The HUSIR W-Band Transmitter

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The HUSIR transmitter leverages technologies developed for diverse applications, such as plasma fusion, space instrumentation, and materials science, and combines them to create what is, to our knowledge, the most advanced millimeter-wave radar transmitter in the world. Overall, the design goals of the HUSIR transmitter were met in terms of power and bandwidth, and the images collected by HUSIR have validated the performance of the transmitter system regarding phase characteristics. At the time of this publication, the transmitter has logged more than 4500 hours of trouble-free operation, demonstrating the robustness of its design.

» **The Haystack Ultrawideband Satellite Imaging Radar** (HUSIR) operates at a frequency three times higher than and at a bandwidth twice as wide as those of any other radar contributing to the U.S. Space Surveillance Network. Novel transmitter techniques employed to achieve HUSIR's 92–100 GHz bandwidth include a gallium arsenide amplifier, a first-of-its-kind gyrotron traveling-wave tube (gyro-TWT), the high-power combination of gyro-TWT/klystron hybrids, and overmoded waveguide transmission lines in a multiplexed deep-space test bed.

Transmitter Technology

A radar transmitter is simply a high-power microwave amplifier. Nevertheless, as part of a radar system, it is second only to the antenna in terms of its cost and complexity [1]. The HUSIR transmitter was developed on two complementary paths. The first, funded by the U.S. Air Force, involved the development of a novel vacuum electron device (VED) or "tube"; the second, funded by the Defense Advanced Research Projects Agency (DARPA), leveraged an existing VED design to implement a novel multiplexed transmitter architecture. The former effort yielded a full-bandwidth, one-kilowatt peak-transmit-power capability, which is operational in HUSIR. The latter effort experimentally validated a more complex high-power capability suitable for deep-space operations, but its completion was deferred to a future upgrade to the system. Both systems were housed in a facility, shown in Figure 1, that was sized to accommodate the fully populated deep-space transmitter.

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FIGURE 1. Construction of the 10,000-square-foot HUSIR transmitter equipment shelter took place in 2005. High-voltage modulators and VEDs occupy the ground floor; waveguide, combiners, and multiplexers occupy the mezzanine level. The floor area and positioning of the vertical columns were dictated by the need to keep up to 17 superconducting magnets at least two meters away from each other and from the nearest column.

Table 1. Parameter Definitions

PARAMETER	HUSIR REQUIREMENT
Center frequency	96 GHz
Instantaneous bandwidth	8 GHz
Pulse-repetition frequency	40–4000 pulses/sec
Pulse width	50–1000 μsec
Peak power at flange(s)	500 W nominal
Duty factor	40% maximum
Other losses to feed	1.4 dB nominal

Many of the enabling technologies for the HUSIR transmitter, such as gyrotrons and overmoded waveguide transmission lines, were first developed for W-band plasma heating in nuclear-fusion test beds. The needs of HUSIR in comparison to those of plasma heating are that the radio-frequency (RF) power must be phase coherent and much wider in instantaneous bandwidth. The comparatively lower power requirements permit the use of air-filled waveguide transmission lines rather than the evacuated lines necessary for avoiding arcs in megawatt-level systems. The HUSIR transmitter requirements are highlighted in Table 1.

System Architecture

The transmitter architecture comprises a full-bandwidth, medium-power VED as the driver-power capability with a multiplexed, combined array of partial-bandwidth, high-power VEDs as the high-power or deep-space capability. In its current state, HUSIR is limited to low-Earth-orbit (LEO) satellite observations. Discussion of the deep-space test bed is deferred to the end of this article.

The block diagram of the as-built HUSIR transmitter is shown in Figure 2. A 250 MHz linear-frequency-modulated (LFM) waveform centered at 3 GHz is multiplied

and then amplified to approximately 600 mW in a solid-state gallium arsenide (GaAs) amplifier. This initial step is followed by the gyro-TWT amplifier, which serves as the final power amplifier in the operational radar. The electromagnetic mode at the gyro-TWT output is then converted into a mode that is suitable for feeding the HUSIR reflector antenna. The gyro-TWT electron beam is powered from a 30 kV pulsed-power system comprising a direct-current (DC) power supply, capacitor bank, and floating-deck modulating-anode pulser.

