When a satellite is detected and an initial orbit determined, the problem remains to identify it or at least establish the object class. In many cases, the object defies identification with a known launch or function and is called an uncorrelated target (UCT). Most UCTs are believed to be debris from a payload or booster fragments. UCTs also include miscellaneous launch hardware and objects dropped by astronauts: a screwdriver and a Hasselblad camera are cataloged.

At Millstone the mean radar cross section, polarization and Doppler spread (components of the signature) are combined with the orbital characteristics to determine the satellite class, and in many cases the actual satellite.

High-Resolution Radar Imaging

In the mid-1960s Lincoln Laboratory researchers discovered that high-range-resolution radars could provide unique discrimination capabilities for ballistic missile defense.[5] The fundamental requirement was to obtain a range resolution smaller than the range extent of a target. Such high-resolution data could provide an estimate of a target's length, isolate individual scattering centers and therefore distinguish the target from other targets in an incoming missile complex.

Range resolution is inversely proportional to signal bandwidth. For example, a 500-MHz bandwidth provides 0.5-m range resolution. However, new technology for RF, signal processing and data processing had to be developed before the wideband radar could be built. Lincoln Laboratory, recognizing the challenging issues, obtained funding from ARPA and began developing these new technologies. The effort led to the construction of the ALCOR on Roi-Namur Island in the Kwajalein Atoll. ALCOR, a wideband (500 MHz) C-band radar, began collecting data on U.S. ballistic missile tests late in 1969.

The technology of synthetic-aperture radar (SAR) had been developed and widely used by this time. SAR systems produce two-dimensional images of terrain by processing the phase of the returned signal. The phase changes as the radar platform moves and rotates with respect to the ground. The cross-range resolution is inversely proportional to the radar platform rotation angle and is directly proportional to the radar wavelength. In the late 1960s, SAR images could be produced with moderate radar range resolution of five to ten meters.

The SAR principle can also be used to image satellites from the ground with a coherent radar if the range resolution is smaller than the range extent of the satellite. The rotation of a satellite about its own center of mass provides the necessary rotation for Doppler processing. The cross-range resolution is achieved by processing (resolving) the fine differential Doppler across the satellite due to its rotation. This technique is called inverse synthetic-aperture radar (ISAR). Matching the cross-range resolution to the range resolution by using microwave radars (e.g., at C-band or X-band) requires coherent processing of data collected over five to ten degrees of target rotation.

Once ALCOR began tracking satellites, Lincoln Laboratory applied these concepts to satellite imaging for the first time. The Laboratory thus played a pioneering role in this field and developed the essential techniques and algorithms for the generation and interpretation of radar images.

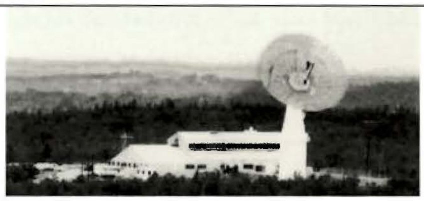
When China launched its first orbiting satellite early in 1970, the upper booster stage remained in orbit. This event generated a high level of interest within the DoD in estimating the size of the stage and determining its potential use in an ICBM. The 50-m resolution inherent to the passive optical tracking system was insufficient to provide a meaningful size estimate. Therefore, the DoD asked Lincoln Laboratory to use ALCOR to track the booster and estimate its size and shape.

Notes

5 Material for this section was provided by Sidney Borison and Israel Kupiec.

6 This event was the precursor to the development of near real time imaging at Haystack discussed later in this section.

1955



Early Millstone radar

G.H. Pettengill

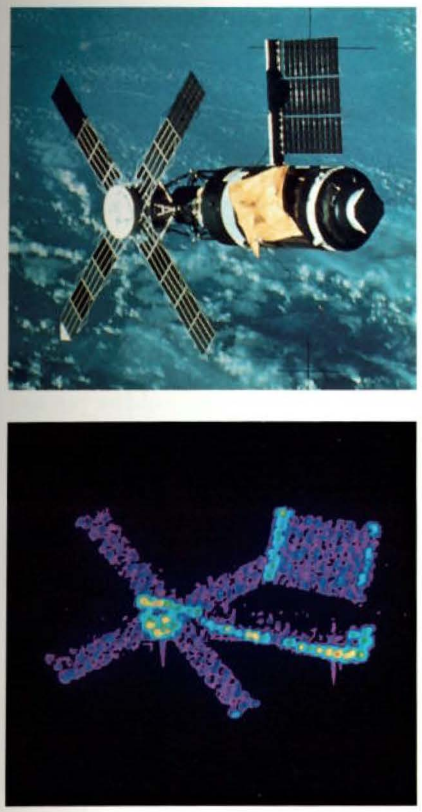


Figure 8-3
Top: Photograph of *Skylab* taken after the remaining solar array had been extended and the crew compartment had been covered by a thermal blanket. Bottom: Computer-generated simulation of a radar image of *Skylab*. Analysis by Lincoln Laboratory of actual radar images of *Skylab* (differing in detail and without the color enhancement) aided in understanding solar-array deployment problems.

