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DARPA TECHNICAL ACCOMPLISHMENTS

AN HISTORICAL REVIEW OF SELECTED DARPA PROJECTS

Volume I

Sidney G. Reed
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This volume describes the genesis of the study, the approach that was taken in carrying it out, and program histories of 28 DARPA projects. Each history describes the genesis of the project or program, the major participants and events in its lifetime, and contains a flow diagram illustrating the complex of interactions among organizations over time that characterize the project. Each project review ends with observations about the project's success and the nature of its impact. Volume II, due in June 1990, will present 27 additional histories, in the same format, and will synthesize the observations about success and influence in such a way that DARPA can apply the results to future program management.

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EXCERPT

X. AMOS: ARPA MIDCOURSE OPTICAL STATION

A. BRIEF OVERVIEW

AMOS (ARPA Midcourse Optical Station) was initiated by ARPA in 1961 as an astronomical-quality observatory to obtain precise measurements and images of reentry bodies and decoys, satellites and other space objects in the infrared and optical spectrum. Located at nearly 10,000-ft altitude atop Mt. Haleakala, Maui, Hawaii, AMOS served as a unique facility for operational measurements and R&D from the early 1960's. AMOS' twin infrared telescopes were transferred to Air Force in the late 1970's as MOTIF: the Maui Optical Tracking and Identification Facility, now regarded as one of the primary sensors of the Air Force Space Tracking System. Transfer of the optical telescope and the remainder of a highly automated AMOS to the Air Force took place in 1984.

B. TECHNICAL HISTORY

The concept of AMOS was originally proposed in 1961 by R. Zirkind of the ARPA staff as an astronomical-quality facility for imaging reentry bodies and other space objects in the infrared, and for performing research in infrared astronomy. Information on the infrared emissions from reentry bodies in midcourse, expensive to obtain in space, was needed particularly for assessment of detection and discrimination systems then under study in the BAMBI and PRESS projects under ARPA's DEFENDER program. The location selected for AMOS, at about 10,000 ft altitude near the top of Mt. Haleakala, the largest dormant volcano crater in the world, was above most clouds and most of the infrared-absorbing water vapor in the atmosphere. The site was also expected to have very good astronomical "seeing." For similar reasons the site had been selected previously for one of the Baker-Nunn Satellite Cameras used to track satellites during the IGY.[1] The AMOS location was favorable for observation of reentry vehicles and decoys, missile bodies and other objects over a considerable portion of the midcourse range of sub-orbital trajectories between the Vandenberg missile launch site and the main reentry location at

1 "Trackers of the Skies," by E. Nelson Hayes, Howard Doyle, Cambridge 1968, p. 33-34. The University of Hawaii operated the Baker-Nunn telescope for the Smithsonian Astrophysical Observatory.

Kwajalein. The low-latitude location was also advantageous for observations of satellites. AMOS was conceived initially to include two high quality telescopes, one for use in the infrared and the other in the visible spectral region, with precision mechanical mounts and computer-controlled drives.

Zirkind had a strong desire also to exploit, part-time, the capabilities of such a system to open a new field of astronomical research in the infrared.[2] Dr. J. Ruina, ARPA director at the time, gave his approval to the project, provided the astronomical community agreed it was a good idea, and would actually do research with AMOS. A meeting of several prominent astronomers was held at Harvard's Smithsonian Astrophysical Observatory in Summer 1961, at which it was agreed that AMOS' planned infrared observing capabilities and its location further south than then existing U.S. observatories, were indeed of interest in astronomy. The conclusions of this meeting, and the results of a careful investigation of astronomical "seeing" a little later by one of the participating astronomers (G. Kuiper), which indicated that resolution of the order of 0.1 seconds of arc was often attained, led to further plans for an additional, somewhat larger telescope at AMOS for use in the optical spectrum.

The AMOS effort formally began with Amendment No. 2 to an existing ARPA Order 236, to the University of Michigan's Institute for Science and Technology, for telescope design, construction, and eventual operation of the observatory.[3] The ARPA order amendment stated the AMOS objectives as: (1) "Identification and signature of space objects; (2) an active program to advance the state of the art of infrared technology and high-resolution imagery; (3) a research program in geophysics and astrophysics including the astronomical community." The Department of Astronomy of the university was involved in the initial design studies for AMOS. The previously mentioned "seeing" investigation was one of the first subcontracts, and was facilitated by the existence of the existing IGY-Smithsonian Baker-Nunn telescope at the site. The AMOS site was leased from the University of Hawaii. The original terms of the lease provided for operation of the AMOS Observatory facility by the University of Michigan, and after 10 years use when

