The 4 GHz Bandwidth Millimeter-Wave Radar

Justin J. Stambaugh, Roy K. Lee, and William H. Cantrell

The Millimeter-Wave Radar (MMW) on Roi-Namur is the highest resolution, highest metric accuracy radar at the Reagan Test Site on Kwajalein Atoll in the Marshall Islands. Originally designed as a 1 GHz bandwidth Ka- and W-band adjunct to the Advanced Research Projects Agency Lincoln C-band Observables Radar, the original charter for MMW was to provide a database of millimeter-wave signature data of missile reentry phenomenology. MMW has been upgraded several times over nearly 30 years of operations in response to evolving missions and requirements. Most recently, a 4 GHz bandwidth capability (33.0 to 37.0 GHz) was added that improves the radar image resolution to 6 cm, making MMW the highest-resolution coherent instrumentation radar in the world.

》 The landmark construction of the Advanced Research Projects Agency (ARPA)–Lincoln C-band Observables Radar (ALCOR) at Kwajalein Atoll in 1970 sparked significant interest in the ballistic missile defense (BMD) and satellite-identification communities [1]. ALCOR's 50 cm range resolution using 512 MHz bandwidth data confirmed the viability of valuable new BMD discrimination techniques and provided invaluable intelligence information to the space community. The revolutionary wideband range-Doppler images of satellites provided by ALCOR stoked a desire within the satellite-identification community for more and higher-resolution data. In addition, there was a strong need to image the increasing number of highly valuable satellites in the geosynchronous belt. In 1978, the Haystack Long-Range Imaging Radar (LRIR) was completed at Millstone Hill in Westford, Massachusetts, with a 1 GHz bandwidth X-band capability to image satellites with 25 cm range resolution at up to 40,000 km range [2]. It was the early success of ALCOR and LRIR that led to the next generation of higher-frequency wideband radars.

Meanwhile in the BMD community, there was growing interest in gathering wideband signature data of reentry vehicles (RV) at millimeter wavelengths to better quantify the potential performance of millimeter-wave seekers on interceptors. The prospect of building a 35 GHz radar with sufficient sensitivity to collect useful RV data was unprecedented. Even if such a radar could be built, its beamwidth would be miniscule, posing a significant challenge to target acquisition. In 1979, Lincoln Laboratory solidified plans for a Ka- and W-band ALCOR-adjunct radar that would take advantage of accu-
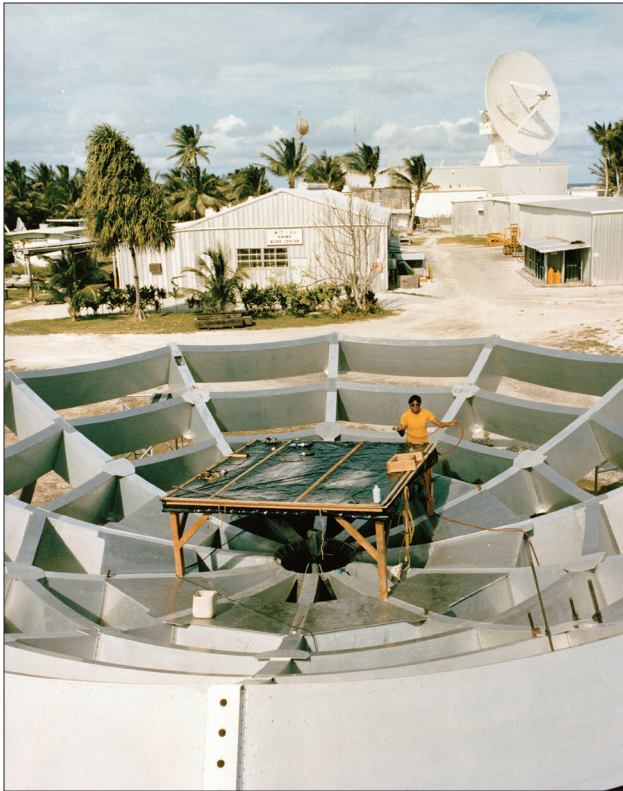
FIGURE 1. In 1983, the Millimeter-Wave Radar (MMW) was installed on Roi-Namur. Here, the radar is in place with initial components of the dome and antenna assembled.

rate pointing vectors from ALCOR and enable collection of the desired signature data. The Millimeter-Wave Radar moved from concept to construction in the early 1980s.

The Millimeter-Wave Radar

In order to manufacture a radar capable of creating a database of millimeter-wave signature data of reentry phenomenology, several technological advances were required. Among these were a high-power, 35 GHz traveling wave tube and a dish antenna with surface tolerance, size, and rigidity to exceed 70 dB gain (one-way) at millimeter wavelengths.

ESSCO Corporation (now L-3 Communications ESSCO) was selected to complete a design for a 45 ft Cassegrain antenna with a surface tolerance of 0.1 mm, which was required for the W-band application. Figure 1 shows two photographs of the antenna during construction. The antenna is composed of 72 reflector panels fabricated from 0.040-inch-thick aluminum shaped into segments of a 200-inch focal length parabola. The 3.6 ft diameter subreflector is fitted with a cone-shaped conducting wedge at the center to reduce the amount of

power reflected from the transmitter directly into the receiver. The antenna sits on a pedestal such that the antenna center is 65 ft above ground level; this height puts the radar above many local obstructions and trees and enables it to accurately track targets to very low elevation angles. In total, the antenna with subreflector and azimuth and elevation mounts weighs nearly 160,000 lb. Figure 2 is a photograph of the radar as it appears today.

