A Terrestrial Air Link for Evaluating Dual-Polarization Techniques in Satellite Communications

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■ This article describes the radio frequency design and test data for an experimental terrestrial air link, which simulates a satellite-to-ground communications link operating in a dual-polarization frequency-reuse mode in the 17.7-to-21.2-GHz band. The terrestrial air link comprises a transmit site located on Mount Pack Monadnock in Temple, New Hampshire, and a receive site 42.2 km away in Westford, Massachusetts. The transmit site uses a 1.8-m-diameter dish, and the receive site uses an 18.3-m-diameter dish enclosed by a 28.4-m-diameter air-supported radome. The terrestrial air link provides a test bed for evaluating atmospheric effects of fading and scintillation, along with amplitude, phase, and polarization distortion that can compromise the performance of satellite-to-ground communications systems. The test data indicate that the terrestrial air link has a high degree of cross-polarization isolation under clear-air conditions and is well suited for evaluating dual-polarization frequency-reuse techniques.

As the information age explodes, so does the demand for high-volume, high-data-rate satellite-to-ground communications links. High data rates in the gigabits-per-second range require large radio frequency (RF) bandwidths on the order of gigahertz. The availability of such large bandwidths, however, is extremely limited. The lower end of the RF spectrum, up to several gigahertz, is crowded with commercial and government traffic, and large contiguous bandwidths have not been allocated for satellite communications. Wider bandwidths are available at higher frequencies of several tens of gigahertz, but signals transmitted in this range suffer atmospheric effects that can limit the performance of satellite-to-ground communications.

In a trade-off between bandwidth and performance, the 17.7-to-20.2-GHz commercial band was merged with the 20.2-to-21.2-GHz government band to produce the 3.5-GHz Kt band. Like the wider bandwidths available at higher frequencies, the Kt band suffers atmospheric effects, but to a lesser extent. To meet the demand for high-data-rate satellite communications links, any portion of the Kt band can be doubled by reusing frequencies on different polarizations—a technique known as frequency reuse. A dual-polarization frequency reuse (DPFR) scheme simultaneously transmits two independent data streams, often using left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP) [1–5].

The performance of a DPFR link, or any satellite-communications link for that matter, can be compromised by hardware effects and common atmospheric phenomena, as shown in Figure 1. Electromagnetic

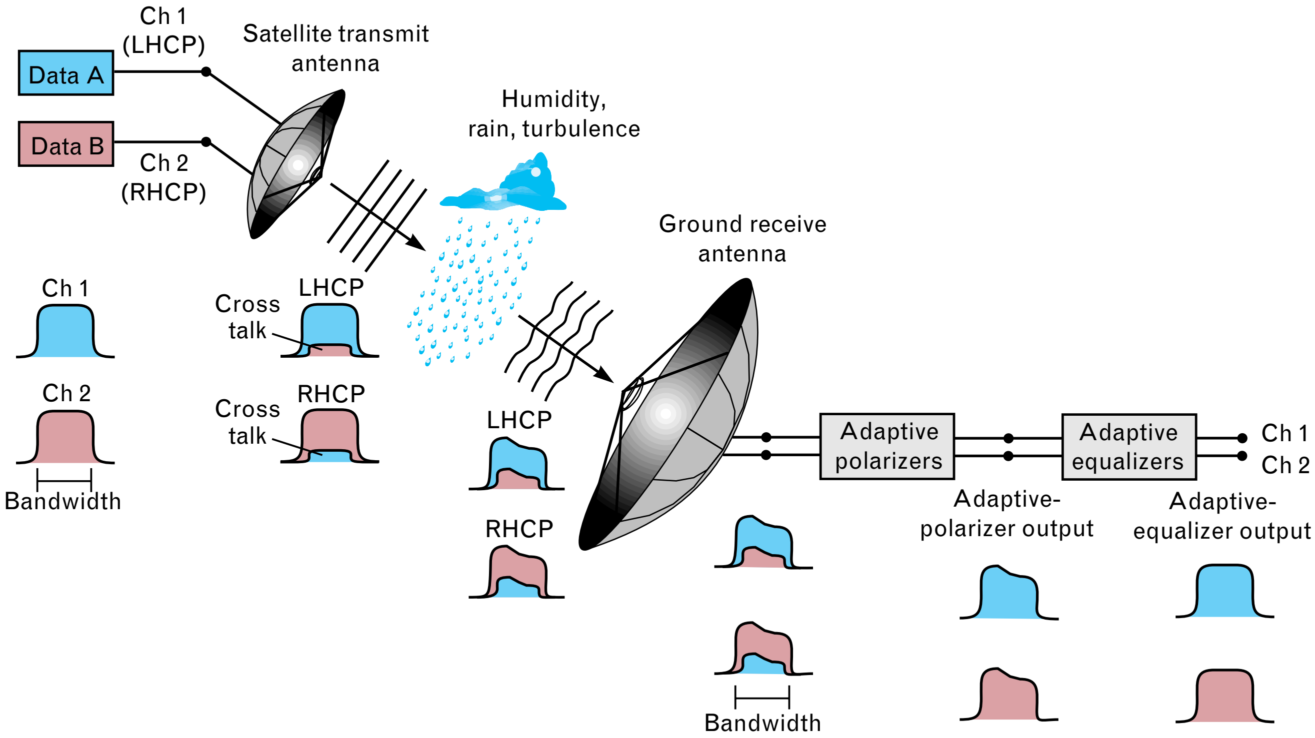

FIGURE 1. The process of satellite-to-ground dual-polarization frequency-reuse communications. A satellite dish antenna transmits independent data streams A and B on channels 1 and 2, respectively. The data streams share a common frequency range. The satellite transmit antenna produces nearly independent left-hand circularly polarized (LHCP) and right-hand circularly polarized (RHCP) electromagnetic waves. Because of normal physical tolerance limitations and hardware imperfections of the transmit antenna, a small amount of contamination, or cross talk, occurs between the LHCP and RHCP transmitted signals. Thus a portion of data stream A appears on the RHCP channel and a portion of data stream B appears on the LHCP channel. As the LHCP and RHCP waves propagate through the humid, rainy, and turbulent atmosphere, they experience attenuation, phase shift, and depolarization. Consequently, the frequency spectrum of the signals reaching the receive antenna contains some amplitude and phase distortion and increased cross talk between the LHCP and RHCP components. Real-time adaptive polarizers reduce the signal-polarization cross talk, and adaptive equalizers restore a flat amplitude and phase response over the communications band.

waves propagating through the atmosphere can be depolarized, attenuated, and phase shifted. Because scientists are still working to understand atmospheric effects on signal phase, this article will discuss only attenuation and depolarization. Depolarization converts a portion of a signal with a particular polarization to a different polarization. For example, when an RHCP wave is depolarized, a small amount of RHCP wave energy is transferred into LHCP wave energy. In this case, the desired polarization (RHCP) is called the co-polarization and the undesired polarization (LHCP) is called the cross-polarization.

Depolarization poses a special problem to the DPFR communications link by creating signal cross talk between channels. Cross talk is undesired signal in a communications channel in the same frequency band as the desired signal, and depends on the isolation between two polarizations at the output of the receiving antenna. The cross-polarization isolation—the ratio of power levels of the desired co-polarization signal to the undesired cross-polarization signal—is a benchmark for quantifying the performance of a DPFR link. (Another common expression for this benchmark is cross-polarization discrimination.)

To improve the capability of DPFR systems, scientists are researching techniques that compensate for the atmospheric effects on dual-polarized communications signals. For example, an adaptive polarizer can reduce atmospheric-induced polarization cross talk in real time [1, 3, 6], as shown in Figure 1.