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2 "Project AMOS: An Infrared Observatory," by R. Zirkind, *Applied Optics*, Vol. 4, 1965, p. 1077, and discussion with R. Zirkind, 11/

3 AO 236 of 6/61 for BAMIRAC had been set up with the University of Michigan previously for a broad set of responsibilities connected with data for ballistic missile defense largely in the infrared. Amendment # 2 was for $8.3M.

construction and shakedown were expected to be completed, it would be turned over to the University of Hawaii.[4]

Soon after these initial steps by ARPA, a directive arrived from Harold Brown, then DDR&E, giving space object identification (SOI) and tracking a high priority in DoD. Since AMOS' capabilities were designed for this purpose, its funding was increased. The University of Michigan undertook the design of two 48-in. infrared telescopes, on a common mount and shaft, one mainly for tracking and the other for special observations, and of a 60-in. telescope separately mounted, mainly for work in the optical spectrum. Design was completed in 1963 and construction of the foundation and buildings commenced by the Army Corps of Engineers.[5] The Corps constructed the entire facility except for telescopes and domes. The three high quality mirrors were completed to diffraction limited tolerances, successfully and at quite low cost. Special coatings were added to the IR mirrors to enhance reflectivity over the 1-30 micron range. Telescope mounts were of cast steel, a bit unusual, since most astronomical mounts involve welded pieces. This decision was made by ARPA, and the risk accepted to reduce costs. Successful casting saved $1M.[6] The bearings were formed with very close tolerances, in order to allow the desired pointing and tracking accuracy of ~ 1" arc at angular rates required to track satellites and reentry objects. No telescopes of this size and weight had previously been constructed to the tracking specifications of AMOS.[7] However, the only hitch that developed in the construction occurred in the domes, which also had to have rapid motion capabilities, something new for such structures. A separate contractor made the first domes, but these were found to vibrate excessively. The previously helpful astronomers pitched in again to correct the problem.[8] Considerable re-work was involved, which caused an overrun, in turn forcing cancellation of plans for advanced instrumentation, which included, in 1964, an interferometric spectro-radiometer and computer-controlled articulated mirrors.[9]

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4 The initial lease was for 25 years from the University of Hawaii, beginning in 1963, R. Zirkind, ibid.

5 AO 389 of 8/62 and 482 of 5/63 to the Army Corps of Engineers.

6 Discussion with R. Zirkind 11/88.

7 The Baker-Nunn satellite tracking camera was smaller and lighter with 20" aperture, and achieved a tracking accuracy of about 2". "The Baker-Nunn Satellite Camera," by Karl Heinze, *Sky and Telescope*, Vol. XVI, Jan. 1957, p. 3. This system also had several successes in SOI, see e.g., Hayes, loc. cit., p. 121-2.

8 A. Meinel of the University of Arizona was particularly helpful. Discussions with R. Zirkind 11/88.

9 R. Zirkind, ibid.

Construction of AMOS was completed by 1967. Between then and about mid-1969 there was an initial phase of evaluation, calibration and testing of the telescopes' computer control and tracking algorithms, and of the associated infrared arrays, radiometric, photometric and imaging equipment. A data link with a radar at another location in the Hawaiian area was established, to facilitate tracking.[10] As originally envisioned, astronomical objects were used for calibration. Initial attempts were made with some success to acquire and track satellites and other space systems. An early success was a photograph and tracking of one of NASA's APOLLO modules.[11]

Figure 1, from a current Air Force brochure,[12] shows pictures of the telescopes, housed in the largest dome shown in Fig. 2, which also exhibits other features of the AMOS facility as it is today. The optical systems provided for several instrument mounting platforms for different detection and imaging systems. Both IR and optical systems had long focal lengths to allow fine image definition.

A second data link with a tracking radar on another island was establish and this and other radars were relied upon, together with information from the NORAD . work for initial tracking inputs. A low-power ruby laser was also installed, as a first step toward a laser radar target illumination technique.

By 1969 the quality and potential of AMOS had been demonstrated and a second phase began in which the Air Force became the ARPA agent. The Air Force also began to support projects to measure properties of reentry bodies at the facility under its ABRES project. The University of Michigan was replaced, as AMOS manager and operator, by industrial contractors, AVCO and Lockheed.[13] Computer and software advances further improved tracking capabilities. In the early 1970's advances in semiconductor state of the art allowed a much improved, larger infrared sensor array to be combined with a contrast

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10 AMOS Advanced Electro-Optical Program, RADC TR-86-215, Feb. 1987, p. 2. This report contains a brief history of AMOS since 1963.