By 1980, engineers at Varian Corporation had submitted a design for a novel 35 GHz traveling wave tube (TWT) with 1 GHz bandwidth (25 cm range-resolution, similar to Haystack LRIR) and 25 kW peak power to serve as the high-power amplifier. A photograph of the VTA-5700 tube is shown in Figure 3. Although MMW was built to have its own transmitter and an antenna that was 5 ft larger than ALCOR's, MMW was initially designed as a true ALCOR adjunct—meaning the radars would not be able to independently track different objects; and if one was in track, the other would be slaved to that track.

In 1983, MMW demonstrated initial operational capability (IOC) with a live Ka-band reentry track. By 1985, W band was operational, also with 1 GHz bandwidth.

FIGURE 2. MMW is enclosed in a new Gore-Tex® dome, which eliminates many of the issues associated with weather-related reductions in sensitivity.

MMW began performing space-object identification (SOI) tasking, and by 1988, it was providing the U.S. Air Force Space Command with nearly 60 satellite image sets per year [3]. New demands to collect even higher-resolution data on objects at longer ranges, independent of ALCOR and other sensors, provided the incentive for upgrading MMW. Significant advances in real-time processing, high-power TWT design, and radio-frequency (RF) feed design were necessary to meet the increasingly stringent requirements. By 1990, MMW was in the midst of a series of upgrades that, at completion, doubled its range resolution and nearly quadrupled its tracking range [4, 5].

MMW Upgrades

At IOC, MMW sensitivity was significantly limited by the computing technology available in the early 1980s. The radar was not capable of processing all of the RF pulses it was receiving for its real-time tracker. It was also not able to efficiently phase-align the pulses for coherent integration or perform noncoherent integration on sets of coherently integrated pulses.

From 1988 to 1994, a series of improvements to the digital processing software and hardware more than doubled the tracking range of the radar. First, a new Kalman ballistic tracking filter was implemented, improving the range estimation of the system and hence improving the radar's ability to align received pulses over long time periods for increased integration gain. At the same time, a capability to post-sum (noncoherently integrate sets of coherently integrated pulses) was added, further improving sensitivity. A year later, advances in pulse processing enabled the radar to use all pulses (up to 2000 per second) in the track loop; this capability further improved sensitivity by allowing all the energy being received to help keep the target in track. Finally, a pulse preprocessor was installed in 1994, further enhancing the coherent integration capabilities of the radar and providing a further enhancement to tracking range. Although advances in digital processing provided the largest sensitivity gains, ongoing hardware improvements provided further sensitivity gains and enabled 2 GHz bandwidth and higher range resolution.

As the central piece of the MMW upgrade to higher range resolution, a new 2 GHz bandwidth high-power amplifier tube was needed. The existing tubes were only capable of 1 GHz bandwidth, and no higher bandwidth tubes were available. Lincoln Laboratory challenged the tube manufacturers to develop a 2 GHz bandwidth tube capable of 50 kW peak power.

FIGURE 3. MMW required a high-power, high-frequency traveling-wave-tube amplifier. VTA-5700 tubes, similar to the one shown, were used from 1983 to 1991.

In response, the new VTA-5701 35 GHz HPA TWT was designed for MMW by Varian. First installed in 1991, the tube produced up to 50 kW peak power at 2 GHz instantaneous bandwidth at 10% maximum duty cycle, thereby increasing the sensitivity of the radar by 3 dB. However, before the new tube could be utilized, significant changes to the feed were needed.

The VTA-5701 tubes produced twice the power of the previous tubes, and the long rectangular waveguide used to transmit the power to the antenna significantly attenuated that power, converting it into heat. The increased heat load doubled the waveguide cooling requirements and put a significant strain on the system. A drastic redesign of the feed structure was necessary to realize the benefits of the higher-power tubes.

Lincoln Laboratory designed a novel quasi-optical beam waveguide technology to replace the legacy rectangular waveguide feed. The quasi-optical design was installed in the early 1990s. It dramatically decreased waveguide transmission loss and enabled two-tube power combining on transmit with bandwidths up to 2 GHz [6, 7]. Figure 4 is a drawing of the MMW beam waveguide system.

In 1993, the Haystack Auxiliary Radar (HAX) in Massachusetts became the first radar to track with 2 GHz bandwidth waveforms, using a quasi-optical beam waveguide design leveraged from MMW. MMW 2 GHz bandwidth waveforms were made operational in 1995, following a receiver, software, and RF signal generator upgrade. With an independent tracking system and similar tracking range to ALCOR, MMW had become a self-sufficient and capable system, no longer a mere ALCOR augmentation.