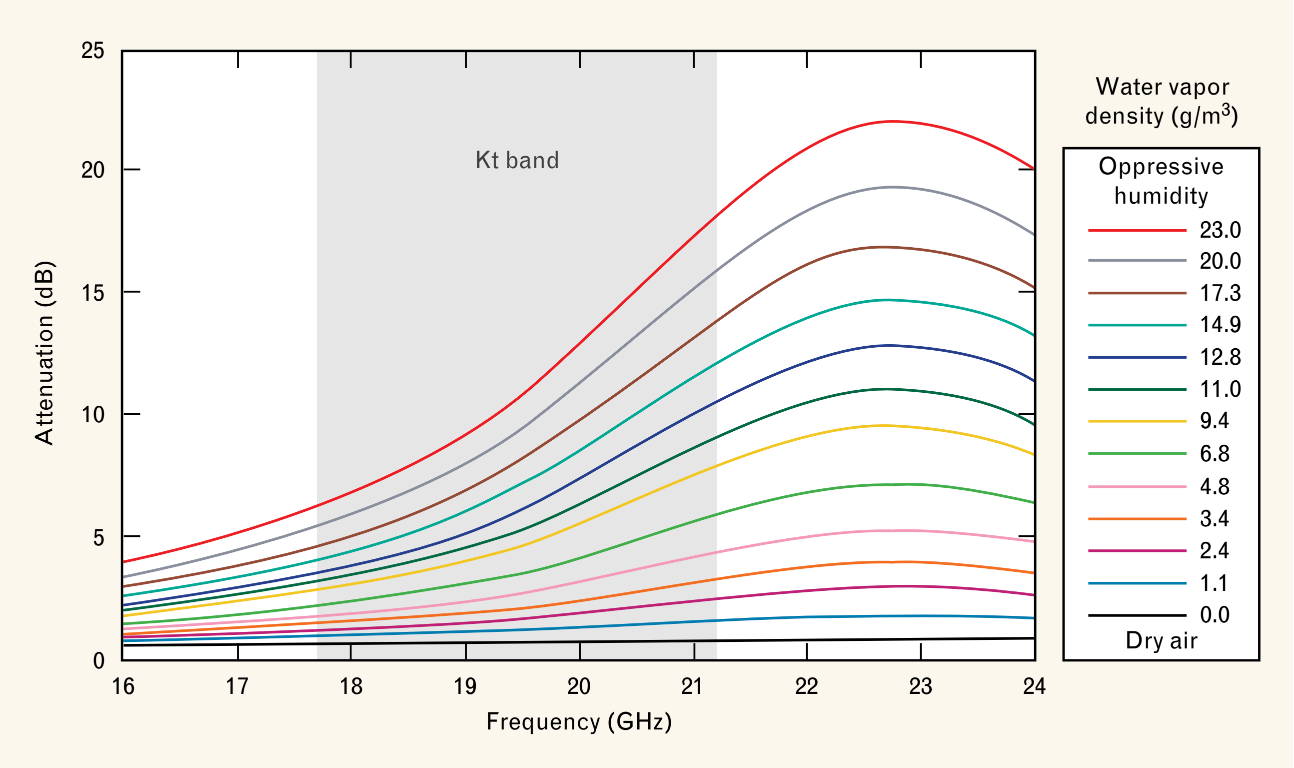

FIGURE 2. Calculated attenuation of electromagnetic waves over a 42.2-km terrestrial air link for a range of water vapor densities. The resonance frequency of water vapor contributes to a substantial tilt in attenuation at higher frequencies during humid conditions.

Attenuation and depolarization effects, which tend to be additive, stem from the presence of water vapor and rain in the atmosphere and atmospheric refraction of electromagnetic waves. At frequencies near 20 GHz, water vapor—and to a small degree oxygen—attenuate microwave signals by molecular absorption. Water vapor dominates the attenuation because it has a resonance frequency just above 22 GHz. The close proximity of the Kt band to this absorption resonance causes a tilt in the attenuation over the frequency band such that signals propagating through the atmosphere at 21.2 GHz have a higher attenuation than signals at 17.7 GHz. The attenuation tilt depends on the atmospheric humidity, with the effect more pronounced as humidity increases. The Kt-band tilt on a hot, humid summer day in New England, as shown in Figure 2, can be on the order of 5 to 10 dB higher than that observed on a clear, dry day.

The presence of rain in the atmosphere and on the surface of the radome protecting the ground terminal antenna affects the performance of a communications link. Shaped by gravity and aerodynamic forces, falling raindrops produce an anisotropic propagation medium for electromagnetic waves. Water droplets in drizzle and fog tend to be spherically shaped symmetrical scatterers that attenuate the propagating wave but usually cause no depolarization. Larger raindrops, however, generally take on a flattened shape, indented on the bottom and raised on the top. This lack of spherical symmetry produces significant depolarization, which increases when the raindrops share the same orientation, or canting angle, as described in Figure 3 [4, 7, 8]. The raindrop canting angle is a function of the local wind velocity. In addition, as the rain rate increases, raindrop size tends to increase; hence attenuation and depolarization also increase.

When rain falls over portions of the terrestrial air link, large variations in received signal power can be expected, depending on the rain rate and the diameter of the rain event, or cell. As the rain rate varies from 10 to 100 mm/hr, the average rain cell diameter varies from about 5 km to 2 km. Figure 4 shows that

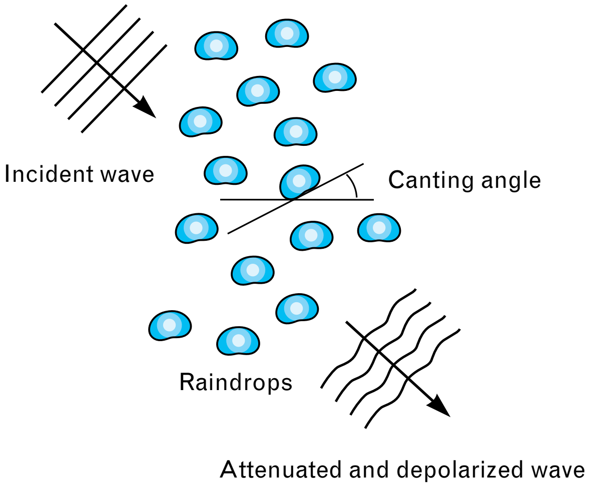

FIGURE 3. Raindrops falling through the air form nonspherical shapes that attenuate and depolarize an electromagnetic wave. Larger raindrops and a heavier rain rate increase signal attenuation and depolarization. Depolarization also increases when the raindrops share the same orientation, or canting angle, which is a function of the local wind velocity.

for a moderate rain condition of 10 mm/hr, the rain-induced co-polarization attenuation at 20 GHz is approximately 4 dB and the cross-polarization isolation is approximately 24 dB [2, 7, 9, 10]. For an intense rain rate of 100 mm/hr, the approximate co-polarization attenuation and cross-polarization isolation values are 22 dB and 10 dB, respectively. At rain rates above 100 mm/hr, the combination of high co-polarization attenuation and low cross-polarization isolation can render a DPFR link inoperable.

The possible distributions for rainfall on a ground terminal radome—droplets, rivulets, and thin water films [11, 12]—attenuate electromagnetic waves, as shown in Figure 5. Droplets and rivulets, which cause attenuations of about 2 dB, form on a hydrophobic (water shedding) surface such as a freshly waxed car even under heavy rain conditions. On a nonhydrophobic surface such as a radome, the water tends to form a thin film even during light rain, which typically attenuates 20-GHz waves by 5 dB or more. A loss of 5 dB corresponds to a water-film thickness on the radome of about one-tenth of a millimeter. Figure 6 shows how the co-polarization attenuation increases with increasing water-film thickness. Significant wave depolarization occurs for rivulets, large non-spherical droplets, and thin water films. These depolarization effects have yet to be adequately quantified, a goal of the terrestrial air link program.

Electromagnetic waves propagating through the atmosphere are also bent by refraction toward the densest part of the atmosphere, which generally occurs nearer the earth because air density normally increases with decreasing altitude. Consequently, the propagation path of electromagnetic waves is bent toward the earth. If the atmosphere is stable, the refraction effects can be compensated for by using a small pointing correction of the receive antenna. Under turbulent conditions, however, such as those created by thermal gradients and high levels of humidity, refraction effects become dynamic and the electromagnetic wave changes its direction of propagation. These turbulent conditions commonly occur during mid-morning hours, when the atmosphere is warmed by the sun and dew evaporates from the ground, creating thermal drafts of water vapor. The random wave bending requires beam tracking to avoid significant signal fades. The beam-tracking function keeps the main beam of the receive antenna pointed at the correct angle of incidence for the received signal.

