A PROTOTYPE DETECTOR FOR THE ASTROMETRIC TELESCOPE FACILITY

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ABSTRACT. The Multichannel Astrometric Photometer (MAP) now in use in the Allegheny Observatory astrometric program is the detector chosen for the strawman design of the Astrometric Telescope Facility (ATF) proposed for the U.S. Space Station. Extrapolation of ground based performance to above atmosphere observing conditions indicates an approximate precision of 0.00001 arc seconds per annual normal point.

1. ASTROMETRIC DETECTORS

Astrometric electronic detectors may be divided into two categories, those that image the star onto the detector surface and those that modulate the light as it passes through the focal plane toward the detector's photosensitive surface. The use of imaging techniques demands a very high linear and photosensitive stability of the detector surface. For example, to sense the relative positions of images with a precision of 0.01 milliarcseconds (0.01 mas), using an optical system with an effective focal length of 20 meters, requires a spatial and photosensitive stability equal to one nanometer. This is approximately one ten-thousandth of the diameter of the pixel size of the best currently available CCDs. This demand is further exacerbated by the long-term nature of astrometric programs which often extend into decades.

The second class of detectors employ transmissive (although reflective versions have been contemplated) media that are designed to modulate the light at the focal plane. Inscribed over lengths usually exceeding that of the field of the intended instrument, these phase encoders employ thousands of measuring edges that are brought progressively to each stellar image. Thus the error of the dividing device, usually a laser interferometer, can be averaged down to its systematic limit (generally measured in small fractions of a wavelength of red light). While this accuracy is sufficient for all foreseeable uses, it is notable that this class of detectors can actually be used

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as self improving measuring devices that are limited only by the stability of the ruling substrata. This detector concept is used in the Multichannel Astrometric Photometer (MAP) (Gatewood et al. 1980) (hereafter referred to as Paper I) and has been chosen for the Strawman design of the Astrometric Telescope Facility (Levy et al. 1986, Scargle et al. 1987).

2. ATMOSPHERIC LIMITATIONS

Gatewood (1987) (here after referred to as Paper II) has completed a series of tests that strongly indicate that the MAP is limited primarily by the Earth's atmosphere. From 77 hours of observation it was found that the variance of an observation is related to the inverse of the photon count rate:

$$SE^2 = 13.04 + 11.97 / \text{Millions of Photons} \qquad (1$$

where SE is the standard error in mas for a given number of photons collected over an integration period of 20 minutes. The standard errors of the variance intercept and slope respectively are 5.28 and 0.22 mas squared. The intercept indicates that, during average seeing conditions of 2.0 arc seconds FWHM (image diameter Full Width at Half of the Maximum intensity), a 20 minute observation, from the Allegheny site, of even the brightest region will be limited to an accuracy 3.6 mas. This non-zero intercept is explained by the fact that the moment-to-moment position of the target is not totally predictable from those of the reference stars (Lindegren 1980). That the intercept is time dependent and not an instrumental limitation, was shown by gathering the observations into sequential groups of three and finding their average. The variance of the resultant average positions was found to be, within the errors of the data, one third that of the individual observations.

If the effects of atmospheric seeing on each field star were exactly the same the Lindegren limitation would not exist. The amount of correlated motion, over angles of tens of arc minutes has been the subject of a number of studies, including Schlesinger (1916), Hudson (1929), Stein (1978), KenKnight et al. (1978) and Christian and Racine (1985) and in Paper I. In paper II the effect of correlated motion on astrometric precision was tested by comparing the dependence of the variance on the angular extent of the reference frame. Two frames, centered on a 7.7 magnitude, star were observed simultaneously for a total of 12.7 hours. The inside frame spanned 15 arc minutes, the outside frame spanned 28 arc minutes. The standard error of the target star about its linear motion was 4.6 mas per 20 minute observation when its position was determined from the smaller frame, 7.5 mas when determined from the larger frame. The ratio of the errors (1.6) was somewhat larger than expected, but clearly indicated that the extent of the frame (and therefore the degree of correlated motion) is an important factor.

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Paper II found additional evidence of the limitations of the Earth's atmosphere on observations with the MAP by correlating astrometric precision with the quality of the seeing. The relationship between the estimated image diameter (D) FWHM and the standard error of an observation in mas (SE) was found to be:

$$SE = 2.18\ D \qquad (2$$

The zero intercept was in accord with the observations.

3. EXTRAPOLATION TO ABOVE ATMOSPHERE

Paper I suggests an optical system, which when used with several medium-width bandpasses (Scargle et al. 1987) and Paper II, can map the sky onto it's focal plane with a precision of a few microarcseconds. The inherent characteristics of the MAP also suggest that it is capable of achieving such precision when used with an instrument of moderate field scale, however, direct data is still lacking. While extrapolation beyond the range of a data set is fraught with dangers, it is reasonable to examine the trend of a data set to see if it contains any evidence that the goals sought are unattainable.

If we assume no relative motion between the image of the target and those of the reference stars, the Lindegren effect becomes zero. Common motions, such as those caused by motions of the telescope platform, will be canceled out by the standard affine transformation that models each observation into the reference frame. (This is also true of scale changes and rotations.) As the Lindegren effect approaches zero, so does the intercept in equation 1). Another limitation is the error caused by the optical system and by the detector. The apparent direct averaging down of the variance as integration period is increased, discussed above, indicates that these effects are too small to detect in the available data and we will for now assume that they are primarily dependent upon the quality of design and construction and therefore can be controlled with effort.

This leaves the effects of image diameter and photon count rate. Image diameter is apparently directly related to accuracy; equation 2). As discussed in Paper II, there is no detectable indication of a non-zero intercept in the analyzed data. However, the images formed by the ATF optics will not have zero diameters. They will instead approach the diffraction spot size of the 1.25 meter aperture. Thus the slope of equation 1) is of concern.

As proposed, the ATF will have eight times the bandpass of the Allegheny refractor, which works at 6420 +/- 250 Angstroms, and it will be approximately five times as efficient in detecting each photon (better quantum efficiency over the generally bluer bandpass as well as less loss at glass surfaces). Finally the effective aperture ratio is approximately 1.5 to 1. Thus the ATF will record approximately 90 times as many photons, at each magnitude, as the Allegheny instrument. For example, a 10th magnitude star could be reasonably expected to produce a billion photons every three hours of integration.

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The slope in Equation 1) is related to the image diameter. If we assume an ATF FWHM image diameter of 0.13 arc seconds, and that the standard error of an observation is directly related to the image diameter (Equation 2) then the slope term becomes 0.04. Thus equation I becomes approximately:

$$SE^2 = 0.04 / \text{millions of photons} \qquad 3)$$

or for three hours of integration on a 10th magnitude star, SE is approximately 6 microarcseconds.

Admittedly, this is an oversimplification. For example, at least an equal number of photons is required from the reference frame and the variances are additive. Secondly, there will always be an instrumental error, at some level. To understand the underpinnings of that term is the purpose of the intensive study described by Levy et al. (1986), an effort which includes the study of strawman designs and prototype detectors.

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