Solid-State Power Amplifier

The solid-state power amplifier, shown in Figure 3, was realized by combining the output of multiple GaAs monolithic microwave integrated circuit (MMIC) devices. The MMIC devices were developed by Northrop Grumman [2]. The National Aeronautics and Space Administration's Jet Propulsion Laboratory integrated these devices as power amplifiers to drive multiplier chains for the Heterodyne Instrument for the Far Infrared spectrometer launched aboard the Herschel Space Observatory in 2009 [3]. HUSIR used devices left over from this effort.

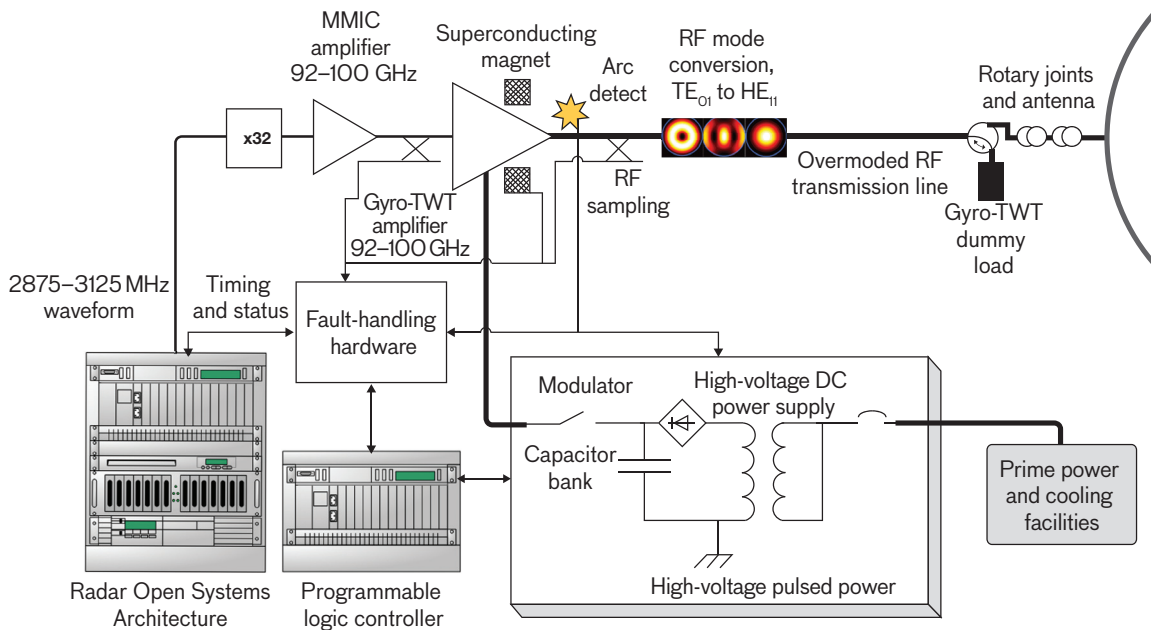Initially, two MMIC devices were combined to

FIGURE 2. Configuration of the as-built HUSIR W-band transmitter system. A frequency-multiplied wideband waveform undergoes two stages of amplification: the first in a solid-state GaAs amplifier and the second in a gyro-TWT amplifier pulsed by a solid-state high-voltage modulator. The high-power output undergoes mode conversion and is transmitted approximately 100 meters to the feed in an overmoded corrugated waveguide transmission line.

achieve approximately 240 mW from the preamplifier. When initial tests of the gyro-TWT revealed that its gain was less than expected, a more capable preamplifier that combined four GaAs MMICs to produce approximately 600 mW across the 92–100 GHz band was fabricated. To our knowledge, this output is the highest power demonstrated over that bandwidth generated from GaAs. Subsequently, W-band gallium nitride devices, which may be a more cost-effective and efficient solution than the current HUSIR system, have become available.

