The Space Mission at Kwajalein

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The United States has leveraged the Reagan Test Site's suite of instrumentation radars and its unique location on the Kwajalein Atoll to enhance space surveillance and to conduct space launches. Lincoln Laboratory's technical leadership at the site and its connection to the greater Department of Defense space community have been instrumental in the success of programs to detect space launches, to catalog deep-space objects, and to provide exquisite radar imagery of satellites.

The Reagan Test Site (RTS), located on Kwajalein Atoll in the central western Pacific, has been a missile testing facility for the United States government since the early 1960s. Lincoln Laboratory has provided technical leadership for RTS from the very beginning, with Laboratory staff serving assignments there continuously since May 1962 [1]. Over the past few decades, the RTS suite of instrumentation radars has contributed significantly to U.S. space surveillance and space launch activities.

The space-object identification (SOI) enterprise was motivated by early data collected with the Advanced Research Projects Agency (ARPA)-Lincoln C-band Observables Radar (ALCOR), the first high-power, wideband radar. Today, RTS sensors continue to provide radar imagery of satellites to the intelligence community. Since the early 1980s, RTS radars have provided critical data on the early phases of space launches out of Asia. RTS also supports the Space Surveillance Network's (SSN) catalog-maintenance mission with radar data on high-priority near-Earth satellites and deep-space satellites, including geosynchronous satellites that are not visible from the other two deep-space radar sites, the Millstone Hill radar in Westford, Massachusetts, and Globus II in Norway. Another chapter in RTS space history began in 2000 when the RTS missile-launch infrastructure was utilized to launch a satellite into orbit. The existing launch infrastructure and remote equatorial location are ideal for space launch into low-inclination orbits and for early flights of new, unproven launch vehicles. The catalyst for these and future contributions to the U.S. space mission has been

Table 1. KREMS radar characteristics relevant to the space surveillance mission

	ALTAIR	TRADEX	ALCOR	MMW
Year operational	1970	1962	1970	1983
Year joined SSN	1982	1998	2004	2005
Center frequency (GHz)	0.162 (VHF) 0.422 (UHF)	1.320 (L band) 2.950 (S band)	5.672 (C band)	35 (Ka band)
Bandwidth (MHz)	7 (VHF) 18 (UHF)	18 (L band) 280 (S band)	512	4000
Space mission	Deep-space tracking, new foreign launches (NFL) tracking, narrowband space-object identification (SOI)	Deep-space tracking, NFL tracking, narrowband SOI	Low Earth orbit (LEO) imaging for SOI	LEO imaging for SOI

Lincoln Laboratory's technical role at RTS and its connection to the greater Department of Defense (DoD) space community.

The core of the RTS instrumentation suite is the Kiernan Reentry Measurements Site (KREMS), which consists of four exceedingly capable radar systems: ALCOR, the ARPA Long-Range Tracking and Instrumentation Radar (ALTAIR), the Target Resolution and Discrimination Experiment (TRADEX) system, and the Millimeter-Wave (MMW) system. All of the KREMS radars are designated contributing sensors to the U.S. Space Surveillance Network (SSN), as are the three radars at the Lincoln Space Surveillance Complex in Westford, Massachusetts—Millstone Hill, Haystack, and Haystack Auxiliary (HAX). The reason that each of the KREMS sensors was built differs, but the common theme is that they were built to expand the U.S. understanding of ballistic missile systems. Through the years, Lincoln Laboratory staff have continually recognized and exploited the relevance of these sensors in other mission areas and scientific endeavors. Among the more significant of these enterprises are space surveillance and ionosphere science (see the later article, "Ionospheric Science at the Reagan Test Site").

The relevant characteristics of the KREMS radars are summarized in Table 1. More complete descriptions of the four radar systems can be found in other articles in this issue of the *Journal*.

Space Launch and Deep-Space Satellite Tracking

The ALTAIR and TRADEX sensors, shown in Figures 1 and 2, serve three functions for the SSN: space launch tracking, deep-space satellite tracking, and timely tracking of low Earth-orbit (LEO) satellites. The geographic location of RTS either enables or enhances all three of these functions.

RTS is tasked to track almost all foreign and domestic space launches. Early data are critical for maintaining tracking custody of newly launched satellites.

ALTAIR and TRADEX have enough power aperture to track geosynchronous (GEO) satellites, which are about 40,000 km slant range from ground-based sensors. Since GEO satellites do not move relative to Earth, some satellites over East Asia and the Pacific can only be tracked by RTS radars. RTS contributes more than 70,000 satellite tracks to the SSN each year, most of them on deep-space objects and many that no other radar sensor can track.

The third SSN function of ALTAIR and TRADEX is the timely tracking of LEO satellites. The SSN's dedicated radars perform the vast majority of the LEO catalog-maintenance mission. Dish radars like ALTAIR and TRADEX do not contribute significantly to the quantity of these measurements. However, the threat of LEO collisions has increased the importance of orbit accuracy, which is critical for robustly predicting collisions in time to implement avoidance maneuvers. Orbit accuracy is

FIGURE 1. ALTAIR provides coverage of the deep-space geosynchronous belt, tracking ~1300 deep-space orbiting satellites every week.

FIGURE 2. TRADEX became operational in 1962 but was not employed for space missions until 1994 as a substitute for ALTAIR, and only officially became a contributing sensor to the Space Surveillance Network in 1998.

improved by decreasing the time between measurements or by improving the accuracy of the measurements. RTS excels at both goals because the location is significantly displaced from the North American dedicated radars, thus decreasing time between revisits, and the measurements are instrumentation quality. The importance of the timeliness of tracking data is likely to increase as the LEO regimes become more congested with payloads and debris, and the probability of collisions increases. The 2009 collision of an operational Iridium satellite with a defunct Russian satellite was an eye-opening reminder of the need to do this job well.

ALTAIR and TRADEX have been operationally engaged in SSN functions since 1982 and 1998, respectively. Typically, ALTAIR is operated 128 hours per week in support of the SSN mission; TRADEX is operated for 10 hours per week. About twice per year, TRADEX will take over the 128 hours per week of space surveillance while ALTAIR is in a multi-week maintenance shutdown. In addition to RTS radars' regularly scheduled shifts, the space track mission is a 24-hour, 7-days-a-week (24/7) operation at RTS. Even when the space track mission is not typically conducted, the radars and operators are on call for tasking on high-priority space events.

History of the RTS Space Tracking Mission

By the early 1970s, the Space Surveillance Network (at the time called SPACETRACK) consisted of two dedicated radar systems, plus the Ballistic Missile Early Warning System (BMEWS) radars and a network of Baker-Nunn cameras. The first dedicated radar system, NAVSPASUR (Navy Space Surveillance System), became operational in 1961. NAVSPASUR remains operational today as a network of multistatic, VHF radars that are strung across the southern United States. The other dedicated radar, the AN/FPS-85 phased-array radar located at Eglin Air Force Base in Florida, became operational in 1969 [2].

