Microwave Propagation in the Upper Troposphere

Amateur microwave work need not be restricted to operation from hilltop locations. Let's explore the use of scattering in the upper regions of the troposphere, which offers the possibility of communications over highly obstructed paths.

By Bob Larkin, W7PUA; Larry Liljequist, W7SZ, and Ernest P. Manly, W7LHL

The selection of propagation modes for amateur microwave stations is often progressive. Most of us start with simple equipment and the contacts are usually by line-of-sight propagation. Longer distances are then accomplished by going to high locations. As equipment gets better, the use of various objects for reflections and scattering becomes a possibility. Hills, mountains, water tanks are attractive, since they are generally available at any time. Aircraft are also attractive reflectors when they are at high altitudes.[1] Scatter from raindrops can be effective and many stations have used this propagation mode.[2]

Better-equipped stations are able to work others beyond their horizon by use of the propagation mode called *tropospheric scattering*. This mode occurs to some degree at all times. It involves reflection in multiple directions (scattering) of the microwave signal using irregularities in the material of the troposphere. Most definitions of this mode do not make a distinction of the particular material. This allows inclusion of variations in the water content, water or ice particles, dust, insects or possibly other materials. This scattering is strongest in the lower portions of the troposphere, but can occur throughout the region.

The troposphere starts at the Earth's surface and includes all portions of the atmosphere where convection caused by changes in the air temperature is a major effect. This is the region of weather production. The top of this layer varies between about 6 and 15 km (20,000 to 50,000 feet), depending on the region of the world and the local weather conditions. The best opportunity for tropospheric scatter is generally in the lower portion, where the air density is greatest; however, because of the Earth's curvature and local terrain blockage, this region may not be available for propagation. To extend our range of contacts, we must use the upper portions of the troposphere. In a sense, we are doing the reverse of going to the mountaintops to work over the horizon. We stay at home and scatter the signals from the material high in the troposphere. This

[1]Notes appear on page 11.

Bob Larkin, W7PUA
2982 NW Acacia Pl
Corvallis, OR 97330
boblark@proaxis.com

Larry Liljequist, W7SZ
2804 SE 347th Ave
Washougal, WA 98671
LLL@pacifier.com

Ernest P. Manly, W7LHL
PO Box 1307
Graham, WA 98338-1307
epmanly@ispwest.com

Fig 1—Map of the station locations in Washington and Oregon. The Cascade Mountains extend north and south through the area and portions of these are directly north of W7SZ.

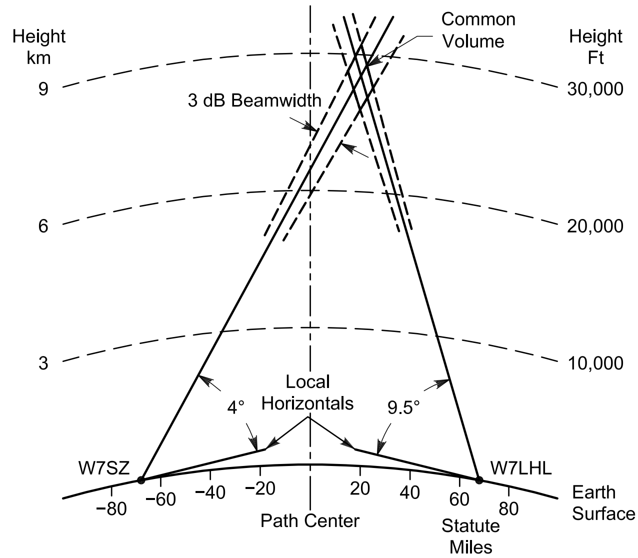

Fig 2—Close-in hills at each end obstruct the path between W7LHL and W7SZ, setting minimum usable elevation angles of 9.5° and 4°, as shown. This plot has very different scales for the height above ground and the horizontal distance. This makes the small angles look very large and distorts the scaling between the angles. The commonly viewable volume is at a height of about 8.5 km (28,000 feet). The beamwidths are only about 0.7°, making the common volume about 1.5 km (5000 feet) in height. The total path length is 159 km (99 statute miles).

article will discuss our measurements of tropospheric scattering from locations where the terrain restricts the path to the regions above about 4.5 km (15,000 feet).

