*The Use of Baker-Nunn Cameras for Tracking of Artificial Earth Satellites**

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ABSTRACT: *For the fast and/or precise tracking of artificial earth satellites special tracking cameras such as the Baker-Nunn camera are used. Some general aspects of such satellite tracking are discussed and a short description of the Baker-Nunn camera is given. Also, the calibration of such cameras is discussed briefly. For fast satellite tracking it is desirable to have a star atlas and star maps available which have the same scale as photography produced with a tracking camera. The design of such a star atlas from photography taken with Baker-Nunn cameras is discussed.*

PREFACE

TRACKING of artificial earth satellites is the subject of extensive research by The Department of Geodetic Science of The Ohio State University. Considerable research has been done in this field under the sponsorship of The Air Force Cambridge Research Laboratories, Electronic Systems Division. The following sections deal with a portion of this research.

INTRODUCTION

Artificial earth satellites are launched for various scientific purposes such as for radiation studies, meteorological studies, communication techniques, geodetic investigations and for other purposes. This paper is concerned only with some aspects of the geodetic applications of artificial earth satellites.

Such satellites have an elliptic or circular orbit and travel with an average speed of about five miles-per-second with an average height above the earth surface of the order of 1,000 miles. Most satellites which have been launched up to present time have an East-West orbit. Recently, the use of geodetic satellites with a polar orbit is also considered with the purpose of obtaining more precise geodetic information. Such geodetic satellites will be spherical with a diameter of about 20 inches and a high-power light source. It is expected that from the tracking of geodetic satellites more precise information will be obtained concerning the flattening of the earth, the precise form of the geoid, and continental ties. It is conceived that this goal is achieved by tracking a sufficient number of orbital points from ground stations. The following tracking methods are considered: *Electronic Tracking,* (by means of electronic measurement systems); *Optical Tracking* (by means of telescopes, theodolites etc.); and *Photographic Tracking* (by means of tracking cameras such as the Baker-Nunn camera).

In this paper there is discussed only the photographic tracking of artificial earth satellites. The present tracking programs operate with a number of camera stations distributed over the earth. Usually, the so-called "star background method" is used i.e. each tracking camera photographs the satellite and the surrounding stars. By measuring relative photographic coordinates of the satellite image with respect to the surrounding star images, the satellite can be located for the tracking time in terms of Right Ascension and Declination. This yields the directions from the camera stations to the satellite position (orbit point). For *geodetic purposes* usually only an orbit segment is considered. By means of a sufficient number of trackings and a least square fit, the orbit segment can be determined with high accuracy. Due to the

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fact that the orbit is affected by the earth gravity, geoid sections can be determined from such orbit segments.

At present the following organizations are concerned with photographic tracking of artificial earth satellites:

The United States Air Force; for space control and Geodetic applications.

Smithsonian Astro-Physical Observatory; for geodetic and other scientific applications.

National Aeronautics and Space Administration; for various scientific applications.

A joint United States Army, Air Force and Navy group; for geodetic purposes.

This paper is particularly concerned with the tracking program of the United States Air Force. At present the Air Force operates five tracking cameras (Baker-Nunn Satellite Tracking Cameras, Mark II); these up to now were located at Edwards Air Force Base, California U.S.A.; Cold Lake, Royal Canadian Air Force Base, Canada; Universidad Santiago, Chile; Harestua, Oslo, Norway; and in Massachusetts, U.S.A.

A similar program is operated by the Smithsonian Astro-Physical Observatory using twelve Baker-Nunn Satellite Tracking Cameras, Mark I. The camera stations are located in New Mexico, Florida, Hawaii, Japan, India, Iran, Spain, South Africa, Australia, Curaçao, Argentina and Peru.