The launch of Cosmos 520 by the Soviet Union in 1972 accentuated the inability of the existing SSN to adequately keep track of deep-space satellites. Cosmos 520 was the first use of a deep-space orbit for a military mission, and the only tracking capability available at the time was provided by the Baker-Nunn cameras. A more tactical capability was needed.

All-weather, 24/7 radar tracking was desired, but since the signal-to-noise ratio falls off as the inverse of range to the fourth power, tracking at deep-space ranges was a formidable technical challenge for even the most powerful radars. The answer to this problem was to add real-time coherent integration to a high-power radar.

In the early 1970s, Lincoln Laboratory demonstrated tracking of a geosynchronous satellite using the Millstone Hill radar and real-time coherent integration [3]. This tracking was a great achievement for the Millstone radar system, but to be truly useful to the SSN, Millstone's technology needed to be transferred to at least two other radars so that the entire geosynchronous belt could be tracked. The ALTAIR radar in Kwajalein and the AN/FPS-79 in Turkey would eventually complete the global coverage.

A recurring theme in the RTS space surveillance story is the repurposing of existing technology and hardware to demonstrate space mission capability. In the case of deep-space surveillance, both technology and hardware were borrowed from other efforts. At ALTAIR, a number of fortuitous enhancements occurred just prior to the Millstone Hill deep-space experiment. Without these enhancements, which were undertaken for other reasons, the space mission could not have been demonstrated without significant additional expense. It is unclear whether the DoD would have invested in RTS space capability without the early success of these low-cost demonstrations.

ALTAIR Simulation of the Perimeter Acquisition Radar

In its original configuration, ALTAIR was a VHF range and monopulse angle tracker and an ultra-high-frequency (UHF) range-only tracker. Even with coherent integration, the VHF radar at ALTAIR did not have enough sensitivity to track geosynchronous satellites. The UHF radar is almost 20 dB more sensitive but was initially only capable of range tracking. Fortunately, a major upgrade was initiated in 1972 to enable ALTAIR to simulate the Perimeter Acquisition Radar (PAR), an element of the Safeguard anti-ballistic missile system.

The Safeguard system consisted of the Sprint and Spartan interceptors, the Missile Site Radar (MSR), and the PAR. Almost 100 intercept tests at Kwajalein were conducted to test Safeguard. The test program went to great lengths to ensure high-fidelity testing of the system, including the construction of an MSR on Meck Island at the Kwajalein Atoll. The PAR, however, was enormous (housed in North Dakota in a massive concrete building over 40 m high), and it was deemed impractical to build a PAR on Kwajalein for the test program. Instead, key elements of PAR were added to ALTAIR for the test campaign.

Two elements of the Simulation of the Perimeter Acquisition Radar (SIMPAR) program were crucial to the later success of deep-space surveillance demonstrations: UHF monopulse angle tracking and a system for getting digitized signature data into the Reentry Designation and Discrimination (REDD) system computer. The former involved a complete redesign of the antenna feed. Many feed topologies were considered to add UHF monopulse while maintaining monopulse at VHF. Ultimately, the chosen approach left the VHF feed at the prime focus of the antenna and added a UHF four-channel monopulse horn at the Cassegrain point. This topology required the design and use of a frequency-selective subreflector to reflect UHF and transmit VHF onto the main reflector. SIMPAR also added two complete UHF analog receiver channels and a hardware subsystem to compute the off-boresite angles from the sum and difference signals.

The REDD program, executed by Lincoln Laboratory, developed and tested real-time detection and identification algorithms for the Site Defense system. The REDD program deployed a Control Data Corporation (CDC) 6600 to KREMS for use in testing algorithms in real time during missile tests. The CDC 6600 is generally regarded as the first commercially available supercomputer, with performance exceeding a megaflop (a million floating-point operations per second).

The SIMPAR program connected ALTAIR to REDD's CDC 6600. The core of this connection was the SIMPAR signal processor (SSP), which digitized up to two analog receiver signals from ALTAIR and buffered and transmitted these data to the REDD computer. A bidirectional digital link was also established between the ALTAIR real-time computer (at the time, a DDP 224) and the CDC 6600 to facilitate closed-loop control of the radar by the REDD computer. These interfaces between ALTAIR and the CDC 6600 computer were an essential capability for the demonstration of real-time coherent integration and other algorithms for the SSN mission.

Real-Time Coherent Integration at ALTAIR

About a year after real-time coherent integration was demonstrated at the Millstone Hill radar [4], Lincoln Laboratory staff at KREMS developed and demonstrated a similar capability at ALTAIR to enable deep-space tracking [5]. Because of the extensive hardware that had been deployed by the SIMPAR and REDD programs, this was mostly a modest software development effort.

The first deep-space tracking program at ALTAIR was developed and deployed on the CDC 6600 in 1975. Although this program was developed for demonstration purposes only and on a modest budget, it included most of the features that are currently associated with deep-space tracking. The signal processing algorithms included coherent pre-summing, coherent integration based on the fast Fourier transform (FFT), and noncoherent post-summing. The program had both search and track modes, and acquisition logic for automatically transitioning from one to the other. Using this program, ALTAIR demonstrated real-time tracking of geosynchronous satellites.

As an example of how much this effort leveraged existing hardware, consider how this early program implemented coherent integration of the monopulse receiver channels. Recall from the earlier discussion that the SSP only had two analog-to-digital (a/d) channels. To effectively track in angles, the monopulse channels must be coherently integrated just as the sum channel must be. Therefore, a minimum of three a/d channels were needed to digitize the primary polarization sum signal and the two monopulse difference signals. Rather than add an additional a/d converter to the SSP, one of the existing a/d converters was dedicated to the sum channel and the other was multiplexed on a pulse-by-pulse basis between the azimuth (strictly speaking, traverse) and elevation monopulse channels. This scheme resulted in 3 dB less coherent processing gain in the monopulse channels relative to the sum channel, but allowed the system to be demonstrated without an investment in additional hardware.

Despite this clear early success, it would be many years before deep-space tracking would become an operational capability at ALTAIR. The reasons for the delay were primarily bureaucratic, but there were also key technical limitations. For instance, the search capability was limited because of a combination of short maximum pulse width and only modest real-time computing resources for coherent integration. The operational impact of this limitation was that ALTAIR could not successfully acquire synchronous satellites that drifted slightly from their planned orbit.