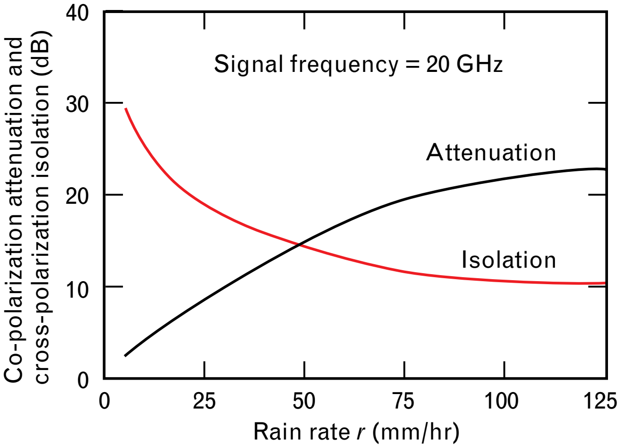

FIGURE 4. Simulated rain-induced co-polarization attenuation and cross-polarization isolation versus rain rate for 20-GHz waves propagating through an average-diameter rain cell. Attenuation increases as the rain rate r increases and cross-polarization isolation decreases. The attenuation (dB) is calculated from ar^bd, where $a = 0.0719$, $b = 1.09$, and d is the average rain cell diameter in km. This equation, adapted from Reference 2, is valid for 20-GHz signals. The cross-polarization isolation was calculated by using a semi-empirical equation from Reference 10.

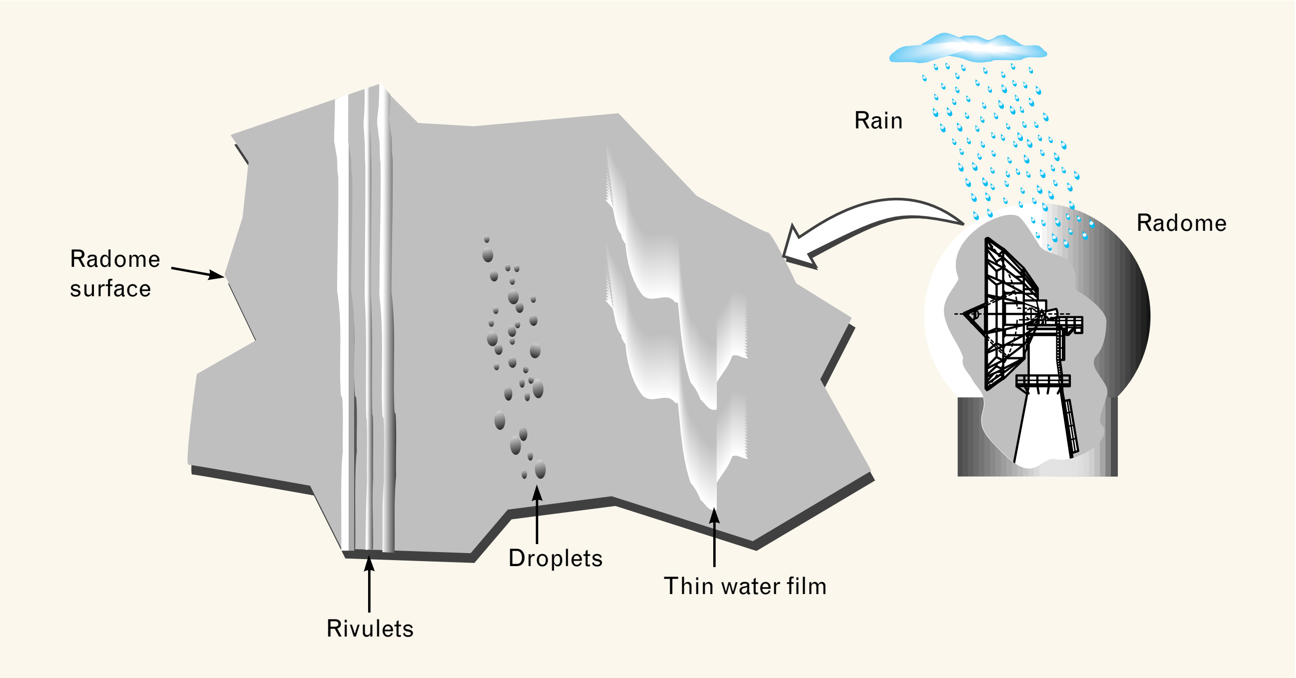

FIGURE 5. Rain water flowing down a radome surface forms three basic distributions—droplets, rivulets, and thin water films. For a hydrophobic (water shedding) surface, droplets or rivulets (or both) form, depending on the rain rate. When the radome surface is dirty or made of a nonhydrophobic material, the rain can form a thin water film on the radome. A 20-GHz electromagnetic wave passing through the thin water film on the radome surface can experience a transmission loss 2 to 3 dB higher than the loss from rivulets or droplets. Similarly, significant wave depolarization occurs for rivulets, large non-spherical droplets, and thin water films.

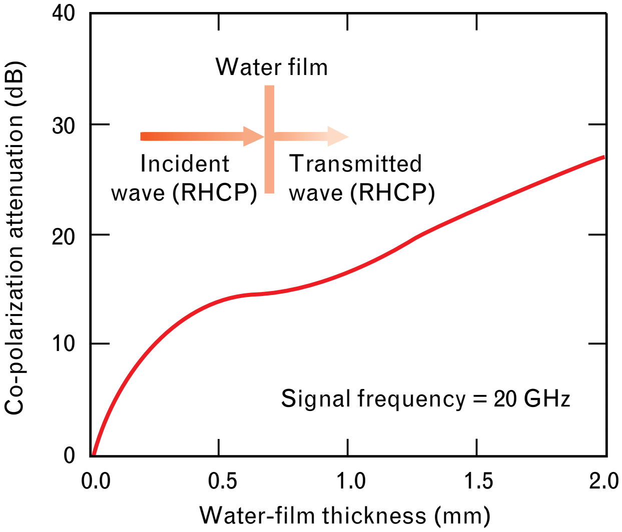

FIGURE 6. Simulated 20-GHz co-polarization attenuation versus water-film thickness for a nonhydrophobic radome. Rainfall on the radome tends to form a thin film of water. As the water-film thickness increases, co-polarization attenuation increases and the amount of transmitted power decreases.

The Terrestrial Air Link

Lincoln Laboratory has developed a terrestrial Kt-band air link that approximates many of the dynamic atmospheric conditions encountered by a satellite-to-ground link. The ground-based link also provides a more accessible and less expensive testing facility than a satellite-to-ground system. Tests conducted on this terrestrial air link allow us to quantify how the atmosphere affects signal propagation and how adaptive polarizers improve the communications performance of the system.