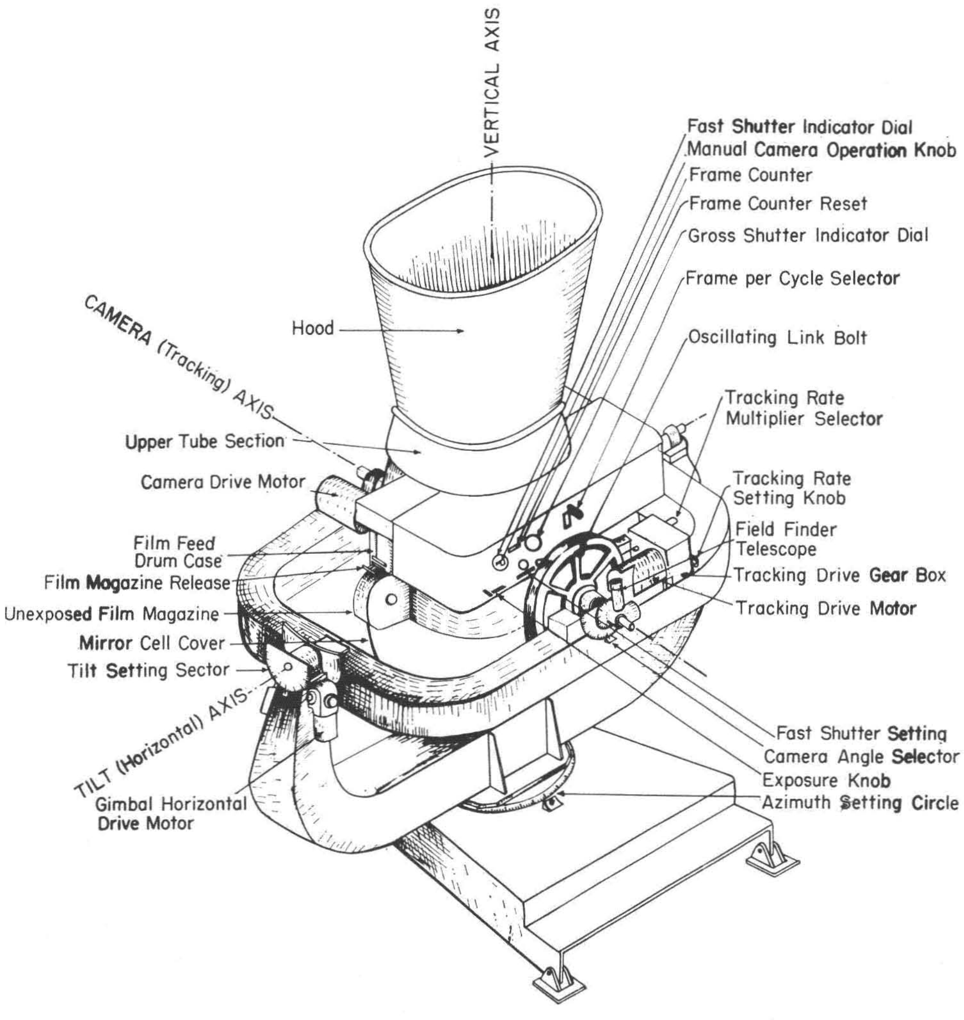


FIG. 1. Baker-Nunn Satellite Tracking Camera No. 13 located at Edwards Air Force Base, California.

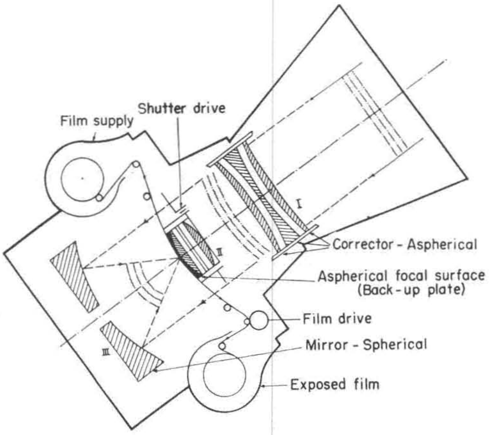


FIG. 2. Optical Elements of the Baker-Nunn Satellite Tracking Camera.

The operation and examination of such hugh tracking cameras requires considerable photogrammetric experience. This is emphasized by the fact that each camera is about three meters high, 2.5 meters long, and 1.5 meters wide. The cost for the complete equipment of one camera station is approximately $200,000.

As mentioned above the United States Air Force is concerned with the use of such tracking cameras for space control as well as for geodetic purposes. In the first case a directional accuracy (accuracy of the direction from the camera station to the satellite) of about 1′ is considered as being sufficient. Main emphasis is put on fast satellite location. In the second case a directional accuracy of 2″ is desirable, and considerable time is necessary for precise orbit computations. To achieve the necessary accuracy, satellite images are referred to up to 60 star images.

DESCRIPTION OF THE BAKER-NUNN SATELLITE TRACKING CAMERA— MARK II

In order to make the reader more familiar with the operation of the tracking cameras a schematic of the Baker-Nunn Satellite Tracking Camera, Mark II, No. 13, located at Edwards Air Force Base is shown in Figure 1.