In the late 1990s, it became clear that the radars on Roi-Namur needed to be modernized to take advantage of revolutionary advances in computer hardware technology and digital equipment. Lincoln Laboratory developed a program through which the radar hardware was replaced with common commercial off-the-shelf (COTS) hardware and a common system design, to the greatest practical extent. The modernized hardware was complemented by common modern software and operator displays. This new system architecture became known as the Radar Open System Architecture (ROSA) [8]. Figure 5 shows the MMW ROSA equipment located in the ALCOR building on Roi-Namur. The sensor control was also remoted,
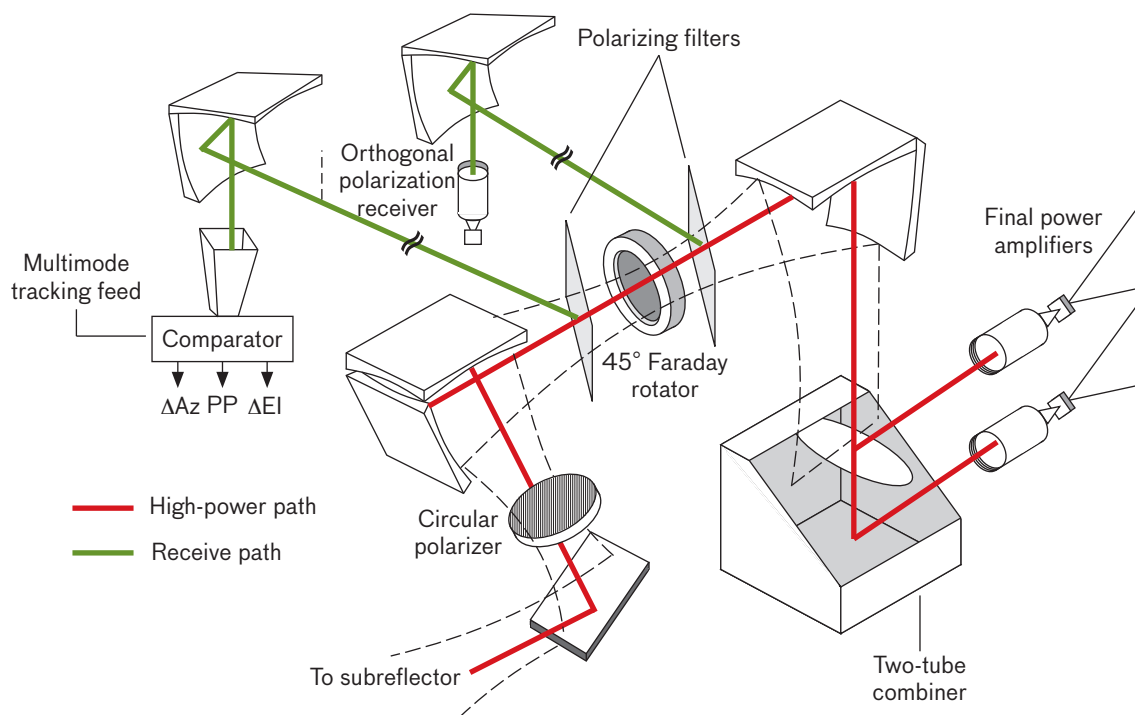
FIGURE 4. The new quasi-optical beam waveguide configuration replaced a conventional legacy waveguide feed. This improvement enabled wider bandwidth, higher power, and greater sensitivity by eliminating the loss and dispersion of the legacy feed. (Adapted from Figure 20 in [6].)

FIGURE 5. The ROSA hardware is shown as installed for MMW.

with ALCOR, ALTAIR, MMW, and TRADEX radars all being controlled from Kwajalein Island. The overall program was called Kwajalein Modernization and Remoting (KMAR), and MMW was the second sensor to be completed (after ALCOR) in 2000.

By the early 2000s, it was clear that MMW required an update to many of its critical hardware components. The radome leaked during rain showers, and the leaks endangered many of the expensive one-of-a-kind transmitter, receiver, and feed components. In addition, MMW encountered a series of incidents in which critical mission data could not be collected because the radome exterior remained wet for more than 15 minutes after rain cells had passed (35 GHz radiation is strongly absorbed by liquid water). It was decided to replace the original MMW radome (a W-band optimized ESSCOLAM® material) with a new Ka-band optimized Gore-Tex® material that

would reduce RF loss and dry quickly after a rain shower. The radome was replaced in 2003, and the upgrade provided a 2 dB increase in radar sensitivity. This upgrade significantly reduced radar down time, with the radome drying within a few minutes after a shower. Figure 6 is a photograph of MMW during the radome replacement.

With the turn of the millennium, rapid advances in computer processing speeds and miniaturization made it affordable for almost any nation to put very capable satellites into orbit with payloads smaller than 50 cm in size. The ongoing evolution to smaller payloads and the need for higher-fidelity images on larger payloads motivated a further upgrade to MMW. Radar imagery with better than 10 cm resolution is helpful in characterizing newer satellites. At the same time, several MMW components were becoming obsolete and a refresh was necessary to keep the radar operational.

FIGURE 6. The MMW radome was replaced with Gore-Tex® material to help eliminate issues related to water absorption. The image shows MMW undergoing radome replacement in 2003.

A Revolution in Resolution: The 4 GHz Bandwidth Radar

Initiated in 2005 by the U.S. Army Ronald Reagan Ballistic Missile Defense Test Site (RTS) and managed by Lincoln Laboratory, a project to double the bandwidth and the sensitivity of MMW involved the design and fabrication of a new 4 GHz bandwidth transmitter tube, an enhanced receiver, and a Laboratory custom-designed upgrade to the RF feed. The new hardware provided an increase in average transmit power and a reduction in receiver noise that nearly doubled the tracking range of MMW. A project to upgrade the data processing hardware and to utilize ROSA II (an advanced version of the original ROSA software) running on modern computers doubled the data throughput of the radar, providing a capability to capture ultrahigh-resolution 4 GHz bandwidth imaging data on objects as large as 60 m.

By 2010, MMW was in the midst of an upgrade that would ultimately culminate in doubling both the bandwidth and the tracking range of the radar.