All modes that can scatter or reflect from high regions are attractive for amateur microwave operation since they can be exploited from home locations. In many parts of the country, this can add six months or more to the microwave season! It also allows many more hours of operation than is practical using portable equipment. This attracted us to this type of operation, as the terrain in the Pacific Northwest is mountainous and thus far from line-of-sight as well as inaccessible for much of the year.

We began trying to make contacts between home stations on 10 GHz over some very mountainous paths. This was surprisingly successful, and most often, the propagation mode was determined not to be from aircraft or rain scatter. After finding that microwave contacts were possible, we started making measurements of the signal strengths and signal spectra, trying to correlate this to the weather conditions. We also extended the measurements to 1296 MHz. We found almost certain indications that the signals were being scattered by material in the upper troposphere. The nature of the material is still uncertain. Neither do we know how well our results would apply to other parts of the world. This report is to let other operators know about our observations

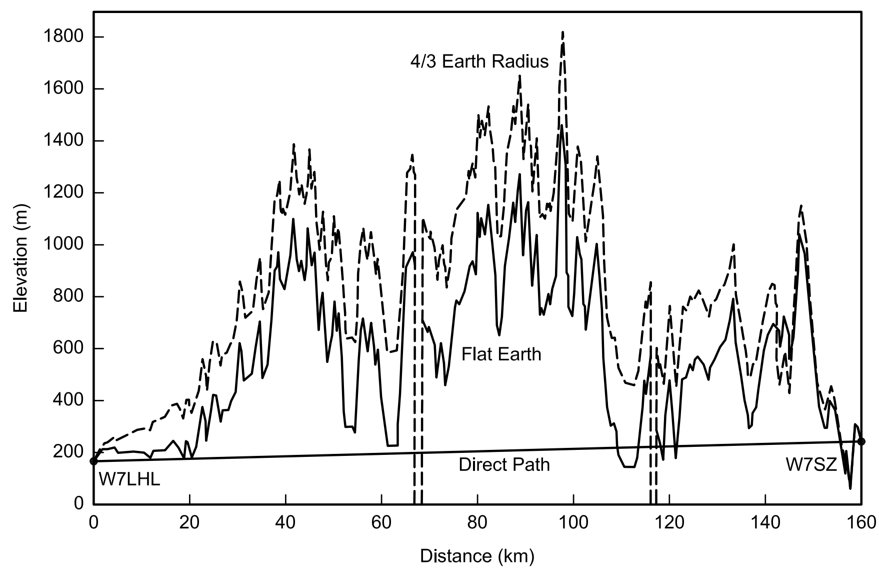

Fig 3—Cross section of the terrain between W7LHL and W7SZ. It is far from a direct path. The tallest peak, shown at about 100 km from the W7LHL end, is the side of Mt St Helens. The upper trace shows the effect of the Earth's curvature, including a 4/3 correction for refraction. The "Flat-Earth" trace is about 400 meters lower in the center of the path. (Plot by KB1VC; users.rcn.com/acreilly/los_form.html**)**

Table 1—Path Summary

Stations 1 - 2	*Distance (km)*	*Take-off Angle 1 (°)*	*Take-off Angle 2 (°)*	*Common-Volume Height (km/kft)*
W7LHL-W7SZ	159	9.5	4	8.6/28
KD7TS-W7SZ	198	1	4	4.1/13
W7SZ-W7PUA	138	4	3	4.5/15

Fig 4—The 10-foot parabolic-dish antenna used for both 1296 MHz and 10 GHz by W7LHL. This is a surplus TVRO antenna. The RF equipment is mounted at the center feedpoint.

Fig 5—This photo shows W7LHL's 10-GHz equipment that is mounted at the feed for the parabolic dish shown in Fig 4. A DB6NT transverter, along with an MKU-101B receive preamplifier (0.8-dB noise figure), a driver amplifier and an MKU-102XL output amplifier (all from Kuhne Electronic) are at the feed. A waveguide TR switch minimizes losses at the feed horn. A frequency-reference signal comes from the shack on a coaxial cable to phase-lock the crystal oscillator in the transverter.

Table 2—Equipment Used

Station	*Dish (m)*	*Power (W)*
KD7TS	1.0	1
W7LHL	3.0	5
W7SZ	3.0	10
W7PUA	1.2	9

and encourage further exploration of microwave paths.