Gyrotron Amplifiers

A gyrotron is a VED or "tube" that employs an intense magnetic field to "gyrate" the electrons in a beam so that they follow a helical path through the tube. This gyration arises from the Lorentz force accelerating the electrons axially via the electric field and rotationally via the magnetic field, and efficiently couples the electrons to electromagnetic field patterns or "modes" in the tube with components transverse to the direction of propagation (along the axis of the tube). The electrons are emitted from a heated thermionic cathode along the axis of the tube, as is the case with many conventional tubes;
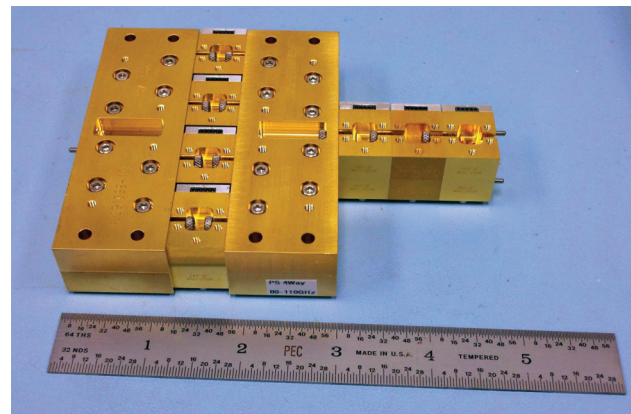

FIGURE 3. The solid-state predriver amplifier combines the output of four monolithic microwave integrated circuit (MMIC) devices in a WR-10 waveguide.
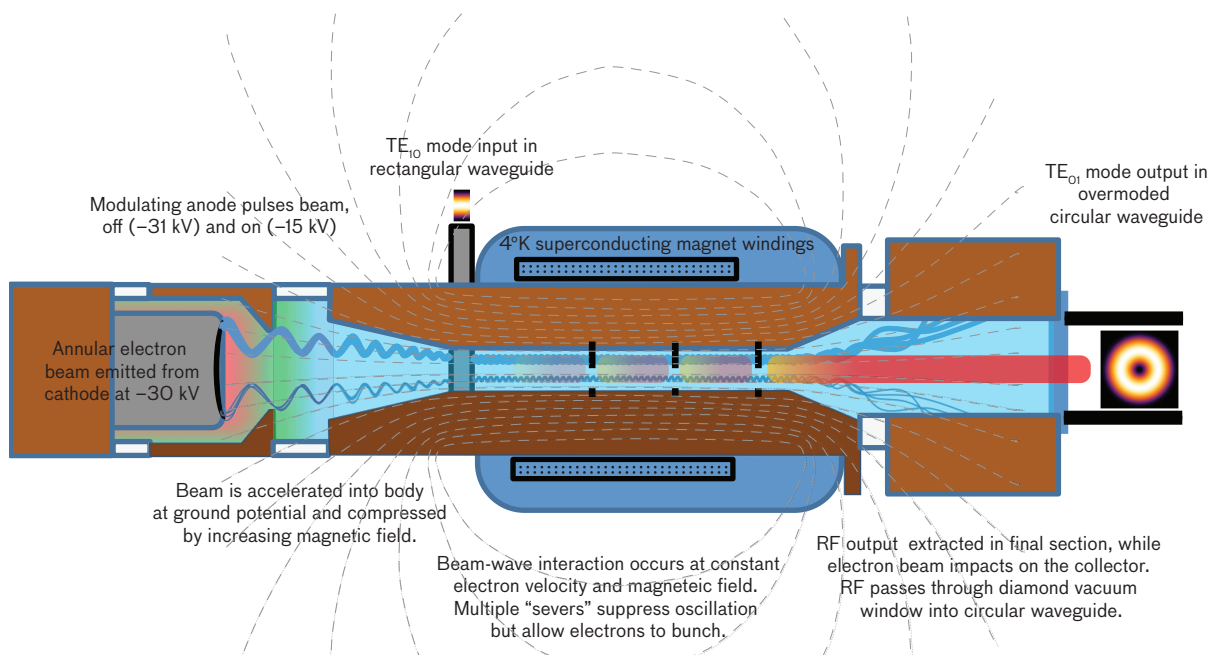
Modulating anode pulses beam,
off (−31 kV) and on (−15 kV)