11 Discussion with Glen Rogers, AMOS, 11/88.

12 AMOS/MOTIF brochure, undated.

13 A.O. 2320 of 11/22 and RADC, ibid.

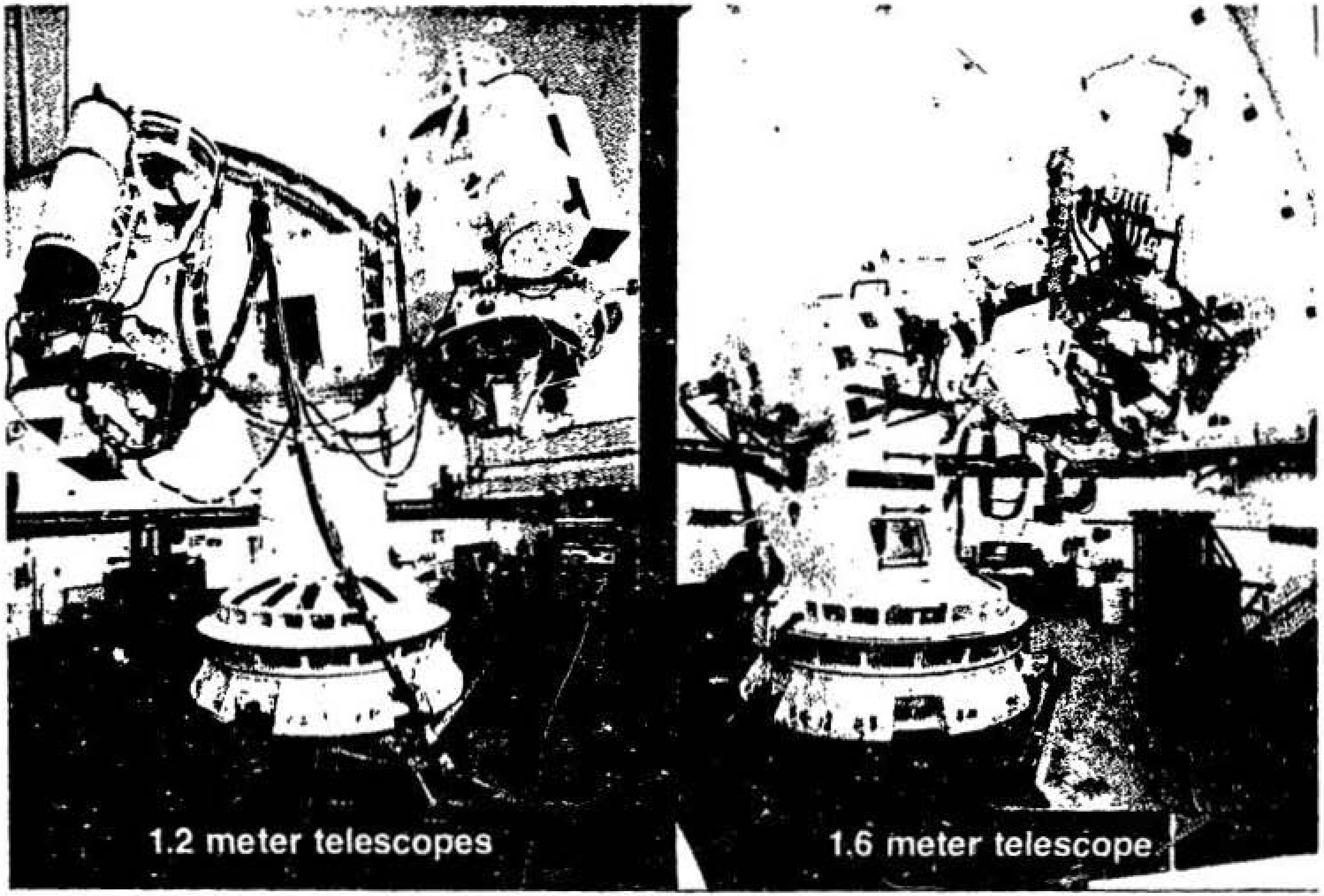

Figure 1. First AMOS Telescopes

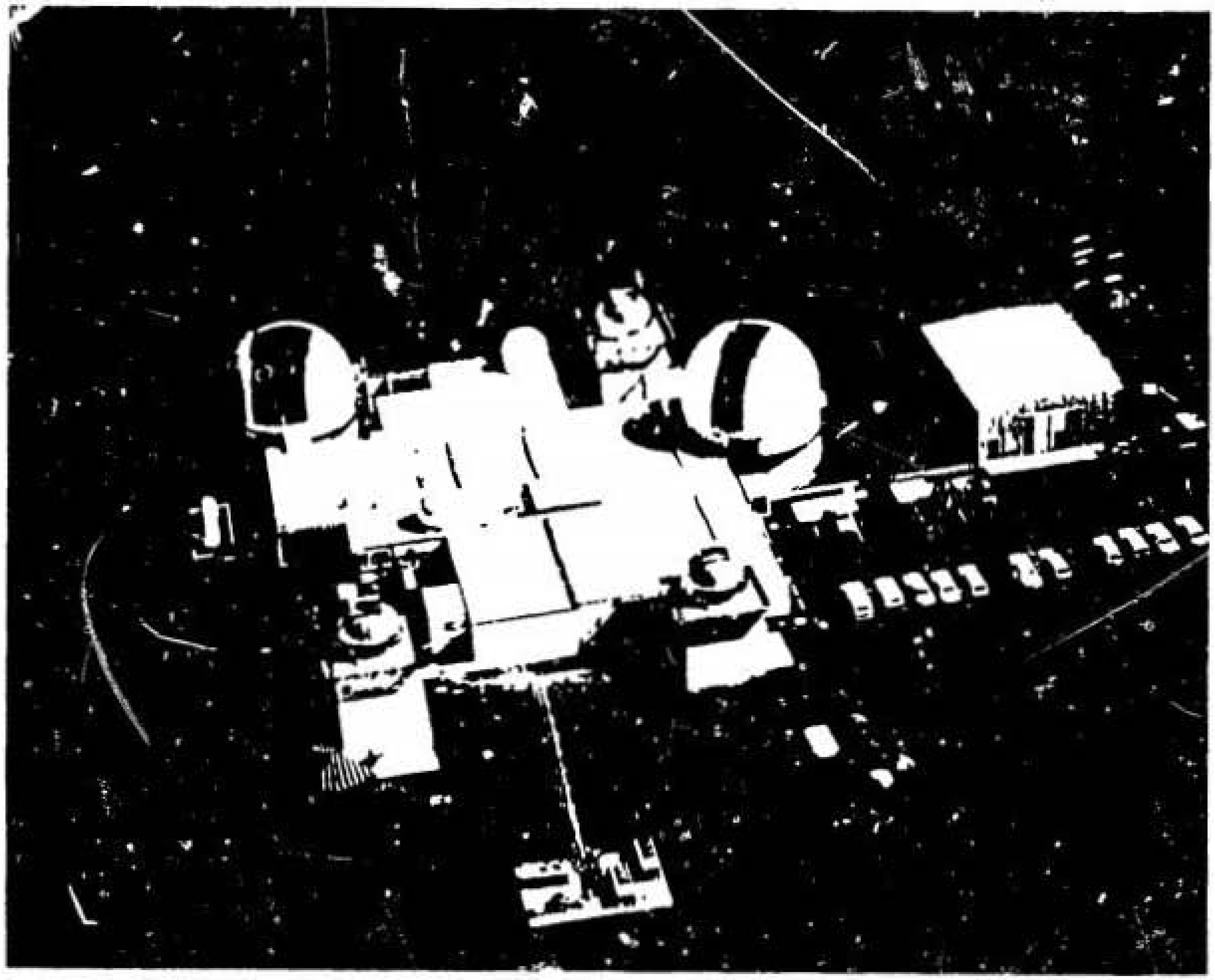

Figure 2. AMOS/MOTIF/GEODSS Observatory Buildings

photometer and television camera in an "Advanced Multicolor Tracking" system. A higher power ruby laser was designed and installed to work with one of the infrared telescopes, to conduct initial ranging experiments. These improvements allowed IR and visible measurements to be obtained on reentering vehicles and penetration aids of the Minuteman Series and on several satellites.[14] Assistance was also provided to NASA to help with problems on the SKYLAB.

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[14] RADC, ibid.

In the late 1970's successful space object measurements continued in the infrared and visible, and laser ranging and illumination experiments began.[15] Eventually, a dedicated laser beam director was constructed. Preparations began for the installation of the ITEK compensated imaging system (CIS) which had also been developed by DARPA, to be used with the 60-in. telescope on low-altitude space objects because of the limited effective field of view.[16] A number of measurements of high atmosphere turbulence related to CIS performance were made. Precision tracking improvements continued, particularly in characteristics affecting hand-off to local and distant tracking systems.

A higher power CO_2 laser was installed and used for experiments for ranging and illumination of more distant objects. In 1979 AMOS' twin infrared telescopes and associated systems became part of the Air Force Space Track Network and was renamed MOTIF: Maui Optical Tracking and Identification Facility.

