better pixel to pixel uniformity than the TI chip with the penalty that it has higher dark current and therefore

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must be run at a lower temperature than the virtual phase chip.
For integration times of less than 30 seconds broad band images
are limited by sky background for both cameras and the lower dark
current of the TI 4849 chip at the relatively warm temperatures
of the thermoelectric cooler offers no advantage.

Camera and transfer optics:

A schematic diagram of the relay optics used in the guider is
shown in figure 3. Highly efficient optics have been used inorder
to obtain the best possible thruput. The IR beam splitter is a gold
film with a visible (7000 A) anti-reflection coating which has about
50% transmission in optical band used by the CCD. The windows and
all lens elements are also AR coated with an average loss of no more
than 2% per surface. Both of the relay mirrors are coated with a
multilayer silver coating which has virtually no polarization loss
and a reflectivity of 98% in the optical band.

The optical arrangement shown in the figure is designed to relay
the light from the telescope focal plane to the CCD chip with a
reduction in image size so as to optimize the match between the
22um CCD pixel size and the diameter of a stellar image. This focal
reduction has been achieved using a 300mm collimator lens and a 50mm
commercial camera lens. Thus the focal plane reduction is 6:1. It
was also important to the design of the optics to place the exit
pupil as formed by the collimator near the camera lens in order to
make the f number of the camera lens as large as possible for a
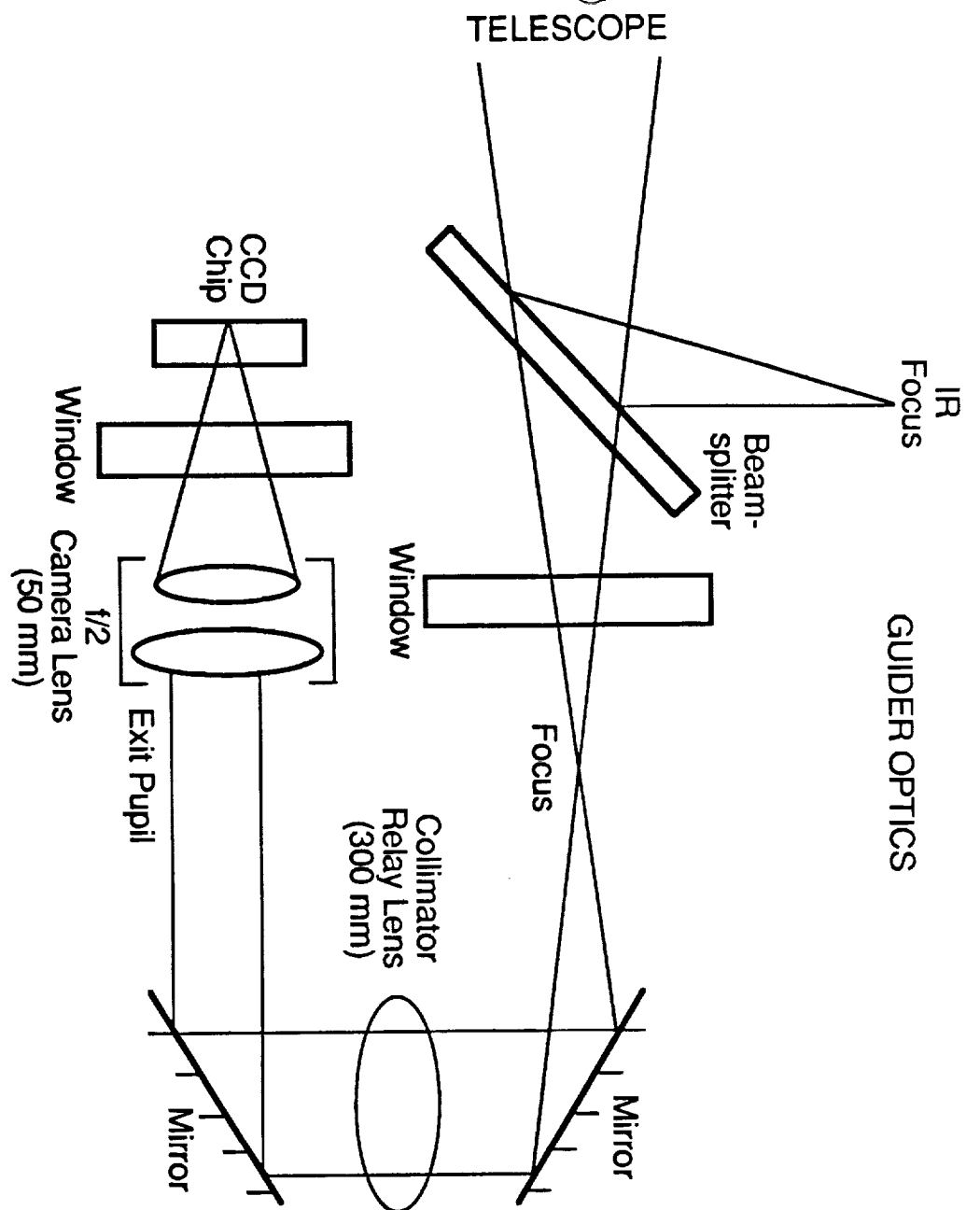10 arc minute unobscured field of view.

