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Cambridge, Massachusetts

ON THE EFFECTS OF IMAGE MOTION
ON THE ACCURACY OF MEASUREMENT
OF A FLASHING SATELLITE

by

J. Allen Hynek [1]

Artificial satellites carrying flashing lights that can be triggered by internal programming or by command from earth have frequently been proposed as a means of increasing the geodetic usefulness of the satellites. Individual flash durations of less than a millisecond, or a pattern of such bursts, have been suggested. According to this proposal, such flashes would allow us to fix the linear position of a typical close satellite to within 25 feet, and simultaneous observations of a given flash from two or, preferably, more stations would permit us not only to fix the position with a high degree of accuracy, but would also obviate the necessity for precision timing of the observations.

These suggestions, insofar as they concern positional accuracy, overlook salient astrometric facts relating to atmospheric unsteadiness and image motion, which can cause the instantaneous photographic position of the satellite image to differ from its "true" position by easily as much as 2 or 3 seconds of arc.

Observers have long known, for instance, that if exposures are too short -- under a minute of time -- the accuracy of measures of stellar parallax is apt to suffer. The mean position of the wandering image will not be the same as the centroid of an image formed by a longer exposure. Instantaneous visual measures will likewise suffer. It has also been recognized that asteroid positions obtained from relatively long exposures are more accurate than those made visually by filar micrometer, since the photographic method integrates the random [2] motion of the image, while the visual observation does not.

The motion of a stellar image, apart from its scintillation (defined solely as changes of brightness with time, independent of image size or motion), can be measured in a number of ways. For measurements in the focal plane, motion pictures of an image and the associated focal-plane reticle can be made, or the images can be allowed to trail on the film by diurnal motion or by motion of the film itself. The stellar image can also be photographed extra-focally, preferably by rapid sequence photographs. The successive frames then show the motion of the motley array of bright image elements, each arising from a separate portion of the incoming wavefront, warped by atmospheric irregularity in the neighborhood of the telescope. From the motion of the elements of the extra-focal image, the motion of the centroid of the focal image can be derived.

Observations of the "dance" of stellar images have been made by many astronomers. As part of a research program on fluctuations of starlight, carried out several years ago by a group associated with the writer at the McMillan Observatory,[3] R. Hosfeld made quantitative measures that apply directly to the problem of flashing satellites.

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[1] Associate Director, Smithsonian Astrophysical Observatory.

[2] Private communication from J. Ashbrook.

[3] Work sponsored by Geophysics Directorate, Air Force Cambridge Research Center (Contract No. 19(604)-41).

It is particularly instructive to study the motion of the two small, extra-focal, image-elements formed by admitting starlight to the telescope through two relatively small, equal apertures; Hosfeld used two circular apertures of 3-inch diameter whose centers were separated by 9 inches. The separation of these two elements is related to the motion of the focal image, in that the latter motion is one-half the motion of the two extra-focal images as measured by the difference between their maximum and minimum separations.

It is also instructive to observe focal plane images directly. Motion pictures of the movement of focal images of stars reveal a surprising amount of change of image structure, and of the motion of the "centroid" of the image. Deviations of an image from a mean position can also be recorded by allowing an image to trail on a photographic plate, or by having a film or plate move linearly while being exposed. These and successive frame photography of extra-focal images showed that the average image motion is 2.2 seconds of arc during night hours, and 3.1 during the daytime. The random motion of Capella during the daytime is shown in figure 1. The consecutive points are separated in time by 1/32 second; points can be as far apart in distance as 5 seconds of arc.

The image of a satellite flash, therefore, may appear at a position several seconds of arc away from the "true" position of the satellite. Simultaneous observations from two or more stations will not necessarily tend to cancel the effect; if the errors are of opposite sign, they can yield a position error as great as 10 seconds of arc.

A pattern of bursts of individual short flashes would, in the mean, tend to produce a reliable position, although the position of each individual flash would be subject to large error. It would appear unfortunately, therefore, that as long as satellites must be observed through an appreciable atmosphere, the use of short flashes for geodetic purposes will tend to increase rather than to decrease the positional error, if accuracies of a second of arc are required.

The study of image structure and motion carried out by the Ohio State group and others shows that such motions are to be ascribed to atmospheric disturbances in the general neighborhood of the telescope, and not to the disturbances at the heights of the order of the height of the tropopause that cause scintillation. That is, the positional errors under discussion are not introduced by stellar twinkling, as might at first be thought, but by local wavefront changes. Since these atmospheric disturbances are local, a proper location of the observing sites would help to minimize the effects of the disturbances.

Several independent lines of evidence indicate that stellar scintillation does not cause shifts in image position. The immediate cause of scintillation is the play upon the telescope objective of the interference pattern induced by the atmosphere. One can easily observe this by placing his unaided eye at the focal plane of a telescope of moderate size that is trained on a bright star. The entire telescope objective is then seen to be illuminated. If the observer uses his eye as a field lens, he discerns the rapidly moving and changing pattern of starlight.

A more slowly moving pattern of light, suggestive of a viscous flow, is apparent if the image is examined at a point slightly beyond the focal plane of the telescope. These relatively slow-moving light patterns represent deformations of the wavefront responsible for image motions and explain the fact that elements in an extra-focal image tend to persist in form and position for large fractions of a second, quite unlike the kaleidoscopic changes seen on the objective itself which even successive photographic exposures of 1/100 second are generally unable to "stop."