TE$_{10}$ mode input in
rectangular waveguide

TE$_{01}$ mode output in
overmoded
circular waveguide

4°K superconducting magnet windings

Annular electron
beam emitted from
cathode at −30 kV

Beam is accelerated into body
at ground potential and compressed
by increasing magnetic field.

Beam-wave interaction occurs at constant
electron velocity and magneteic field.
Multiple "severs" suppress oscillation
but allow electrons to bunch.

RF output extracted in final section, while
electron beam impacts on the collector.
RF passes through diamond vacuum
window into circular waveguide.

FIGURE 4. The components of the gyrotron are shown with an overlay of the magnetic field lines produced by the superconducting magnets. Images of the shape of the electromagnetic beam are shown at the entry to the regions (rectangular waveguide) and at the exit from the electron dissipation regions (circular TE$_{01}$ mode). The latter beam feeds into the circular corrugated waveguide that converts it to the near-lossless HE$_{11}$ mode.

however, the electrons encounter sufficiently high axial fields that their paths become primarily circular, as in a cyclotron. Figure 4 is a depiction of the layout of the components of the gyrotron and the corresponding electron bunching and dissipation geometry.

The 3.4 Tesla magnetic field is adjusted so that electrons orbit at a frequency near the HUSIR frequency-band center. This "cyclotron resonance" is intimately dependent on the relativistic mass of the electron, which is perturbed through mass-energy equivalence by interactions with the input RF field. These perturbations, as with other tubes, cause the electrons to bunch together so that RF energy can be extracted at high power from the electron beam at the tube output. In the case of a gyrotron, however, the bunching of the electrons is not axial but occurs in their rotational phase. To further optimize efficiency, the beam radius is set to occur at the peak field location of the TE$_{01}$ mode in the cylindrical waveguide making up the tube's beam-wave interaction circuit.

In summary, the gyrotron shapes an azimuthally bunched electron beam pattern to excite a low-loss electromagnetic mode in a simple smooth-walled RF waveguide. The simple internal geometry of the gyrotron, large beam-to-body clearances, and control of the electron beam via an external magnet yield a VED that is capable of very high output power at millimeter wavelengths with reasonable manufacturing tolerances.