TELESCOPE

IR Focus

Beam-splitter

GUIDER OPTICS

Window

Focus

Collimator Relay Lens (300 mm)

Mirror

Mirror

CCD Chip

Window

Camera Lens (50 mm)

f/2

Exit Pupil

figure 3

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4) CCD performance and Guider stability

A series of simple calculations have been performed inorder
to evaluate the observed performance of the Lick CCD autoguider.
The calculation determines the error in the centroid position of an
image produced by the addition of random noise to each image pixel.
Figure 4 shows the results of these calculations by comparing
theoretically the expected rms centroid motion of an image vs the
signal to noise in the pixels which form the image. Also plotted
in the figure is the stellar magnitude required to obtain a given
signal to noise ratio using the Lick autoguider on the KAO. (36"
telescope). This graph represents a convenient and compact summary
of the performance which can be expected with CCD auto guiders and
it may easily scaled to the SIRTF telescope with some provisos.
The simple model used to calculate the curves in the figure assumed
uniform illumination of each pixel and only a single row of pixels
surrounding the image was used to subtract the background. In a
real system the light will tend to be more concentrated and more
pixels would be included in the background subtraction. Both of these
effects will tend toward increasing the centroid error for a given
signal to noise ratio by about 50%. Also the affect of flat field
corrections has not been included in the calculation. The effect
of pixel to pixel variations in response on centroid error is
identical to that of random noise as entered in the calculations.
Typically we find rms pixel to pixel variations on the the order
of a few percent for the CCD'S used in these tests and we expect
their effects to be negligible for centroid accuracies greater than
.05 pixels. Both the Amiga system and the C-64 guider operate in

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figure 4

RMS centroid error vs rms S/N per pixel
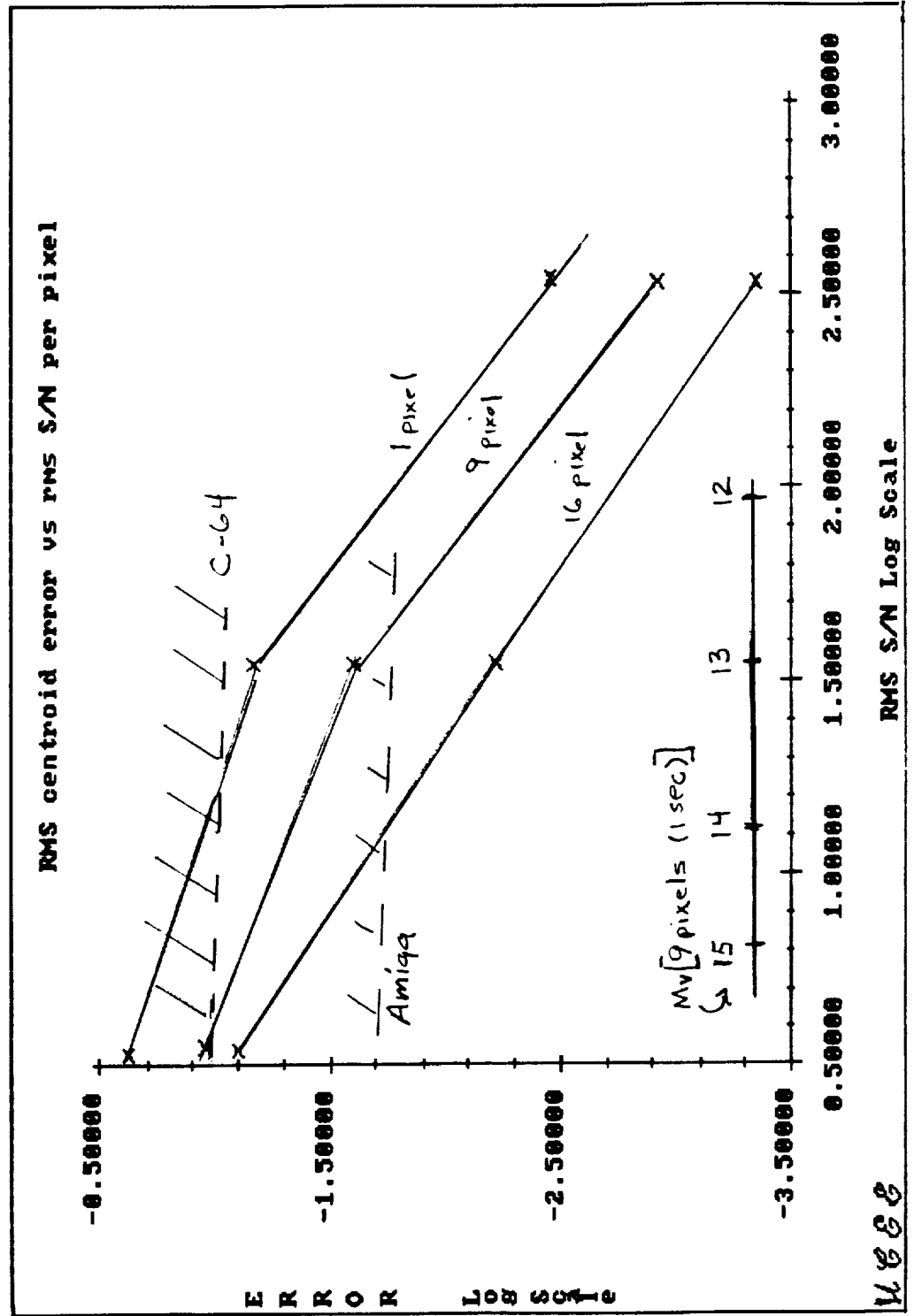
a domain which does not require flat fielding of the CCD'S response.

