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Optical Tracking of Artificial Satellites

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AN artificial satellite, when launched with a full payload of instruments, will prove to be of maximum utility only when we know its orbit to some degree of exactness. Measures of position of the satellite at various known instants are the basic data needed for deriving the orbital characteristics. Various perturbation effects like atmospheric drag, gravitation anomalies and the oblateness of the earth enter such an orbital analysis. At the same time it is possible to study the nature of these perturbations and the secular changes in the orbital characteristics by continued observations of high accuracy of the positions of the satellite.

Three types of observations make possible the derivation of an orbit of the satellite. Visual observations are accurate enough to give an approximate orbit while photographic observations are capable of extremely high accuracy if the techniques available are modified to yield the precision required. A third mode of deriving positions is by having a radio transmitter in the satellite thus facilitating triangulation from ground stations. The radio observations are dependent on the functioning of the satellite transmitter and its source of power.

The visual observations are carried out by 'Moonwatch' teams that are scattered all over the world. Each team consists of about fifteen observers each of whom is equipped with a telescope of about two inches aperture. The telescopes are arranged in such a way that each observer looks at a fixed region of the sky in the meridian plane. Since there is an overlapping coverage of the regions, a satellite transit across the meridian at a given station will be observed at least by one observer. An eyepiece reticle and a tape recorder facilitate the determination of the position to an accuracy of better than one degree of arc and about one second of time, in the determination of the epoch.

'Moonwatch' observations, despite their low accuracy, are exceedingly important in both early and final stages of the lifetime of the satellite. Both 'Moonwatch' and radio tracking data are the only means of providing an approximate orbit immediately after launching. Similarly, in the final crucial days of the satellite, when very likely the radio transmitter may have ceased to function, and air drag effects become too conspicuous and do not permit the derivation of correct ephemeris predictions for photographic tracking, the visual observations are the only means of supplying vital information regarding the air density at heights in the earth's atmosphere lower than the original perigee altitude.

A precise determination of the position of a satellite at a given instant, when it is visible over a station, can be derived only by photographic means. A limitation imposed on optical techniques is that at a given region a satellite can be observed optically only in the twilight sky and when the geometrical conditions affecting the illumination of the satellite are favourable for visibility. Radio measures of position with the aid of 'Minitrack' stations, while less precise than the photographic measures, have the advantage that the object can be observed on every passage regardless of the time of day or weather conditions. During the current International Geophysical Year numerous countries have been co-operating in the establishment of optical and radio tracking stations for satellite observations. A major share of the credit in this enterprise goes to the IGY National Committee in the United States of America for their efforts in setting up a worldwide network of observing stations, with the co-operation of the local National Committees. Indian contributions to this effort are in the field of precise photographic tracking. This programme was allotted by the Indian National Committee to the Uttar Pradesh State Observatory at Naini Tal. The project is a co-operative effort between the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, and the observatory at Naini Tal. On Manora Peak, Naini Tal, is thus one of the twelve precise photographic stations which encircle the globe. The tracking camera and associated equipment have been supplied by the Smithsonian Astrophysical Observatory. Approximate positions obtained by projecting the film containing the image of the satellite and starry background on to a B.D. chart are cabled immediately to Cambridge. The frames obtained are sent later for precise measurement.

The camera used is a 20 in. aperture f/1 Schmidt system in an altazimuth mounting with an extra degree of freedom to facilitate tracking. The primary mirror is 31 in. in diameter with the focal plane located 20 in. away. The 20 in. focal length provides a scale of 401 sec. of arc per millimetre. The corrector plate has three components. Two surfaces of the corrector plate system are spherical while the remaining four are aspherical. The system has been made apochromatic by proper choice of the materials that constitute it. Ray tracing data indicate that a circle of confusion of 20 microns contains 80 per cent of the visible and ultraviolet regions of the spectrum. The camera has a field 30° long and 5° wide photographed on a film strip in the focal plane. The focal surface is curved and since the backing plate against which the film rests under tension is curved accordingly, good quality images having diameters close to the resolving power of the emulsion are obtained.