Tropospheric-scatter propagation modes have utility because they may be available when modes like airplane reflections, mountain-bounce and rain scatter are not. In addition, the associated Doppler shift is considerably less than that from either airplane reflections or rain scatter, allowing the efficient use of narrow-band modulation, such as CW or some computerized modes such as JT44 or PUA43.

Fig 6—W7SZ with his dish antenna used on 10 GHz. The microwave equipment is mounted at the focus of the antenna. Equipment for 10 GHz is similar to that used by W7LHL except that the transmitter power amplifier uses a TWT (traveling-wave tube).

The Propagation Paths

The work reported here was between home locations as shown in Fig 1, a general map of the area. The geometry of the path between W7LHL and W7SZ is shown in Fig 2. The distances and take-off angles are in Table 1. The take-off angle is the lowest angle that the station can view clear sky, measured from the local horizon. This angle is in all cases determined by local obstructions, within a few kilometers of the station. The common volume height (lowest altitude that is mutually visible between the two stations) is set by the take-off angles and the Earth's curvature.

The heights shown do not include atmospheric refraction; this has only a small effect. Fig 3 shows more detail of the mountainous path between W7LHL and W7SZ.

All three paths of Table 1 have been explored to varying degrees, but the most intensive data collection was for the path from W7LHL to W7SZ. This path is interesting since not only are the take-off angles poor but almost in the middle is Mt St Helens, with a post-eruption height of over 8500 feet. W7LHL and W7SZ are at 650 and 750 feet, respectively.

Equipment Used

Table 2 summarizes the equipment used on 10 GHz, portions of which can be seen in Figs 4, 5 and 6.

All contacts and measurements described in this article used equipment capable of very accurate measurements of the frequency spectrum. The conversion oscillators in the transverters were phase-locked to 10-MHz frequency standards that, in turn, were phase-locked to the GPS system using W5OJM controllers.[3] The IF radios used were DSP-10s that were again phase-locked to the frequency standards.[4] This system allows accuracy and resolution to a few hertz, even at an operating frequency of 10 GHz. In turn, it is possible to make accurate spectrum measurements, which imply the movement of scattering material.[5]

The only 1296-MHz measurements described are for the W7LHL/W7SZ path. On that band, W7SZ used 20 W and a 3.7-meter (12-foot) parabolic dish while W7LHL used 40 W and a 3-meter (10-foot) dish. The 1296-MHz transverters were again phase-locked to the station frequency references.

All stations had sensitive receivers. For the terrestrial paths, the system noise temperature includes quite a bit of ground-noise contribution.

Microwave scattering from moving media results in a Doppler-shifted spectrum in the received signal. By measuring this spectrum, it is possible to learn much about the path. The tool used for these measurements was the DSP-10 transceiver. The spectral resolution of the DSP-10 could be set to 2.3, 4.7 or 9.4 Hz. Provision was made for averaging of the received signal-plus-noise power over long periods of time to increase the apparent sensitivity. The resulting spectra were displayed either as amplitude-versus-frequency traces or as a waterfall display where the intensity of the display represents received power plotted against both time and frequency.

Observations—10 GHz

In February 2001, W7SZ and W7PUA exchanged signals on the first attempt at 10 GHz. The signals were weak, but adequate for an easy contact using digital modes. The signal had a few hertz of spectral broadening to it, and both stations observed an upward frequency shift of about 45 Hz. The night sky was clear and and there was an ice-crystal halo around the Moon. The frequency shift was consistent with Doppler shift from a decreasing path length, such as would occur with a scattering medium that was falling. (See the sidebar "Doppler Shift from Moving Media.") Other observations were made on later days and the signal was found to vary in both amplitude and amount of Doppler shift.

In July 2001, W7SZ and W7LHL were pleasantly surprised to find they could exchange signals on 10 GHz. As discussed above, this 159-km path is highly obstructed. The signals were present for long periods and possessed none of the Doppler spectra associated with aircraft and rain. Enhanced signals from aircraft over this same path confirmed the differences in the spectra.