The distinction between image motion and stellar scintillation can be illustrated in many ways (Hosfeld, 1954). For example, the images of double stars show random scintillation but coordinated motion; with increasing zenith distance, scintillation increases more rapidly than does image motion; we can induce image motion artificially, but not scintillation except by interfering with the beam at relatively large distances.

One might suppose that since the images of components of a double star move coordinately, as do indeed the images of stars in a field nearly a degree across, the flashing satellite and the stars would exhibit the same image motion. This supposition, of course, does not hold, since the stellar exposure would obviously be many times as long as that for the satellite flash, and the image of each star would therefore represent the integral of many excursions from the mean position.

In long exposures of faint stars, a larger number of developable emulsion grains accumulate near the mean stellar position than elsewhere. The rapid motion of images to points away from the mean position contribute, at most, to the slight halo around the stellar image. For the average stellar image, 30 to 40 microns in diameter and corresponding to many seconds of arc, the position can be measured within an accuracy of about 2 microns. Because the centroid of a stellar image corresponds to the true position of the star, such accuracy is meaningful; in the case of the image of a short flash from a satellite, it is apt to be misleading.

Reference

HOSFELD, R.

1954. Comparisons of stellar scintillation with image motion. Journ. Opt. Soc. Amer., vol. 44, pp. 284-288.

RANDOM WALK OF CAPELLA DURING TWO SECONDS OF TIME

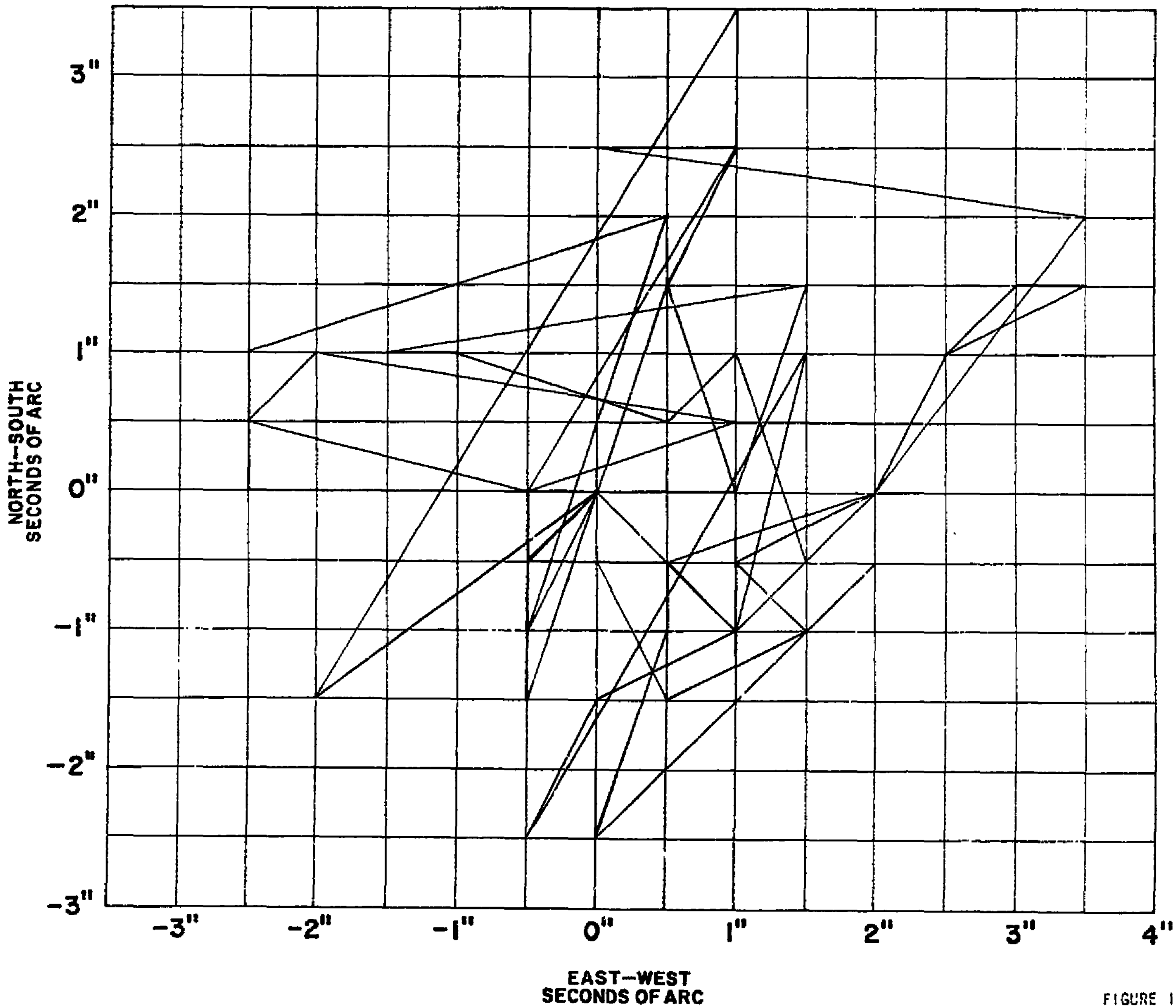

FIGURE 1

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