Transmitter Upgrade

By 2000, new VTA-5701 tubes were significantly less reliable and produced less than half the power of the original VTA-5701 tubes from the mid-1990s. MMW was operating with a limited number of spares, and the manufacturer was having difficulty making new ones. A redesign and prototyping effort was initiated with Communications and Power Industries (CPI) to develop a new model (VTA-5701C) that could reliably sustain operations into the future. The radar was reconfigured to operate in single-tube mode in an effort to conserve the remaining tube stock until the new tubes were built.

To enable an increase in duty factor from 15% to 20%, the MMW high-voltage regulator was replaced in 2008. The new VTA-5701C tube, shown in Figure 7, achieved IOC in March 2011. Table 1 shows key performance parameters for the three Ka-band tubes that have been used in MMW. When the new VTA-5701C tube was installed, it provided an average sensitivity increase of more than 4 dB, compared to the legacy VTA-5701 that was in use prior to the upgrade. A second VTA-5701C tube was made operational in July 2011, and two more tubes are in production. The AC power feed was also upgraded with a 1 MVA transformer in July 2012, increasing the power-handling capacity of the radar. The Faraday rotator in the beam waveguide was upgraded in August 2012. Because MMW is now capable of combining two VTA-5701C tubes at full output power, an additional 3 dB increase in sensitivity is achieved. The additional tubes added to the inventory have enabled an increase in MMW SOI tasking. As more tubes are delivered, SOI tasking may continue to increase.

Receiver and Transmit Signal Generating Circuitry

To take advantage of the 4 GHz bandwidth capability of the new transmitter tubes, much of the RF circuitry in MMW had to be redesigned. New 33–37 GHz linear frequency-modulated (LFM) chirps were required to drive the transmitter amplifiers. The receiver hardware also needed to be redesigned to achieve 4 GHz bandwidth. A chirp-doubling design (whereby two successive 2 GHz chirps are used to create the desired 4 GHz chirp) was implemented by reusing the existing waveform generators; this reuse minimized cost and risk to the project. Figure 8 shows a simplified block diagram of the transmit waveform generating hardware, and Figure 9 shows

| Table 1. Ka-band transmitter high-power amplifier tube performance				
	VTA-5700	VTA-5701 (original specification)	VTA-5701 (in use, January 2011)	VTA-5701C
Peak power (kW)	25	50	15	30
Bandwidth (GHz)	1	2	2	4
Expected lifetime (filament hours)	1000	2000	2000	3000

a simplified block diagram of the receiver. The receiver front end was redesigned with 4 GHz bandwidth components, including new low-noise amplifiers (LNA). This redesign significantly reduced receiver noise and improved radar sensitivity by more than 2 dB.

RF Feed

Some of MMW's beam waveguide components required upgrades to handle the wider bandwidth and the increase in average power. In particular, the original "Venetian blind" circular polarizer design was limited to less than the 11% fractional bandwidth necessary for 4 GHz operation. The circular polarizer serves a dual purpose in the radar. On transmit, it changes the linearly polarized radiation exiting the transmit horns into circular polarization; on receive, it turns the mix of left- and right-hand circular polarization into a corresponding mix of horizontal and vertical linear polarizations that are filtered into principal polarization (PP) and orthogonal polarization (OP) signals. PP and OP returns provide valuable target characterization information, and the PP/OP isolation is the main indicator of radar performance in effectively measuring these signals. A new circular polarizer, shown in Figure 10, was fabricated and installed, leveraging the conductor/dielectric waffle-pattern design of the HAX circular polarizer. The new polarizer performs at a 12% fractional bandwidth.