KD7TS and W7SZ found similar success on 10 GHz in August 2001. Local terrain blocks this 198-km path, particularly on the southern end. Signal-to-noise ratios of around 7 dB in a 4.7-Hz bandwidth allowed them to easily complete a digital-mode contact (see Fig 7). Signals again showed broadening by about 20 Hz and the Doppler shift from the moving media was about +15 Hz, corresponding to a net shortening of the path. The weather was clear.

Beginning in November 2001, W7LHL and W7SZ conducted a series of experiments at 10 GHz. This path has a major local obstruction at the W7LHL end. Some tries produced no measur-

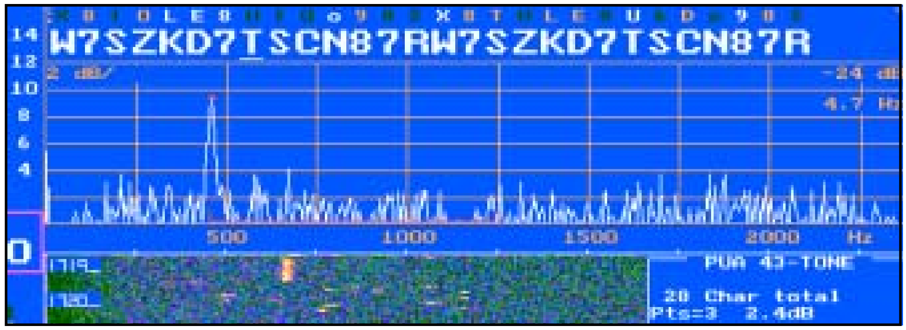

Fig 7—Partial screen shot of KD7TS's 10-GHz signal being received at W7SZ. The top lines of text show the most likely (large letters) and the second most likely characters being received in PUA43 mode. Below the letters is the latest spectrum of the multitone FSK signal. A portion of the waterfall display appears at the bottom.

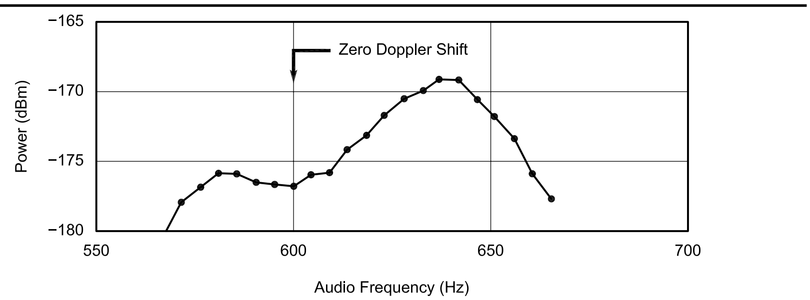

Fig 8—Frequency spectrum of W7SZ's 10-GHz signal, as received at W7LHL on 10 February 2002. The resolution bandwidth, or "bin size" is 4.7 Hz. This small bandwidth shows the details of the spectrum but makes the peak power appear to be 10 dB less than the total received power. The main spectral peak shows a Doppler shift of 37 Hz. This data has been processed to remove the noise power, based on measurements taken outside the spectrum of the signal. The double-humped response was observed frequently and would seem to represent two types of scattering material as is discussed in the text.