GYRO-TWT AMPLIFIER

The 1 kW final power amplifier in HUSIR is a gyro-TWT manufactuerd by CPI [4]. This gyrotron, shown in Figure 5, has multiple traveling-wave sections separated with high-loss sections to damp out oscillations while progressively bunching the electrons in such a way that high RF power is extracted in the last traveling-wave section. The circular waveguide then tapers to a 0.8-inch diameter and the electrons follow magnetic field lines to impinge on this last waveguide section, which also serves as the spent-beam collector. Magnet fields are adjusted to spread this impact over a sufficiently large area to minimize localized heating, ensuring a long operational lifetime for the gyro-TWT. The RF output exits the gyro-TWT through a chemical-vapor-deposited diamond vacuum window and enters the waveguide. Diamond was selected to simultaneously minimize heating via RF losses and maximize heat conduction, resulting in high reliability.
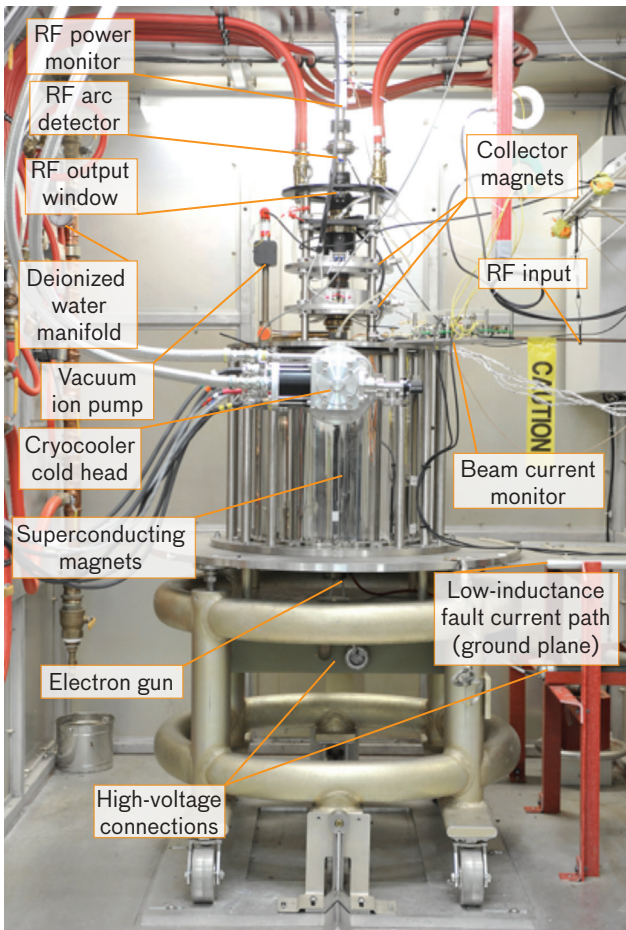
FIGURE 5. The gyro-TWT amplifier is shown mounted in its superconducting magnet. The gyro-TWT itself extends from the electron gun to the RF output window and is almost entirely obscured by the magnets. The gyro-TWT and magnet are mounted on a wheeled cart whose ample spacing and rounded contours inhibit corona discharge at the 30 kV operating voltage and minimize stray capacitance (and thereby the energy of any high-voltage arc in the tube).

The gyro-TWT is immersed in an adjustable ~3.4 Tesla field produced by a cryogenically cooled niobium-titanium (NbTi) superconducting magnet manufactured by Cryomagnetics, Inc. This superconducting magnet (see sidebar) has two main solenoid coils that permit the field strength to be tapered along the interaction circuit of the gyro-TWT. Three other coils enable steering of the electron beam to minimize impact with the body of the tube, and permit adjustment of the helical pitch of the electron trajectory, which strongly influences gain.

The operation of the gyro-TWT requires a highly uniform field to obtain good RF performance with low

Table 2. HUSIR Waveguide Summary

WAVEGUIDE	MAIN PROPAGAT-ING MODE	W-BAND LOSS (dB/ft)
WR-10 rectangular		0.78
WR-28 rectangular		0.17
0.8-inch-diameter circular		0.0020
1.284-inch-diameter corrugated circular		0.00048
1.25-inch-diameter corrugated circular		0.00091
2.5-inch-diameter corrugated circular		0.00024

*All listed waveguide types are overmoded (that is, they support multiple modes in addition to the intended one) at W band except for WR-10.

beam intercept by the interaction circuit. The field in the circuit is uniform to less than 0.25% and has a maximum transverse component of less than 0.15%. This transverse field requirement led to magnet-magnet and magnet-column distances of greater than 2 meters—the primary factor driving the size for the layout of the equipment shelter. Each magnet was tested extensively with Hall-effect sensors in precision fixtures to verify the alignment of the magnetic field.