Measurements of the sensitivity of the Lick CCD camera to star light have been carried out using the 3M, 1M and KAO telescopes. The data points in figure 5 represent some of the results of these tests for one second integration periods. The solid line in the figure is a plot of the RMS signal to noise vs stellar magnitude for a detector having a quantum efficiency of 30%. The dashed line in the figure represents the rms per pixel signal to noise ratio for an ideal system having 30% optical efficiency and a fixed 25 electron readout noise. It can be seen that the two lines intersect at about 14 magnitude demonstrating that the CCD is read noise limited at Mv = 15th magnitude for one second exposures. The signal to noise measurements made for the Lick camera including losses associated with the transfer optical components fall very close to the calculated lines indicating that the that the effective quantum efficiency of the guiding system is in the range of 20 to 25%. The expected losses in the telescope and transfer optics of the camera system should limit the transmission of light to the CCD chip to about 35% of that which is incident on the primary mirror. Since the CCD device has a measured quantum efficiency of about 50% we should expect a total system efficiency of no more than 15 to 20%. This discrepancy is within the errors of measurement and it would seem likely that the actual efficiency of the system is about 20%. The efficiency of the CCD camera used on the 1M telescope as shown in figure 5 should be nearly a factor of two higher than the KAO system since the 1M test setup did not include an infrared beamsplitter in the optical train.
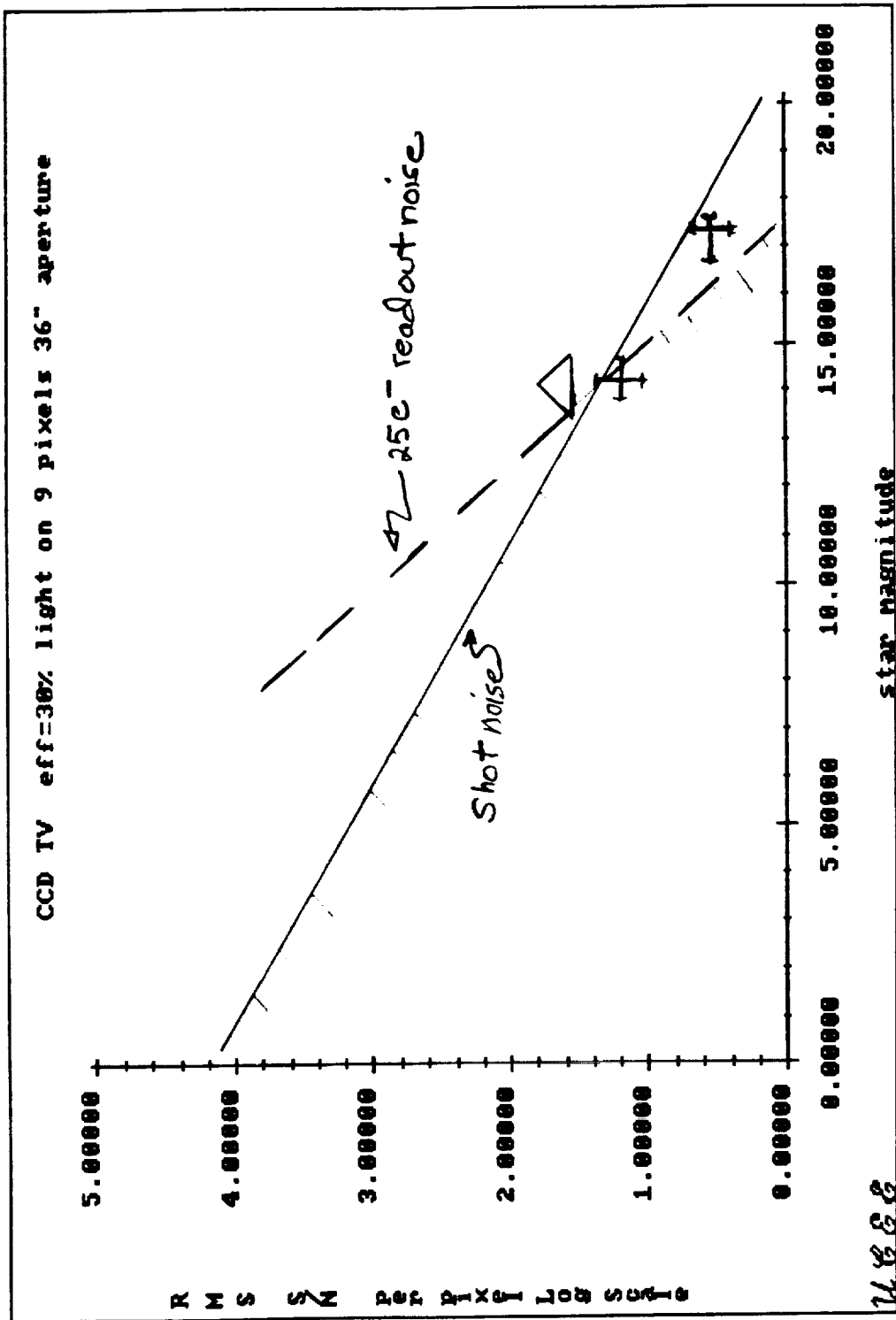
CCD TV eff=30% light on 9 pixels 36" aperture

figure 5

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5) Conclusions relating to SIRTF requirements

Sensitivity:

One of the primary requirements placed on the SIRTF FGS is that it be able to acquire suitable guide stars available in its FOV more than 90% of the time. Stauffer has concluded that with a 15 to 20 arc minute field of view the FGS would be need to use stars of visual magnitude 14.5 in order to satisfy this requirement at the galactic poles. It is clear from an analysis of the data presented in figures 4 and 5 that presently available CCD chips fall short of this goal. A simple example will demonstrate this point. Due to its smaller aperture the SIRTF will be collect approximately 2 times less light than the KAO telescope thus the magnitude limit imposed by Stauffer would translate into Mv = 14.8 for the KAO. If the middle curve in figure 4 (9 pixel) is then used to estimate performance used we could then expect to obtain .1 pixel rms error centroid positions with the Lick guider using 1 second integrations. For a telescope scale of 1 arc second per pixel the guiding jitter induced solely by the signal to noise ratio of the image would be .1 arc second and the FOV of the the CCD would be only 5 arc minutes. Thus the scaled performance of the Lick guider falls about a factor of two to three short of the 10 to 15 arc minute FOV and .05 rms jitter required for the FGS. Clearly a larger FOV can be obtained with a larger format CCD chip, 800x800 or 1000x1000 chips may be available and in practical use by the time the FGS is designed. The sensitivity to reach .05 arc second pointing and guiding at Mv= 14.5 is likely to be a much more difficult specification since it will require the FGS to have a very high (greater than 40%) optical efficiency which may be incompatible with the low heat leak design of the SIRTF focal plane.

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figure 1

Block diagram of the KAO auto guider showing the interconnection

of components. The interfacing between the C-64 and the CCD TV is

performed by a sync stripper and a video comparator. The syc stripper

provides the raster drive signals to the CCD frame buffer memory and

the video comparator allows the C-64 to measure the position of an

image within the frame buffer raster.

figure 2

Block diagram of the Amiga based TV image processor system.

The basic component of the system is a commercial frame grabber

manufactured by A Squared Corp. of Oakland Calif. The frame grabber

provides the complete interface between the CCD TV/controller and the

processing computer.

Figure 3

General layout of the CCD guider optics. The lens in the system are

a commercial 35mm camera lens f/2 50mm focal length and an f/5

achromat 300mm focal length which gives a focal plane scale reduction

factor of 8.7.

Figure 4

Guiding error as a function of signal to noise in the image. Three

curves are presented where centroid errors have been calculated for

an unchopped image having a uniform distribution of light spread over

1, 9, and 16 pixels. The horizontal axis is also displayed as function

of visual magnitude based on CCD sensitivity measurements made on the

KAO using the Lick autoguider. The domain of operation of the C-64

and Amiga CCD systems as autoguiders is also indicated by cross
hatched lines in the figure.

Figure 5

Comparision of the sensitivity of the Lick CCD TV camera to an
ideal detector. The crosses represent measurements of the rms signal
to noise ratio for the TI CCD TV made on the KAO using unchopped
images. The triangle data point is typical of the performance of
the camera used with the Lick 1M telescope (scaled to a 36" aperture).
The solid curve in the figure is a calculation of the photon shot
noise rms signal to noise ratio for an ideal detector having an
optical band width of 4000 angstroms and a quantum efficiency of 30%.
The dashed curve represents the expected signal to noise ratio for
a 30% efficient system limited by a fixed readout noise of 25
electrons. Both calculations and measurements have been normalized
to an image which is uniformly spread over 9 CCD pixels.

Appendix D : Examples of raw data from various telescopes

Figure 1D

Histogram image of images and tracking plot from the 3M telescope on
Mt.Hamilton. These data were taken at a telescope scale of .5 and
.78 arcseconds per CCD pixel. The histogram on the right of the figure
shows one of the double images of MK 463 (approximate Mv = 14.7). The
left image of the object is falling on a spectrograph slit and appears
to be cut off. The tracking plot represents about 2 min. of data
The upper curve labeled (i) is the instantaneous image size in the
x coordinate which on average was 5.8 pixels. dx and dy are the
instantaneous image centroids plotted with a resolution of about .1
pixels per point. The scatter plot (lower left) represents the image
motion in xy coordinates. During this time period the rms tracking
of the telescope was about .2 arcseconds.

Figure 2D

Scatter plot of image position from on the KAO under stable conditions
using the Lick autoguider. Plots for two stars are shown one 6th magnitude
the other 12th magnitude. RMS tracking for the telescope was about
1 arc second during the measurements. The telescope tracking is not
limited by the statistical noise in the autoguider images but rather
by the high frequency stabilization system on the KAO which has a
magnitude limit of Mv =14.

Figure 3D

Test of the Amiga image processing system using a "hot" pixel on
the CCD. This plot is analogous to figure 1D except that the "hot"
pixel acts like a stationary star. The rms jitter in the frame grabber