The Pacific Barrier Trial

In the mid-1970s, with the Soviet Union intensifying its use of deep-space orbits for military missions, the DoD realized the importance of early tracking of space launches to ensure robust tracking custody of foreign military payloads. A study of the probable launch trajectories revealed that a network of radars on the islands of the western Pacific was needed. Lincoln Laboratory staff suggested that ALTAIR could be used as one of these radars.

A formal, three-month trial period of ALTAIR's space-tracking capabilities was planned and executed in late 1977 and into 1978. The trial focused on two main areas: catalog maintenance and the so-called new foreign launch (NFL) capability. It did not evaluate deep-space tracking or (narrowband) space-object identification. During the three different phases of the trial, ALTAIR was operated as a dedicated sensor (24/7 space tracking), a shared sensor (128 hours/week space tracking, 24/7 NFL standby), and an NFL-only sensor.

As in the previous real-time coherent integration demonstration, the Pacific Barrier (PACBAR) trial would have been significantly more expensive (and may not have happened at all) without the preexisting SSP and CDC 6600. The code developed for the trial included a local satellite catalog and orbit propagator, real-time coherent integration for deep-space tracking, a digital interface to the SSN, and a completely new NFL capability (see sidebar "RTS Tracking of New Foreign Launches"). All of the space-tracking code was developed and executed on the CDC 6600, which had become the main KREMS computer after the completion of the REDD program in 1976.

The PACBAR trial was an unequivocal success and cemented the future of ALTAIR and RTS as contributors to the SSN. During the 12-week trial, the newly developed NFL capability was demonstrated successfully on seven out of nine actual space launches. The NFL system was also tested on satellites, treating them as if they were previously unknown, new launches. Over 150 of these high-fidelity simulations were conducted and ALTAIR successfully acquired the desired satellite in 84% of the cases. For both the real and simulated NFLs, the vast majority of the failures were due to an incomplete catalog: the system acquired an uncataloged object instead of the desired target. The ability of ALTAIR to conduct the catalog-maintenance mission was already well understood, but the trial proved that an operational cadence could be

RTS Tracking of New Foreign Launches

To acquire space launch complexes, ALTAIR and TRADEX scan the horizon, using a bow-tie pattern to create a leak-proof fence. The basic pattern of the scan is shown in Figure A.

To understand the utility of the bow-tie pattern, it is instructive to first consider a barrier scan, in which elevation does not vary. In the barrier scan, the antenna simply scans back and forth, and the azimuth rate is held constant (ignoring the acceleration limitations at the extents). Note that the revisit period of the barrier scan varies linearly from half the period of the scan at the scan center to the whole period of the scan at the extents. The bow-tie scan compensates for the revisit period variation by raising the elevation at a constant rate to allow for the elevation rate of the target.

The parameters of the scan are designed to be leak-proof for a target that has an elevation rate less than 0.08 deg/s. When the scan was first designed in the late 1970s, many historical launch trajectories were analyzed to determine this maximum elevation rate. Beyond this basic parameter, the design of the scan depends on the particulars of the radar on which it is being implemented. It is instructive to briefly focus on the design of the scan for the ALTAIR VHF system because this is the preferred sensor for acquiring new foreign launches (NFL) at RTS.

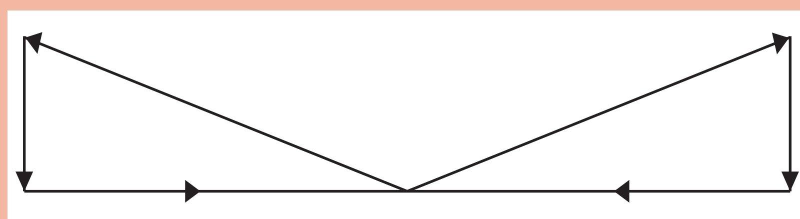


Figure A. Bow-tie scan pattern used by ALTAIR and TRADEX to acquire launch complexes. The elevation extent of the scan is exaggerated in the figure so that the pattern can be seen more clearly.

The 3 dB one-way beamwidth of the ALTAIR VHF radar is 2.8°. To simplify the analysis, the beam is conservatively presumed to only consist of the 2° inscribed square (2.8/√2). The period of the scan must be short enough that a target in the center of the scan that is just missed below the beam will be caught on the next pass.

achieved and that the data could be integrated into the Space Detection and Tracking System (SPADATS). During the three-month trial, more than 6000 satellite tracks were conducted and the data successfully transferred to the Air Force Space Command's Cheyenne Mountain Complex in Colorado.

The Road to Operations

Immediately following the PACBAR trial, Lincoln Laboratory personnel started to plan for an operational SPACETRACK capability at ALTAIR. The plans included a dedicated SPACETRACK computer, sensitivity improvements, new waveforms, and communication infrastructure improvements. The underlying theme of these modifications was to create a robust, high-availability system.

On the strength of the PACBAR trial and the Lincoln Laboratory planning, the Air Force decided in June 1979 to fund a program to make ALTAIR SPACETRACK operational. GTE Sylvania executed the program under Lincoln Laboratory's direction. The program was completed in 1982, and ALTAIR officially became a contributing sensor to the SPACETRACK network on October 1, 1982.

Other ALTAIR Improvements to the Space Surveillance Capability

The original ALTAIR UHF transmitter had a maximum pulse width of only 40 µsec. In order to achieve high enough average power for deep-space tracking, a high pulse-repetition frequency (PRF) was necessary to compensate for the short pulse. The original transmitter was capable of a high PRF, but the resulting small ambiguity zone size (distance between transmit pulses) limited the ability of ALTAIR to perform a timely search.

In 1982, the missile-tracking ship, USNS *General H. H. Arnold* was retired from service. In November 1984, the *Arnold's* UHF radar transmitter replaced ALTAIR's original klystron-based UHF transmitter [6]. The new transmitter combined the output of 24 traveling wave tubes (TWT) to produce 5 MW peak power with a 5% duty cycle. The maximum pulse width increased from 40 μsec to 1 ms. The increase in pulse width and average power greatly improved the deep-space search and tracking capability of ALTAIR.

In the early 1990s, the USNS *General Hoyt S. Vandenberg,* sister ship to the *Arnold*, was retired from service. An additional eight-TWT transmitter group from the *Vandenberg* was added to ALTAIR in 1994, increasing peak power to 6 MW. The 32-tube transmitter is still in use today [7].

For missile tests and LEO satellite tracks, ALTAIR uses two frequency observations to remove the effects of ionospheric refraction. The VHF system, however, is not sensitive enough for deep-space. A real-time, ionospheric correction system based on the Global Positioning System (GPS) was added in 1998. This system greatly improved the metric accuracy of deep-space observations. An accompanying article on ionospheric science provides more detail on the effects of ionospheric refraction.

