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THE ABILITY OF THE SPACE TELESCOPE TO DETECT EXTRA-SOLAR PLANETARY SYSTEMS

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ABSTRACT

The Space Telescope can play a key role in searching for and investigating the contents of extra-solar planetary systems. For about 90 nearby stars, positional variations due to major planets would be well within the astrometric capability of the Wide-Field/Planetary Camera system. Since the centroids of star images will be determined to within a milliarcsecond down to 22nd magnitude, there will be an abundance of reference stars at very small angular distances from each planetary system candidate, and they will have small enough motions of their own to provide a reference frame of the stability required.

In the decades ahead, one of the most exciting adventures in astronomy, particularly from space, will be the search for planets around stars. If planets are found to be as abundant in the Universe as some of us suspect, the impact on human philosophy may be greater than that of any other astronomical discovery of our time, and the challenge to send spacecraft to visit these newly discovered "Other Worlds" could well become the driving force of space science.

Several methods for the detection of extra-solar planets have been discussed in the literature. Among these methods, the quest for radial velocity variation can be pursued fairly well from observatories on the ground. Interferometric methods also are being explored. Direct imaging detection may ultimately be possible from space, but it puts formidable demands on optical and detector performance. In the present paper I want to focus attention on astrometry, which can particularly benefit today from a telescope in space.

Astrometry also has the advantage over the radial velocity approach in that the likelihood of detection is not dependent on the spatial orientation of a planetary system. No matter how a planetary system is oriented, the resulting positional wobble of the star will have roughly the same amplitude, whereas the amplitude of the star's radial velocity variation has a first-order dependence on the orientation of its planetary system. Nevertheless, there is a lot to be said for pursuing all feasible approaches simultaneously (even astrometry from the ground), so as to learn as much as possible about each planetary system candidate. Therefore, an astrometric search for planetary systems with the Space Telescope should be only a part of a broader effort.

There are two instruments aboard the Space Telescope that have potential for participating in this astrometric search. One is the Wide-Field/Planetary Camera and the other is the Fine-Guidance System. Jefferys (1979) has described the astrometric capability of the Fine-Guidance System. To summarize: it utilizes three detectors behind movable optics at three widely separated locations near the edge of the f/24 focal plane. A positional displacement of 1 micron corresponds to 3.6 milliarcseconds. It will obtain a usable signal from stars between 10th and 17th magnitude.

Let me now describe the Wide-Field/Planetary Camera so that the overall astrometric potential of the Space Telescope for planetary detection can be examined. Figure 1 shows the optical configuration of the camera. The unique element is the pyramid mirror, which lies at the f/24 focal plane of the Space Telescope. It has four slightly curved faces (only two of which are illustrated in this sketch) splitting the image into four equal quadrants and reflecting them simultaneously into four identical channels with relay optics and CCD image detectors. For wide-field imaging, the relay optics reduce the beams to f/12.9, resulting in a total field coverage (all four CCDs) of 2.7 x 2.7 arcminutes.

Whenever desired, the pyramid can be turned 45° about the input optic axis so as to throw the four beams into four other channels with relay optics producing f/30, resulting in a total field coverage of 1.1 x 1.1 arcminutes. This portion of the system, known as the "Planetary Camera," utilizes the full resolution of the Space Telescope. In other words, the complete camera system includes eight relays and eight CCDs, four for f/12.9 wide-field imaging and four for f/30 high-resolution imaging. The so-called Planetary Camera at f/30 is not at all limited to bright objects. It can be used for long exposures and faint objects just as the f/12.9 Wide-Field Camera can. Thus, for any astronomical purpose such as the planetary detection problem, one can freely consider the tradeoff between field coverage and resolution when deciding which focal ratio to choose.

Figure 2 illustrates how the total field is covered by four CCDs, each having 800 x 800 pixels 15 microns square. By providing a slight overlap (about 10 pixels) of CCD coverage at the junctions, there will be no gaps, and it will be possible to tie the four sub-fields together geometrically by suitable calibration. However, this joining of the four sub-fields cannot be expected to have milliarcsecond stability, so planetary detection astrometry should be limited to data from a single CCD.