The Faraday rotator was also redesigned to handle the increased average power from the new transmitter tubes. It is a key component in the quasi-optical feed, and it isolates the receiver from the transmitter. Although the original Faraday rotator was designed to handle up to 10 kW average power, it suffered from excessive heating and was ineffective above 8 kW. Even at lower power levels, unwanted reflections from the legacy Faraday rotator sent a significant amount of
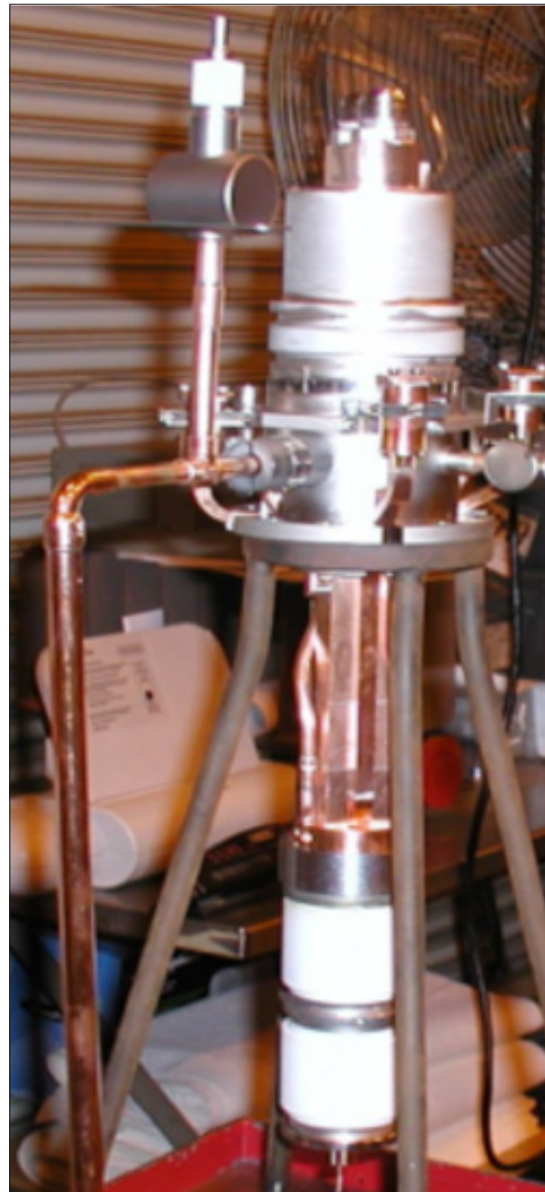
FIGURE 7. The VTA-5701C transmitter tube is shown with its external cover removed. It replaced the obsolete VTA-5701 and enabled 4 GHz bandwidth operations.
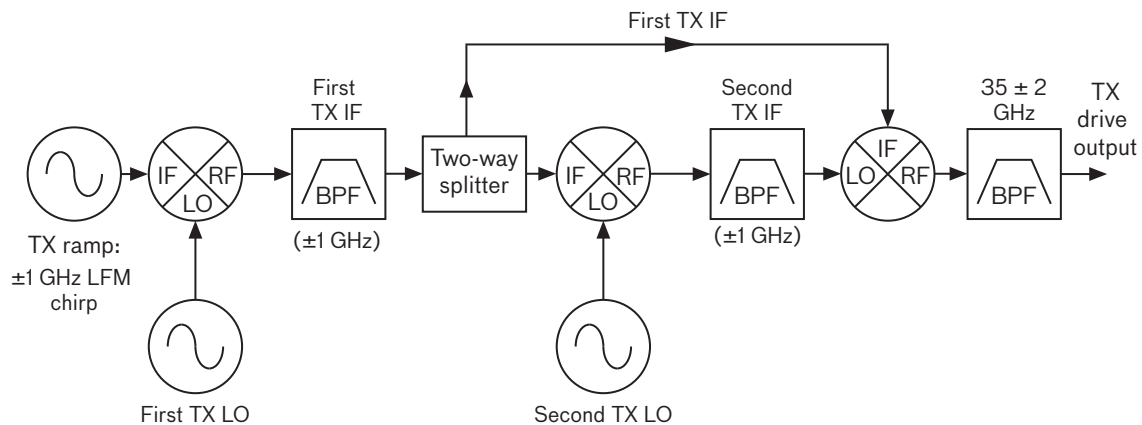
FIGURE 8. This simplified block diagram of the new 4 GHz bandwidth transmit waveform generation hardware shows how the 4 GHz waveform is generated on its way to the transmitter. The 4 GHz chirp at the output (right edge of the diagram) is made by mixing two 2 GHz chirps that originate from the same source. In this figure and in Figure 9, TX stands for transmit, IF is intermediate frequency, RF is radio frequency, LO is a local oscillator, BPF is a band-pass filter, and LNA is a low-noise amplifier.
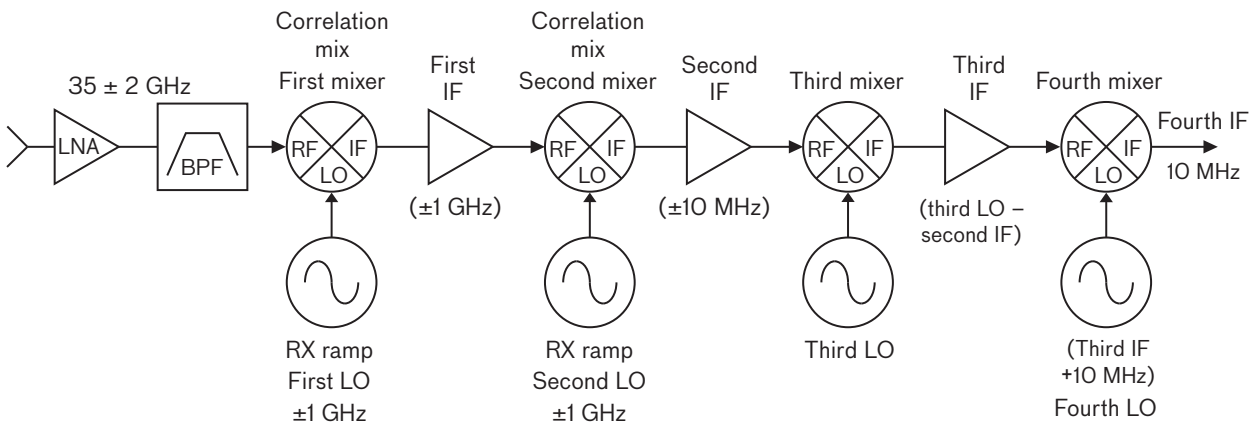
FIGURE 9. This simplified block diagram of the new receiver lineup shows how a 4 GHz received signal passes through the two correlation mixer stages and the two additional down-conversions prior to digitization at 10 MHz.

transmit energy directly into the OP receive channel and decreased its reliability. A new Faraday rotator was fabricated that allows the radar to radiate the full power by using two VTA-5701C tubes. The new Faraday rotator, shown in Figure 11, was designed to minimize coupling between the transmit and receive channels and to provide a factor of 7 improvement in thermal performance, resulting in greater reliability at high power levels. The new Faraday rotator was installed and made operational in August 2012. The MMW high-power Faraday rotator design can be used as a model for future upgrades at HAX and other radars.

Digital Processing Hardware and Software

In 2009, the MMW digital pulse compression subsystem (DPCS) was upgraded to replace obsolete KMAR components and facilitate future improvements to the radar. The new DPCS was capable of increased data throughput over the legacy system, but this advantage could not be realized without an upgrade to the aging 1990s main radar computer. The upgrade to this computer, which was completed in June 2012, provided significant performance improvements.