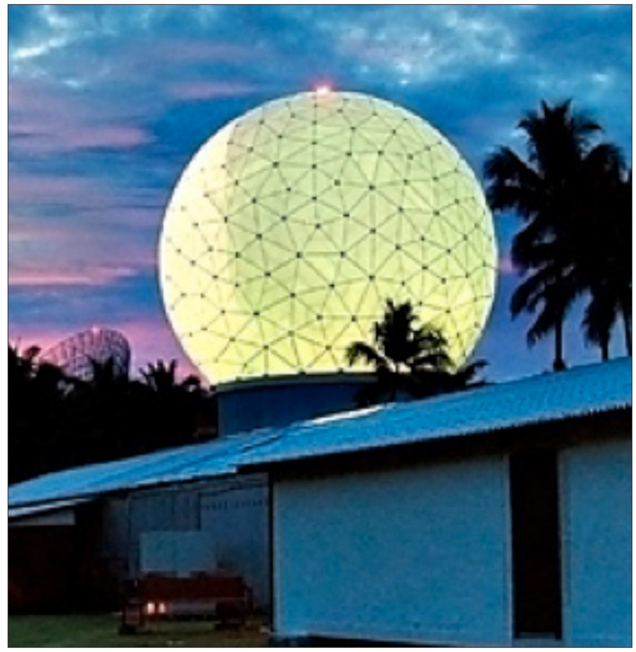


FIGURE 3. The Millimeter-Wave radar has the best range resolution of the radars at Kwajalein, and indeed, the world. Its coherent, high-resolution data allow the generation of exquisite images of satellites.

TRADEX

In the original planning for RTS participation in SPACETRACK, TRADEX was considered as a possible backup to ALTAIR when that system was down for maintenance, but TRADEX was dismissed at that time for a variety of reasons. First, the longest pulse at TRADEX was only 50 μsec, and to achieve adequate probability of detection on the desired NFL targets, coherent integration of many pulses was required. But TRADEX did not yet have the ability to coherently integrate pulses in real time. Second, even if coherent integration had been developed, the average power of the transmitter would not allow a wide enough scan to bound the uncertainty in launch trajectories at the time.

The fundamentals for TRADEX participation in the SPACETRACK mission were evident in the late 1970s, but the combination of capability and mission need would not materialize for two more decades. In 1986, real-time coherent integration was added [8], along with other extended-range signal processing techniques that had been used previously at ALTAIR and the Millstone Hill radar. In the late 1980s, the maximum pulse width was increased from 50 μsec to 565 μsec. In the early 1990s, quasi-continuous wave (CW) versions of the 565 μsec waveforms were implemented, finally giving TRADEX a viable NFL search and deep-space acquisition capability. The 50 kHz bandwidth version of the 565 μsec waveforms along with a new digital pulse-compression system gave TRADEX a very capable coherently integrated range window.

Despite its having a space-tracking capability similar to ALTAIR in the early 1990s, TRADEX would not become a contributing sensor to the Space Surveillance Network until much later in the decade. A nine-month shutdown was planned at ALTAIR to implement the Kwajalein Modernization and Remoting (KMAR) project in 2001. In anticipation of this extended downtime, TRADEX was certified as a contributing sensor to the SSN in 1998. TRADEX was the prime sensor for the space surveillance mission during the nine-month KMAR shutdown of ALTAIR and had a perfect record on NFL tasking during this period.

In 2002, TRADEX was modernized under the KMAR program. The KMAR program combined the space surveillance capabilities from both ALTAIR and TRADEX into a common code base. The radars now share common algorithms for extended range processing and NFL search.

Space-Object Identification

The ALCOR and MMW radars supply radar image sets to the Air Force National Air and Space Intelligence Center (NASIC). These data are used by NASIC analysts to improve U.S. understanding of foreign satellite capabilities and to assess their health and status. The MMW radar (Figure 3) is the primary RTS radar for this mission, and ALCOR fills in when MMW is in maintenance shutdown [9].

Prior to this year, the number of radar image sets had been limited to preserve the few existing MMW transmitter tubes, which the manufacturer had no longer been able to produce reliably. A new transmitter tube was designed in order to ensure a reliable supply of tubes for future operations, and MMW was declared operational with the newly designed tube in 2011. This year, RTS secured additional funding to allow an increase in the number of image sets per year. More details on the MMW radar, including the recent upgrades, can be found in a companion article in this issue.

FIGURE 4. ALCOR's wideband capability was adapted to satellite imaging, leading to Lincoln Laboratory's pioneering work in developing techniques and algorithms for generating and interpreting radar images.

Early ALCOR Data Collections

ALCOR (Figure 4) was the first high-power, wideband radar system [10]. Like the other KREMS sensors, it was built for missile testing, but its utility for space surveillance was immediately recognized and put to good use [11].

About the time ALCOR became operational in 1970, China launched its first orbiting satellite. The final booster from this launch remained in orbit, and there was speculation within the DoD that the same booster design could be used as part of an intercontinental ballistic missile (ICBM). The optical trackers of the day had insufficient resolution to determine the size of the booster, a key parameter in evaluating its utility in an ICBM system.

ALCOR has 512 MHz of bandwidth and a corresponding range resolution of half a meter, which was, in principle, sufficient for measuring the dimensions of the Chinese booster [12]. However, the inverse synthetic aperture radar (ISAR) imaging techniques that are used today for satellite imaging had not been developed. The dimension of the rocket along the radar line of sight could be measured directly, and because the rocket was tumbling, it could be observed over all body aspect angles. These direct measurements of range extent, combined with crude Doppler measurements and the radar cross-section (RCS) time history, were used to successfully determine the size of the rocket body. These data were immensely valuable to the DoD and led to increased interest in the use of wideband radar for space surveillance [13].

In 1971, the Soviet Union launched its first space station, *Salyut-1*. ALCOR data were used with ISAR imaging algorithms to produce range-Doppler images of *Salyut-1*. The images were spectacular and led to the space-object identification (SOI) program at Lincoln Laboratory, and indeed, were the seeds of the entire DoD satellite imagery enterprise [13].

Skylab, the first U.S. space station, was launched on 14 May 1973. The National Aeronautics and Space Administration (NASA) determined that the solar panels had not deployed properly and that the micrometeorite shield had deployed prematurely and was torn off the vehicle. In order to evaluate this damage, NASA negotiated with ARPA to use ALCOR to image *Skylab*. Although this imaging capability was far from operational, the task was completed with remarkable speed. ALCOR collected data on the day after the launch and on two additional passes over the next few days. The data were transferred to Lincoln Laboratory, and ISAR images were computed and analyzed (Figure 5). The conclusion of the radar imagery analysis, delivered only eight days after the first ALCOR data collection, was that one solar panel was missing, the other was only partially deployed, and no remnants of the micrometeorite shield remained on the spacecraft. This analysis was critical in helping NASA formulate and execute a plan to repair and man the space station [13].

