

The Early Development of Satellite Characterization Capabilities at the Air Force Laboratories

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Abstract

This paper overviews the development of optical Space Object Identification (SOI) techniques at the Air Force laboratories during the two-decade “pre-operational” period prior to 1980, when the Groundbased Electro-Optical Deep Space Surveillance (GEODSS) sensors were deployed. Beginning with the launch of Sputnik in 1957, the United States Air Force has actively pursued the development and application of optical sensor technology for the detection, tracking, and characterization of artificial satellites. Until the mid-1980s, these activities were primarily conducted within Air Force research and development laboratories, which supplied data to the operational components on a contributing basis. This note describes the early evolution of optical space surveillance technologies and experimental sensors that led directly to the current generation of deployed operational and research systems. The contributions of the participating Air Force organizations and facilities are reviewed with special emphasis on the development of technologies for the characterization of spacecraft using optical signatures.

Many military, government, educational, and contractor agencies supported the development of instrumentation and analysis techniques. This overview focuses mainly on the role played by Air Force System Command and the Office of Aerospace Research, and the closely related activities at the Department of Defense Advanced Research Projects Agency. The omission of other agencies from this review reflects the limitations of this presentation, not the significance of their contributions.

1. Introduction

The first optical observations for characterization of orbiting spacecraft were made within a few weeks of the launch of Sputnik in 1957. Photographs were obtained using existing long-focal length, missile-tracking telescopes at the Air Force Missile Test Center, Cape Kennedy, Florida. These earliest Space Object Identification (SOI) data were analyzed to obtain “reasonably accurate” estimates of the satellite’s size and tumble rate [2, 12]. During the nearly five decades since these first SOI observations, optical sensors have evolved from photographic film, to vacuum tube cameras and photomultiplier tubes, to solid-state charge coupled devices (CCDs), and the observing spectrum has been expanded beyond the visible well into the ultraviolet and infrared.

SOI data are divided into two distinct types: imagery and signatures, each with their own specialized instrumentation and analysis techniques. The analysis of the optical SOI data, while making increasing use of computers, is still, however, primarily dependent on the experience and insight of the human analyst.

The objective of this note is to document the early development of optical SOI instrumentation and techniques. As with any history, especially a brief review such as this, the first requirement is to define the scope of the study. We have limited this review to the “pre-operational” period through about 1980 when the Air Force GEODSS (Ground Based Electro-Optical Deep Space Surveillance) sensors were deployed. Although optical “metric” sensors (systems that primarily measure the positions of satellites) are very closely related, this review is focused on SOI sensors. During these two decades, a large number of military, government, educational, and contractor agencies supported the development of instrumentation and analysis techniques. The scope of the study has been further narrowed to an overview of the role played by the Air Force Systems Command (AFSC) and Office of Aerospace Research (OAR)

laboratories, in particular, the AF Avionics Laboratory (AFAL), Aerospace Research Laboratory (ARL), and Range Measurements Laboratory (RML). Closely related to these centers was the Department of Defense Advanced Research Projects Agency (ARPA) facility on the island of Maui, Hawaii, which was later transitioned to the AFSC Space and Missile Systems Organization (SAMSO) and then to the Rome Air Development Center (RADC). All of these organizations have undergone considerable changes over the years; tracing their history, name changes, consolidations, and closures would be an interesting study in itself. The omission of other agencies from this review reflects the limitations of our study, not the significance of their contributions.

2. Sulphur Grove, OH, Observatory

The earliest optical SOI observations were made using long-focal length film cameras designed for missile launch support. The limitations of these sensors soon became apparent. The atmosphere limited the best resolution that could be obtained to approximately 1.5 meters [2], many times the diffraction limit of the 24-inch apertures then in use. Immediately after the Sputnik launch in 1957, the Air Force undertook a major initiative to improve the ability to resolve satellites. The initiative was based in the Reconnaissance Division of the AF Avionics Laboratory (AFAL) at Wright-Patterson Air Force Base, Ohio, because of the resident expertise in low-light-level imaging. An experimental test site was established at Sulphur Grove, an Air Force weather station just northwest of the base in what is now Huber Heights. The purpose of the site was to determine the optical characteristics of satellites, demonstrate sensor technology, and develop tracking techniques. Astronomical photomultiplier-tube photometers were used to measure the range of satellite brightnesses and image orthicon television cameras were evaluated for high-speed satellite imaging. One of the telescopes used in these early measurements is shown in Fig. 1.