ALCOR's half-meter range resolution was sufficient for estimating the booster's length along the radar line of sight. Other dimensions were estimated by analyzing the angular lobe width of the radar cross section (RCS) scattering pattern of the target. Analysts at Lincoln Laboratory also studied the fine Doppler of the radar return and applied the ISAR principle to derive a cross-range size estimate that corroborated the estimates from the RCS pattern analysis.

The USSR launched *Salyut-1,* its first space station, in the spring of 1971. Images produced from ALCOR data were remarkable, even showing such details as solar panels that were not apparent in the photograph released by the USSR and published in *Time* magazine. This success led to the space object identification (SOI) program at Lincoln Laboratory. Subsequent images of *Salyut-2* and *Salyut-3* provided the means to monitor their activities. An image of the docked *Soyuz-14* revealed, among other features, the location of the docking site on the space station.

Over the next few years, with ARPA sponsorship the effort at the Laboratory focused on acquisition and analysis of ALCOR data on many types of Soviet satellites and on development of special techniques for radar image interpretation. During that time Laboratory staff members routinely reported the latest findings on wideband data analysis at the annual NORAD Space Identification Conference. These findings were superior to the results of narrowband RCS scattering lobe pattern analyses and became the last word on satellite shape and size. Little by little, analysts from other organizations followed Lincoln Laboratory and began to depend heavily on wideband analysis results.

The details of wideband radar image analysis of Soviet satellites are classified and cannot be discussed here. In general, it can be said that the Lincoln Laboratory effort in this area has been very productive and has provided an independent, all-weather, day/night resource to assess Soviet activities in space. Several types of Soviet satellites have been analyzed by Lincoln Laboratory staff, in each case generating a detailed model of the satellite components and inferring its mission.

The technique of radar imaging was also applied to U.S. satellites when malfunctions occurred. A case in point is that of the first U.S. space station, *Skylab-1,* launched on May 14, 1973. Shortly after launch, NASA determined that several problems had developed. It appeared that the micrometeorite (and sun) shield had deployed prematurely and been torn away. Furthermore, the solar panels were improperly deployed. As a result of discussions between ARPA and NASA officials on the day after the launch, Lincoln Laboratory was asked to acquire radar data and use identification techniques to evaluate the satellite (Figure 8-3). Three tracks were taken by ALCOR between May 15 and May 18. Telephone conversations between Lincoln Laboratory staff members on the Kwajalein Atoll and in Lexington identified important sections of the data, which were then sent via satellite to a ground terminal at Boston Hill in North Andover, Massachusetts, and brought to the Laboratory for analysis. The mainframe computer at the Laboratory was dedicated for a night to image analysis, and the next day, May 23, the results were presented to NASA officials in Huntsville, Alabama. The basic conclusions were that the left solar panel was missing, the other solar panel appeared to be only partially deployed and no bent or protruding sections of the micrometeorite shield were visible.[6] On the basis of this analysis and other information, NASA decided to send up a crew to repair and man the space station. Additional radar data were recorded after the crew properly deployed the right solar panel and rigged a sun shield to protect the space station from overheating, and the results confirmed the corrected configuration.

1975

L.G. Kraft, Jr.

ALCOR Roi-Namur

V.A. Nedzel

Another application relates to a U.S. Defense Meteorological Satellite that failed to deploy its solar panel properly and went into an uncontrolled tumble. Lincoln Laboratory explained to Johns Hopkins Applied Physics Laboratory personnel how wideband radar data could reveal the orientation of the tumble axis and the rate of rotation, and also provide an image of the satellite. The information could then be used to calculate the required correction torques by attitude-control jets. The Applied Physics Laboratory accepted the suggestion and asked Lincoln Laboratory to acquire the data. Lincoln Laboratory delivered the detailed tumble motion parameters and a satellite image, and over the next several weeks incremental attitude controls were applied. The satellite assumed a stable and properly oriented orbit, and the solar panels were deployed.

The initial success of satellite imaging with ALCOR data prompted considerable interest in extending the capabilities of the imaging radars. Higher resolutions required more bandwidth, so the radar center frequency had to be shifted up to make it possible to realize wider bandwidth with existing technology. In 1974, after sorting out available options, Lincoln Laboratory proposed the addition of a high-power wideband X-band capability to the Haystack radar. In addition to higher range resolution, the X-band subsystem was designed with enough sensitivity to track and image satellites in deep space. ARPA sponsored construction of this addition to Haystack, the Long Range Imaging Radar (LRIR), and it was completed in 1978.

The 25-cm resolution of the LRIR yielded fine details and more information about imaged satellites. The real challenge, however, turned out to be the imaging of deep-space satellites, particularly for satellites at geosynchronous altitude.

Lincoln Laboratory staff members developed new techniques, including stroboscopic imaging and extended coherent processing, that used coherent integration of a large number of pulses and the knowledge of the precise motion of a satellite to image satellites. Extended coherent processing, which allows coherent integration over a large rotation angle, is still in use and has been shown to be essential in other, newer image analysis techniques.