CCDs have very high quantum efficiency over a broad spectral range. For the planetary detection problem, the consequence of this high quantum efficiency is that milliarcsecond astrometry can be done on very faint stars, providing an abundance of reference objects within the available field. One virtue is that angular distances between program stars and reference stars will be small. Another virtue of faint reference stars is that their intrinsic positional variations are typically small so that they provide a reference frame definable at the milliarcsecond level in a reasonable length of time. In this respect, the Wide-Field/Planetary Camera System is superior to the Fine-Guidance System.

Another important property of CCDs is their photometric linearity. For astrometry this means that the centroid of a star image is not dependent on stellar magnitude, despite optical aberrations and guiding errors; i.e., there is no "magnitude equation." Each star image produces a mound of charge carriers a few pixels wide on the CCD. Therefore, the centroiding of a star image will be precise if there are enough charge carriers in the image for the statistical uncertainty ($n^{-1/2}$) to be small, and if there are enough pixels within the star image to sample its profile adequately.

There is, in fact, an optimum relationship between the size of a star image and the size of a pixel. If the effective focal length is too short so that the optical image is excessively compressed, the point-spread function (i.e., the star image profile) will occupy too few pixels to determine its centroid precisely. On the other hand, if the effective focal length is too long so that the optical image is excessively magnified, the point-spread function will occupy more pixels than necessary to determine its centroid precisely, while the CCD will cover too small a field in the sky to provide enough reference stars for astrometry. The optimum relationship, of course, lies somewhere between these two situations; and one can show that the f/30 and f/12.9 systems fall in the desirable range of point-spread functions and field sizes.

Using a very simple "worst-case" model, I have calculated the expected astrometric error shown in Figure 3 as a function of star magnitude for our two CCD cameras and for Space Telescope exposures of 1000 seconds. This plot indicates that an accuracy of about 1 milliarcsecond should be achieved down to 22nd magnitude with the f/30 planetary camera, whereas the f/12.9 wide-field camera has a 2-milliarcsecond error at that magnitude. However, the f/12.9 camera covers a field five times larger in sky area, so more reference stars would be available. Bars at the left-hand ends of the curves here indicate approximate saturation magnitudes for 1000-second exposures. For shorter exposures, these curves (and the saturation exposures) march toward the left.

Many of the nearby stars that are astrometrically desirable to test for the presence of planetary systems are bright compared with the saturation magnitudes for any reasonable exposure times that provide enough reference stars. The planetary-system candidates therefore have to be separately attenuated without introducing variable astrometric errors. A suitable attenuation factor (6 or 7 magnitudes) can be produced rather easily at the f/24 focal plane by providing a tiny bare spot (non-aluminized) on one face of the pyramid mirror and putting an antireflection coating on it.

Let us now consider how much positional wobble of a candidate star we are looking for and therefore how many candidates are in reach of the Space Telescope instruments. If one plots the actual wobble of the Sun due to the planets of our own Solar System, it is not a simple sine wave with a 12-year period due to Jupiter. It is a surprisingly complex curve in which all the major planets play significant roles. Using solar wobble, the existence of a planetary system around our Sun might be detected by distant alien observers in a few years, but the specific contents of our Solar System would take them many decades to figure out.

Nevertheless, the contribution of Jupiter is a good yardstick for the typical amplitude of variation within any decade-long interval. So as a criterion for the astrometric detectability of other planetary systems, I have imagined each nearby star to possess a hypothetical "Jupiter" (a planet of Jupiter's mass and orbital semi-major axis) and have calculated the resulting amplitude of positional oscillation that would be expected. Since about 90% of nearby stars are main-sequence dwarfs, I have used a simple linear mass-luminosity relation to translate absolute magnitudes into approximate masses. The inappropriateness of this relation for giants and subgiants (which comprise most of the remaining 6%

of nearby stars catalogued) can be shown to have almost no bearing on the inferred number of good astrometric candidates for planet detection.

The fact that existing catalogs of nearby stars are incomplete near their limits should not greatly concern us, because we can draw the desired information mainly from candidates that are not near catalog limits. The question of catalog completeness is of only academic interest anyway, because an actual Space Telescope observing program will have to be based on the targeting of individual stars we know well. I chose Gliese's (1969) catalog, updated with some Naval Observatory data, because it was conveniently at hand in machine-readable form. I thank James Westphal and his colleagues at CalTech for providing me with a magnetic tape suitable to the present exercise.