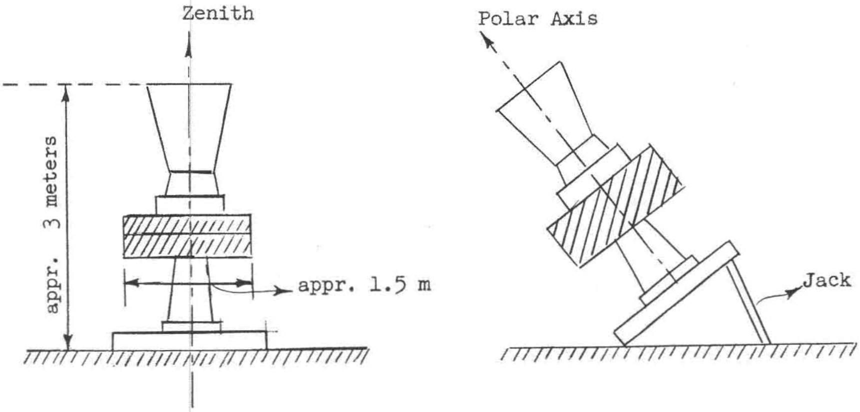
Such a camera consists of the following principal parts.

a. Base with azimuth adjustment.
b. Fork which carries the tilt axis.
c. Tilt frame which can be rotated about the tilt-axis and which is the carrier of the tracking axis.
d. Camera which is rotatable about the tracking axis.
e. Hood.

The optical system of the Baker-Nunn camera is a modified Schmidt type and has a 20 inch aperture with a f/1 focal-ratio, the nominal focal-length being 500 mm. Figure 2 is a schematic of the optical system of the Baker-Nunn camera.

Basically, the path of the light rays passes through the Aspherical Corrector I and the light rays are then reflected at the Spherical Mirror III to be focused on the slightly aspherical focal-surface (back-up plate) II on which the photographic image is generated.

The camera is operable in the horizontal as well as in the equatorial system (see Figure 3).



Horizontal System

Equatorial System

FIG. 3. Baker-Nunn Satellite Tracking Camera in horizontal and equatorial system.

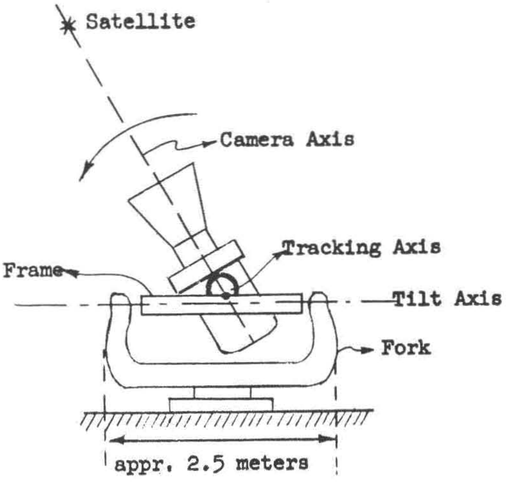


FIG. 4. Rotation of the camera around the tracking axis during tracking of a satellite.

The optical system is achromatized for three colors. All lens and mirror surfaces are spherical except the focal-surface which is slightly aspherical. This means that there are slightly different curvatures in the focal-surface. The focusing is somewhat dependent on the air temperature.

The camera is equipped with two hoods. The larger one is used when tracking (always at night) is performed in moonlight.

The camera case is made of a combination of steel and invar. The temperature expansion of the case is equal to that of Pyrex glass used for the mirror and the film back-up plate.

Fifty-Five millimeter film without perforation is used (Kodak Royal X Recording Safety Film, 55.625 mm.×950′, thickness =0.006 inch). The film must be stretched to conform to the aspherical shape of the focal-surface prior to exposure (required stretch 14 pounds). Each exposure covers an area of the sky 5°×30° and the resultant frames are 12 inches long and 2 inches wide. The frame length allows 1.5 inches for photographic registration of information from the slave clock. The film transport is automatic.

The considerable relative velocity of artificial earth satellites requires very exact time recording. One second of arc represents 0.0001 inch=0.0025 mm. on the film (focal-length f=500 mm.). This is equal to 25 feet =7.5 m. at a distance of one thousand miles =1,600 km. (assumed average height of the orbit of satellites relative to the earth surface). One millisecond of time and one second of arc=0.0001 inch on the film, are considered as an accuracy standard of the camera. Consequently, determination of image positions requires ability to locate image points on the film at a particular millisecond of time with an accuracy of 0.0001 inch or 2.5 microns. This is difficult to fulfill and experience indicates that it is doubtful whether this high accuracy is attainable.