In considering sites in eastern Massachusetts for the terrestrial air link, we evaluated three receive antennas: a 7.3-m-diameter antenna enclosed within a 16.7-m space-frame radome in Sudbury; a 9.1-m-diameter antenna with no radome in Waltham; and an 18.3-m-diameter antenna enclosed in a 28.4-m air-supported radome in Westford. Our potential transmit sites were Mount Pack Monadnock in Temple, New Hampshire, and in Massachusetts,

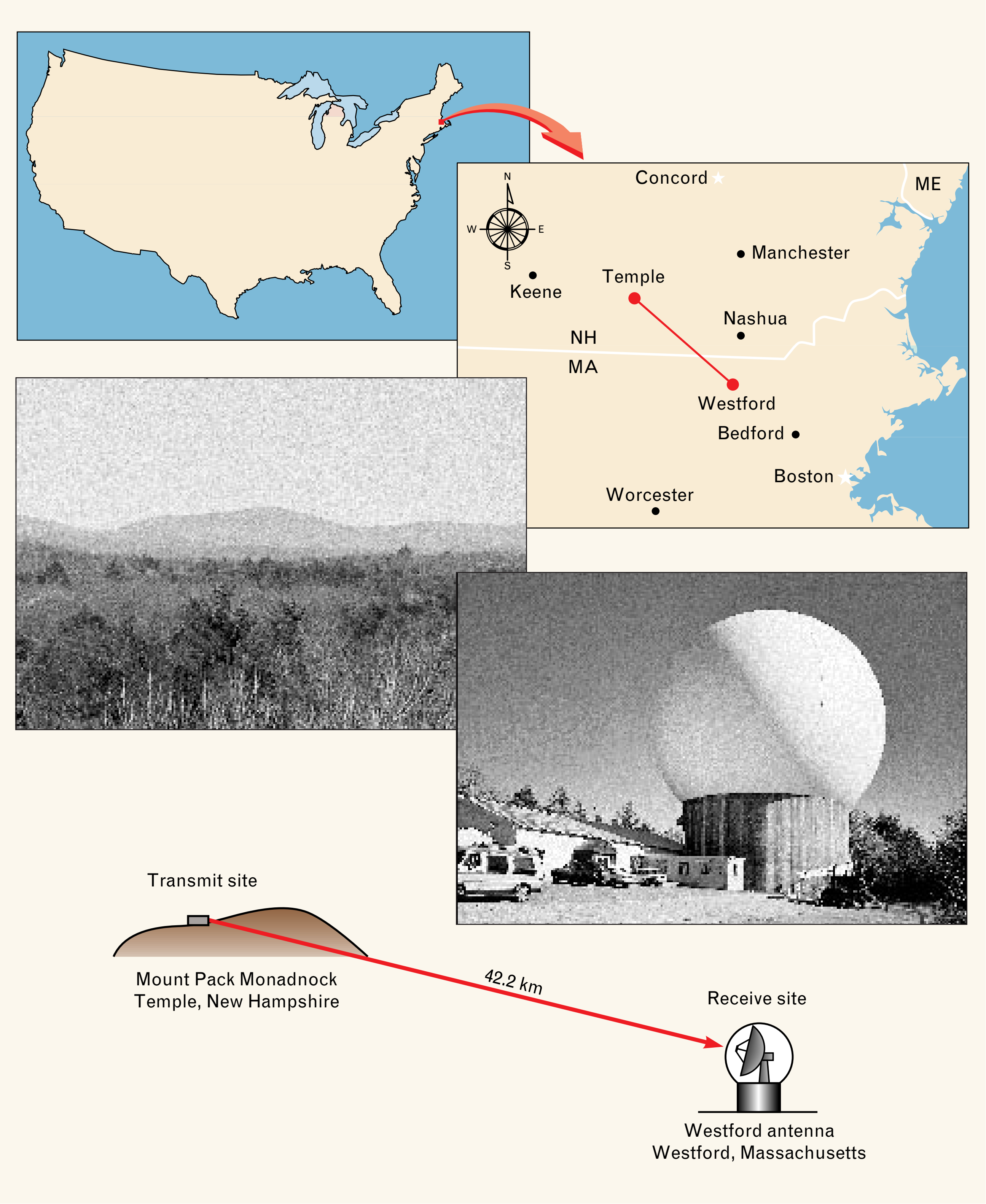

FIGURE 7. Locations of transmit and receive facilities for the clear line-of-sight 42.2-km terrestrial air link. The transmit antenna site is located on Mount Pack Monadnock in Temple, New Hampshire, and the receive antenna site is located in Westford, Massachusetts.

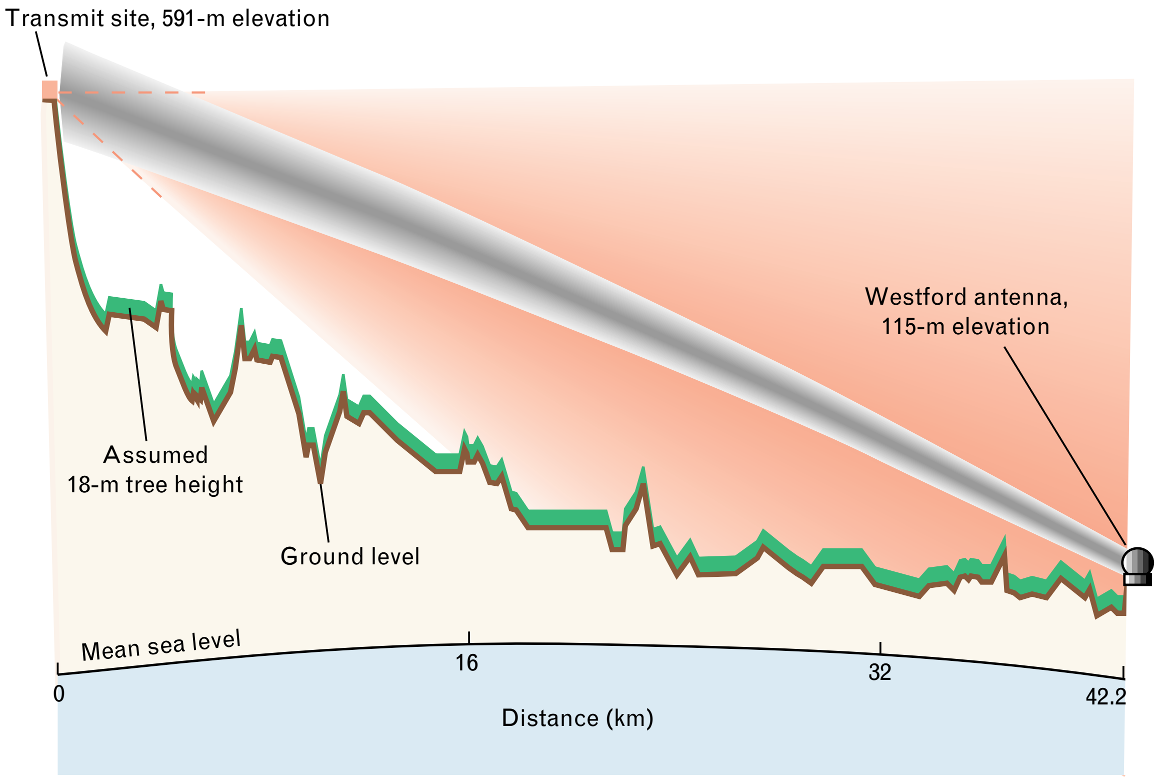

FIGURE 8. Profile of the clear line-of-sight 42.2-km terrestrial air link. Because of atmospheric refraction effects, the beam follows a curved path between the transmit site and the Westford antenna. In the course of a day, the atmospheric refraction varies, causing an apparent angle-of-arrival variation in the beam at the receive antenna. Thus the receive antenna must be reoriented during significant changes in atmospheric refraction.

Nobscot Hill in Wayland, Mount Wachusetts in Princeton, and Prospect Hill in Waltham.

After studying propagation path profiles between potential transmit and receive sites and conducting preliminary measurements on the antennas at Sudbury and Westford, we judged Mount Pack Monadnock and Westford to be the best combination for the terrestrial air link. Figure 7 shows the location of the terrestrial air link and photographs of Mount Pack Monadnock and the Westford receive facility.

From the transmit site at Mount Pack Monadnock, signals propagate along an unobstructed 42.2-km path to the large radome-enclosed receive antenna at the Westford site. The terrestrial propagation path begins at a 591-m elevation (above mean sea level) and ends at a 115-m elevation. Figure 8 shows a profile view of the terrain between transmit and receive sites. Because of refraction, the actual propagation path follows a slightly curved trajectory. The path length of the terrestrial air link is sufficiently long to approximate the far-field radiation conditions (incident signal wavefront is nearly planar over the receive aperture) for a large dish antenna in a satellite-to-ground link.

Housed in a temporary shelter on Mount Pack Monadnock, the transmit antenna is a 1.8-m-diameter, dual circularly polarized Cassegrain reflector. This antenna has a half-power beamwidth of 0.5° at 20 GHz. An awning protrudes over the doorway in front of the reflector to protect it from rain, thereby more accurately modeling the condition of a dry spaceborne antenna. A wet feed or reflector surface could depolarize the transmitted RHCP and LHCP waves. For the transmit antenna, the axial ratio, which indicates the purity of the transmitted circular polarization, is less than 0.5 dB over the 17.7-to-21.2-GHz band. An axial ratio of 0 dB corresponds to perfectly circular polarization.