When AFAL completed their demonstration program in 1960 and began construction of their new imaging facility (described below) at Cloudcroft, NM, the Sulphur Grove facility was transitioned to the Aerospace Research Laboratory (ARL). ARL's mission at the site was to pursue basic research into improving SOI capabilities. A variety of experiments into the characterization of the light reflected from satellites were conducted including imaging, polarimetry, spectrometry, and lightcurve analyses, exploiting techniques used in astronomy. A number of these research efforts were conducted in conjunction with graduate theses at the Air Force Institute of Technology at Wright-Patterson AFB [8, 13, 14, 17] and research efforts with the British RAF and Canadian Forces.

ARL installed a 24-inch (0.6-meter) aperture, $f/16$, Cassegrain telescope (Fig. 2). A four-axis mount, a modified Baker-Nunn mount (Fig. 3) designed by Joseph Nunn and Kenneth Kissell, was used to match the apparent small-circle trajectories of low-altitude satellites and allow tracking to be performed primarily in one axis [5]. The telescope was housed in a sliding roof observatory (Fig. 4). Initially all satellite tracking was done manually. The operator looked through a small boresighted telescope to acquire the target satellite and brought it onto the detector aperture using a rate control for the track axis with his right hand and a position control for the cross-track axis with his left hand. A tone whose frequency was set by the intensity of the light detected by the photometer provided an audio feedback to the operator for tracking. In the mid-Seventies, an analog computer was added for computer-assist in the track axis. The primary sensor was a photomultiplier photometer with a feedback circuit designed by H.M. Sweet (Fig. 5) to provide a logarithmic output improving the dynamic range and time response [15]. A 40-arc-second sensor aperture was used routinely; a ten arc-second aperture was successfully employed for some special observations. The photometer signal and WWV time signals were recorded on a rapid-response optical strip chart recorder using light-sensitive paper (Fig. 6) and on analog magnetic tape.

The calculations for the mount set up were performed manually using an updated version of the medieval astrolabe [9]. A United States Geological Survey (USGS) equal-area projection meridional net (Fig. 7a), a planer projection of a spherical coordinate system grid, formed the basis of the analog computing device. This meridional net corresponds to the "plate" of the astrolabe and a series of transparent overlays corresponded to the "rete". A hole through the poles of the overlays fit over a rod passing through the origin of the meridional net allowing the overlays to be rotated relative to the net. The first overlay was marked with Earth-centered stereographic projections of the observer's latitude and longitude position and an observer-centered "equatorial" curve marked with azimuth points (Fig. 7b). The target satellite latitude and longitude subpoint listings as a function of time were obtained from the Air Force, NASA, or the Smithsonian Astrophysical Observatory and were plotted in grease pencil on an unmarked overlay using the meridional net coordinates. The satellite subpoint azimuths and great circle distances were determined by joining the subpoints to the observer position along great circles by rotating the meridional net. The

satellite's elevation angles were then calculated from the satellite altitude and great circle distance using a nomograph. The satellite's entry and exit points from the Earth's shadow and phase angles could also be computed using an additional overlay (not shown). The Earth-centered overlays were then replaced on the meridional net by an observer-centered overlay and the computed satellite azimuths and elevations were plotted. This overlay was rotated relative to the meridional net until the best fit of a great circle to the points was obtained. The mount angles could then be determined relative to the pole of that great circle. An example of the final mount setting solution for a typical satellite pass is shown in Fig. 7c. An experienced analyst required about five to ten minutes to perform these calculations for each satellite pass.