For a star of mass $\mathcal{M}$ and parallax π, the presence of a "Jupiter" would produce a positional oscillation of the star with a half-amplitude of

$$\alpha = 5\ \pi\ \mathcal{M}^{-1} \text{ milliarcseconds},$$

where π is in arcseconds and $\mathcal{M}$ is in solar masses. After translation of masses into absolute bolometric magnitudes and then into absolute visual magnitudes M_V, this "Jupiter" condition becomes the family of upward sloping lines in Figure 4, which is a plot of M_V

versus π for the stars in Gliese's catalog. These lines represent half-amplitudes α = 1, 2, and 3 milliarcseconds, and one may think of them as approximate upper limits for stars whose "Jupiters" could realistically be detected by instruments having astrometric thresholds of 1, 2, or 3 milliarcseconds. The downward sloping lines represent the loci of stars having the indicated values of apparent magnitude V and are therefore lower limits for detection. For particular upper and lower limits, the stars falling in the wedge-shaped area at the right of those limits are the planetary-system candidates of interest.

Based on that, Figure 5 shows how the number of "Jupiter" detection candidates will depend on the astrometric threshold. We see that each factor 2 improvement in the astrometric performance should result in having three times as many candidate stars. Reaching fainter stars also helps, but not equally at all threshold magnitude levels. Beyond 12th magnitude, the lines in this figure become closer together, indicating that the gain in the number of candidates tapers off. Although the incompleteness of the catalog doubtless plays a role, part of the tapering off beyond V = 12 should be inherent in the luminosity function. Brighter than about V = 12, the number of "Jupiter" detection candidates increases roughly 1.7-fold per magnitude.

It is evident from Figure 5 that the Space Telescope cameras could choose from among more than 500 candidates at the 1-milliarcsecond threshold. For a more conservative selection, there are about 90 candidates at the 3-milliarcsecond level. And that list might wisely be reduced to about ten prime cases for Space Telescope imaging, excluding cases with close stellar companions, with unfavorable distributions of reference stars, or with excessively long expected periods. For those prime cases, the probability of detecting any planetary systems similar to our own should be excellent.

References

Gliese, W.: 1969, Catalogue of Nearby Stars, Verlag G. Braun, Karlsruhe.

Jefferys, W. H.: 1979, Celest. Mech., in press [this volume].

FIGURE CAPTIONS

Figure 1. Schematic diagram showing part of the Space Telescope Wide-Field/Planetary Camera system. The incoming f/24 image falls onto a pyramid-shaped mirror which splits it into four quadrants and sends them through relay optics with f/12.9 output to four cooled CCDs. When the pyramid is rotated 45° about the incoming optic axis, the image is similarly relayed at f/30 to another set of four cooled CCDs.

Figure 2. Each set of four 800 x 800-pixel CCDs provides mosaic coverage of a 24 x 24-mm image area with 15-μm pixel resolution.

Figure 3. Error in locating the centroid of a star image, plotted as a function of star magnitude, for a single 1000-second exposure through a photovisual filter. Bars at the left-hand ends of the curves represent saturation magnitudes (in 1000 seconds) for the Wide-Field Camera (WFC) and Planetary Camera (PC), respectively.

Figure 4. The absolute magnitude-parallax distribution of nearby stars plotted from Gliese's (1969) catalog. Upper and lower limits for the detection of hypothetical "Jupiters" are indicated by lines representing possible values for the astrometric accuracy (arcseconds) and magnitude threshold of an instrument.

Figure 5. The number of "Jupiter" candidates that can be investigated with an instrument of given astrometric accuracy and magnitude threshold. These data are based on Figure 4.