In the early 1980's DARPA-supported AMOS activity included more detailed measurements of background, high cirrus cloud properties and atmospheric turbulence. Measurements were made on meteor trails in the infrared, and on the core of the M-87 galaxy in the visible.[17] Atmospheric compensation experiments began using Lincoln Laboratory deformable mirror technique for directing a laser through the turbulent atmosphere. Several supporting experiments have been made for SDI in the atmospheric infrared windows.[18] The compensated imaging system was tested and installed on the 60-in. telescope. A LWIR capability was also added to the 60-in. on a side mount, and the 60-in. mirror was coated to improve its IR reflection.

By 1984 AMOS had become a highly automated system, and DARPA transferred AMOS to the Air Force. RADC is now responsible for AMOS' R&D and the Air Force Space Command for the operation of MOTIF. A summary of current AMOS-MOTIF capabilities is routinely issued by the Air Force. SDI now supports a substantial fraction of AMOS' activity.[19]

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15 E.g., A.O. 2837 of 7/74.

16 A description of this Itek system is given in the chapter on "Adaptive Optics," by J.R. Vyce and W. Hardy, Chapter 8, p. 101 of *Arms Control Verification*, Pergamon 1986.

17 *Direct Infrared Measurements of Thermal Radiation From the Nucleus of Comet Bennett*, by James A. Myer, Ap. L., V. 175, 1972, p. L49.

18 RADC, ibid.

19 Summary of AMOS-Technical Activities - 1987, RADC TR-87-301, May 1988.

One of the original objectives for AMOS, astronomical infrared research, has been carried out only to a very minor extent.[20] However, academic IR astronomy is now beginning to flourish with several telescopes in the U.S. and also at Mauna Kea (near the active volcano). What has caused this area to bloom is the availability of larger IR focal plane arrays, developed largely with DARPA support. Some of these arrays had been tested at AMOS.[21]

Suggestions have been made by some members of the astronomical community, notably the Meinels (who have been involved with AMOS from the beginning) to begin planning for larger (10-meter range) aperture, computer-controlled, articulated mirror telescopes for the next-generation AMOS.[22]

C. OBSERVATIONS ON SUCCESS

AMOS was an ARPA initiative to construct an astronomical-quality facility for observations of satellites and for astronomical research. The Air Force had used the IGY's Baker-Nunn telescope-camera for satellite observations, but AMOS was to be a larger, more complex and heavier telescope, with angular tracking quality at least as good as the Baker-Nunn. The step to construct AMOS was considered risky at the time, but not excessively so by competent astronomers, who were interested enough to provide help with design at the early and later stages of the project. The sudden increase in priority for satellite observation techniques enabled AMOS construction and use to proceed quickly. An academic contractor, University of Michigan, built the telescope. Initial plans were to turn AMOS over to the University of Hawaii, after ten years operation. After its construction, however, operational use of AMOS became predominant, and the plans for academic uses were on the one hand awkward, and on the other hand academic groups were, at the time, distancing themselves from military-related programs. Industrial operation of these facilities was therefore considered more appropriate.

Over a nearly 20-year period AMOS has met its primary objective of serving as a unique facility for electrooptic R&D and operational use, and is now considered a national asset. During this time many advances in electrooptic and related technology developed by DARPA have been efficiently tested and used at AMOS. A key feature was that

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20 Discussion with James Myers, Photon Research, Inc. 11/80. See Fn. 17.

21 See e.g., "Astronomical Imaging With Infrared Array Detectors," by I. Gatley, et al., *Science*, Vol. 242, 2 Dec. 1988, p. 1264.

22 "Summary of AMOS Technical Activities 1987" ibid., p. 16.

astronomical objects of known brightness and spectral characteristics could be used for calibration purposes. The success of AMOS is attested to by its past and current use for reentry and penetration aids studies by the Services and SDI, and as a part of the AF Space Track Systems. While DARPA support is now in the mode of support of "users," the challenges in the operational areas do not seem to have diminished.

While the original objective for AMOS also included astronomical research, this has occurred only to a very minor extent, for reasons outline above. AMOS, however, has been a unique test bed for focal plane arrays developed by DARPA, which have made a substantial contribution to the presently blooming field of IR astronomy.

After its initial demonstration of operational capability, transfer to the Air Force occurred gradually. The Air Force has collocated at the AMOS facility three of its GEODSS systems, developed also partly with DARPA support,[23] to automatically detect and track satellites at geosynchronous distances.