In operating the camera it is anticipated that the path of the satellite through the heavens lies in the direction of the 30° length of the film frame, and that the path will lie somewhere within the 5° width of the frame. It has been presumed in designing the camera that all satellites will rise in a westerly direction and travel easterly. Therefore, the tilt axis and the fork have to be pointed at the horizontal point of rise and set for the satellite in question. During the tracking of the satellite the camera rotates around the tracking axis on a great circle in such a way that the camera follows the satellite which means that the camera axis should point always toward the traveling satellite. (See Figure 4.)

For this purpose the "Analytical Center" provides for the approximate satellite velocity. This velocity is set on the tracking drive of the camera as mean angular velocity of the camera. The "Analytical Center" also keeps record on the various satellites launched.

All camera motions are generated by motor drives which are controlled by push buttons on a portable control panel. (This includes azimuth, tilt, and tracking motion.)

The camera shutter is basically a double shutter which operates as an interrupting shutter. The double-shutter consists of a gross-shutter and a fast-shutter.

Each operation cycle of the camera consists of two phases, the first phase being known as the satellite phase and the second as the star phase. In the middle of each phase the gross-shutter of the camera is fully open for 1/10 cycle (1/5 phase). During each exposure the fast-shutter rotates around the film strip and interrupts the exposure. This fast-shutter consists of two barrel staves making 20 revolutions-per-cycle. Therefore, there is an interruption of the exposure for 1/40 of the cycle. These interruptions are arranged in such a way that the exposure streak on the film consists of four identical dashes occurring during the time the gross-shutter is fully open, plus two additional short dashes which occur during the period of the opening or closing of the gross-shutter. There are, therefore, five interruptions of the exposure streak of any light source. During the middle interruption, when the barrel stave is exactly centered over the film, a strobe flash is acti-

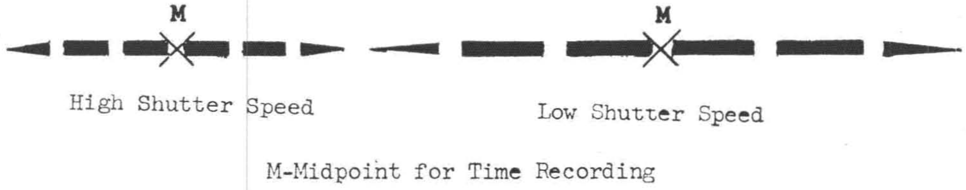


FIG. 5. Star Pictures on film for high and low shutter speeds.

vated to produce an image of the slave clock on the film. This time corresponds to the midpoint *M* of the middle break in any image streak on the film (see Figure 5).

The following exposure times (gross-shutter speeds) can be adjusted by means of a special knob:

0.2 sec., 0.4 sec., 0.8 sec.,
1.6 sec., and 3.2 sec.

also, an arbitrarily long exposure time can be adjusted (see Figure 6).

Long exposure times (low shutter speeds) are used to detect a satellite. Since the camera moves approximately with the speed of the satellite, satellite images are either points or short dashes, while the stars produce much longer dashes which are caused by the considerable speed difference between stars and camera (see Figure 6).

As already mentioned, the tracking time of a satellite is recorded on each frame by photographing the slave clock. Such a time recording is shown in Figure 7.

The resolving power of the optics of the camera allows portrayal of stars with a minimum image diameter of 20 microns on the film. To reduce light reflection loss and as protection against humidity the front surface of the front lens of the optical system is coated.

The camera is equipped with a sidereal time drive by motor to be used in equatorial mount. The sidereal time drive rotates the camera around the polar axis with an angular velocity of 1°/4 min.

The camera is provided with several safety devices. For instances, the operation of the camera shutter motor is stopped in case of film jamming or breaking. Furthermore, the camera drive is automatically stopped when the camera axis moves within 10° from the horizon. Red warning lights and alarm bells are activated when the limits of the various motions are reached.

When satellites, or stars, are photographed it is advisable to photograph in periods without any moonlight.