The mounting departs considerably from the standard form commonly used for astronomical purposes. Since the camera is designed specially for work on faint satellites, it is necessary for it to 'follow' the satellite in order to build up exposure, particularly when it is near the threshold of detection. This principle is well known in cometary or minor planet photography for position determinations. The difference between the

FIG. 1 — THE BAKER-NUNN CAMERA AT NAINI TAL [The time standard is seen in the background]

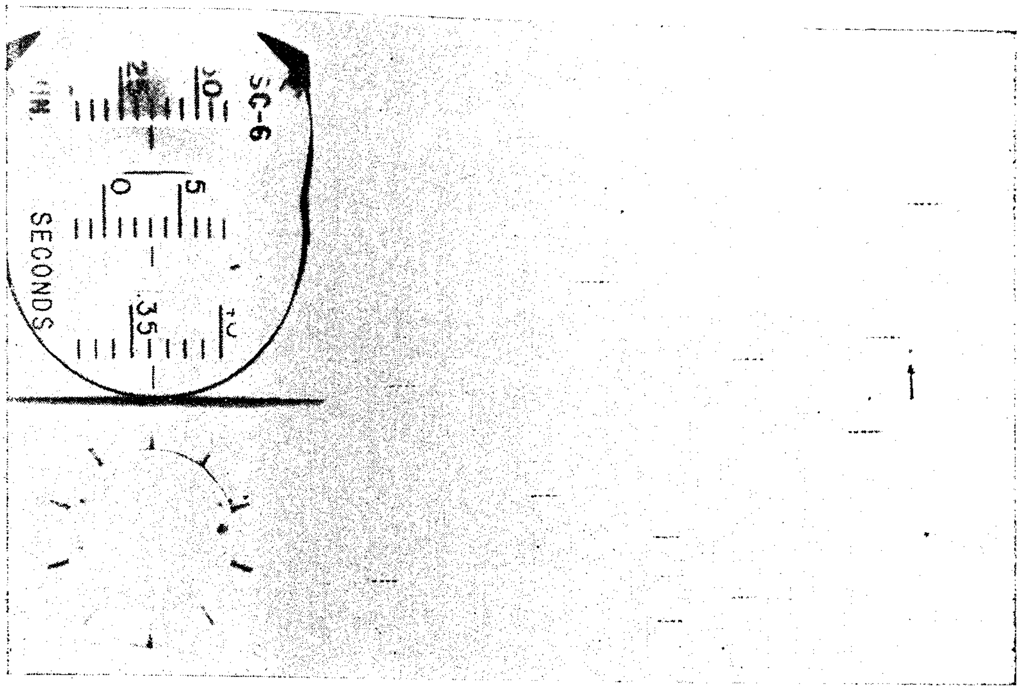

FIG. 2 — PHOTOGRAPH OF 1958 α_1 TAKEN WITH THE BAKER-NUNN CAMERA AT NAINI TAL ON 4 OCTOBER 1958 [The time presentation is seen on the left of the picture and reads 23 hrs 27 min. 3·3612 sec. The oscilloscope yields fractions of 10 millisec. The angular velocity of the satellite was 541 sec. of arc per second of time. The total exposure on the satellite equals 1·6 sec. The satellite image is marked by an arrow]

cometary case and that of the satellite is the comparatively large angular velocity that the latter has. Special tracking facilities are, therefore, called for to drive the camera at the prescribed angular velocity. The altitude axis of the altazimuth mount consists of a gimbal ring in which the camera is fixed. The camera is supported on an axis in the plane of this ring and in a direction perpendicular to the altitude axis as can be seen in Fig. 1. This permits the setting of the camera towards any point in the sky along the track of the satellite and the tracking is done by swinging the camera about the third axis. The rate of tracking depends on the angular velocity of the satellite. Information on the angular velocity and the azimuth and altitude of the culmination point is cabled from the computing centre of the Smithsonian Astrophysical Observatory prior to the transit. These are obtained in the early stages of the life of a satellite from an approximate orbit derived from the 'Moonwatch' and 'Minitrack' data.

The reduction procedure to be used for the derivation of a position necessarily follows the normal principles employed in photographic astrometry. To enable such procedures without large errors, the camera can be made to track alternately at sidereal and at satellite rates, so that in the first case the satellite leaves a trail with the star images as points and in the second the satellite image is a point. Since all these events can be recorded on the same frame of exposure of the film, the point image of the satellite can be measured against the faint star background with adequate correction for the motion of the satellite during the exposure.