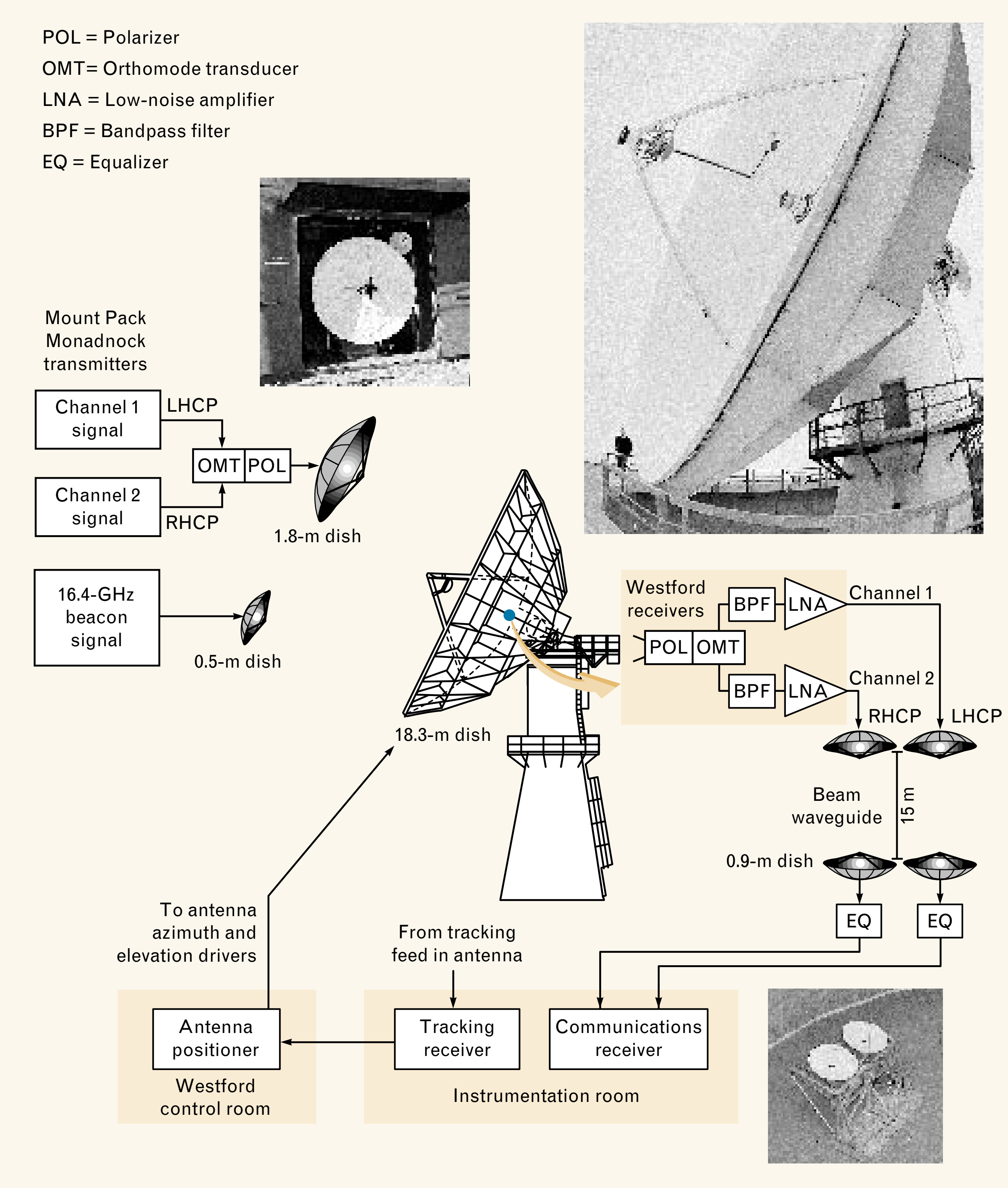

FIGURE 9. System diagram for the terrestrial air link from Mount Pack Monadnock to Westford. A data-communications transmit antenna and a beacon-signal transmit antenna are located at the mountain facility. At the receive facility, a four-horn feed (see Figure 11) is used to perform angle-of-arrival measurements. The communications signals are received by a feed horn and polarizer with an orthomode transducer (see Figure 10). These signals are filtered and amplified, and then sent over a beam waveguide to the communications receiver.

The Westford antenna, which serves as the receiving terminal in the terrestrial air link, was one of two identical 18.3-m-diameter dish antennas built for Project West Ford, conducted by Lincoln Laboratory in the early 1960s [9, 13]. Recent work with the Westford antenna has been in a prime-focus configuration with feeds at 2 and 8 GHz for NASA experiments examining continental drift [14].

The Westford antenna is equipped with a modern low-loss hydrophobic air-supported radome installed in 1992. The radome material, manufactured by Chemfab Corporation, Merrimack, New Hampshire, is a hydrophobic, teflon-coated fiberglass fabric known as Raydel R60 [11]. This material has a dry insertion loss at 20 GHz of about 0.7 dB. At 20 GHz, the measured wet insertion loss of the radome under moderate rain conditions of 10 mm/hr is about 1.1 dB; under heavy rain conditions of 50 mm/hr, the insertion loss is about 1.3 dB. Recent measurements indicate that the cross-polarization isolation of the link degrades to about 25 to 30 dB at 10 mm/hr and 20 to 25 dB at 50 mm/hr when simulated rain water produces rivulets and droplets that run off the radome.

Figure 9 shows the signal path through the terrestrial air link. Independent LHCP (channel 1) and RHCP (channel 2) signals are generated by two transmitters. An orthomode transducer (OMT) and polarizer combine the transmit signals and couple them into the feed horn of the transmit dish that operates from 17.7 to 21.2 GHz. A separate 16.4-GHz beacon signal with a 0.46-m-diameter prime-focus parabolic dish radiates outside the communications band to measure the angle of arrival of the receive signal. A four-horn tracking receiver processes the linearly polarized beacon signal at 16.4 GHz while a separate feed horn and receiver process the dual-polarized data-communications signals in the 17.7-to-21.2-GHz band. The receiver responds to the 16.4-GHz beacon signal by sending commands to the antenna positioner, which adjusts the azimuth and elevation drivers to align the main beam of the receive antenna with the incident beacon signal.

For the terrestrial air link, the Westford receive antenna was modified to operate as a dual-circularly polarized antenna in a Cassegrain configuration. The original subreflector for Project West Ford proved adequate at 20 GHz, but a suitable feed horn had to be developed for the Kt band of our project. A corrugated conical feed horn with a 16.5-cm-diameter aperture was designed to provide full illumination of the Westford antenna. The feed horn attaches to a polarizer and an OMT, which transfer the received signals from the feed horn into LHCP and RHCP output ports. The upgraded Westford receive antenna has a gain of 66.5 dBi (decibels relative to an isotropic receiving antenna) and a half-power beamwidth of 0.052° at 20 GHz. Our measurement of the axial ratio—below 0.5 dB in both polarizations—included the distortion effects of the dry radome. The low axial ratios of the transmit and receive antennas assure that, in the absence of atmospheric depolarization, the isolation between the LHCP and RHCP signals is 30 dB or more. Figure 10 shows the Westford receive antenna and photographs of the associated electronics.

Receive Electronics, Cables, and Beam Waveguides

Once signals reach the Westford antenna, they pass through an arrangement of receive electronics to the instrumentation room 20 m below the antenna feed by using low-loss microwave coaxial cable and 15.2-m beam waveguides. A bandpass filter and low-noise amplifier (LNA), installed in each channel at the feed outputs, reject out-of-band signals, boost the signal power, and conserve the signal-to-noise ratio. Because the atmosphere in the radome is not temperature controlled, we use a hot/cold plate to maintain the LNAs at a constant temperature. The amplified signals output from the LNAs are routed through coaxial cable to the inputs of a pair of beam waveguides, which transports the signals over a 15.2-m path down to the test instrumentation room with a signal loss of less than 2.5 dB. Alternative means of routing these signals with coaxial cable or waveguides would respectively be too lossy or too dispersive.