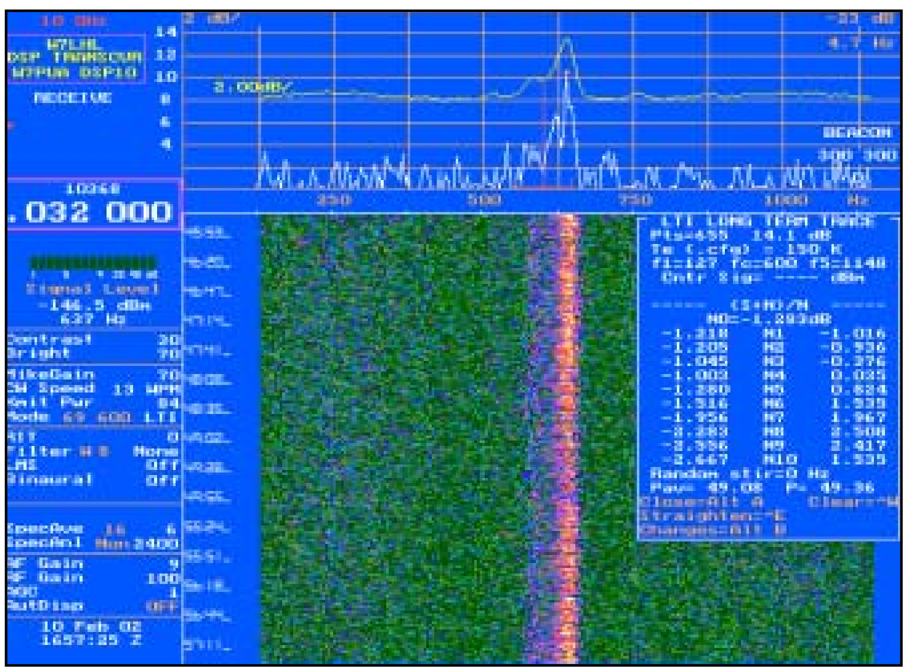

Fig 9—DSP-10 screen shot of W7LHL's 10-GHz signal being received at W7SZ over a 159-km mountainous path. The upper trace in the top spectral graph is the average spectrum being received. The lower trace in the same graph is the last received spectrum. The waterfall in the lower-right display shows many of the received spectra with time going from top to bottom. Brighter areas are stronger signals. The strongest (S+N)/N is about 7 dB, which occurs at 637 Hz. This is a Doppler shift of about 37 Hz to the high side of the transmitted frequency, corresponding to an approaching velocity of 1.1 m/s. The second, weaker peak is about 20 Hz to the low-frequency side. The total received power over the entire signal spectrum is about –155 dBm.

able signals other than from infrequent airplane reflections, which are easily identified by their characteristic high-to-low Doppler shift. Most tries produced weak signals on direct headings that would persist for hours. Over a period of 38 tests on different days during the winter and spring, measurable signals were observed on about 80% of the tests. Fig 8 is typical of the observed spectrum. The received power was –157 dBm, corresponding to a path loss of 291 dB between isotropic antennas. This is about 134 dB below the free-space loss and 70 dB above that predicted for a tropospheric scatter path.[6]

The antenna beamwidth for both stations was less than a degree, allowing some exploration of the scattering medium in azimuth and elevation. In all cases, the antennas needed to be elevated to clear the local hills. Past that, signals would most often drop off with increasing elevation angles. Both stations could move their antennas to the western side of the direct path by several degrees and still receive signals, but the strength dropped. Moving to the eastern side was less productive, probably because of increased local hills at W7SZ's location. Moving to the sides showed Doppler shift that was consistent with the prevailing upper winds. Spectral spreading, as can be seen in the figure, was always observed; but this is far less than occurs with rain scatter.

On many occasions, the 10-GHz signal between W7LHL and W7SZ had a spectrum that suggested two different scattering media. A hint of this effect was seen in Fig 9, but Fig 10 makes this spectral pattern very obvious. The waterfall display shows one signal at about 600 Hz and a second signal at about 55 Hz higher in frequency. The first signal has very little Doppler shift, whereas the second represents a path shortening of about 1.6 m/s. Both signals tend to fade at the same time but not entirely. There are times when only the first or second signal is present.

As the W7LHL/W7SZ experiments progressed, there was speculation about the propagation media involved. One candidate for 10 GHz is scattering by ice particles. KD7TS suggested the use of aircraft icing plots, prepared by NOAA. These didn't seem to correlate, but they led to our discovery of the GOES IR3 water-vapor plots that are updated on a regular basis and available over the Internet.[7] Considerable assistance in understanding the nature of the IR3 data was provided to us by Don Hillger, WDØGCK, of Colorado State University. The IR3 plots, such as Fig 11, indicate the radiation temperature for the highest levels of water vapor or clouds. The areas of the plots with lower temperatures are often associated with higher elevations.[8] The only common volume on the propagation path was at the upper levels of the troposphere, so it is not surprising that water content at these heights could be important.