is about .15 pixels. Under ideal conditions in the laboratory the
Amiga system has a stability of about .02 pixels rms. The difference
between the lab measurements and in flight measurements of system
stability results from a long cable run and none ideal video signals
 with extra video noise which degrades the lock between the frame
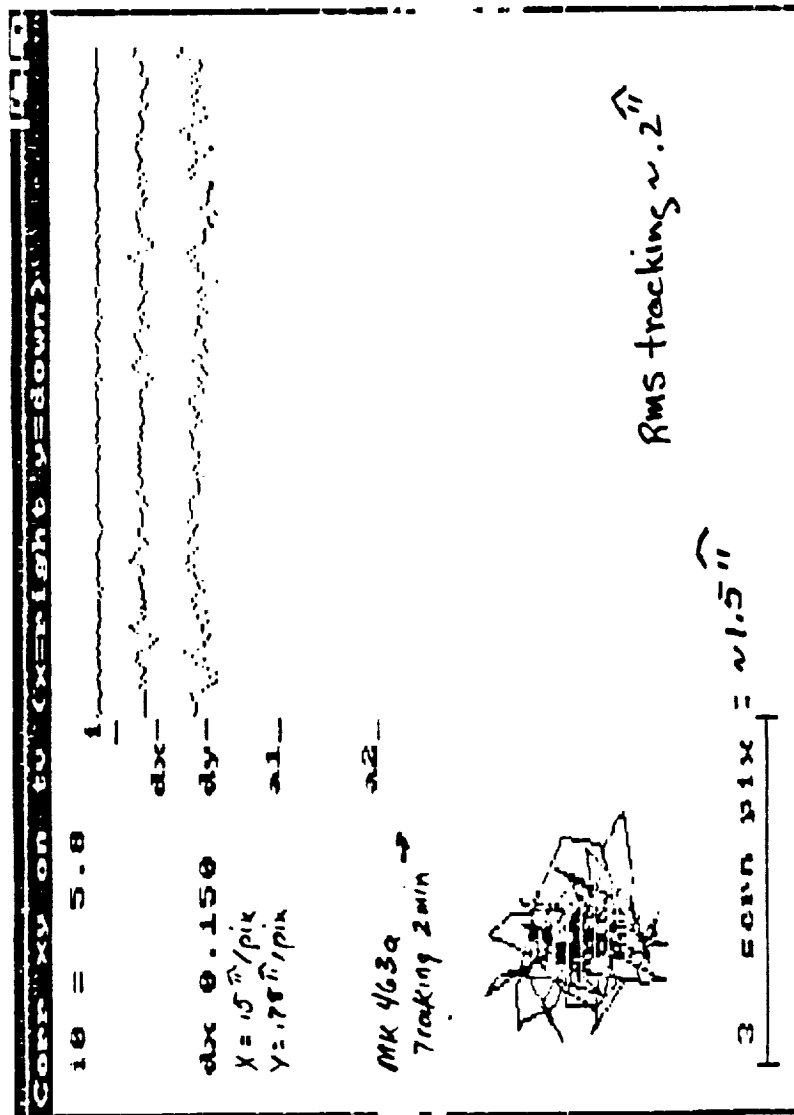grabber and the actual CCD image.

Figure 4D

Image histogram and KAO tracking for a 12th magnitude star. The image
size on the KAO is variable typically being 15 to 20 arcseconds. The
tracking plot has an rms deviation of the centroid of about 1.5 arc
seconds which is somewhat worse than the performance demonstrated
in figure 2D.

Figure 5D-6D

Raw 1 second CCD images of the regions around Mon R2 and SgrA. The
faint stars labeled A and B in figure 6D are about 30 arc seconds from
the SgrA source IRS1 and commonly used as guide stars on ground
based telescopes.

6/13/68   120"

MK 463a   MV≤14.7

guiding on a

image from MK463b
in S.I.t

∂x∂y scale ~ .1"/point

Copr xy on to (x=right y=down)

18 = 5.8

dx   dy   ~1   ~2

dx 0.150
X = .5"/pix
Y:.78"/pix

MK 463a
Tracking 2 min

RMS tracking ~.2"

scan pix = ~1.5"

3

3m telescope

figure 1D

figure 2.D

Corr xy on tv (x=right y=down)

i0 = 2.3

i
dx
dy

x = 91
dx 0.100

Hot pixel in flight with sky
rms ≈ .15 pixel

KAO 6/24/88

1
scale

figure 3D

3d 20x20 on tv (x=right ,y=down)
07-01-1988 00:06:16

1107 19%

y|x

x/'_y

Mv ~ 12th

Corr xy on tv (x=right y=down)

i0 = 4.5

% = 30
dx 0.500

i

dx

dy

---

rms tracking ~.5pix

~ 1.5"