The initial AMOS facility cost appears, from project records, to have been approximately $12M. The cost of the later phases, including operations and improvements such as the CIS, and support of AMOS operations for some DARPA R&D projects, appears to be about $90M.

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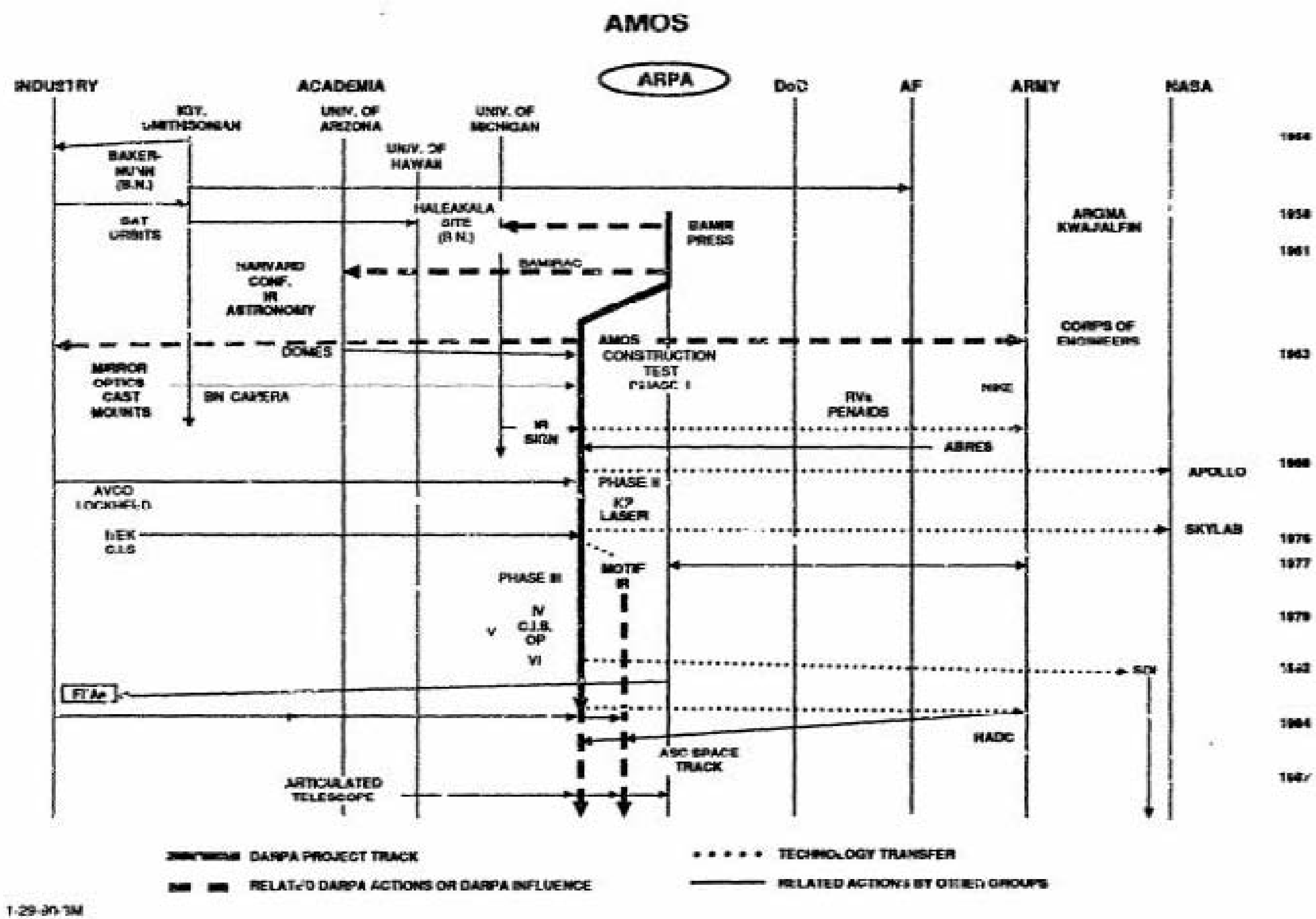
23 AMOS user's manual, RADC.