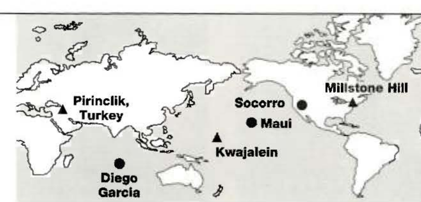
ARPA was satisfied with the outcome of the program and in 1978 declared that the project had been completed successfully. However, the feeling at Lincoln Laboratory was that the new technology could and should be put to use. Because the intelligence community strongly concurred with the Laboratory viewpoint, ARPA initiated funding through the Air Force Space and Missile System Organization (SAMSO) to operate the LRIR for two years. Lincoln Laboratory obtained support for data collection and operations for the radar from the ADCOM and the Air Force Foreign Technology Division (FTD).

ADCOM required delivery of satellite images within one hour after track, even though the then prevailing delay between satellite track and image generation was several weeks. The Haystack LRIR radar team met this requirement by developing a near-real-time imaging capability. They simplified and accelerated the various processing stages and successfully imaged satellites within one hour. In less than a year, an operational system was connected to the NORAD Cheyenne Mountain Complex (NCMC) via a high-speed data line. From this point on, Haystack LRIR became a contributing sensor and part of the ADCOM Space Surveillance Network. In 1983, after the Air Force permitted the generation of radar images outside the continental United States, a similar capability was installed at ALCOR.

1980

GOEDSS ETS, Socorro, N. Mex.

Modular design of Haystack antenna allows LRIR capability



Deep-space surveillance network, radar (▲) and optical (●)

Skylab again played a role in proving the utility of radar images. The orbit of the space station had decayed, and NASA anticipated that it would reenter the atmosphere in July of 1979. To accelerate the reentry of *Skylab,* NASA needed to stabilize it and then put it in a high drag orientation. During June and July of 1979, LRIR was asked to image *Skylab,* determine its motion and then corroborate the orientation after NASA reoriented it to maximize the drag. The near-real-time imaging capability provided timely data on the motion and orientation that would otherwise have been unavailable. By the mid-1980s the Haystack and ALCOR C-band and K_a-band radars had become contributing sensors and were helping the NCMC intelligence sector perform its function of mission and payload assessment.

The satellite image analysis effort continued in the Laboratory largely in support of FTD. New and better algorithms for radar image interpretation led to an in-depth analysis capability that helped both modeling and understanding the operational modes of satellites. In several cases, data from this analysis were the first sources used in modeling a new foreign satellite.

In 1984 the development of small computer workstations led to a major effort sponsored by the U.S. Space Command and FTD to package the radar-image analysis software in a workstation. The principal objective was to automate and simplify the process of radar-image analysis and interpretation. The workstation was then to become a vehicle for technology transfer from Lincoln Laboratory to the user community. New computer graphics tools were added to the software package. The delivered workstation software helped both the U.S. Space Command and FTD perform independent routine wideband image analyses, which freed Lincoln Laboratory to focus on developing new and better analysis techniques.

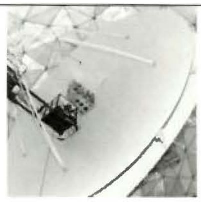
Other efforts followed. An electromagnetic scattering prediction software capability was packaged into a workstation and delivered to the same user community. This package, the Lincoln Laboratory RCS prediction software, TooLLBox, enhanced the ability of an analyst to interpret radar images. Another package, the narrowband workstation, used narrowband satellite radar signature data and modern pattern recognition techniques to monitor and identify satellites. This package is being used routinely with great success by personnel at the NCMC.

The Haystack Auxiliary Radar

Throughout this period, the LRIR had shared its antenna mount with the NEROC radio astronomers at the Haystack Observatory. According to the terms of the agreement between Lincoln Laboratory and NEROC, satellite imaging could be conducted for only about eight weeks per year. This arrangement proved unsatisfactory to the U.S. Space Command, which needed continuous availability. The most cost-effective solution proposed was to build a K_u-band auxiliary system with a smaller antenna that could share much of the LRIR signal and data processing equipment. The antenna, transmitter and receiver of the auxiliary system would be located close to the LRIR and connected to its equipment via underground signal and control cables. The auxiliary system could then operate whenever the radio astronomers were using the Haystack antenna. The proposal also recommended that the bandwidth be doubled to obtain a range resolution of 12 cm.

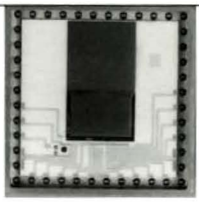
The funding for the Haystack Auxiliary (HAX) radar came in a roundabout way. Haystack's high sensitivity and wavelength combination made it ideal for detecting very small objects in space. In the late 1980s, NASA was looking for reliable data to help model the space debris environment for use in the shielding design of the space

1990



HAX radar antenna

SBV telescope package



CCD focal plane for SBV telescope