Another early use of ALCOR radar imagery was in the recovery of a U.S. Defense Meteorological Satellite. The satellite was in an uncontrolled tumble, and ALCOR imagery data were used by Lincoln Laboratory personnel to calculate a motion solution. The Laboratory's scientists worked with the satellite operator to develop a plan to command the satellite's attitude control system to counteract the measured motion and stabilize the satellite. After several weeks of iteration on motion solutions and attitude corrections, the satellite was stabilized in its proper orbit [13].

ALCOR was built to advance missile defense technology, but Lincoln Laboratory personnel immediately recognized the utility of wideband radars for space surveillance and worked diligently to leverage the capability to great effect on the missions described previously. Because of the success of these early demonstrations, the Laboratory successfully convinced ARPA to fund the long-range imaging radar (LRIR) upgrade to the Haystack radar in Westford. The LRIR became operational in 1978 and was the first high-power wideband radar built specifically for space surveillance. Until LRIR became operational, ALCOR was the only source of wideband radar data on satellites. These data were used extensively for high-priority missions such as those discussed earlier and for refining satellite image processing techniques.

Remote Operation of the RTS Space Mission

The KREMS radars on the island of Roi-Namur historically have been operated from local console rooms at each of the radars. The Kwajalein Modernization and Remoting (KMAR) program, which was completed in 2002, enabled remote operation of the KREMS radars from Kwajalein Island. In 2007, the satellite-tracking, NFL, and SOI operations were transferred to a new control center on Kwajalein, called the Kwajalein Space Surveillance Center (KSSC). In April 2011, the satellite-tracking mission was transferred to the Huntsville Space Operations Center and was the first RTS mission to become operational from Huntsville, Alabama, as part of the RTS Distributed Operations (RDO) program. The NFL mission and the data analysis part of the SOI mission became operational from Huntsville in October 2011. The SOI sensors, ALCOR and MMW, are currently jointly operated from Huntsville and Roi-Namur. More details on the RDO program can be found in a subsequent article entitled "Reagan Test Site Distributed Operations."

The Extended Space Sensors Architecture (ESSA) program installed sidecars on many SSN sensors, including all of the KREMS radars. The ESSA program was an Advanced Concept Technology Demonstration funded in 2007 and executed by Lincoln Laboratory. The addition of the ESSA sidecars made sensor data and advanced data products available in near real time to authorized users on the Secret Internet Protocol Router Network (SIPRNet). Enabled by ESSA, ALCOR and MMW produce satellite images automatically within a few minutes after data collection begins, and ALTAIR and TRADEX tracking data are available seconds after they are collected and are higher fidelity than the operational data routinely transferred to the JSpOC. In addition, ESSA data include radar cross section versus time, and archived data are available via ESSA.

Space Debris Measurements

In the 1990s, RTS sensors participated in NASA and Air Force Space Command debris measurement campaigns [14]. These were significant efforts to find, track, and characterize debris objects that were not in the SSN catalog. The first of these campaigns that RTS participated in was the NASA Multifrequency Space Debris Radar Tests (MSDRT) in 1991. During this campaign, TRADEX was fixed at zenith, in so-called *stare mode,* to detect debris as it transits through the beam. The range window was centered at an optimal altitude, and 19 objects with estimated sizes as small as 3 cm were detected during 4.4 hours of staring. The stare mode was exercised again at TRADEX during the NASA debris study in August 1994, but the

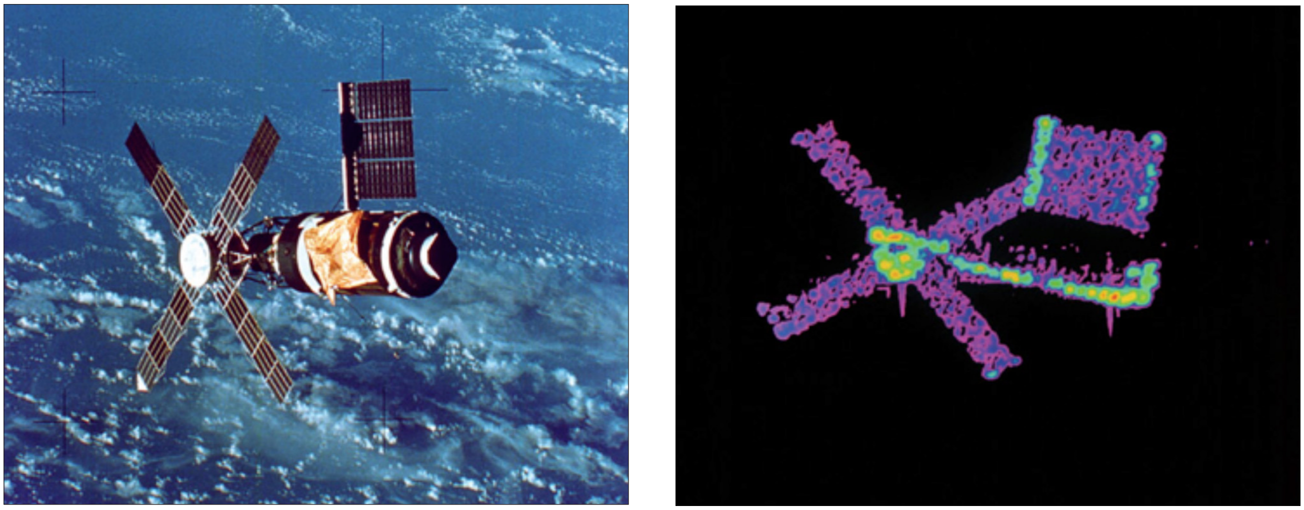


FIGURE 5. At left is a photo of *Skylab* after repairs had been made (photo courtesy of NASA); at right is a computer-generated, color-enhanced simulated radar image of *Skylab.* This simulation illustrates the caliber of imagery that can be generated from ALCOR data.

range window was centered at a lower altitude for 20 hours, and a significantly lower detection rate was found than at the higher altitude. An additional 5 hours of stare mode were conducted at a higher altitude and confirmed the higher detection rate observed in 1991 [15].

Lincoln Laboratory personnel at TRADEX also developed a new capability, called *stare and chase,* for the 1994 NASA debris study. Instead of just letting debris pass through the beam, track was initiated on detections to enable orbit determination and better signature characterization. This capability was first used operationally between 3 and 11 August 1994, during which 25 hours of stare-and-chase operations were conducted for the NASA debris campaign. Fifty-three objects were found, 26 of which did not correlate with objects in the SSN catalog [15].