AMOS
INDUSTRY
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CORPS OF ENGINEERS
DOMES
AMOS CONSTRUCTION TEST PHASE I
MIRROR OPTICS CAST MOUNTS
BN CAMERA
RVs PENAIDS
NIKE
IR SIGN
ABRES
APOLLO
PHASE II
AVCO LOCKHEED
K2 LASER
SKYLAB
MOTIF IR
PHASE III
IV C.I.S. OP
V
VI
SDI
HADC
ASC SPACE TRACK
ARTICULATED TELESCOPE
DARPA PROJECT TRACK
RELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS
1958
1961
1963
1968
1976
1977
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1984

ANNEX
AMOS/MOTIF FACILITY CAPABILITIES

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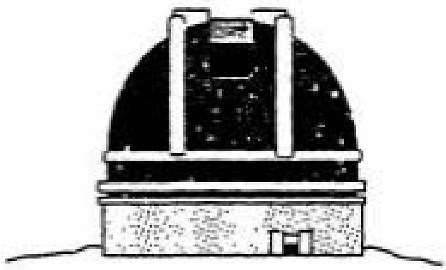

U.S. AIR FORCE OBSERVATORY
MT. HALEAKALA, MAUI, HAWAII

AMOS/MOTIF FACILITY CAPABILITIES

The Air Force Maui Optical Station (AMOS), and the Maui Optical Tracking and Identification Facility (MOTIF) are co-located at an altitude of 10,000 feet on the crest of Mt. Haleakala, located on the island of Maui, Hawaii. This high altitude location is characterized by a relatively stable climate of clean, dry air. The low levels of particulate matter and absence of significant scattered light from sea-level sources provide excellent conditions for the acquisition and viewing of space objects. The facility was constructed during a two year period beginning in 1963. During the past twenty years, the site has evolved to its present configuration, which includes four primary optical testbeds: the 1.6-meter telescope, the dual 1.2-meter telescopes, the Laser Beam Director (LBD), and the Beam Director/Tracker (BD/T). These four optical telescope systems, along with the facility's sensors and computer resources, form the basis for both the Air Force Systems Command's (AFSC) AMOS Program, and for the Air Force Space Command's (AFSPACECOM) Spacetrack MOTIF program. Both organizations share the facility. AFSPACECOM maintains and operates the site as facility host, and AFSC, through it's executive agent, the Rome Air Development Center (RADC), is the tenant supporting measurement programs, special testing, and visiting experiments.

The AMOS 1.6-meter telescope is one of the finest optical instruments of its size in the world. In the absence of atmospheric-induced image distortion, the telescope permits diffraction limited performance (approximately 0.1 arcsecond resolution, or 1 ft. at a distance of 500 miles) at all mount attitudes above the horizon. The clear aperture is 1.57m and the effective focal length is 25m. Broadband mirror coatings (Al plus an SiO overcoat) allow spectral coverage from the visible through the LWIR. The telescope is attached to an equatorial mount on an azimuth turntable. The mount has hydrostatic bearings, 23-bit shaft angle encoders on each axis, and is servo-driven by direct current torque motors under control of a Harris 500 computer. This system allows absolute pointing to ±2 arcseconds and tracking to ±1-3 arcseconds (depending on target velocity) at tracking velocities up to 2 degrees/sec and accelerations to 2 degrees/sec^2. An acquisition telescope with three switch-selectable fields of view is mounted piggyback on the north face of the 1.6-meter telescope.

Two instrument mounting surfaces are available for sensor packages on the 1.6-meter telescope. The rear surface is currently dedicated to the Compensated Imaging System (CIS), an adaptive optical device that compensates in real-time for atmospheric turbulence-induced distortion of satellite images. The side surface supports a sensor package which currently includes the Enhanced Longwave Spectrometer/Imager (ELSI), which is a dual infrared acquisition/imaging array, and the AMOS Spectral Radiometer (ASR), which is a 26 detector element MWIR/LWIR radiometer. An 8000 element Platinum Silicide (PtSi) infrared Charge Coupled Device (CCD) is also included for infrared imaging in the 3-5 micrometer spectral band. A sensitive Intensified Silicon Intensifier Target (ISIT) Camera is also present in the package.

The AFSPACECOM 1.2-meter telescope complex represents a unique capability which functions as a fully integrated sensor in the Spacetrack Network. Two 1.2-meter telescopes are mounted on opposite sides of a single polar axis, and are fixed to a common declination axis. The mount shares the same operating systems and performance parameters as the 1.6-meter mount. Both 1.2-meter telescopes are classical Cassegrain optical systems, having parabolic primaries and hyperbolic secondaries. One telescope (B29) has a back focal distance of 29 inches, a relative aperture of f/20, and a focal length of 24.5m, while the other (B37) has a 37 inch back focal distance, a relative aperture of f/16, and a focal length of 19.8m. Both telescopes have primary mirror support systems which incorporate air bags for axial support and mercury filled belts for radial support. An acquisition telescope is mounted piggyback on the B29 telescope.