For time measurement on the emulsion a rotating shutter produces sharp breaks in the trails. These can be seen in Fig. 2 which is a photograph of 1958 α_1 taken at Naini Tal. The camera tracked at the satellite's angular velocity for the duration of the exposure and hence the satellite image can be seen as a point with the star images trailed.

The camera tracking rate changes from sidereal to satellite values in an operating cycle. This cycle can be set to last 2, 4, 8, 16 or 32 sec. The total exposure on a frame lasts one-tenth of a cycle. The film transport rate, the duration of the cycle, the tracking speed, etc., can all be preset into the camera. These operations are all well synchronized and are powered by two synchronous motors fed with alternating current having a well-stabilized frequency.

Near perigee, when the satellite has an angular velocity in the neighbourhood of 5000 sec. of arc per second of time, we need a time measurement to an accuracy of 1/2500 of a sec. of time in order to attain a measuring accuracy of 2 sec. of arc. This is attained by means of an associated quartz clock which is readable to 1/10,000 of a sec. A slave clock inside the camera is photographed on every frame by an auxiliary camera when a stroboscopic flash illuminates the slave clock time presentation unit. The time recorded in this way on each frame relates actually to the satellite exposure made two frames previously. The time presentation on both ' master ' and ' slave ' clocks has a rotating dial reading to 1/100 sec. and an amplitude modulated circular sweep oscilloscope readable to 1/10,000 sec. These are seen in Fig. 2. The master clock is frequently compared with WWVH time signals for exact data on clock performance.

An important requirement for proper functioning of such a satellite tracking station is a very rapid communication facility between Cambridge and Naini Tal. A few hours before a transit, the latest data giving settings of azimuth, altitude, angular velocity and the expected instant of culmination of the satellite at the station are cabled from the Smithsonian Astrophysical Observatory. A transit observation may contain over a hundred photographs. The films are immediately processed and searched for the satellite images. If the transit is successful, the epoch and B.D. positions are cabled to Cambridge within a few hours after the transit. These cablegrams are given very high priority so that a message can be received at Cambridge from Naini Tal or vice versa within an hour.

The study of secular changes of the orbital parameters of an artificial satellite has opened new vistas in the fields of atmospheric density determinations and geodetic measurements. The effect of the earth's atmosphere is to produce a negative tangential acceleration which increases with the atmospheric density and the orbital velocity of the satellite. Since atmospheric density decreases very rapidly with height above the earth's surface and as the orbital velocity decreases relatively slower with height, the effect of atmospheric resistance will be most conspicuous for an eccentric orbit only in the portion of the orbit near perigee. Atmospheric drag thus produces secular changes in the eccentricity and semi-major axis of the orbit. It can be shown that if the density falls off rapidly enough, very little change takes place in the perigee distance, while the apogee distance decreases. For an eccentric orbit this decrease in apogee distance continues until the eccentricity is small enough, when the satellite experiences a drag all along the orbit. Consequently, the secular changes of the orbital elements permit the derivation of atmospheric models to heights above the earth's surface never reached before. The rapid spiralling of the satellite into the deeper layers of the atmosphere can be observed mainly by ' Moonwatch ' techniques.

We now have a new and exceedingly sound technique for determining the figure of the earth, and intercontinental distances. When we consider the motion of an infinitesimal particle about an oblate spheroid, we find that the longitude of the ascending node of the satellite orbit on the earth's equatorial plane shifts continually. A similar change is to be expected in the line of apsides or the line joining perigee and apogee. These changes are a function of the inclination of the orbit of the satellite, in the sense that the effect is zero for a satellite having an orbital plane perpendicular to the equator. Measurements of the precession of the plane of a satellite orbit of known inclination will provide a value of the oblateness more accurate than any available before the satellite era. Recently derived values of the oblateness are the results of such efforts.

An important field that can be tackled efficiently is the measurement of intercontinental distances. The Markowitz moon camera discussed in an article appearing elsewhere in this issue is expected to achieve a similar goal. At stations like Naini Tal, where both programmes are run concurrently, it will be of interest to compare the values obtained by two independent instrumental techniques.