Air Force Space Command conducted the 1994 Space Debris Campaign from 11 October to 8 November 1994. This campaign involved nearly all of the SSN sensors from around the globe. The participating RTS sensors included TRADEX, ALTAIR, ALCOR, MMW, and the Super Recording Automatic Digital Optical Tracker (Super RADOT) visible-band sensors. The RTS support fell into three areas: TRADEX stare and chase, ALTAIR debris tracking, and multispectral debris characterization [16].

TRADEX stare-and-chase mode was used for 39.5 hours, and 77 objects were detected with 39 of these not correlated with objects in the SSN catalog. ALTAIR was used to follow up on debris objects discovered during the campaign. In this capacity, ALTAIR conducted a total of 233 tracks on 100 unique debris objects. Finally, all of the RTS radars and the Super RADOT optical sensors jointly responded to campaign tasking requests for a total of 21.5 hours. During this period of the campaign, 55 debris objects were tracked by two or more sensors, and five objects were tracked simultaneously by radar and optics [16].

The data from the RTS sensors on these debris campaigns yielded some unique findings. First, the RTS data revealed an unexpected number of high-RCS, uncataloged objects in low-inclination, high-eccentricity orbits. TRADEX data also revealed a dearth of small objects in low-altitude orbits, which was inconsistent with then current debris models.

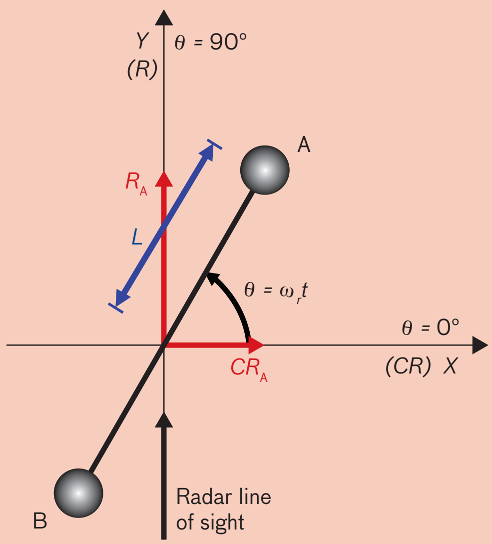
Space debris remains a formidable challenge to the space control enterprise. On 11 January 2007, the Chinese successfully tested a direct-ascent, anti-satellite weapon on one of their own defunct weather satellites, polluting the LEO regime with over 3000 pieces of debris. The unintentional collision of a defunct Russian communications satellite and an active Iridium payload in 2009 created over 2000 additional pieces of debris. As more debris and more satellites enter orbit, the probability of collision increases and the possibility of a snowball effect becomes more imminent.

NASA continues to use data from the Haystack and HAX radars to study uncataloged debris. In addition, an increasing interest in debris-mitigation techniques is focusing on not only preventing further debris but also reducing debris already in orbit.

Range-Doppler Imaging

Wideband radars can resolve individual scattering centers on targets along the slant range dimension, even at long ranges, because of the fine range resolution that they achieve. Resolution in the cross-range or angular dimension, however, is much coarser because it is dependent on the radar beamwidth. Inverse synthetic aperture radar (ISAR) processing, also known as range-Doppler imaging, can significantly improve the cross-range resolution. ISAR processing extracts resolved target cross-range information from the received radar signal by exploiting Doppler frequency shifts that result from target rotational motion with respect to the radar, after the target's translational motion along its trajectory is removed. Doppler frequency is determined from pulse-to-pulse changes in the phase of the received signal, so the radar signal must be coherent, i.e., the phase reference must be consistent from pulse to pulse.

To illustrate how target motion relates to Doppler frequency, consider a tumbling dumbbell that consists of two perfectly conducting spheres, A and B, connected by a rigid radar-transparent rod of length 2*L*, as illustrated in Figure A. The dumbbell is rotating about its center of gravity (CG), which is at a fixed distance from the radar and located a distance L from each sphere, at a rate of ω_r. It is assumed that the radar line of sight (RLOS) is in the tumble plane of the dumbbell. Construct a coordinate system in the tumble plane such that the *y*-axis is aligned with the RLOS and the *x*-axis is perpendicular to this and thus aligned with the cross-range dimension. The angle that the body axis of the dumbbell makes with respect to the *x*-axis varies as a function of time according to the target rotation rate. The apparent slant range of scatterer A, R_A, relative to the target CG is the projection onto the *y*-axis and also varies due to the rotation rate. Similarly, the apparent cross range of the scatterer relative to the target CG, CR_A, is the projection onto the



$$R_A = L\sin(\omega_r t),\quad CR_A = L\cos(\omega_r t)$$

$$\dot{R}_A = \omega_r L\cos(\omega_r t) = \omega_r CR_A$$

$$f_{d-A} = \frac{2\dot{R}_A}{\lambda} = \frac{2\omega_r CR_A}{\lambda}$$

R_A = projection of scatterer A onto *y*-axis
CR_A = projection of scatterer A onto *x*-axis
L = distance of scatterer A from target center of rotation
ω_r = target rotation rate
f_{d-A} = Doppler frequency of scatterer A
θ = angle of target axis from *x*-axis
λ = radar wavelength

Figure A. Doppler processing for dumbbells.