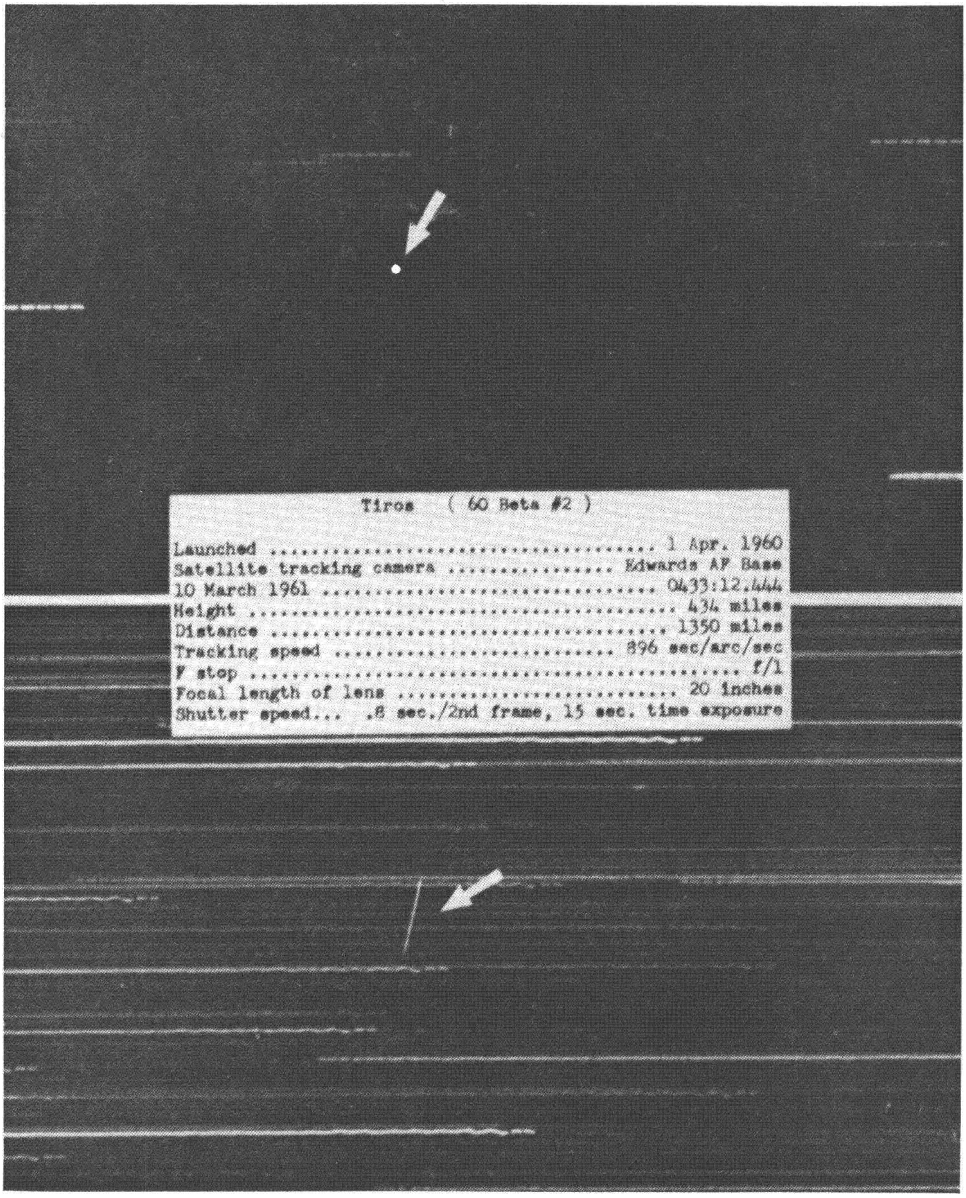
The camera is housed in a special pavilion with removable roof (see Figure 8). When the roof is open during the daytime the front side of the camera optics has to be covered with the front cover. If this is not done there is the danger that entering sunlight will soon melt the back-up plate (Pyrex glass) due to the tremendous focusing effect of the camera optics.

Design of a Special Star Atlas from Photography Taken With a Baker-Nunn Camera for Fast and/or Precise Satellite Tracking

For satellite tracking with Baker-Nunn Cameras it would be convenient to have star maps and star atlases available which have the same scale as the photography produced by such cameras. The existing star maps and star atlases do not fulfill this condition. It is, therefore, necessary to compile a new atlas which concurs with this requirement. It was decided that this should be done by mosaicking star photographs made with a Baker-Nunn camera. This will have the additional advantage that such a star atlas would contain many more stars than the existing star atlases such as the "Bonner Musterung." An evaluation revealed that such a new atlas would contain more than one million stars while the best existing star atlas contains about 30,000 stars.

For satellite tracking it is desirable that each star map is provided with grid lines from 1° to 1° (lines of equal Right Ascension and Declination). Such a star atlas was designed by The Department of Geodetic Science, The Ohio State University. It consists of 212 star maps in Cassini projection each covering an area of 15°×15° at the sky. These 212 maps are composed of 94 maps for the Northern Calotte (from $7\frac{1}{2}^{\circ}$ North Declination to the celestial North Pole), of 24 maps for the Equatorial Belt (from $7\frac{1}{2}^{\circ}$ North Declination to $7\frac{1}{2}^{\circ}$ South Declination), and of 94 maps for the Southern Calotte (from $7\frac{1}{2}^{\circ}$ South Declination to the celestial South Pole). Figure 9 shows the sheet lay-out for the Northern Calotte and the Equatorial Belt.