The original SGI Origin 2000 computers that were installed at the RTS radars as part of KMAR are now
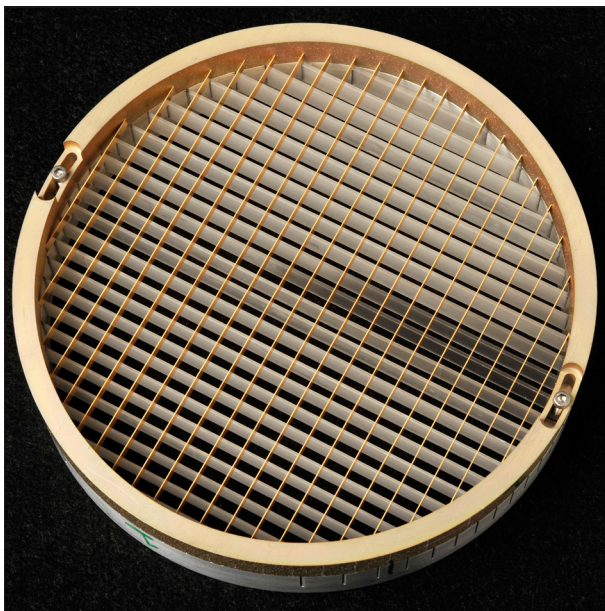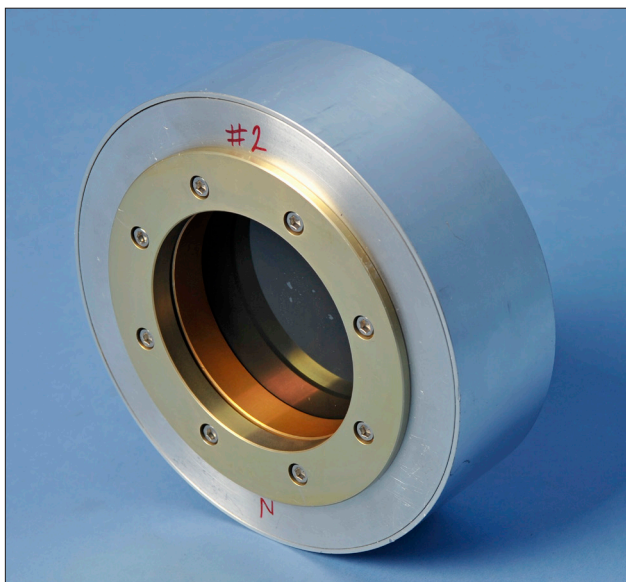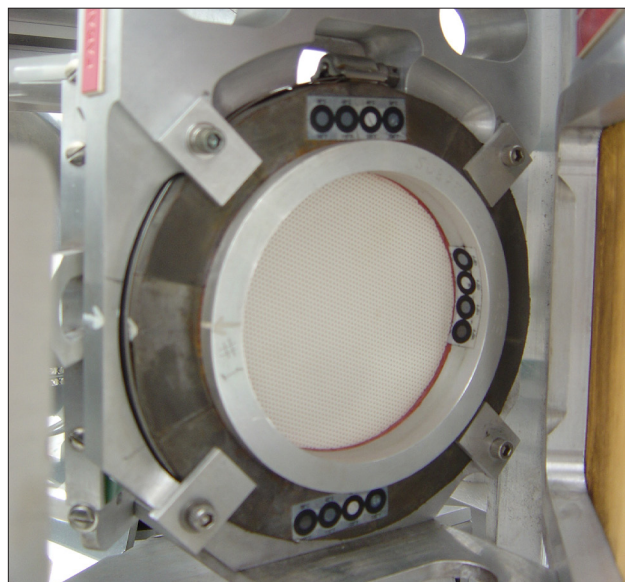
(a)

(b)

FIGURE 10. The new circular polarizer (a) was installed in MMW in March 2010. This significantly improved principal polarization/orthogonal polarization (PP/OP) isolation and increased the beam waveguide bandwidth to 4 GHz. The legacy circular polarizer (b) was leveraged from an earlier Haystack Auxiliary Radar (HAX) design.

(a)

(b)

FIGURE 11. The new Faraday rotator (a) was installed in MMW in August 2012. The upgraded rotator improves radar reliability and enables operations at full power with two VTA-5701C tubes. The legacy Faraday rotator is shown in (b).

at the end of their lives. They are no longer supported by the vendor and have become more difficult to maintain and repair. Performance with the 4 GHz bandwidth waveforms is also an issue; because of Origin 2000 processing constraints, the recorded range window of the 4 GHz waveform was limited to 37.5 m, of which only returns in the center 18 m could be displayed and tracked in real time.

As part of the effort to replace the main radar computer, the radar software was also upgraded to ROSA II. Figure 12 is a conceptual diagram of the ROSA II software architecture which makes use of "building blocks" to develop a full suite of applications [8]. ROSA II software is written in modern object-oriented languages and is designed to eliminate platform dependence, making future software and hardware refresh projects much less costly [9, 10]. In addition to the flexibility afforded by the ROSA II design, the new main radar computer hardware provides a significant boost in processing power. In July 2011, the new computer demonstrated tracking at full PRF with 4 GHz bandwidth

waveforms and performed live tracking of a test mission and several satellites, including the space shuttle Atlantis during the final flight in the shuttle program.