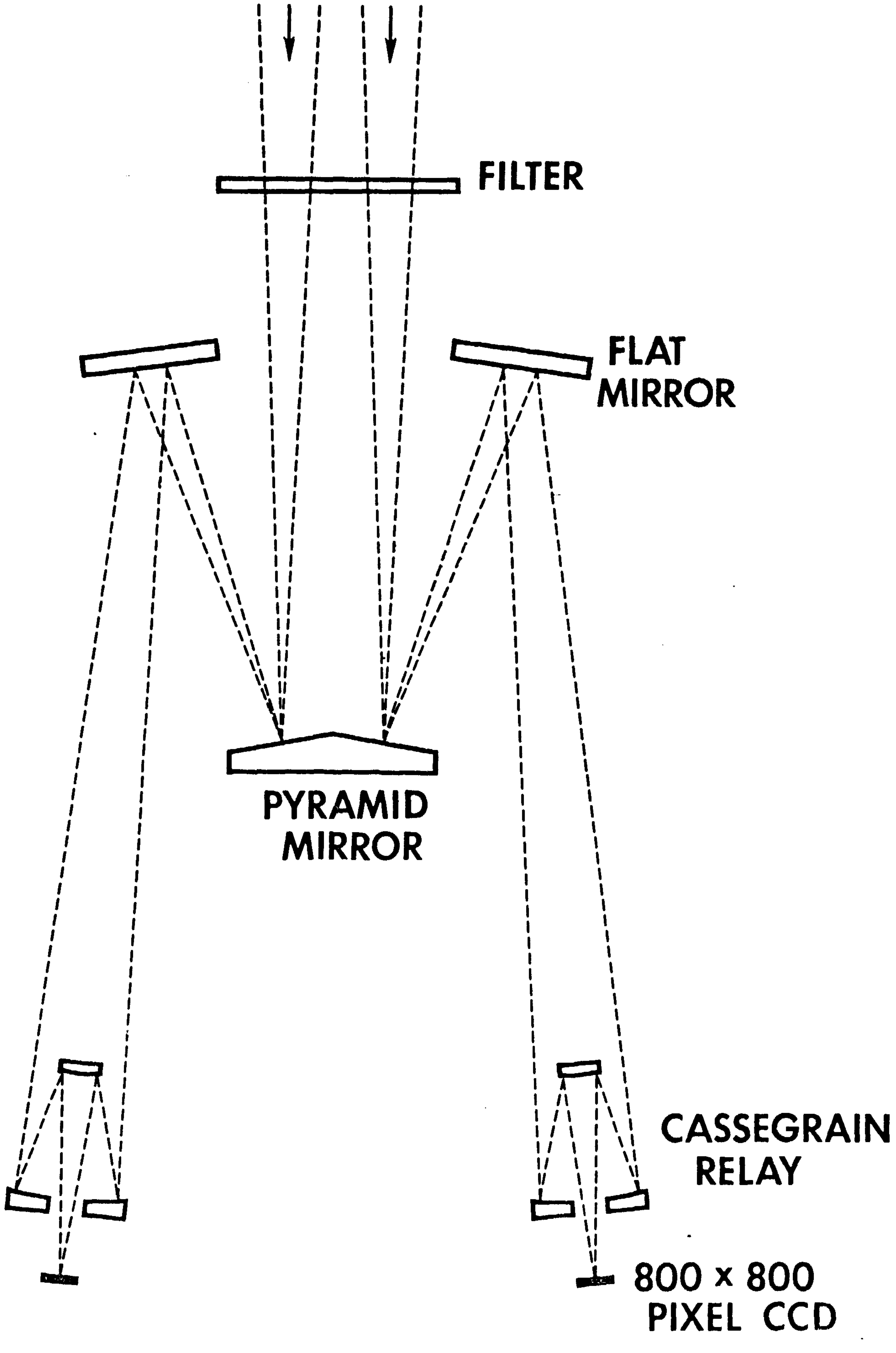

FILTER
FLAT
MIRROR
PYRAMID
MIRROR
CASSEGRAIN
RELAY
800 x 800
PIXEL CCD

Figure 1.