RF Transmission

A variety of waveguide geometries are utilized in the HUSIR transmission line (see Table 2 and Figure 6), including rectangular, smooth-walled cylindrical, and corrugated cylindrical. The HUSIR corrugated waveguide, illustrated in Figure 6, was manufactured by General Atomics [5]. The waveguide is fabricated exclusively as a straight length; mirrors are used to obtain right-angle bends where necessary.

The inputs to the amplifiers all require the use of the fundamental TE_{10} rectangular mode in WR-10 waveguides. The high-energy electron beam in the gyrotrons is designed to amplify the signal in the TE_{01} circular waveguide mode. Following amplification, the RF output is transitioned to the HE_{11} mode in the corrugated

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Basics of Superconducting Magnets

Superconductivity represents a phase change in which electrons become bound into pairs. These "Cooper pairs" are not subject to the Pauli exclusion principle; thus, all charge carriers in a superconductor can mutually enter a minimum-energy quantum "ground" state that exhibits many unique properties, one of which is zero DC resistance. HUSIR magnets employ windings that become superconducting below a transition temperature T_c at which the DC winding resistance is zero (9.3 K in the case of niobium-titanium (NbTi), reduced to ~7 K at full field). The gyro-TWT magnet has more than 8000 turns in each of the two main solenoid coils. The NbTi wire is clad with copper to provide thermal and electrical control if superconductivity is lost during a "quench" (i.e., the undesired transition back to the normal conducting state,

initiated at some location in the windings) that rapidly spreads throughout the magnet as the ~30 kJ of energy stored in the magnet field are thermalized in the windings. Generally, this quench occurs only when a magnet is first energized after transport or storage. The coils are contained in a vacuum cryostat with a two-stage Gifford-McMahon cycle cryocooler having a first-stage temperature of 35 K and a second-stage temperature of 3.3 K. The cryocooler is a closed-cycle refrigerator so no liquid helium is employed. The first stage is tied to a radiative shield in the cryostat, while the second stage is thermally coupled to the magnet windings. The magnet is maintained at its operating temperature continuously and only returned to room temperature for cryocooler maintenance.

FIGURE 6. On the left is the W-band single-mode rectangular waveguide WR-10 (TE_{01} mode). Center and right are the 1.25-inch- and 2.5-inch-diameter corrugated waveguides (HE_{11} mode).
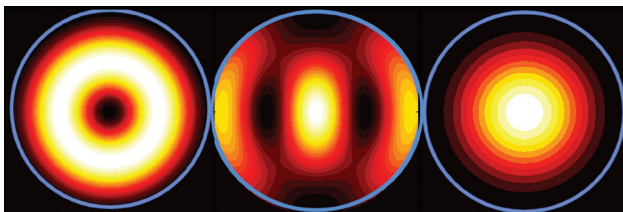

FIGURE 7. The evolution of TE_{01} mode to HE_{11} mode within a cylindrical waveguide is shown left to right as RF passes through the mode converter. The low loss of the HE_{11} mode is associated with the absence of RF fields at the waveguide walls.

waveguide for efficient, low-loss propagation with linear polarization.

HE_{11} mode is of particular utility because it has a near-Gaussian beam cross section, simplifying the feed design for the HUSIR antenna, and it propagates with near-zero loss in a corrugated waveguide. In addition, as Figure 7 illustrates, it can be readily created from the TE_{01} mode of the gyrotron amplifiers without suffering significant losses.

Losses in the waveguide transmission line come primarily from mode conversion at the mirrors. The overall loss from all components, including mode conversion, RF transmission, rotary joints, diplexers, and polarizers is less than 2 dB over a distance of roughly 100 meters from the gyro-TWT to the antenna feed. This loss is remarkably low at W band, highlighting the effectiveness of the corrugated waveguides as a transmission medium.