To compile these maps a special photo-



Tiros (60 Beta #2)

Launched .... 1 Apr. 1960
Satellite tracking camera .... Edwards AF Base
10 March 1961 .... 0433:12.444
Height .... 434 miles
Distance .... 1350 miles
Tracking speed .... 896 sec/arc/sec
F stop f/1
Focal length of lens .... 20 inches
Shutter speed... .8 sec./2nd frame, 15 sec. time exposure

FIG. 6. Short and Long Exposure for Satellite Tiros.

graphic program was worked out to photograph both calottes as well as the equatorial belt by means of the Baker-Nunn camera located at Edwards Air Force Base, California and at Santiago, Chile. Eight hundred forty-eight photographs taken with both cameras in equatorial mount are necessary for the entire coverage of the celestial sphere (for each star map, four frames parallel to lines of equal declination, with appropriate overlap). The mossaicking of the star maps by means of these frames requires about 2,500 match stars to be plotted in terms of Cassini coordinates on transparent film base. The performance of this photographic program requires considerable time and has not been started yet.

Valuable contributions to this project were made by Dr. H. Beat Wackernagel, Project Monitor, Air Force Cambridge Research Laboratories, Office of Aerospace Research; Mr. V. L. Benson, Edwards Air Force Base; Dr. Gunther Mulert, Mr. Kurt Bretterbauer, Mr. O. M. Miller, Mr. J. B. Schreiter, Mr. J.

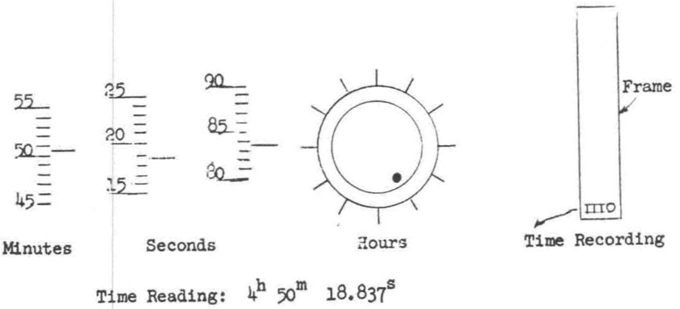


FIG. 7. Schematic showing time recording on each frame.

L. Dennis, Mr. R. B. Forrest, Miss M. W. Hindman, Research Associates and Mr. Peter Wilson, Mr. K. C. Chopra, Mr. K. O. Kaplaneck, Research Assistants.

CALIBRATION AND DETERMINATION OF THE AVERAGE FOCAL-LENGTH OF BAKER-NUNN CAMERAS

A partial calibration of such a camera (Baker-Nunn Satellite Tracking Camera, Mark II, No. 13) was performed, 1961 by Dr. H. Beat Wackernagel, Air Force Cambridge Research Laboratories, Office of Aerospace Research; and by the author of this paper assisted by Mr. R. B. Forrest, Research Associate, and additional research personnel of The Department of Geodetic Science, The Ohio State University.

The principal aim of this calibration was the determination of the average focal-length of the Baker-Nunn Satellite Tracking Camera, Mark II, No. 13, at Edwards Air Force Base, located in the Mojave Desert, California.

The knowledge of this focal-length value is necessary for the compilation of the star maps for the Northern Calotte in Cassini projection to be compiled from star photography exposed with this camera in such a fashion that the star maps have, as nearly as possible, the same scale as satellite photography taken with a Baker-Nunn Camera.

For the test the portion of the sky covered by star maps No. N-64 and N-65 (see Figure 9) was photographed with camera No. 13 in equatorial mount with the shutter cycle 3.2 Sec. This portion of the sky covers the area around the star configuration Hercules. The determination of the average focal length of camera No. 13 was performed with the frame $\delta=24°$ of Star Map No. N-64 (see Figure 9). For 40 stars appearing on this frame, the mean celestial coordinates were taken from the Boss General Catalogue and corrected for proper motion. The corrected coordinates were then transformed to coordinates X, Y in the Cassini projection with a projection distance $f=500$ mm., and with the central meridian approximately coinciding with the center of the frame. By means of the Nistri TA3-Stereocomparator the same coordinates were measured on the frame (coordinates x, y; standard measurement errors $=\pm 8$ microns). Using a coordinate transformation with translations in x and y and a scale factor, the frame was made to coincide with the projection given by the coordinates X, Y. From the scale factor an average focal-length $f=493.891$ mm. for Baker-Nunn Camera No. 13 was determined by using a least square adjustment and by taking into account the refraction effect.