s

scale

CCD KAO

figure 4D

Mon R2 '/ss KAO
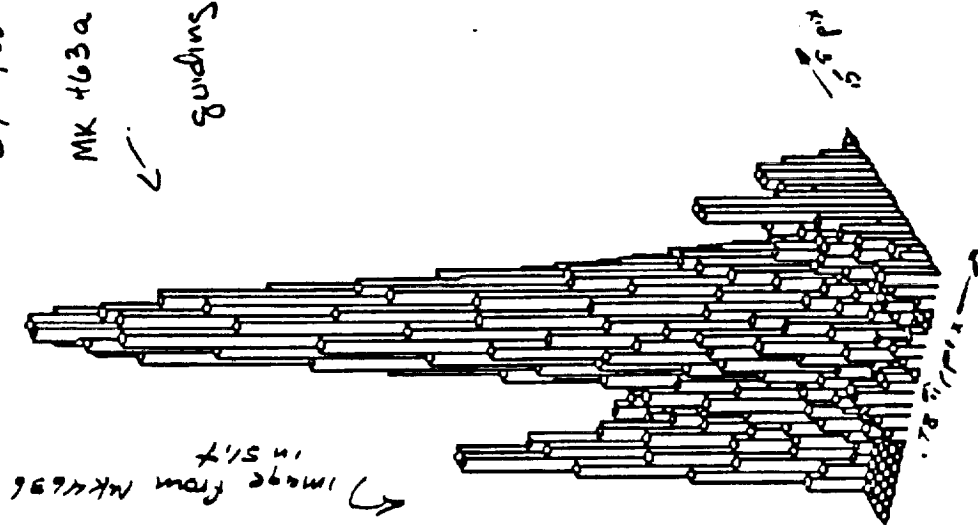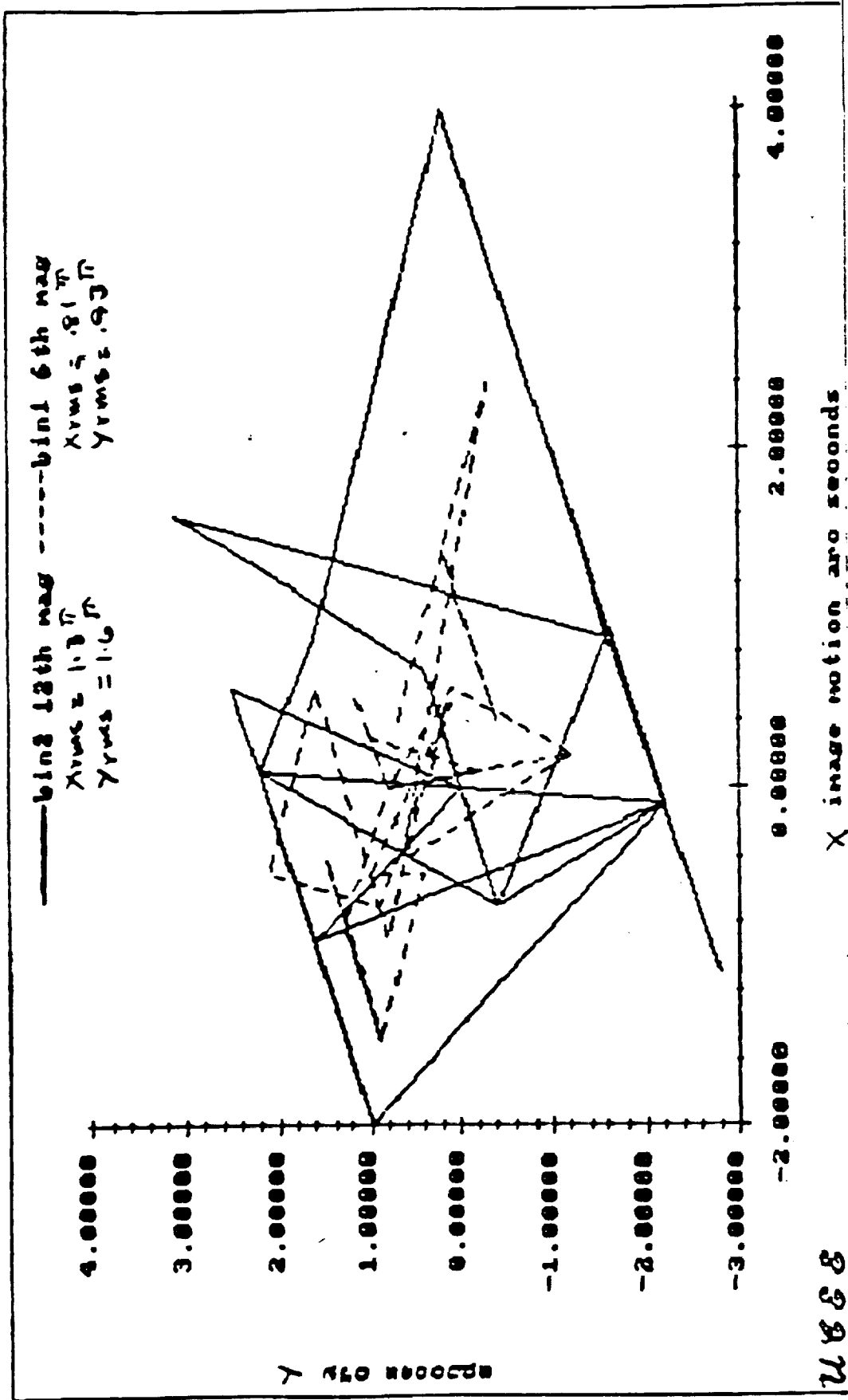