Solid-State Transmitter System

HUSIR's W-band transmitter was the first newly constructed one at the Lincoln Space Surveillance Complex
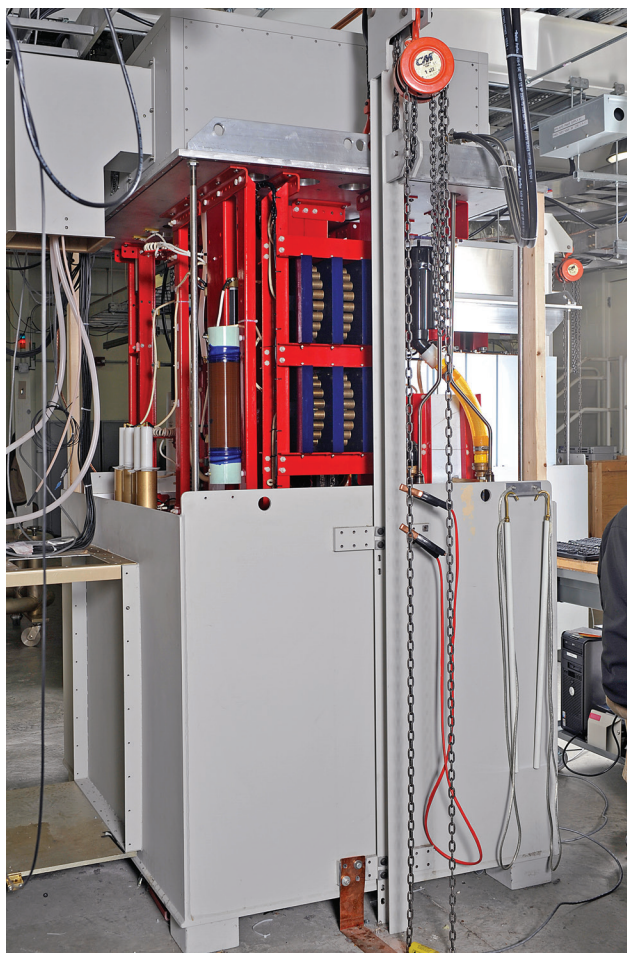
FIGURE 8. (a) The solid-state modulator is shown raised from its insulating oil tank. The insulated-gate bipolar transistors on- and off-deck switches are visible as the blue assemblies. (b) The capacitor bank is shown raised from its insulating oil tank.

in 20 years. Many technological advances were incorporated into its design.

Advances in state-of-the-art insulated-gate bipolar transistors (IGBT) permitted an all-solid-state implementation of the transmitter. Diversified Technologies, Inc. (DTI) was the contractor selected to build the high-voltage electronics and controls [6]. The gyro-TWT system comprises a 35 kV, 50 kW, high-voltage power supply; a 15-microfarad capacitor bank; a floating cathode-referenced pulse modulator; and both programmable logic and hardwired control systems. The modulator is configured as a modulating-anode pulser to match the electrode configuration of the gyrotrons; however, the beam switches are implemented as a series of connected IGBTs

rather than as VEDs, as used on earlier transmitters [1].

Each IGBT stands off a fraction of the voltage drop from each other, and proprietary techniques are used by DTI to ensure that a switch does not suffer a cascading failure of IGBTs. Additionally, there is no "crowbar" in HUSIR to de-energize the capacitor bank in the event of a VED fault; instead, an IGBT switch is placed between the bank and the VED to de-energize it within a few microseconds of an arcing or other fault. The transmitter system is modular, with the modulator and capacitor bank integrated into stand-alone insulating oil tanks, as shown in Figures 8a and 8b. Controls, fault sensing, and high-voltage power are integrated in standard 19-inch equipment racks (see Figure 9).

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FIGURE 9. The gyro-TWT high-voltage supply and system electronics. The helium compressor at the right forms half the cryocooler, along with the cold head mounted in the magnet cryostat seen in Figure 5.