Although some imaging experiments were conducted, the primary emphasis of the ARL observations at the Sulphur Grove Observatory was the collection of optical signatures. Through analysis of the temporal variations in the brightness of a satellite, the configuration and dynamics of the satellite could be determined. Low-altitude satellites of interest to the Air Force were routinely tracked each evening and their signatures were analyzed the next day. An example of one analysis of the Sulphur Grove photometric data in Fig. 6 is illustrated in Fig. 8 [1]. The signature is of the Ariel III spacecraft obtained on 17 July 1967; Ariel III was a spin-stabilized satellite with a surface-mounted set of mirrors to produce glints to support the motion determination. The pattern of glints from Ariel III was analyzed to identify the sequence of glints from each mirror (Fig. 8a). From the time history of the glints from each mirror, the spin and coning motion and spin-axis orientation of the satellite at that time could be determined (Fig. 8b). By combining the analysis results of photometric and optical data collected over several months, it was possible to trace the changes in the orientation of the satellite's angular momentum vector (Fig. 8c). Similar analyses were performed on other satellites using glints from solar cells. In several cases, the number and orientations of the glinting surfaces were not known so the satellite configuration had to be determined as part of the analysis. The first computer analyses of the photometric signatures began in the early-Seventies; the signatures were initially input by manually digitizing the strip-chart recordings. By the mid-Seventies, the signatures were input directly into a computer either by digitizing the analog signals or by recording the digital output of photon-counting photometers.

The first systematic photoelectric SOI observations of geosynchronous satellites were obtained when the Sulphur Grove photometer was taken to the Cloudcroft to support operations in 1970 [17]. Portable ARL photometric sensors were employed at locations around the world to conduct special observations and surveys of potential operational optical sites. In 1973 and 1974, portable photometer systems employing ten-inch aperture telescopes (Fig. 9) were taken to Southeast Asia to observe Eastern Hemisphere geosynchronous satellites. For several years, simultaneous optical and radar signature observations were made in cooperation with Cornell Aeronautical Laboratories near Buffalo, NY. In one of ARL's more interesting overseas experiments, a photometer was mounted on a tracking radar antenna at the Royal Radar Establishment, Malvern, England, to obtain simultaneous radar and optical signatures of low-altitude spacecraft.

ARL transferred the Sulphur Grove facility back to AFAL in the early-Seventies. Operations continued at Sulphur Grove until 1972 when development around the site forced relocation to a darker location. The facility was moved to John Bryant State Park near Yellow Springs, Ohio, where photometric observations and camera tube testing for GEODSS continued until 1975 when a decision was made to close the facility. The 24-inch telescope was upgraded with a full computer control system and transferred to the Canadian Armed Forces as an operational NORAD sensor at St. Margarets, New Brunswick (Fig. 10). After several years of operation, the telescope moved to the Canadian Royal Military College where it resided until recently. The telescope has now been returned to Wright-Patterson AFB, OH, where it is currently being refurbished by AFRL and will resume collection of SOI data for the US Air Force.

3. AFAL Cloudcroft, NM, Electro-Optical Facility

In parallel with its test site activities at Sulphur Grove, OH, AFAL conducted a survey of potential sites in the continental United States for a large (one to two-meter) aperture telescope was undertaken. The goal was to identify a site providing the best possible seeing conditions, accessibility, and local support. Based on a number of studies, the primary site selection criterion was a high-altitude, wooded location elevated above the surrounding terrain. While a site near Yuma, Arizona, was identified as the best candidate, the second choice, near Cloudcroft, New Mexico, was ultimately selected. This site was originally to have been the location for an Air Force solar furnace facility for nuclear effects testing and an investment in infrastructure (roads, electrical power, etc.) had been made before that project was abandoned. The Cloudcroft site was chosen as the location for the new telescope because of

the cost savings realized from the existing infrastructure and Congressional support for utilization of the site. Technical, logistical, and administrative support was available through Holloman Air Force Base thirty miles to the West.

The construction of the facility began in 1962 (Fig. 11). The dome was fifty feet in diameter allowing the telescope to be positioned without interference. The dome slot extended from horizon to horizon and was equipped with a fabric windscreen to reduce wind-induced jitter. The observatory building was designed to minimize the turbulence that would degrade image resolution. The base of the dome was four stories high to place the telescope above local ground effects. A large air handling system kept the dome at the expected nighttime temperature. The observatory had a metal “skin” separated from the concrete block walls and the dome was double skinned. Outside air was drawn in through the gaps to reduce heating during the day. The exhaust from the air handling system was vented underground to an outlet several hundred feet downwind of the observatory.