It has to be pointed out that the value $f=493.891$ mm. does not quite conform with the calibrated focal-length value of the camera which is slightly dependent on the distance of the image-point (star image) from the frame center. The value $f=493.891$ mm. is, however, that focal-length value which makes the scale of the Cassini projection, as near as possible, equal to the scale of the frames. This focal-length value is used for the mosaicking of the individual star maps. By photographic enlargement these mosaics are then brought to a scale corresponding to the nominal focal-length of all Air Force Baker-Nunn cameras which was accepted as being 500 mm.

For precise satellite tracking used for geodetic purposes, a more comprehensive calibration of the Baker-Nunn cameras is necessary. This would include a determination of a sufficient number of individual focal-length values which would permit a precise metrical determination of the slightly aspherical focal surface. Also, the individual curvature of this surface at a sufficient number of points had to be determined. Such a test should include several frames in order to be less dependent on the film shrinkage effect which must be con-

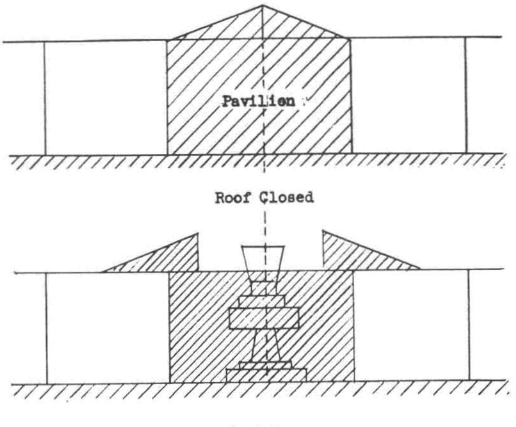


FIG. 8. Pavilion with closed and open roof.

sidered as being one of the most critical points of the Baker-Nunn camera. Some experiments have shown that the film shrinkage caused by stretching the film over the aspherical focal-surface essentially reduces the directional accuracy. It seems to be that this disadvantage can be eliminated only by redesigning the Baker-Nunn camera in such a fashion that exposures are produced on absolutely flat and plane film or, eventually, on plane glass plates.

THE USE OF THE STAR ATLAS FOR TRACKING OF ARTIFICIAL EARTH SATELLITES

A star atlas with star maps which have a scale, as nearly as possible, equal to the scale of photography obtained from Baker-Nunn cameras is useful for fast satellite tracking and location with reduced accuracy (direc-