The beam-waveguide system uses two 0.9-m-diameter prime-focus parabolic antennas, located adjacent to the Westford antenna (see Figure 9). These antennas beam the two signal channels to a similar pair of parabolic dish antennas located on the roof of the instrumentation room below. Short lengths of coaxial cable take the signals in both channels into the instrumentation room and into a two-channel equal-

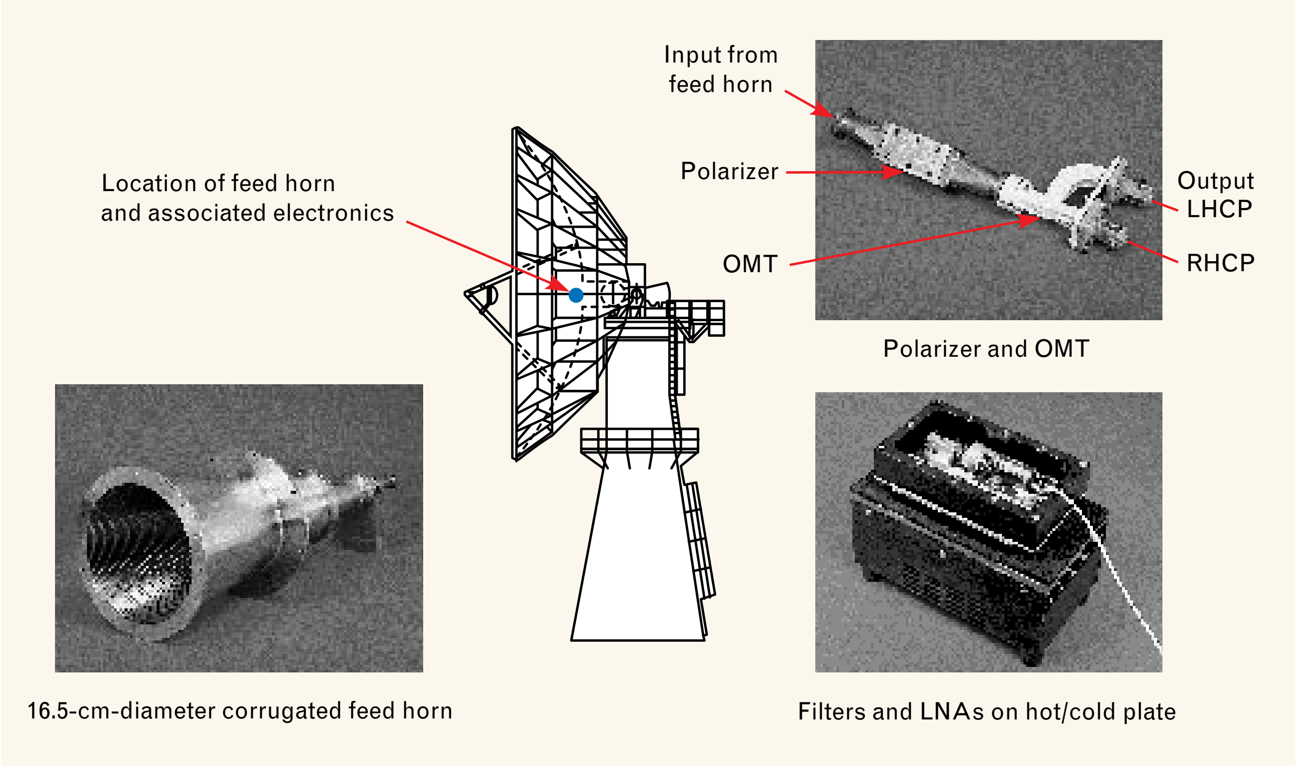

FIGURE 10. Corrugated feed horn, polarizer, and orthomode transducer (OMT) assembly, and filters and low-noise amplifiers (LNAs), which are located in the Westford receive antenna. A polarizer and OMT transfer the received signals from the feed horn into RHCP and LHCP output ports. Bandpass filters and LNAs, installed in each channel at the feed outputs, reject out-of-band signals, boost the signal powers, and conserve the signal-to-noise ratio for each channel. A hot/cold plate maintains the LNAs at constant operating temperatures.

izer. Utilizing tuned, shorted waveguide stubs, this equalizer unit compensates for amplitude and phase distortion introduced by the electronics. Attenuators and line stretchers permit adjustment of the signal levels and time-delay matching between channels.

The coaxial cables for the input and output of the beam-waveguide system have about a 1.0 dB/m loss, so they are kept as short as possible. Because a delay instability occurs if the cable temperature drops below 55°F, each coaxial cable sits in a foam-insulated PVC tube containing a self-regulating heater tape that maintains the cables at a temperature above 67°F.

Angle-of-Arrival Measurements System

Atmospheric refraction causes the angle of arrival of the received communications signal at the Westford site to vary as a function of time. Over a period of several hours, this variation can be several beamwidths of the receive antenna, which would cause the received signals to be lost if an autotrack capability were not included.

The angle-of-arrival measurements system provides a slow autotrack capability and records angle-of-arrival variations of the incident beacon signal every 0.1 sec. The antenna pointing angle is adjusted every 30 sec in 0.0027° increments, about one-twentieth of a beamwidth. This adjustment keeps the antenna beam pointed in the direction of the incident beacon and keeps the communications signal variation, caused by beam-pointing error, below 0.1 dB.

Figure 11 shows a photograph of the four-horn array of the angle-of-arrival measurements system, which is designed to operate independently of the primary Westford communications receive antenna. A 45°-tilted mylar reflector redirects a fraction of the beacon signal (approximately –20 dB) incident on the Westford primary feed horn. This coupled signal travels to a four-horn array and a receiver/processor

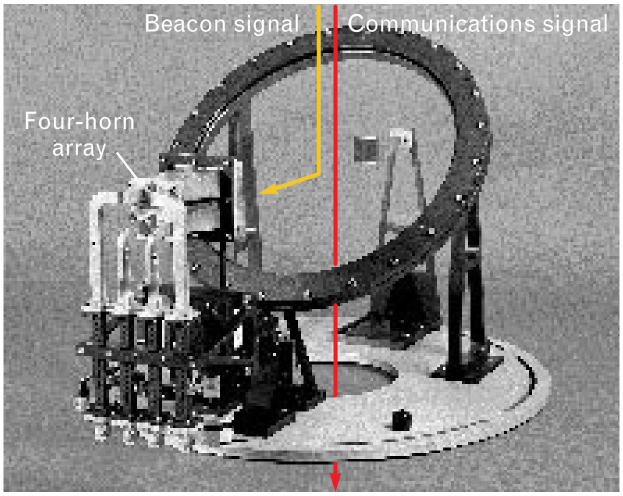

FIGURE 11. Four-horn array of angle-of-arrival measurements system. A mylar sheet (not visible) mounted in the black ring couples a beacon signal to the four-horn array. Signals from the array are used to determine the arrival angle of the beacon signal. The communications signal propagates through the mylar sheet and central hole in the support plate to the feed horn shown in Figure 10. The horn in the background is used for calibration.

that computes the angle of arrival of the beacon signal for azimuth and elevation.

Weather Monitoring

Weather stations are found at the transmit and receive sites and at a mid-path location in Brookline, New Hampshire. Measurements collected by these stations include temperature, humidity, dew point, rainfall, wind speed, wind direction, and barometric pressure—information supplemented by similar data from five National Weather Service stations in the surrounding area. In addition, three NEXRAD weather radars—in Portland, Maine; Albany, New York; and Taunton, Massachusetts—provide weather radar images. These images describe weather conditions in the area and help quantify the amount of precipitation along the link. A dedicated computer archives the weather station data, weather radar images, angle-of-arrival measurements, and signal propagation data to facilitate data retrieval and analysis.