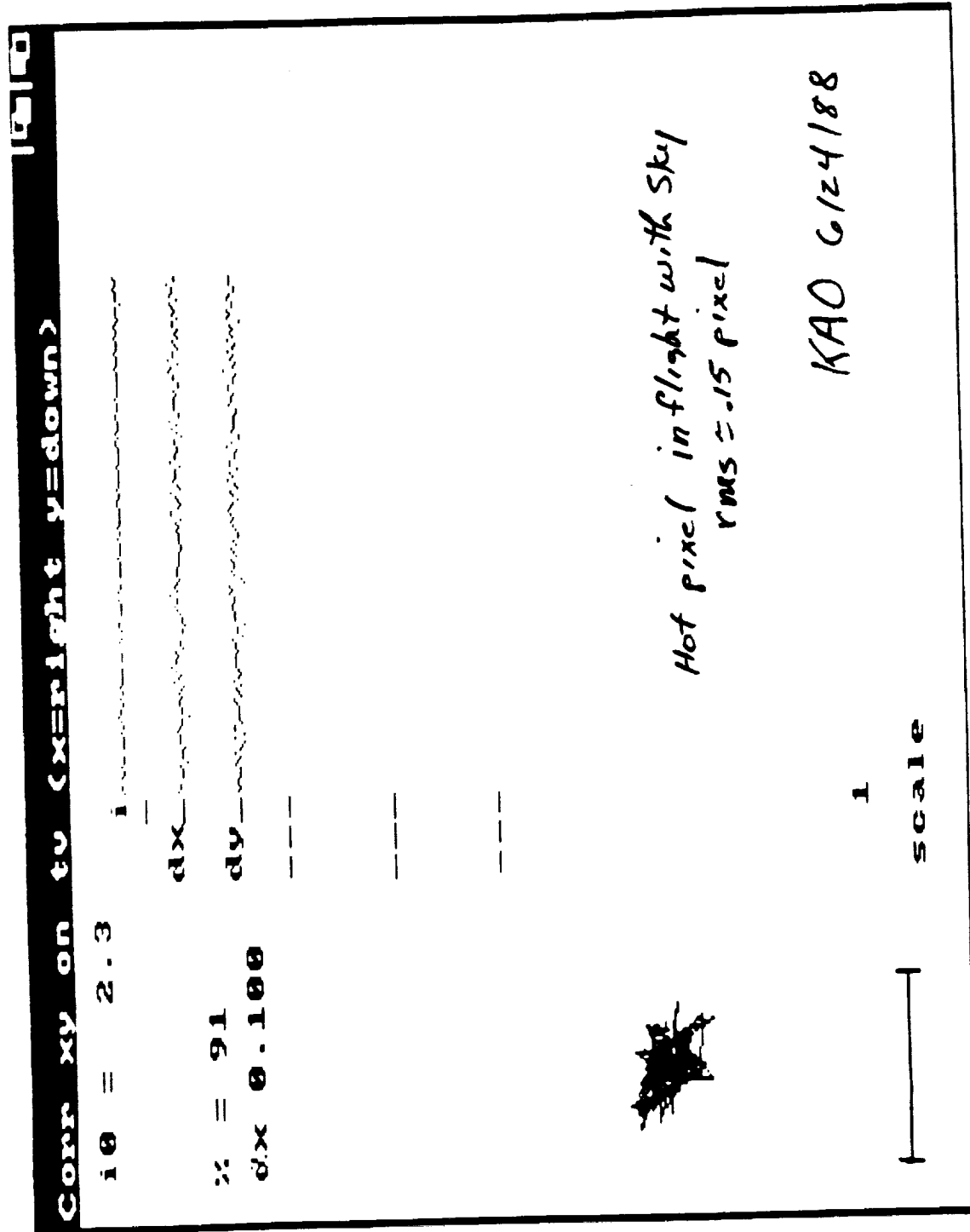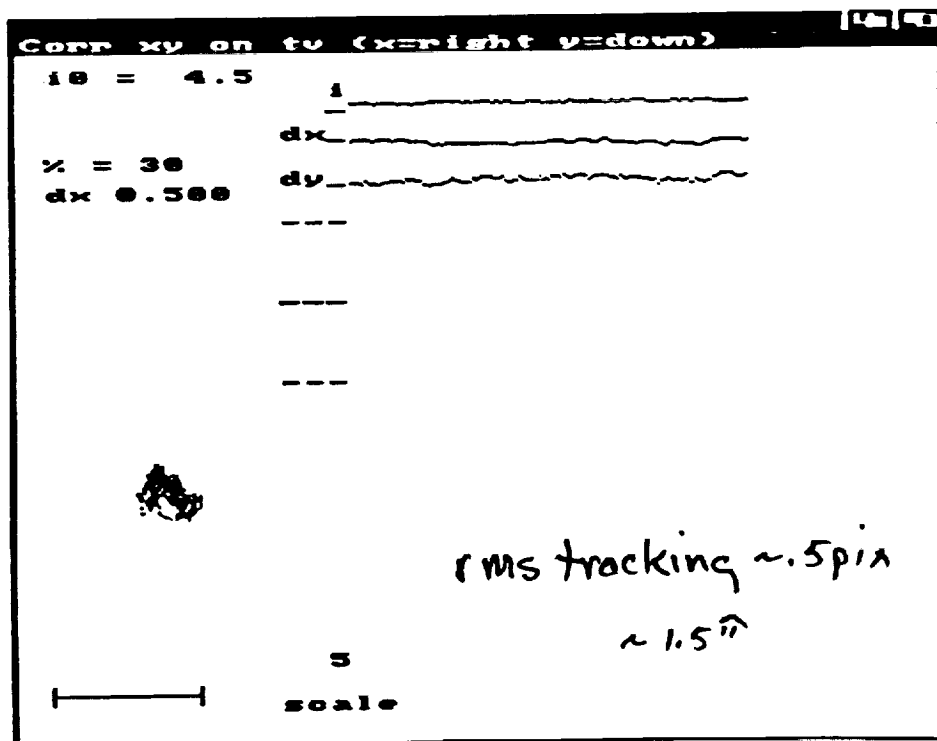