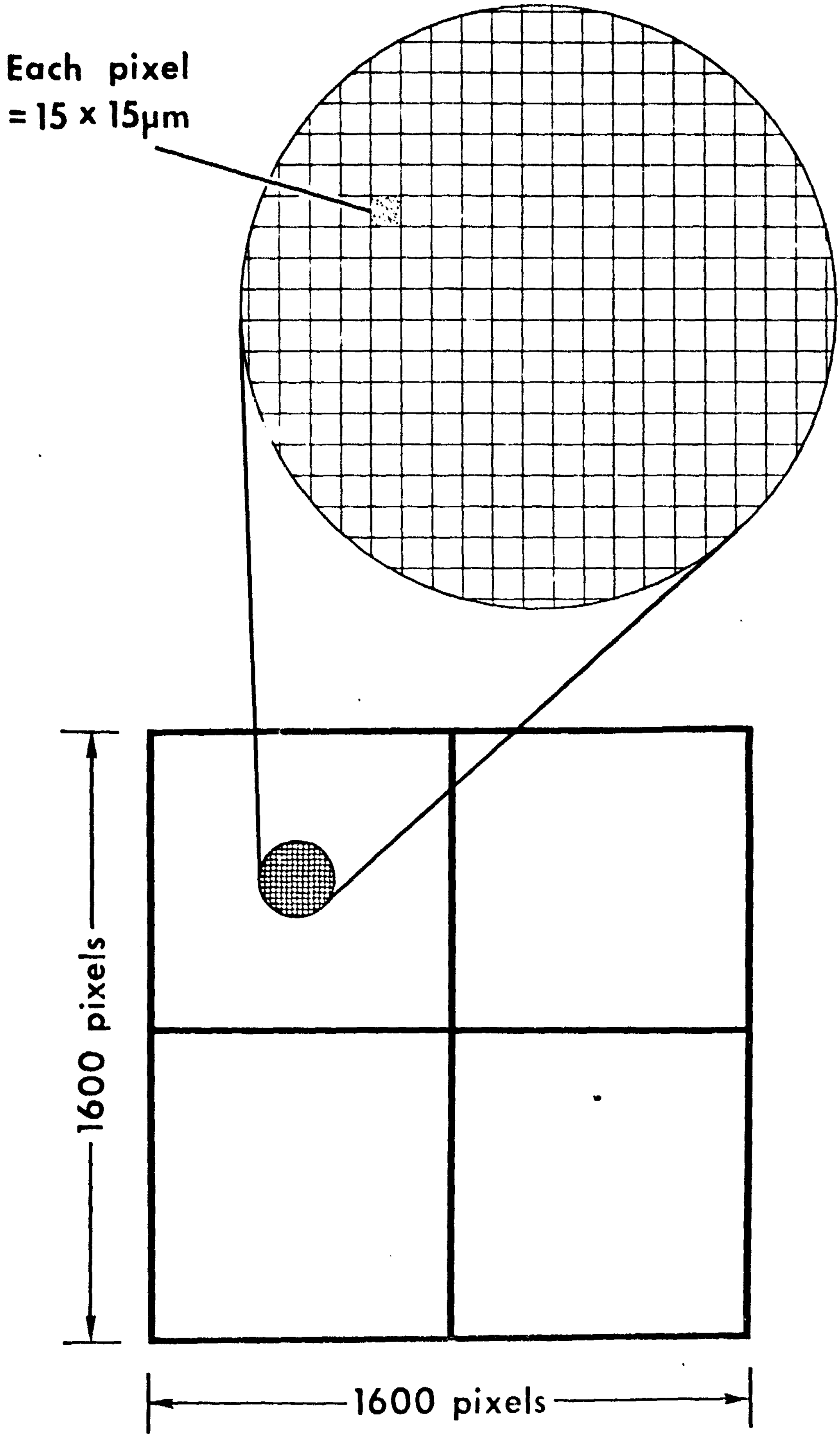