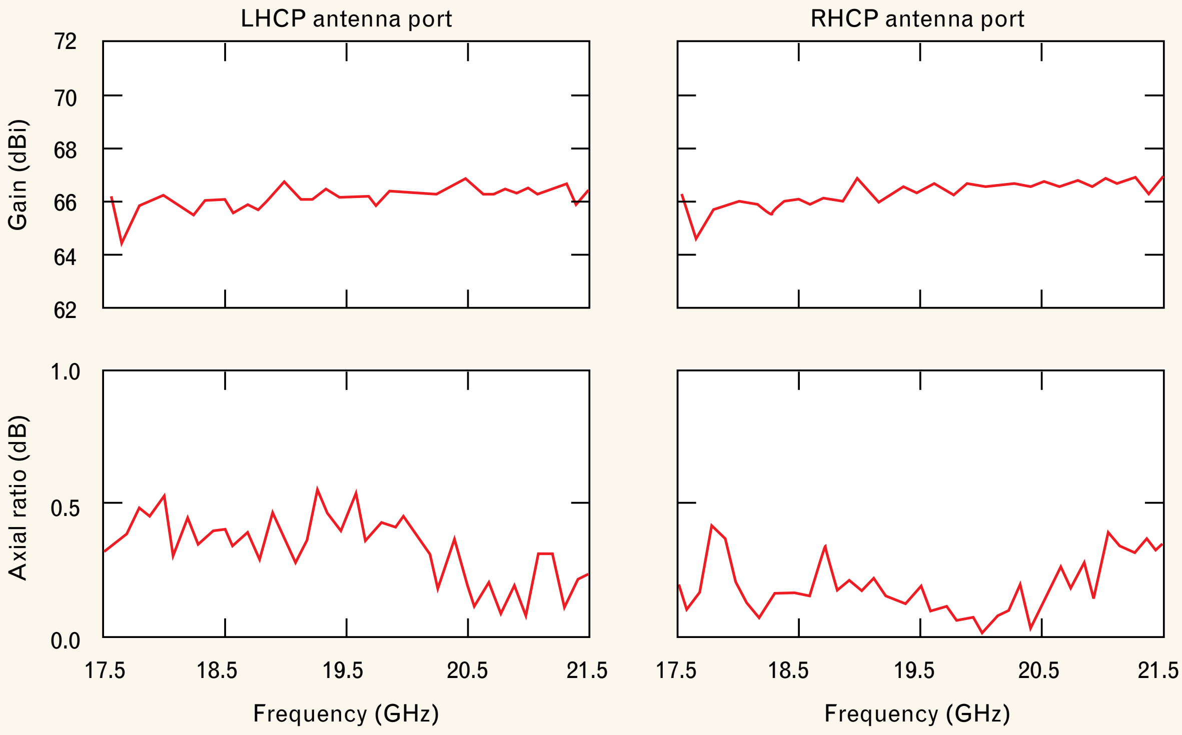

FIGURE 12. Measured gain and axial ratio for the Westford 18.3-m-diameter receive antenna as a function of frequency. The gain sufficiently meets the link requirements of signal strength. The low axial ratio gives desirable larger cross-polarization isolation values.

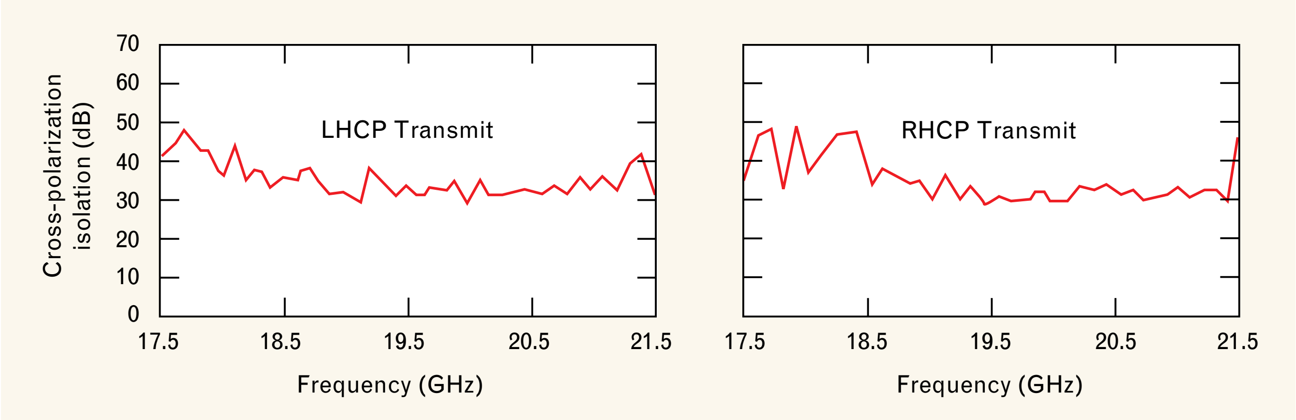

FIGURE 13. Measured cross-polarization isolation for the terrestrial air link under clear-air conditions. The cross-polarization isolation is greater than 30 dB over the entire frequency band, which indicates that the link exhibits little polarization cross talk under these conditions.

Initial Clear-Air Measurements

Because the proposed operating frequencies for the terrestrial air link are about twice those of the original design of the Westford antenna, we conducted an intensive series of measurements of the Westford antenna at Kt-band frequencies. We measured antenna patterns, gain, and axial ratio by using the transmit facility on Mount Pack Monadnock with a stepped continuous-wave radiating source. Because atmospheric scintillation and beam refraction contributed uncertainties to the measurements, we collected data on cool, dry days when scintillation and refraction effects were at a minimum. Each antenna-performance parameter was measured several times on different days and the results were averaged to obtain final

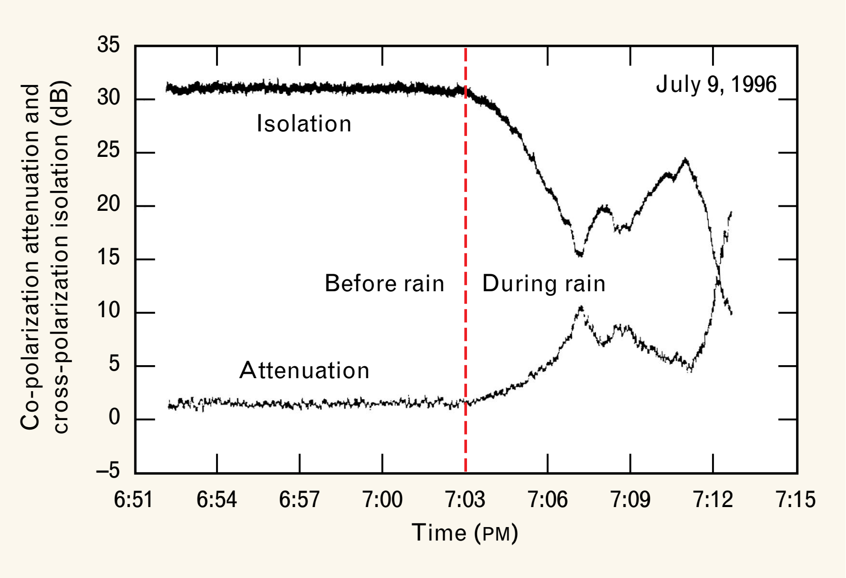

FIGURE 14. Measurements of the cross-polarization isolation and co-polarization attenuation before and during a rain event over the terrestrial air link. At the start of the measurement, weather was cloudy and humid. The cross-polarization isolation and co-polarization levels are steady until the rain begins at about 7:03 PM and then they degrade significantly. The signal frequency is 19.5 GHz.