An aperture of 48-inches (1.2-meters) diameter was selected as the best compromise between diffraction-limited resolution, optical quality, and cost. The telescope (Fig. 12) was a Newtonian design to provide maximum flexibility in the selection of focal lengths. The primary mirror had a 312-inch focal length; using relay optics, focal lengths up to 13,000-inches were obtained. An observer could ride on a couch on top of the telescope tube for direct observations or to assist in target acquisition. Because of the computer processing speed limitations in the early Sixties, the ability to control a large telescope to smoothly track a rapidly moving satellite was a major technological problem. The solution was to design a three-axis mount that could track low-altitude satellites by moving primarily in one axis. The mount design was an azimuth (“track”) over elevation (“cross-track”) mounted on a rotating azimuth platform. The azimuth platform was pointed toward the culmination azimuth of a satellite’s trajectory and locked in position. The satellite could then be tracked by varying the angular rate of the “track” axis and introducing small positional offsets in the “cross-track” axis. The three-axis design also provided the capability to smoothly track a satellite moving through zenith (directly overhead) where the best images could be obtained.

The telescope control system (Fig. 13) was largely analog but was driven by an IBM Model 1800 computer (an industrial process-control version of the IBM 1130). Because of the narrow, two arc-minutes or less, fields-of-view of the telescope and the poor accuracy of the satellite element sets at the time, manual tracking stations were installed in automated domes on the North and the South corners of the observatory building. These stations had small aperture, Naval gun-sight telescopes on three-axis mounts similar to the main telescope. By moving the small telescopes, operators could directly steer the main telescope to bring a satellite onto boresight.

First light for the Cloudcroft telescope was in 1964. The primary emphasis of the facility was the development of techniques for classical (i.e., uncompensated) imaging of satellites [16]. High-speed, short-exposure film and television cameras operating at up to three hundred frames per second were used to “freeze” the atmospheric distortions and obtain a few nearly diffraction-limited images. The approach proved very successful. For example, in one imaging pass of a very large, low-altitude object, the S-IVB upper stage of an Apollo Saturn rocket, surface markings were visible and turbulence cells could be observed transiting the vehicle. Although the atmosphere limited the average resolution at the site to about one arc-second, several frames in a pass would typically have resolutions better than 0.3 arc-seconds. While most satellite imaging was done during twilight, a capability to image during daylight was implemented using red filters and a computer-control polarizer to improve target contrast. The site also routinely used a pulsed ruby laser for satellite illumination until policy changes restricted their use. In the early Seventies, Cloudcroft began to observe geosynchronous satellite and was the first electro-optical site to electronically report photometric signatures and metric positions to the operational Air Force command supplementing the Baker-Nunn photographic cameras used for operational tracking of deep-space satellites. Early infrared satellite detection and tracking experiments were conducted in 1972 using a scanned linear detector array. From its elevated vantage point, the facility also supported missile tests at the nearby White Sands Missile Range.

In the late-Sixties, the first Air Force operational electro-optical space surveillance sensor, the FSR-2, was co-located at the Cloudcroft site. This system employed a wide field-of-view telescope with a light-weighted mirror. Multiple image orthicon cameras were coupled to the focal plane via fiber optics. The sensor scanned the geosynchronous belt and detections were mapped onto a large drum memory. On subsequent scans, the detection maps were registered and compared to identify moving satellites. The FSR-2 proved to be overly ambitious for its time and ceased operations within a year due to delamination of the mirror and other technical issues.

The Cloudcroft facility continued to support SOI development activities until 1975 when it was transferred to the Air Force Space and Missile Systems Organization (SAMS0), now the Space and Missile Center (SMC), to support a satellite laser communications program. In the early Eighties, Air Force Geophysics Laboratory operated the facility in support of astronomical programs at the Sacramento Peak Solar Observatory. The facility was closed in the late Eighties and the telescope and control system were acquired by JPL and moved to their Table Mountain Observatory in California. The observatory building then sat empty for a number of years, until it was acquired by the NASA Johnson Space Center for support of its orbital debris measurements program. NASA installed a three-meter diameter aperture, liquid-mirror telescope (LMT) that began operations in 1996. The primary mirror of the LMT was a shallow dish of mercury that is spun to form a parabolic surface. The telescope stares out of the dome toward zenith and detects satellites moving relative to the background star field. A 0.3-meter aperture telescope equipped with a CCD camera was also been installed in the small dome at the South corner of the building to conduct geosynchronous belt orbital debris searches. Observations using both of these sensors were conducted every suitable night until December 2001. The NASA instrumentation has now been removed and the site is unused.