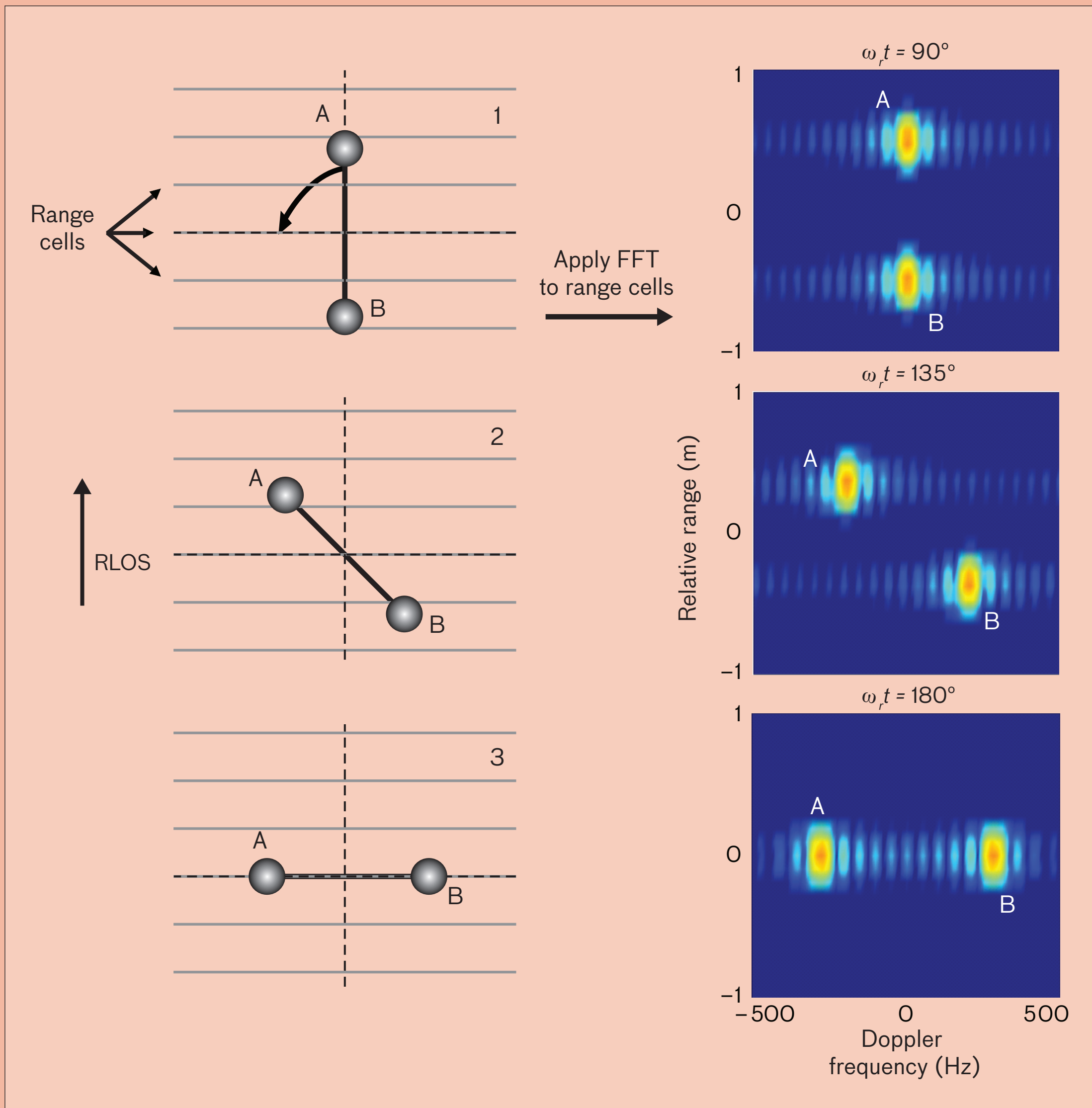


Figure B. Dumbbell range-Doppler images.

x-axis. Range rate about the CG is obtained by taking the time derivative of slant range. Doppler frequency due to motion about the CG is proportional to the target range rate. Substituting for range rate in the Doppler frequency calculation reveals the relationship between cross range and Doppler frequency.

The radar signal received from a more realistic target is a combination of Doppler frequencies from multiple scatterers on the target. By removing the target motion along its trajectory and measuring the Doppler frequencies in the received radar signal, target cross-range information can be obtained. Doppler information is extracted from received signals by using the fast Fourier transform (FFT), which is an efficient implementation of the discrete Fourier transform. The FFT is applied in each range cell of interest across a sequence of pulses to obtain Doppler profiles as a function of relative range, resulting in a range-Doppler image. Figure B shows range-Doppler images of the dumbbell for three orientations: $\omega_r t$ = 90°, 135°, and 180°.

Space Launch

Hundreds of rockets have been launched from Kwajalein Atoll, but until recently the payloads have all been suborbital. Space launch infrastructure is virtually indistinguishable from missile launch infrastructure. Kwajalein has exercised the latter for several decades, and perhaps it was inevitable that a remote equatorial location with existing launch infrastructure would eventually be used for space launch.

In 1992, NASA funded MIT to design the High Energy Transient Explorer (HETE) satellite that would be used to study gamma ray bursts from distant galaxies [17]. The spacecraft had gamma-ray detectors, X-ray imagers, and near-ultraviolet cameras. It was launched from Wallops Island, Virginia, on board a Pegasus XL rocket. Pegasus, a launch system built by the Orbital company, drops a rocket from a modified Lockheed L-1011 airplane to deliver small payloads to low Earth orbit (LEO). Unfortunately, the launch vehicle failed to separate from the spacecraft, dooming the mission.

In 1997, NASA agreed to fund MIT for another satellite that would use spare hardware from the first mission. The original HETE mission was planned for an orbit with an inclination of 38°. Around the time of the original HETE mission, NASA launched another X-ray imager, the Rossi X-ray Timing Explorer, into a 23° inclination orbit, and the Italian Space Agency launched yet another X-ray imager, BeppoSAX, into an equatorial orbit. Data from these satellites revealed that the equatorial orbit was extremely beneficial for instrument sensitivity and longevity because of a more benign electron and proton background. MIT convinced NASA to pay for the added expense of putting HETE-2 into an equatorial orbit.

Despite the flexibility of the Pegasus platform, it had never been used for a low-inclination launch. Because of the extreme amount of fuel needed for inclination changes in LEO, a low-inclination launch to LEO essentially requires a low-latitude launch site. NASA and Orbital chose Kwajalein for the launch site of the HETE-2 mission. The portability of the Pegasus system (essentially, the L-1011 aircraft) and the existing infrastructure on Kwajalein proved to be a very good match.

The HETE-2 spacecraft, aboard a Pegasus XL rocket, was successfully launched on 9 October 2000. To minimize the orbit inclination, the rocket was launched from the L-1011 as far south of Kwajalein as the RTS range safety office would allow, given the coverage of the range instrumentation. The HETE-2 mission was a complete success, and more than 100 papers were written on the data collected by the onboard instruments [17].

Three other successful Pegasus launches were conducted, and Kwajalein remains the only Pegasus launch site for orbit inclinations less than 28° [18]. The Communication/Navigation Outage Forecasting System (C/NOFS) satellite was launched aboard a Pegasus XL rocket on 16 April 2008. The C/NOFS mission is to investigate and forecast ionospheric scintillation. The Interstellar Boundary Explorer, also launched aboard a Pegasus XL rocket, embarked on 19 October 2008 on a mission to investigate the heliosphere by measuring the energetic neutral atoms that are generated by the interaction of solar wind particles with interstellar medium particles. The Nuclear Spectroscopic Telescope Array (NuSTAR), launched on 13 June 2012, is imaging the sky in the X-ray region of the spectrum to study collapsed stars, black holes, and supernovae.