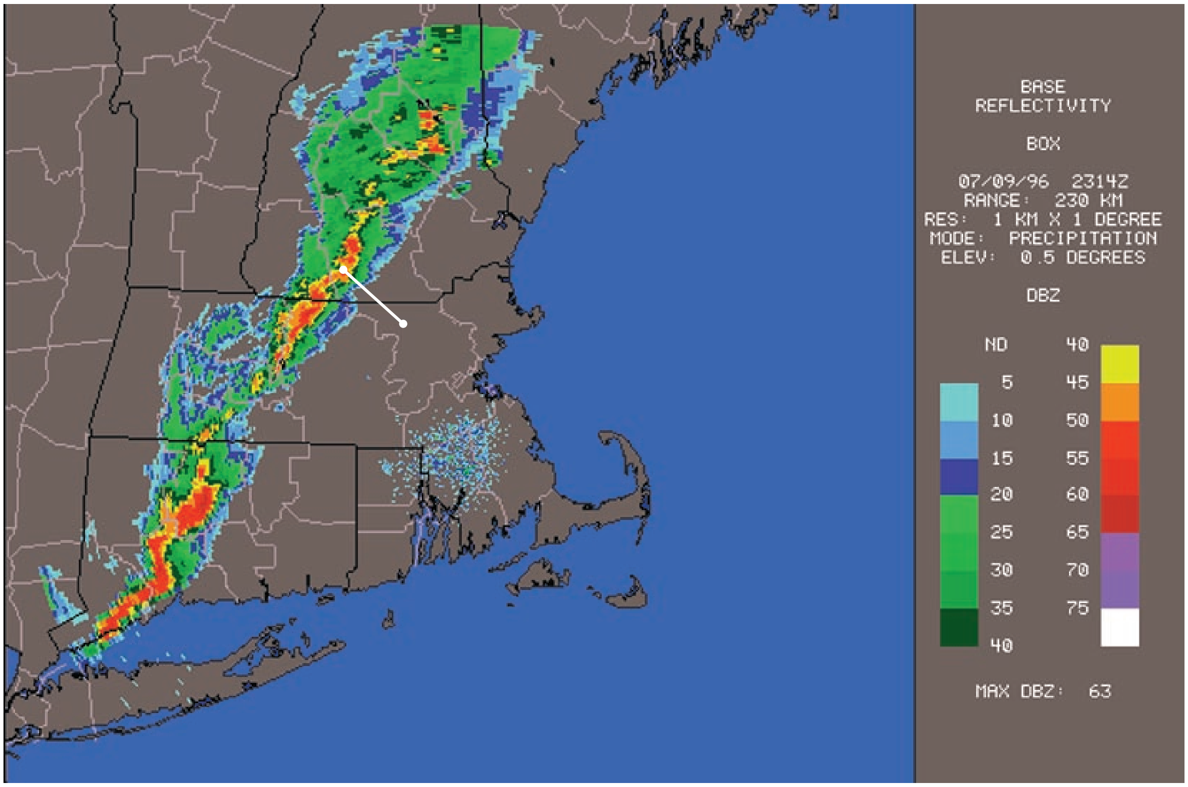

FIGURE 15. Weather image with NEXRAD radar located at Taunton, Massachusetts, at 7:14 PM on July 9, 1996. This image was taken near the end of the measurements shown in Figure 14, and indicates that rain is covering a portion of the terrestrial air link. The rain intensity scale (right) indicates heavy rainfall at the transmit site. (Courtesy of Weather Services International, Billerica, Massachusetts.)

data. A 0.6-m-diameter reflector was used as a standard gain-reference antenna to calibrate the Westford main beam gain. We performed Westford antenna axial-ratio measurements, shown in Figure 12, by using a 1.8-m, spinning, linearly polarized transmit antenna. The average antenna gain over the band is 66.5 dBi and the peak axial ratio over the band is less than 0.5 dB.

In addition, we measured the cross-polarization isolation of the terrestrial air link over the 17.7-to-21.2-GHz band under clear-air conditions, as shown in Figure 13. The measurements were performed by transmitting first with RHCP and receiving with RHCP as the co-polarization channel and LHCP as the cross-polarization channel, and then transmitting with LHCP and receiving with LHCP as the co-polarization channel and RHCP as the cross-polarization channel. The cross-polarization isolation is excellent, exceeding 30 dB over the band for both LHCP and RHCP.

Initial Rain Measurements

During the developmental stages of the terrestrial air link, Lincoln Laboratory conducted measurements before and during rain events to demonstrate the effects of rain on signal attenuation and depolarization. Figure 14 shows measured link co-polarization attenuation and cross-polarization isolation versus time for a summer rain event. The initial condition of the link was clear air, with an attenuation of about 2 dB caused by atmospheric absorption and a cross-polarization isolation greater than 30 dB. About twelve minutes after measurements began, a rain front from the northwest moved into the link. As the rain began to cross the path, the measurements showed an increased co-polarization attenuation and a decreased cross-polarization isolation. Figure 15 shows a NEXRAD weather radar image taken near the end of the rain event, when the rain front clearly covered a portion of the link. During a portion of the rain event

(7:06 to 7:09 PM), the attenuation increased to the level of 8 to 10 dB and the cross-polarization isolation degraded below 20 dB. Near the end of the experiment, as the rain intensified, the attenuation increased to about 20 dB and the isolation dropped to about 10 dB.

The Lincoln Laboratory terrestrial air link is currently being used to evaluate techniques for future satellite-to-ground communications systems in the 17.7-to-21.2-GHz band. We are also investigating modifications to the terrestrial air link that will allow us to characterize atmospheric effects on signal phase and to communicate in the millimeter-wave band.

Acknowledgments

The Westford site was made available by the MIT Haystack Observatory, J.E. Salah, director. Site manager M.A. Poirier facilitated our efforts at the Westford facility. The Mount Pack Monadnock site was made available by the state of New Hampshire, and B. Haubrich facilitated our efforts there.

The terrestrial air link described here was made possible through the efforts of many individuals. W.C. Cummings and E.A. Bucher oversaw the project. A.R. Dion served as technical consultant for all antenna-related subjects and performed the supporting simulations.

R.J. Burns directed the measurements on the Westford antenna. J.M. Perry performed computer control and interfacing of the instrumentation. At the receive site, J.H. Magnuson, M.A. Porrier, and J.M. Perry performed the measurements. Transmit site personnel included E.F. Arbo, H.F. Rittershaus, R.J. Merchant, T.W. Borge, R.F. Piccola, and J.A. Russo.

D.C. Weikle designed the corrugated feed horns for the Westford antenna and for the 1.8-m linearly polarized transmit antenna used in some tests. He also developed the beam-waveguide system. T.W. Borge performed many of the supporting measurements. J.C. Lee designed the polarizer for the Westford antenna feed and procured the requisite orthomode transducer (OMT). R.F. Piccola tuned and measured the performance of the polarizer-OMT assembly. D.C. Weikle directed the implementation of the angle-of-arrival measurement system. D.J. Cipolle designed the transmit beacon and receiver. D.S. Besse provided programming support. T.W. Borge assisted in the assembly and installation. Electronic chassis layout and the design of the cable temperature control equipment were performed by J.A. Russo. J.J. Kangas, J.A. Russo, J.H. Magnuson, R.F. Piccola, T.W. Borge, and E.F. Arbo made system and component measurements. J.A. Russo, J.J. Kangas, T.W. Borge, D.A. Crucioli, and T.G. Moore assembled chassis. E.F. Arbo made the semirigid coaxial cables. G.M. Willman directed the mechanical fabrication of precision waveguide components and accessories. Machining was performed by L.P. Tedstone, D.D. Thompson, T.C. Harris, and M.J. Hurley. H.F. Rittershaus and J.J. Kangas supplied additional fabrication support. Mechanical mounting structures for the transmit antenna, Westford antenna feed, subreflector, and beam waveguide were designed by E.A. Chateauneuf and M.H. Bartalini. These were installed by F.H. Rittershaus, R.J. Merchant, M.A. Poirier, T.W. Borge, J.H. Magnuson, E.F. Arbo, R.J. Likas, and M.J. Gregory.

J.M. Perry programmed and automated the data collection from the weather stations and collection of NEXRAD weather radar images. D.A. Brown interfaced sensors and provided programming assistance. Installation of the weather stations was handled by E.F. Arbo, H.F. Rittershaus, and R.J. Merchant.

D.S. Besse designed and configured the data management system. He also served as consultant for computer-related matters. Technical discussions with W.K. Hutchinson, D.D. Dougas, and D.J. Cipolle concerning electronic components were very helpful.

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