3. Contemporary Sites: Malabar and AMOS

During the Sixties and Seventies, while the Sulphur Grove and Cloudcroft sites were actively supporting the development of SOI techniques, two other DoD facilities were also making key contributions. These were the Range Measurements Laboratory Malabar Site and the ARPA Maui Optical Station (AMOS). Each of these facilities has a history and list of accomplishments as interesting as the two sites described above, but will only be briefly highlighted.

The Malabar Test Facility was created by the Range Measurements Laboratory in the early Sixties with a primary mission to study lasers and laser effects. It rapidly added secondary missions in launch support because of its proximity to Cape Canaveral and in satellite imaging. Instrumentation at the facility consisted of two laser beam directors, a 24-inch aperture infrared telescope, and a 48-inch visible laser receiver telescope. The 48-inch telescope with focal ratios of $f/2.5$ to $f/100$ was the primary SOI sensor used to support imaging. It was mounted on an elevated tower to place it above the ground turbulence. The Malabar facility pioneered the development of techniques for imaging satellites in daylight. Techniques for real-time adaptive tracking were also developed at Malabar. Due to computer limitations in the Sixties, satellite tracking was typically performed by precalculating an ephemeris for the satellite's trajectory, and then commanding the telescope to follow that trajectory. If the satellite was off its predicted trajectory, as was common, the operator added positional offsets to the ephemeris positions. A smooth track needed for good imaging was very difficult to achieve. The adaptive tracking algorithms developed at Malabar allowed the target to be tracked directly from a state vector and the observed positional errors were used to update the state vector in real time. The facility was transitioned to SAMS0 in 1978, to the AF Space Technology Center in 1984, and then to the Phillips Laboratory (now part of AFRL) in 1990. The Malabar Test Facility was closed in the mid-Nineties and its telescopes and other instrumentation relocated to other sites.

The design and construction of the AMOS facility on Mount Haleakala on the island of Maui, Hawaii, was accomplished between 1963 and 1969 under an ARPA contract to the University of Michigan. Two optical systems were installed: a 1.6-meter aperture Cassegrain telescope and twin boresighted 1.2-meter aperture telescopes on a single mount. Like the Cloudcroft telescopes, the mounts were a three-axis design but employing a Right Ascension over Declination axis configuration similar to astronomical equatorial telescopes on a rotating azimuth platform to simplify tracking stars and near-geosynchronous satellites. While a primary consideration in locating the telescope in Hawaii was mid-course observations of missiles launched from Vandenberg AFB, California, the SOI mission also received early recognition. Haleakala, home to an earlier satellite-tracking Baker-Nunn camera, was selected due to the existing road and electrical power. In addition, its ten-thousand foot peak was above the normal cloud layer and provided a better working environment than the fourteen thousand foot peaks on the Big Island. Operations at AMOS commenced in 1969. During the Seventies, space surveillance activities gained importance. A variety of sensors was employed for imaging and signature SOI data collection including electro-optical and film cameras, infrared detector systems, and laser systems. An important milestone occurred in 1977 when the 1.2-meter mount was transitioned to operational SOI data collection. In 1982, one of the earliest compensated imaging systems developed by ARPA through the Rome Air Development Center (RADC) was installed. The development and application of compensated and post-processing imaging techniques continue to be primary missions of the AMOS facility. AMOS is only one of the four SOI facilities that is still operational. It continues to actively support SOI

development and data collection in support of both research and operational requirements. A major new SOI sensor, the 3.7-m aperture Advanced Electro-Optical System (AEOS) and its associated instrumentation, became operational in 2000.

4. Summary

When Sputnik was launched in 1957, the United States was unprepared to obtain high-resolution optical imagery of orbiting satellites in support of what is now optical Space Object Identification (SOI). Early imaging with missile tracking cameras demonstrated the feasibility of direct imaging, but also demonstrated the need for more specialized instrumentation. The Air Force immediately undertook an intensive development effort. A field site was established at Sulphur Grove, Ohio, to characterize satellite optical properties and to test sensors. At the same time, the design and construction of an observatory optimized for satellite imaging was undertaken at Cloudcroft, New Mexico. When the Cloudcroft facility became operational in 1964, research into satellite optical characteristics continued at Sulphur Grove leading to the development of instrumentation and analysis techniques for the SOI exploitation of satellite signatures. Research and operational support activities continued at these sites until the mid-Seventies when the Air Force began the operational implementation of optical SOI. During this time period, two other sites on Maui, Hawaii, and at Malabar, Florida, developed for other missions, began SOI imaging activities. Only one of these early facilities, the Air Force Maui Optical Station, continues to support the development of optical SOI techniques.