System Performance

The result of the recent series of upgrades is a remarkable improvement in nearly all system-level performance parameters. Table 2 lists the system specifications of MMW at significant points in its history (above the columns are simulated images of a satellite for each resolution). Between 2008 and 2012, the maximum bandwidth and tracking range of the radar were doubled. The tracking range window has more than tripled. PP/OP isolation was improved by 16 dB, and the range sidelobe level was improved by 13 dB. For the first time in its history, MMW is the highest bandwidth coherent instrumentation radar in the world. Figure 13 shows the history of satellite imaging radar range resolution and simulated images of a 60 cm satellite versus bandwidth utilizing double-bandwidth extrapolation processing. The impressive improvement in image quality is evident,
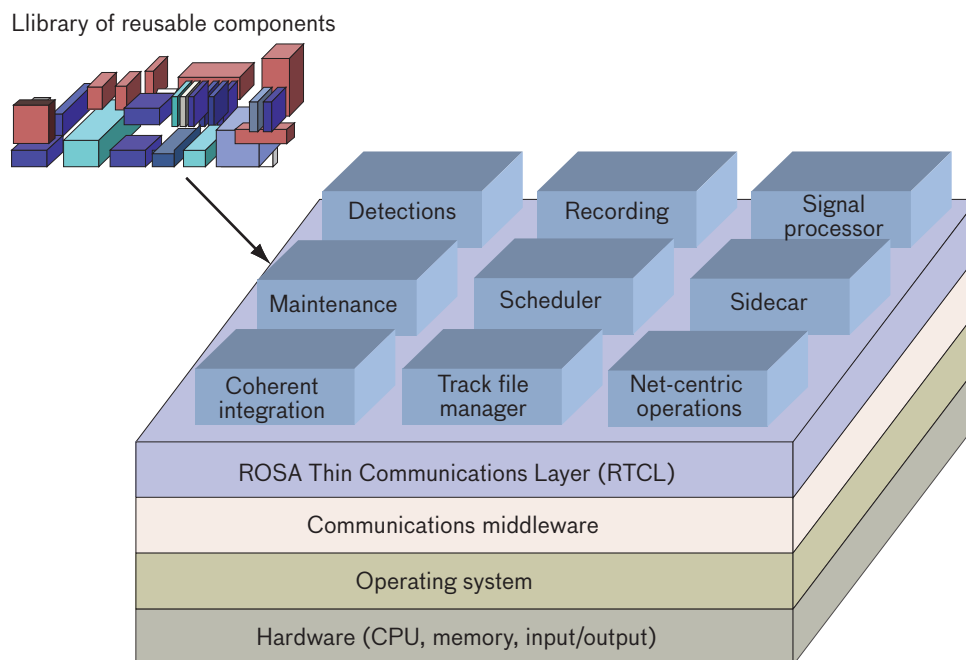
FIGURE 12. The Real-Time Open System Architecture II (ROSA II) software allows developers to quickly produce analytical packages and graphical displays specific to each radar system. Individual components of ROSA II can be added to the base package as needed.

providing a detailed picture of the satellite structure. A long-standing trend of the wideband radar's maximum bandwidth doubling roughly once per decade is also evident in the figure.

Put in perspective against the initial proposal for a "millimeter-wave ALCOR adjunct" radar, the current capabilities are even more impressive. In addition to the total improvement from 1 GHz to 4 GHz maximum bandwidth, Figure 14 illustrates that the tracking range of the radar has increased by nearly an order of magnitude.

Path Forward

Several additional enhancements to MMW are in the planning stages. An inexpensive RF design for bandwidth expansion to 5 GHz (32.5 to 37.5 GHz) has been drafted, with further study required to determine the bandwidth limitations of the current transmitter TWT. The vast majority of the recently installed 4 GHz bandwidth components are designed to function over 5 GHz bandwidth. At 5 GHz, the fractional bandwidth of the radar is 14%, and significant technological advances would be required to achieve higher bandwidth at Ka band.