There are three mounting surfaces on these telescopes, one on the B29 telescope and two surfaces on the B37 telescope. The B29 houses the Advanced Multicolor Tracker for AMOS (AMTA), a square array of 25 cooled Cadmium-doped Germanium (Ge:Cd) detectors. The sensor is fitted with seven remotely programmable spectral filters that operate in the 3-22 micrometer band. The system is used to collect low dispersion infrared spectral data on targets of interest, and to perform manual or closed-loop tracking of non-solar illuminated targets. Sharing the light beam with AMTA is the Contrast Mode Photometer (CMP), which provides visible photometric signature data simultaneously with AMTA infrared signatures.

The rear instrument surface of the B37 telescope houses the Low Light Level TV (LLLTV) Package, for detecting and imaging resolved targets, and for detecting very faint, unresolved deep space objects. The LLLTV consists of a high-gain, astronomical quality Intensified SIT camera with narrow and wide field of view optics. The package also contains a 16 mm cine camera for a classical imaging capability. The camera has a variable frame rate (2-100 frames/sec), a tri-mode shutter providing consecutive exposures in the ratio of 1:3:9, and a filter wheel for color spectral filters. The side instrument surface of the B37 houses an atmospheric turbulence measuring device, and additional mounting space is available for visiting experimenters. Mounted on the B37 telescope housing is a small 1 Joule pulsed ruby laser used as a Cirrus LIDAR Probe (CLIP), and an 18 inch receiver telescope is used to detect backscattered light from the atmosphere.

The Laser Beam Director is an optical system which provides precise laser beam pointing and tracking. The system utilizes a series of fixed mirrors and beam expanders to take the output of a laser system, expand it to 24 inches, and direct it to a 36 inch azimuth/elevation gimbaled tracking mirror, from which it is projected into the atmosphere. The 24 inch beam expander and the 36 inch tracking mirror are mounted on an azimuth turntable which is locked prior to a tracking operation. The LBD has supported the AMOS pulsed ruby laser system, a three stage Q-switched and conventional mode laser producing pulse energies of about 8 and 80 Joules, respectively, for laser ranging and illumination of objects in space. The beam director has been designed to enable user agencies to mount their own laser in the sub-dome area and utilize the existing optics and pointing to conduct measurement programs tailored to a specific laser system.

The new 0.8-meter Coudé Beam Director/Tracker is a versatile system that can accept up to a 15 cm. beam from a variety of lasers, and project it to an object being tracked. The beam may be projected from the BD/T without expansion, or be expanded up to 0.6 meters. In addition to the Coudé path, the system includes a Cassegrain mounting surface. The BDT mount is an altitude-altitude configuration with a Coudé path to bring the laser beam to the projection optics from a fixed point on the observatory floor below. The mount can track at velocities up to 5 degrees/sec and angular accelerations up to 4 degrees/sec^2. The BD/T is operated with a variety of lasers, including systems installed by visiting user agencies. The LIDAR Acquisition/Sizing Experiment (LASE) system is currently in use with the BD/T. This bistatic CO_2 laser transceiver is designed to provide measurements of target range and range rate at ranges in excess of 2 Megameters, independent of time of day. The system was designed to serve as an experimental test bed for precision dynamic measurements, Doppler imaging and micro Doppler measurements.

In addition to the large optical systems and sensor capabilities at the AMOS/MOTIF site, extensive computer facilities have been installed as well. The Mount Control System (MCS) Harris 500 computers direct the operation of the 1.2-meter, 1.6-meter, LBD, and BD/T mounts. The MCS allows each mount to independently acquire and track targets with a high degree of precision, and to employ data from remote sensors, such as off-site radars, to achieve acquisition when necessary. In addition, two MODCOMP computers provide the capability for collecting, recording, displaying, editing, processing, and transmitting AMOS/MOTIF data. One MODCOMP is part of the Data Transmission System (DTS), which is capable of simultaneous, real-time acquisition and storage of metric, photometric, and infrared data. The second MODCOMP is part of the Communication System (CMS), which takes information from the DTS and formats and transmits the data via AUTODIN to AFSPACECOM. Other computers at the facility perform digital image storage and transmission, data analysis, and database management at the site.

Extensive support systems exist at the site to operate and maintain the complex and unique optical systems and sensors at AMOS/MOTIF. These include a satellite-based Global Positioning System (GPS)-referenced timing system, secure 2400 BAUD worldwide AUTODIN, and a secure voice system. A separate support building adjacent to the observatory facility contains a mirror re-coating laboratory with a vacuum tank capable of holding the telescope primary optics. The support building also houses a machine shop, electronics shops, welding shop, carpentry shop, and parts storage.