5. References

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6. Figures



Fig. 1. Early Sulphur Grove Instrumentation Circa 1960.

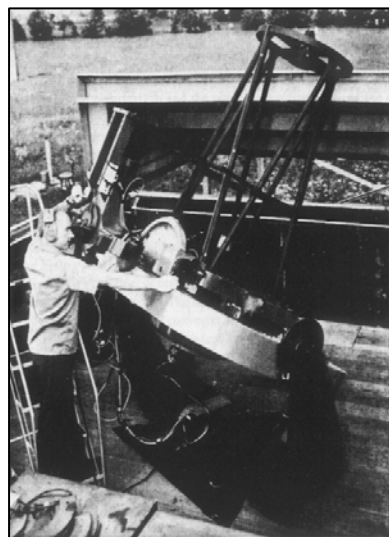


Fig. 2. Sulphur Grove 24-Inch Telescope On Four Axis Mount.

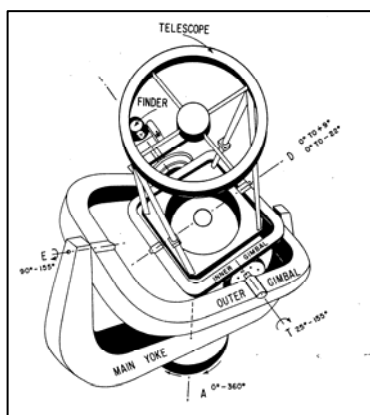


Fig. 3. Schematic Diagram Of The Sulphur Grove Telescope.

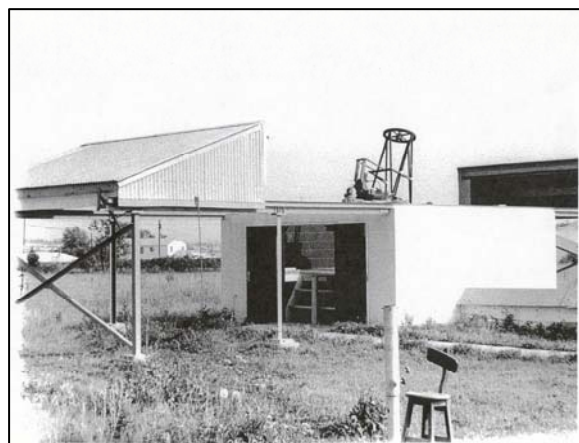


Fig. 4. Sulphur Grove Sliding Roof Observatory.

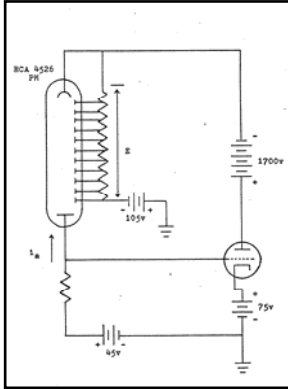


Fig. 5. Schematic diagram of the "Sweet" photometer.

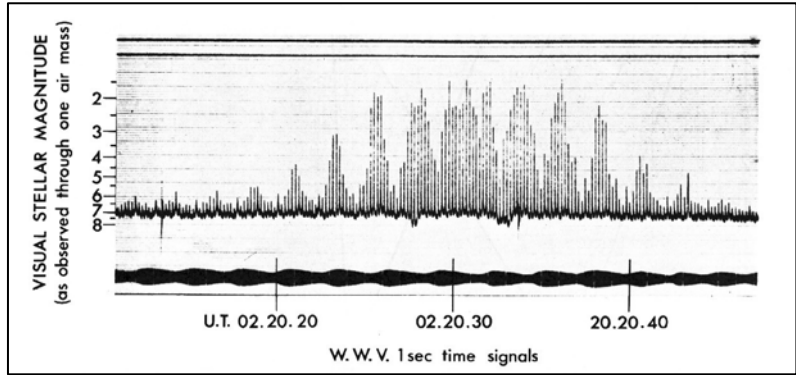


Fig. 6. Example of Annotated Visicorder photometric data record and WWV time signal.