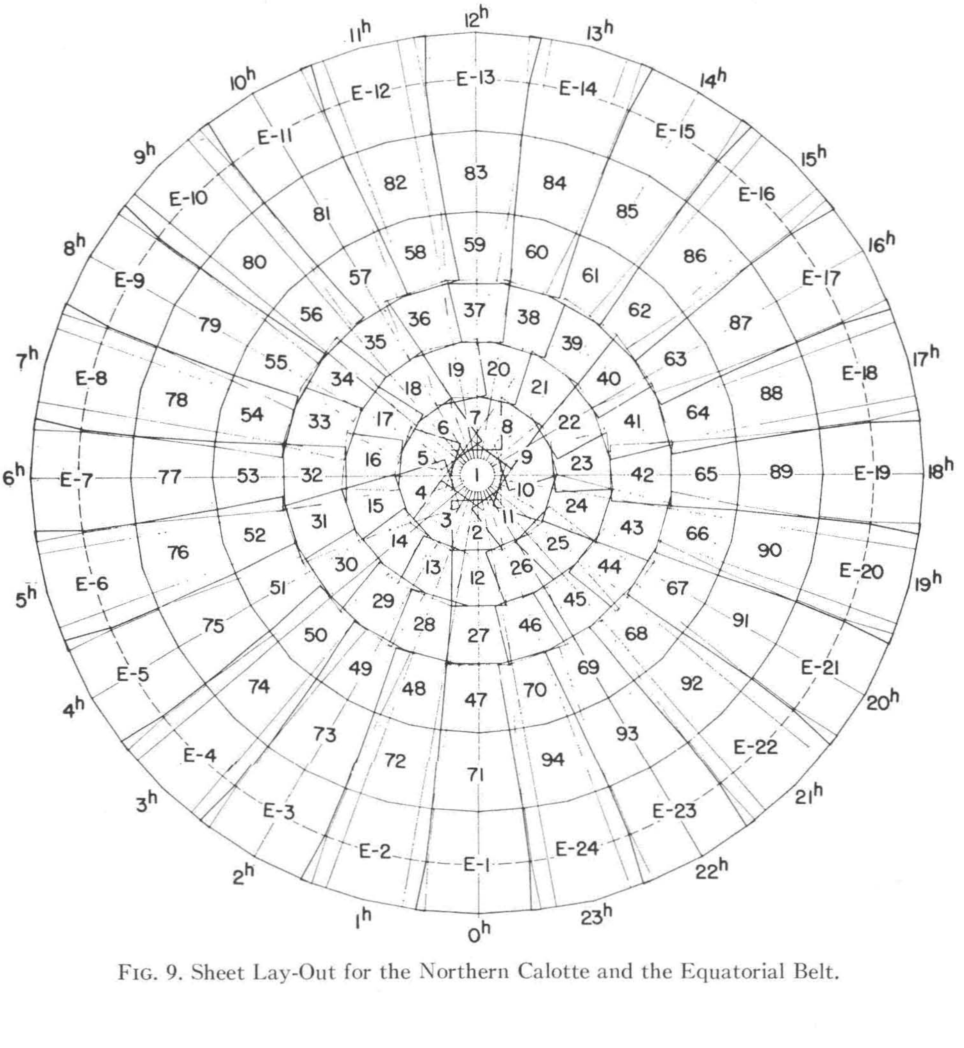


FIG. 9. Sheet Lay-Out for the Northern Calotte and the Equatorial Belt.

tional accuracy approximately 1′) or to obtain in a short time approximation values for precise satellite tracking and location. For this purpose a blink-microscope with three image carriers is used.

Satellite location in the blink microscope takes place by comparison of two consecutive satellite photographs (satellite phase and star phase) placed in two image carriers with the correspondent star map placed in the third image carrier. The position of the satellite is then determined by measuring the righ ascension and declination difference of the satellite image by means of a glass scale with respect to the nearest grid lines.

CONCLUSION

The fast developing space sciences offers new applications for photogrammetry, especially, in the field of satellite tracking. Considerable effort must be made to improve the photographic tracking methods with regard to precise tracking for geodetic purposes. This opens a new field for photogrammetric research with interesting and fascinating problems.

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*A Use of APR for Mapping Control in Difficult Terrain**

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INTRODUCTION

WHEN the Hunting Airborne Profile Recorder was put into general operation ten years ago, it was used largely to provide elevations for aeronautical charts. As the instrument was improved, it became practical to use the profiles as a source of elevation control for photogrammetric mapping. More recently, by synchronizing with air-survey photography, the APR has provided elements for control of photogrammetric map-scale, as well. In effect, ground survey has been entirely substituted for certain conditions.

In operation, the APR provides two records, the first of which is the terrain clearance. For this, the distance between an aircraft and the surface of the earth along its flight path, is measured by a narrow radar beam directed downwards from the aircraft, the clearance being recorded continuously on a moving chart. The height of the synchronized survey camera above the ground, and hence the exact scale of the photography, becomes known.

The second record is the terrain profile, within which the vertical movements of the aircraft have been corrected continuously and automatically by a precision electronic hypsometer. This profile is located on the ground by a synchronized 35 mm. positioning camera. For use of the terrain profile, corrections are made for inclination of the pressure altitude plane to which the hypsometer relates, and correlation may be made with known ground values such as sea level, which have been crossed during flight.

This is an operational report to photogrammetrists on a useful APR-controlled mapping technique for rough, inaccessible terrain.

PROJECT CIRCUMSTANCE

In general connection with development planning for the region east of the Andes in Central Peru, and specifically for hydroelectric power studies of the Mantaro River, the Ministry of Development and Public Works required, with relative urgency, reconnaissance topographic maps of a known reliability. The project location is shown in Figure 1.

The range of relief and severity of slopes throughout the area have almost excluded it from previous exploration, of any type. Rises and falls of 2,000 meters in five kilometers are common in the general relief. There are no roads and only a few trails linking scattered mountain Indian settlements. A typical profile is shown in Figure 4.

In this circumstance, to establish conventional ground-survey control for mapping would be an almost impossible task, costly

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* Presented at the 28th Annual Meeting of the Society, The Shoreham Hotel, Washington, D. C., March 14–17, 1962. The Abstract for this paper is on page 345 of the 1962 YEARBOOK.