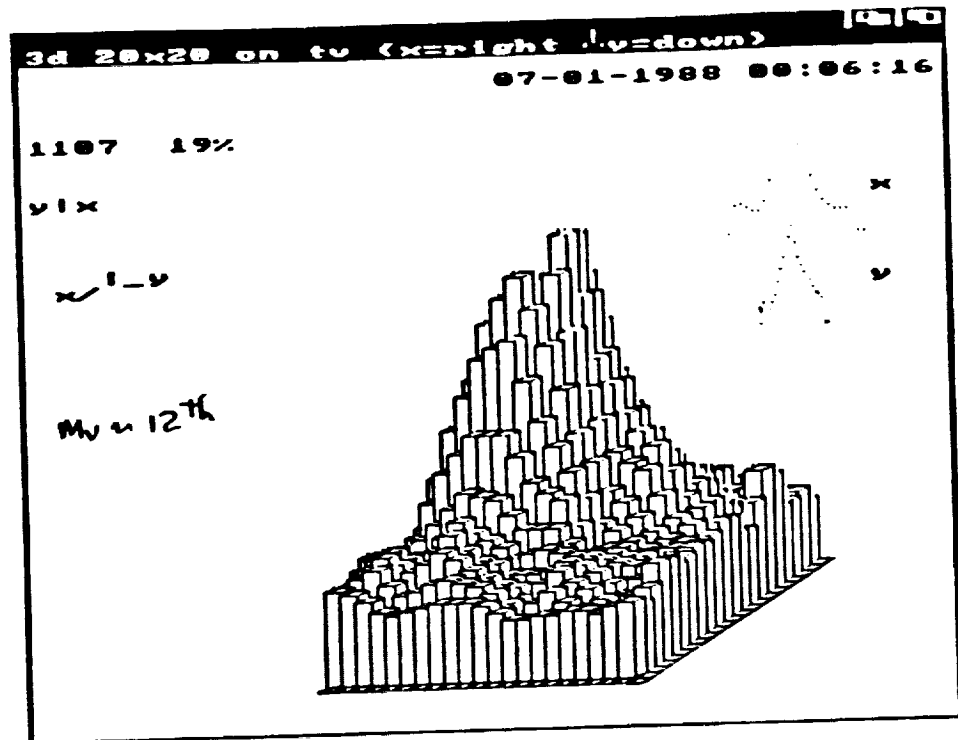
1 Sec
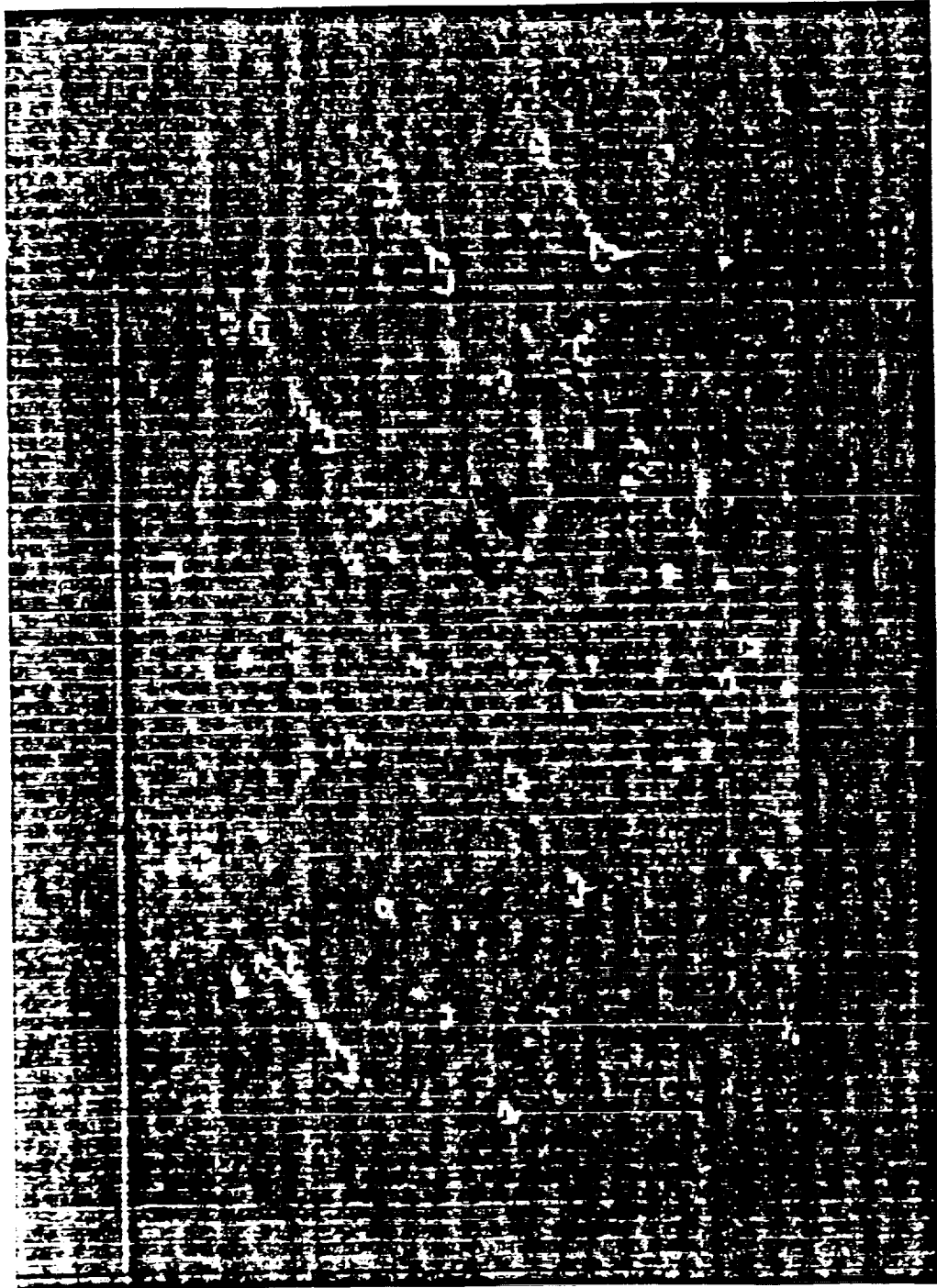
figure 5D

TI chip Sgr A 2 sec KAO

figure 6D