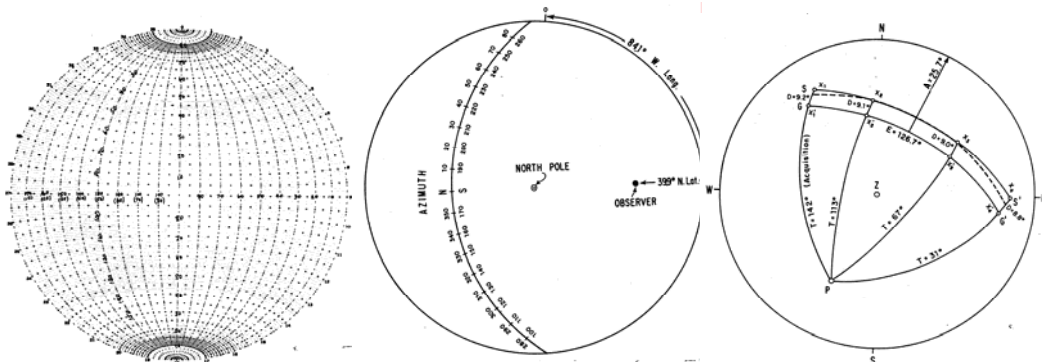


Fig. 7. Meridinal Net system used in computing four-axis mount settings. The USGS Meridinal Net is on the left and an Earth-pole centered overlay is in the center. On the left is an example of a mount setting solution obtained using the meridinal net system. [Ref. 9]

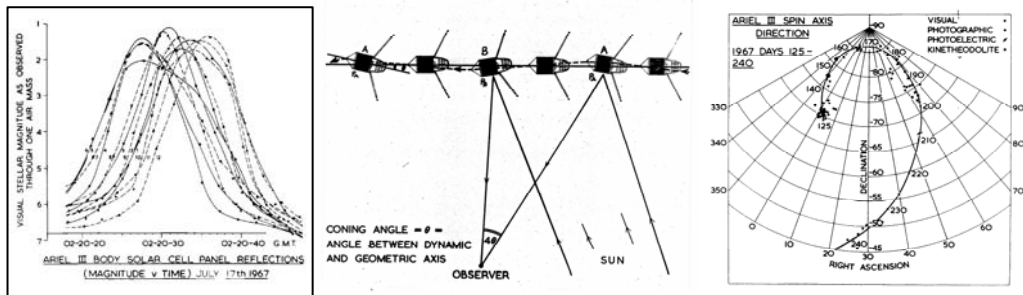


Fig. 8. Manual analysis of Ariel III signature shown in Fig. 6 [Ref. 10].

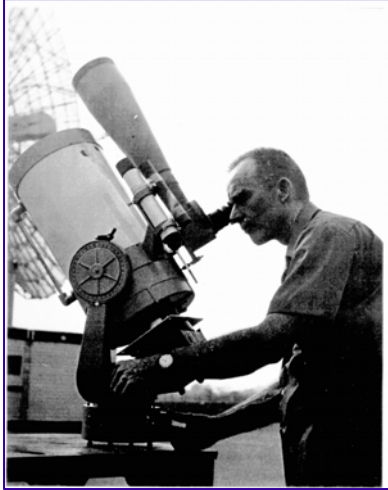


Fig. 9. Portable photometric sensor deployed in Southeast Asia in 1973.



Fig. 10. Transfer of Sulphur Grove telescope to Canadian Forces in 1975



Fig. 11. AFAL Cloudcroft, NM, Electro-Optical Facility.

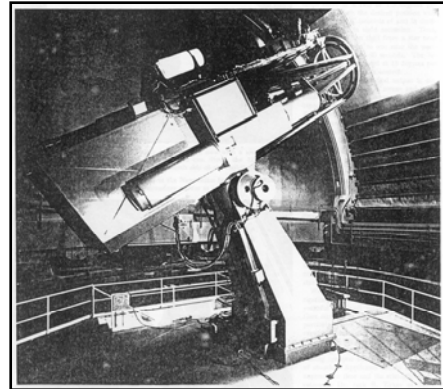


Fig. 12. Cloudcroft 48-inch aperture telescope on three-axis mount.



Fig. 13. Cloudcroft control room circa 1974.