Table 3. HUSIR Transmitter Demonstrated Performance

PARAMETER	HUSIR DEMONSTRATED
Center frequency	96 GHz
Instantaneous bandwidth	8 GHz
Pulse-repetition frequency	40–4000 pulses/sec
Pulse width	50–1000 msec
Duty factor	40% maximum
Peak power	1 kW nominal
Other losses to feed	1.8 dB nominal

Looking Forward

Demonstrated performance of the as-built transmitter and the deep-space test bed are summarized in Table 3. This table highlights many months of experimental demonstrations, during which each element of the radar sensitivity budget was validated.

The completion of the multiplexed high-power transmitter remains the baseline option for extending HUSIR operations to the ~40,000 km range suitable for geosynchronous satellites. Nevertheless, all-solid-state architectures enabled by continuing improvements in W-band GaN power-amplifier technology remain under consideration. In the long run, an all-solid-state transmitter may offer lower lifecycle cost than for a VED transmitter. The facility infrastructure at HUSIR supports deployment of either option.

Acknowledgments

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ABOUT THE AUTHORS

Michael E. MacDonald is a staff member in the Aerospace Sensor Technology Group at Lincoln Laboratory. He led the design, construction, and testing of the HUSIR transmitter. His work is focused on radar systems technology, including associated power and thermal infrastructure. He received a bachelor's degree in electrical engineering from Northeastern University and a doctoral degree in electrical engineering from the University of Colorado at Boulder.

James P. Anderson was a member of the technical staff in the Aerospace Sensor Technology Group from 2004 through 2013. During this time, he helped develop a variety of advanced radar concepts, from multistatic approaches intended for deep-space searches to high-frequency phased arrays. The primary project he worked on in the group was HUSIR, for which his main role was integrating the W-band transmitter system, including the gyrotron amplifier, low-loss transmission line, and antenna feed. He received a bachelor's degree from the University of Wisconsin–Madison, a master's degree from the University of Maryland at College Park, and a doctoral degree from MIT, all in electrical engineering. He is currently working on nuclear fusion technology at General Atomics in San Diego, California.

Roy K. Lee was a member of the technical staff in the Aerospace Sensor Technology Group from 2003 to 2013. He received a bachelor's degree in physics from the California Institute of Technology and a doctoral degree in physics from the University of California–Irvine, and was a postdoctoral researcher at Harvard University before joining Lincoln Laboratory in 2003. He has worked on wideband satellite imaging radars, first at HUSIR, where he developed and demonstrated a technique for high-power frequency multiplexing of W-band gyro-twystron amplifiers and later at the Millimeter-Wave Radar at Kwajalein in the Marshall Islands, where he fabricated and tested new beam waveguide components to handle the higher power levels and wider bandwidths associated with the bandwidth upgrade program. He has also played a key advisory role on the U.S. Air Force Three-Dimensional Expeditionary Long-Range Radar acquisition program, which seeks to replace a legacy ground-based radar with a modern radar with improved performance. Recently, he has studied the role and utility of multistatic radar systems for space surveillance.

David A. Gordon is a supervisor in the Aerospace Sensor Technology Group. He worked on the development of HUSIR and the improvement of radar subsystems in general. He received a bachelor's degree from Northeastern University in computer engineering and an associate degree in electrical engineering from Wentworth Institute of Technology. Prior to joining Lincoln Laboratory in 2012, he worked in industry as an RF/millimeter-wave engineer for Millitech, Millivision, and Steinbrecher and Associates.

G. Neal McGrew is a research engineer working at Haystack Observatory. He currently serves as one of the transmitter engineers for the various radars on Millstone Hill. After serving in the Marine Corps, he worked for GTE at Kwajalein in the Marshall Islands as part of a team to install the ALTAIR (Advanced Research Projects Agency Long-range Tracking and Illumination Radar) transmitter. For the last 28 years, he has been assigned to Lincoln Laboratory's Aerospace Division. He was a part of the teams that developed the Haystack Auxiliary, Cobra Gemini, and HUSIR radars, as well as a member of the Radar Open Systems Architecture development team. He received a bachelor's degree in technical management from New Hampshire College.