The recent radar hardware upgrades that enabled 4 GHz bandwidth have stretched the limits of the radar single-pulse sensitivity to the edge of what is potentially feasible without major additional financial investments. Near-term, the most achievable means of improving radar sensitivity and performance is in improvements to data processing algorithms. Work is ongoing to implement improvements to tracking and integration for increased tracking accuracy and sensitivity; these efforts are part of a larger initiative to automate RTS operations.
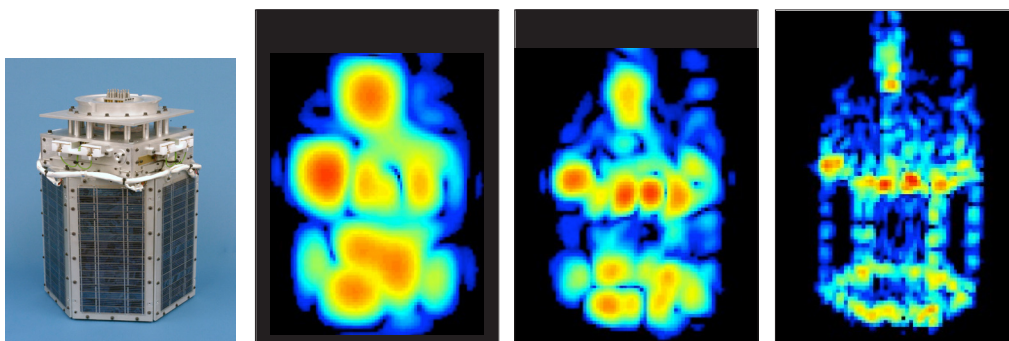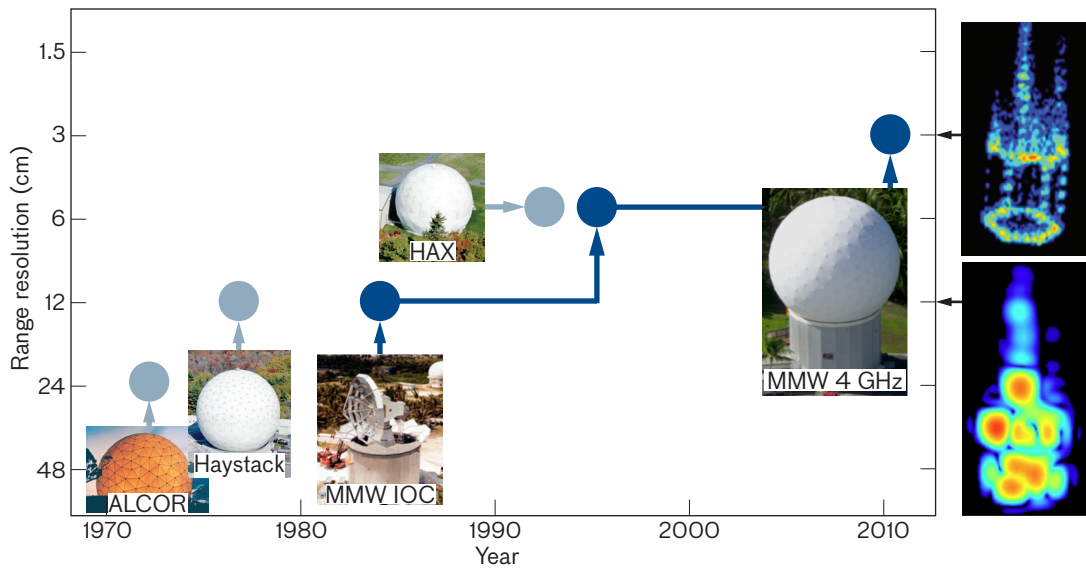
Table 2. System specifications of MMW at notable points in its history			
Year	1983 (IOC)	2008 (prior to 4 GHz upgrade)	2012
Maximum bandwidth (GHz)	1	2	4
Range resolution (cm)	25	12	6

FIGURE 13. Evolution of satellite imaging radar resolution utilizing double-bandwidth extrapolation processing. Simulated range-Doppler images of a 60 cm satellite are shown for comparison, also utilizing double-bandwidth extrapolation processing.
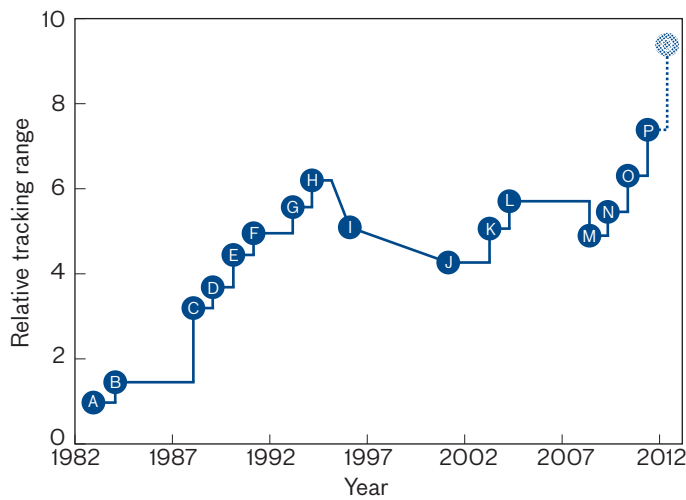
FIGURE 14. The history of MMW tracking range is matched with relevant event markers, assuming a 0.1 s coherent integration time.

A. Initial operation capability
B. Receiver and transmitter improvements
C. Post-sum noncoherent integration and
    ballistic track filter
D. Full-PRF tracking
E. Beam waveguide
F. VTA-5701 transmitter tube
G. Dual-tube combining
H. Preprocessor integration
I. Receiver problems
J. Tube production quality problems,
    single-tube operations
K. Dual-tube operations restored
L. Gore-Tex® radome
M. Single-tube operations
N. 100 μs pulse operations
O. Improved low-noise amplifiers and
    receiver redesign
P. VTA-5701C transmitter tube
Q. Dual-tube operations, RF path
    improvements (potential)

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William H. Cantrell is a member of the technical staff in the Tactical Defense Systems Group. While at Kwajalein, he was the RF architect of the MMW Bandwidth Expansion and Sensitivity Improvement Project. He conceived, designed, tested, and implemented all new RF circuitry and new receivers for the radar, which doubled the bandwidth and improved sensitivity by more than 2 dB. Before joining Lincoln Laboratory, he was an adjunct assistant professor of electrical engineering at the University of Texas at Arlington and a distinguished member of the technical staff at Motorola, where he designed radio communications products for 25 years. He is a Senior Member of the IEEE, is a reviewer for the IEEE Microwave Theory and Techniques Society (MTT-S), and has authored one book chapter and five journal and conference papers. He has given several invited lectures and half-day tutorials and has served as the 2006 AdCom Secretary for the MTT-S. He received bachelor's and master's degrees in electrical engineering from Texas A&M University (Bolton Scholar) and a doctorate from the University of Texas at Arlington (University Scholar). His current research interests include novel RF and receiver architectures.