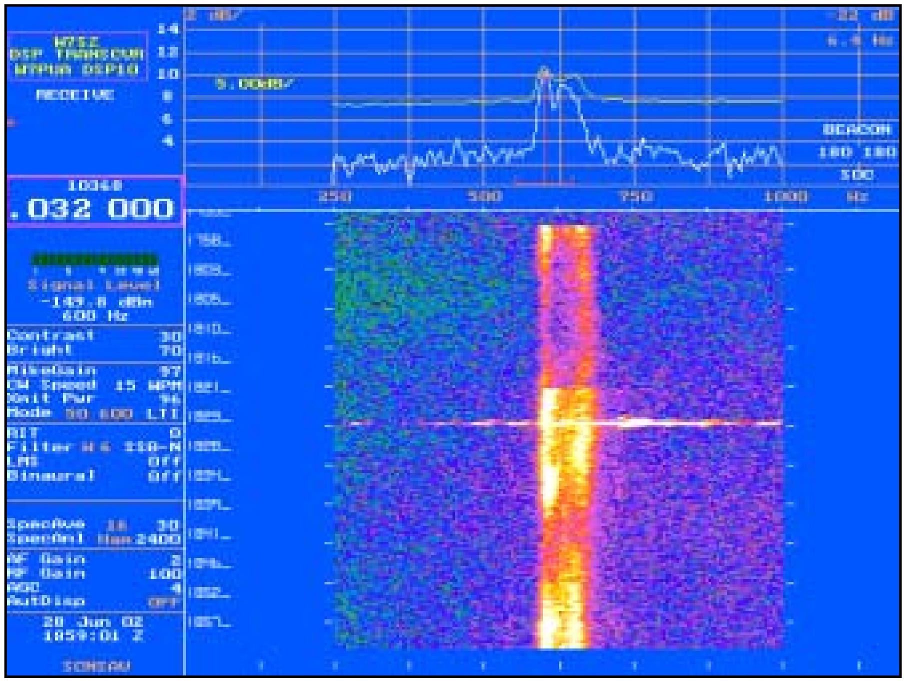

Fig 10—Screen shot of W7LHL's signal on 10 GHz as received by W7SZ. The waterfall display in the lower right portion of the screen shows the spectrum of the signal over a period of about an hour, as indicated by the times on the left. The two stations were transmitting in alternate three-minute periods and causing the abrupt changes in the displayed spectrum. Stronger signals are shown as brighter colors in the waterfall. As set up here, the weakest signal discernible on the waterfall is about –175 dBm. The strongest signals shown are about –150 dBm. The horizontal trace at about 1833 is from an airplane flying through the common volume.

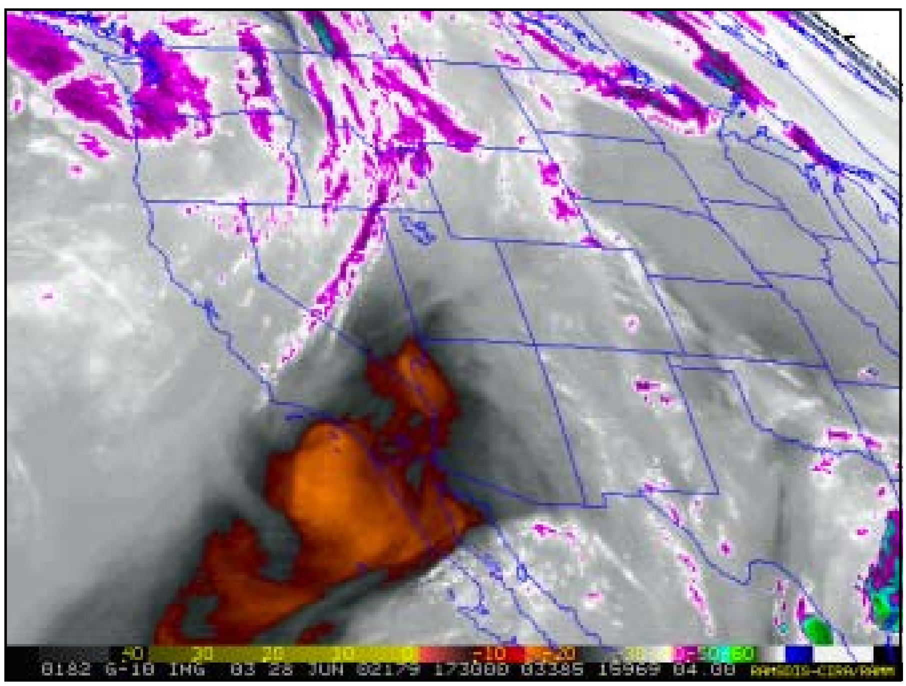

Fig 11—A view of the western United States from the GOES10 satellite. This is the IR3 channel (water vapor) at an infrared wavelength of about 6.7 micrometers. Since this wavelength is absorbed by water vapor, the radiation temperature is close to that of the highest cloud layer. The temperature scale is indicated at the bottom. The Internet pictures are in color, making interpretation easier. For this picture, the dark areas, over western Washington, are in the magenta range, indicating a temperature of –40 to –50°C.