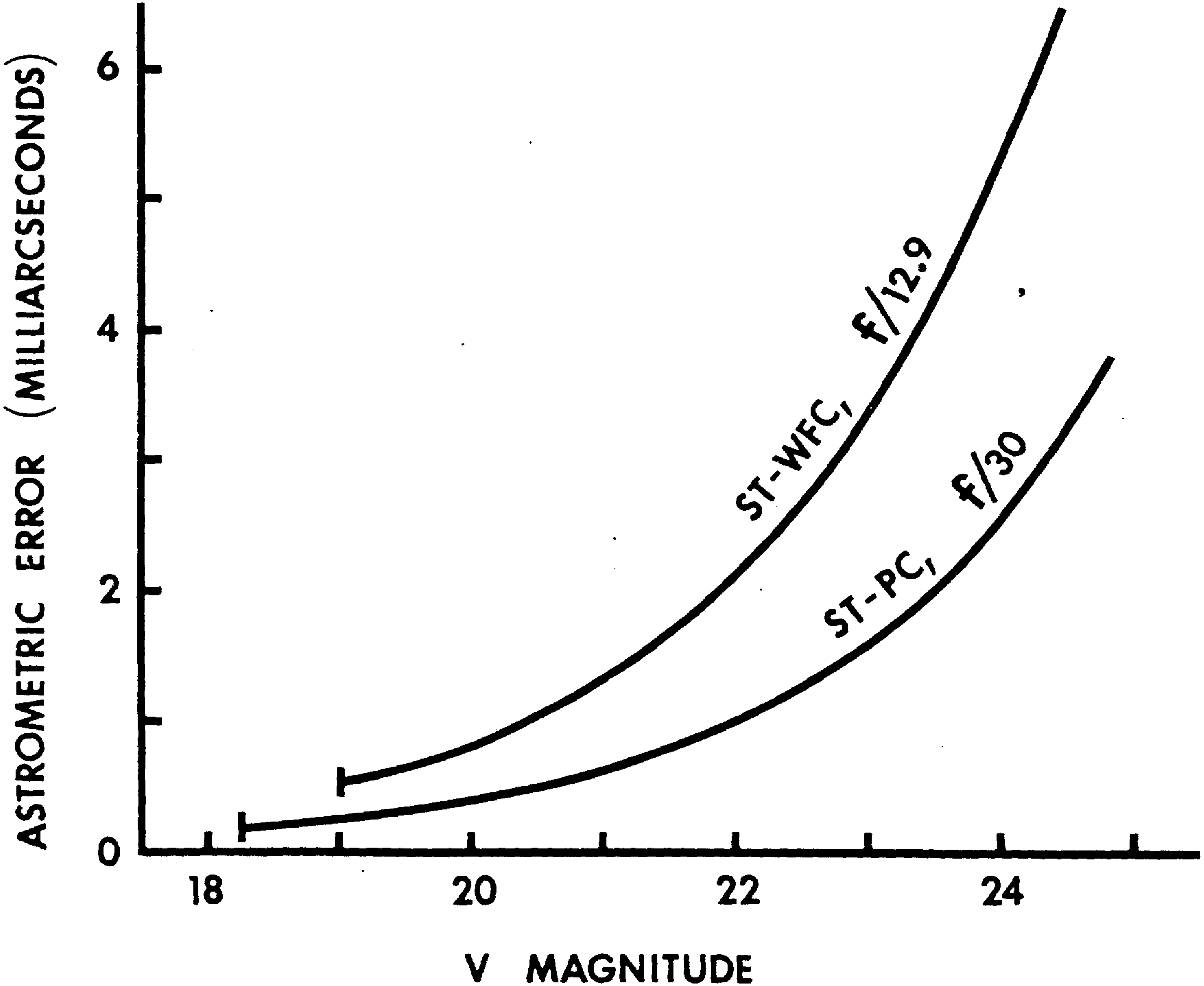