In addition to being well-suited for low-inclination launch, the remote location of Kwajalein is ideal for the early launches of developmental rockets. Space Exploration Technologies (SpaceX) launched their first five rockets from the Kwajalein Atoll [19]. SpaceX was founded in 2002 by Elon Musk, the founder of PayPal, with the goal of reducing the cost of space access by a factor of 10. The SpaceX approach is to build rockets almost entirely in house, including engines, cryogenic tanks, avionics, guidance and control, and ground support equipment. The remote location and unparalleled radar and optics instrumentation at Kwajalein were a perfect match to the completely unproven technology in the first SpaceX rocket, called Falcon 1. SpaceX developed the previously abandoned island of Omelek, on the East Reef of Kwajalein Atoll, into a launch facility for the Falcon 1.

The first three SpaceX missions, launched from Omelek between March 2006 and August 2008, failed to reach orbit. However, a couple of interesting successes on the third mission are worth noting. First, the rocket arrived on Kwajalein via ship on 26 July 2008 and was integrated, rolled out, and launched only seven days later, unheard of agility in the space launch business. Second, prior to the actual launch, the rocket was fired for launch, and the automatic control system detected a fuel temperature anomaly and shut down the engine after a few milliseconds and before liftoff. The fuel temperature was too low, and SpaceX engineers quickly determined that defueling and refueling would sufficiently warm the fuel. The RTS range safety office agreed to this plan, the fuel was taken off and put back on, and the rocket was launched less than an hour after the first firing. This event demonstrates the agility of the SpaceX team and the flexibility of an exceedingly remote launch site.

SpaceX successfully launched a payload mass simulator into the desired orbit on 28 September 2008, less than two months after the third mission. To achieve this aggressive schedule, they purchased a ride for the rocket aboard an Air Force C-17 from Los Angeles International Airport to Kwajalein. The payload simulator is still in the intended orbit of 630 km, 9° inclination.

The fifth SpaceX launch of Falcon 1 successfully carried a Malaysian Earth-imaging satellite, RazakSAT, to the desired orbit of 685 km, 9° inclination (Figure 6). The RazakSAT mission was to provide electro-optical imagery of Malaysia at a much higher cadence than other Earth imagers in more highly inclined orbits [19]. The high revisit rate of the 9° inclination satellite over the equatorial country was intended to combat the ubiquitous cloud cover. Unfortunately, the satellite never worked as intended and all efforts at correcting the problems on orbit were abandoned in December 2010 [20]. This was the first active payload launched into orbit by SpaceX. It was also the last launch of a Falcon 1 rocket as the company shifted focus to the much larger Falcon 9 rocket. It was also the last SpaceX launch from Kwajalein Atoll, as their success gained them access to mainstream continental U.S. launch facilities at Cape Canaveral, Florida, and Vandenberg Air Force Base, California.

Future of Space Launch from Kwajalein Atoll

The success of the launches by Orbital's Pegasus and by SpaceX demonstrated that Kwajalein is well-suited for space launch. The remote location allows range safety flexibility, which is ideal for early launches of new vehicles. The near-equatorial location provides access to low-inclination LEO orbits that are not practical for higher-latitude launch sites, and the rotation of the Earth gives a modest boost to rocket performance for pro-grade orbits.

The remote location is, however, a formidable obstacle in the further development of Kwajalein as a major launch facility. The logistics of launch from the middle of the Pacific are costly and time-consuming. These economics will likely lead to Kwajalein remaining a niche launch facility for low-inclination LEO orbits and developmental rocket programs.

Summary and Future

The RTS space mission is a vital element of the U.S. space surveillance enterprise, and Lincoln Laboratory continues to provide key technical leadership that enables and enhances the rich heritage of this space mission. The KREMS radars, although developed for missile testing, are highly capable space surveillance sensors, and their location enables unique coverage of the GEO belt, early coverage of launches out of Asia, and timely tracking of the increasingly dense LEO regimes.

The MMW system, the highest-resolution satellite-imaging radar in the world, is an underutilized SSN resource. The recent increase in SOI tasking this year is a positive development. However, the potential is greater still. MMW is technically capable of an order of magnitude more image sets. The cost of the increased support is modest and would help satisfy the intense demand for MMW's exquisite imagery. MMW could also be augmented with receive-only antennas, spread appropriately around Kwajalein Atoll, to enable interferometric imaging of satellites. The data from such a multistatic system would enable three-dimensional images of satellites and further increases in imagery throughput.

Another potential area for increased support of the SSN mission is LEO tracking with ALCOR. Since the collision of an Iridium satellite with a Cosmos satellite in 2007, the space tracking community has responded to the very real threat of satellite collisions with increased demand for timely LEO tracking. At RTS, tasking for LEO tracks has increased significantly. Unfortunately, this tasking distracts from the primary deep-space mission of ALTAIR and TRADEX. ALCOR could be used to respond to the LEO tasking, freeing ALTAIR and TRADEX to do their primary deep-space mission.

Automation of RTS space mission activities is another enhancement worthy of consideration. The cost of manning the sensors is relatively modest, but the relevant motivation for automation is increased capacity. With increasing concern for the protection of deep-space satellites, particularly geosynchronous satellites,

FIGURE 6. The launch of Flight 5 of the SpaceX Falcon 1 rocket from Omelek Island on Kwajalein Atoll took place on 13 July 2009. Flight 5 successfully carried the Malaysian Earth-imaging satellite, RazakSAT, to low Earth orbit. The building on the right is the SpaceX final assembly building, a soft-sided tent structure complete with clean room. (Photo courtesy of USAKA/RTS)

the appetite of the SSN for timely radar tracks is acute. Automation could help in several areas. Considerable time is spent tracking geosynchronous clusters, in which multiple satellites are in the radar beam. Automated, parallelized, multi-acceleration, coherent integration algorithms could be implemented on modernized computing platforms to optimally track everything in the beam at once, greatly reducing the time required to track individual objects in clusters. Automation could also enable a more optimal method to track deep-space satellites. Work is ongoing to evaluate other, potentially more efficient, methods.

RTS should continue to invest in net-centric infrastructure as the JSpOC Mission System program modernizes the nation's space enterprise. The RDO and ESSA programs have positioned RTS as a leader in net-centricity. Further work could establish RTS as a pathfinder for how SSN sensors will function in the new paradigm.

RTS will continue to make significant contributions to the space surveillance community. The combination of an unsurpassed sensor suite and a unique location offer great utility to the SSN for geosynchronous surveillance and timely response to tasking in all orbital regimes. The Lincoln Laboratory staff in Kwajalein and those that support RTS in Huntsville, Alabama, and Lexington, Massachusetts, will continue to catalyze technological innovation that is essential for the future success of the space mission at RTS. ■

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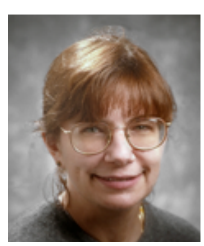

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