Figure 2.


ASTROMETRIC ERROR (MILLIARCSECONDS)
6
4
2
0
18
20
22
24
V MAGNITUDE
ST-WFC, f/12.9
ST-PC, f/30

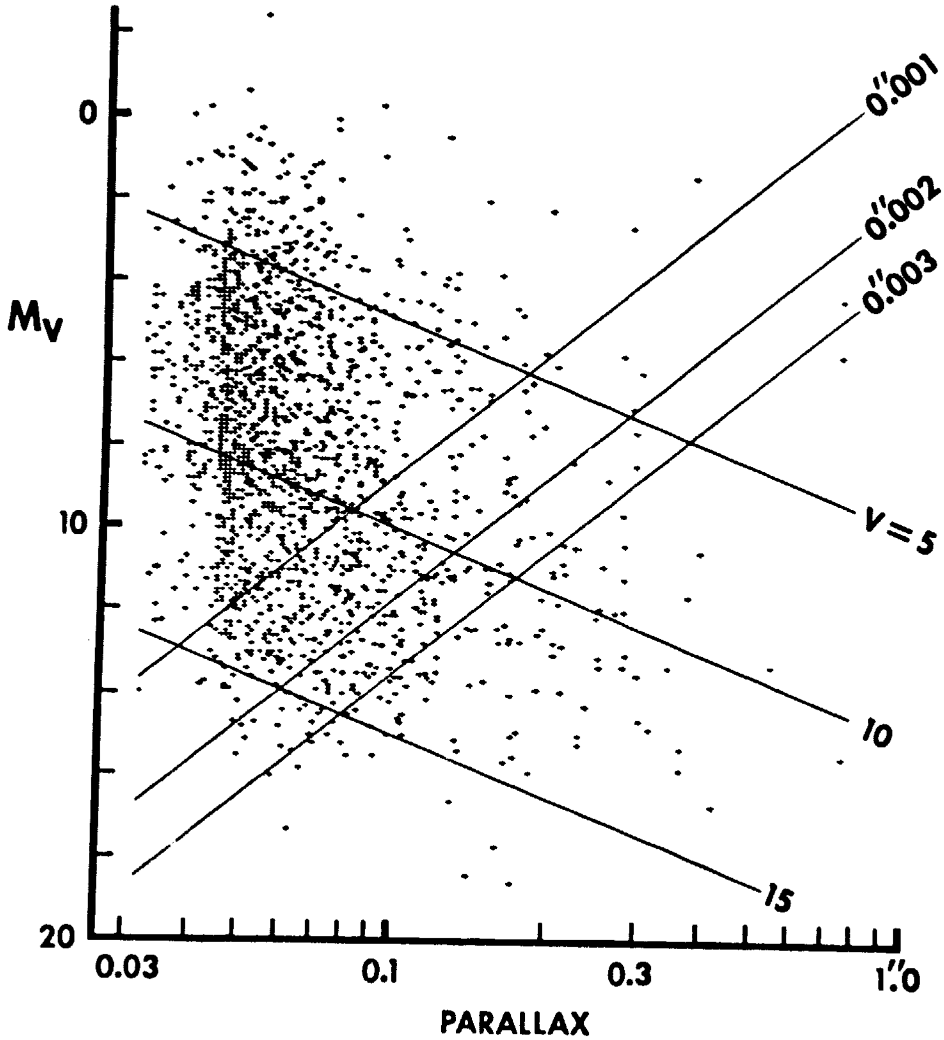


Figure 4.

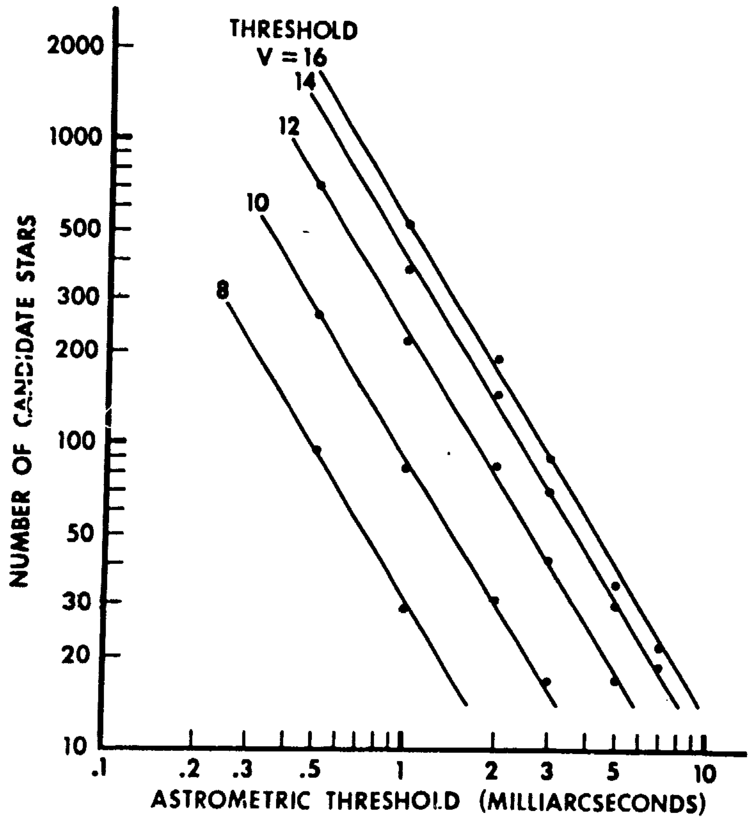

THRESHOLD
V = 16
14
12
10
8
2000
1000
500
300
200
100
50
30
20
10
NUMBER OF CANDIDATE STARS
.1
.2
.3
.5
1
2
3
5
10
ASTROMETRIC THRESHOLD (MILLIARCSECONDS)

Figure 5