The GOES-10 IR3 temperatures showed correlation with the 10-GHz signal strengths. Fig 12 shows the results of 19 measurements taken between 10 Feb and 28 March 2002. The signal strengths were estimated from the appearance of the waterfall by comparing with known levels. A "relative signal" of zero in the plot indicates that no sign of a signal was found. This means the strength was –175 dBm or less. Above this level, the estimates were made in roughly 5-dB steps, shown as relative signal values from 1 to 6. Most notable is that anytime the GOES IR3 temperature was –40°C or colder, the 10-GHz signal was strong enough to measure. The trend line on the plot generally shows an increase of almost 1 dB in signal for each 1°C of cooling. Of course, the colder temperature is probably not the direct cause of the signal changes, but rather it indicates the presence of water vapor at greater height.

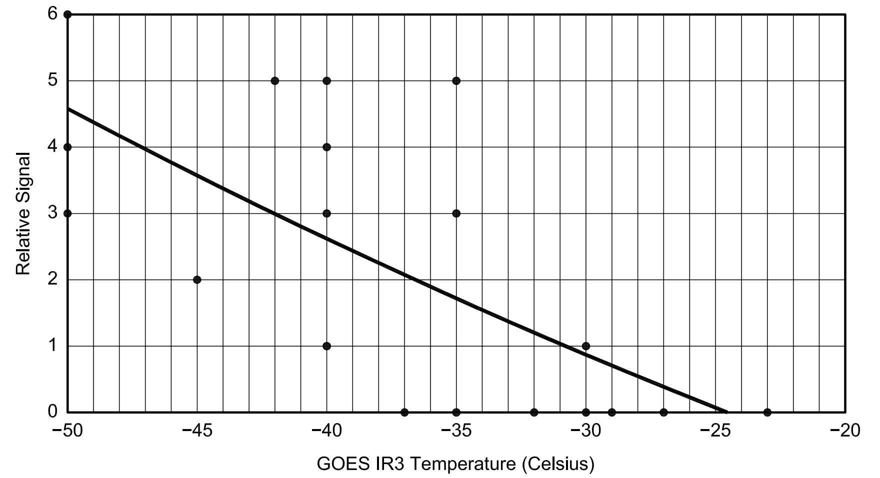

Fig 12—This plot shows the correlation between the GOES-10 IR3 temperature and the received 10-GHz signal strength over the W7LHL/W7SZ path. See the text for the meaning of the relative signal strength. Each of the 19 dots represents a different day's measurement. The straight line in the plot is a linear curve fit to the data, showing the trend between temperature and signal strengths.

Observations—1296 MHz

At this point, our interest moved to 1296 MHz. We thought that an eightfold increase in wavelength might help us to learn more about the scattering media. Tests between W7LHL and W7SZ at 1296 MHz ran for several months starting in April of 2002. Signals proved strong enough to be observed on most days, even without the most obvious feature of frequent strong aircraft reflections. Seeing more aircraft than at 10 GHz was not surprising, since the wider antenna beamwidths produced a higher probability of an aircraft being in the common volume.

We soon determined that, as at 10 GHz, signals associated with tropospheric air masses were present. Signal strengths would vary from day to day, but generally the levels were in the range of –145 to –160 dBm. Like the 10-GHz signals, these showed broadened spectra, typically 10 to 20 Hz at the –3-dB points. Generally, there was only a single peak to the spectrum; but on at least one occasion (4 May 2002), double peaks were observed with a spacing of about 8 Hz. The GOES IR3 was indicating a very cold top cloud layer (below –40°C) at the time, and this may be related. This double peak was of particular interest as it had been seen many times at 10 GHz.

Experiments were run with the antennas moved in azimuth at both ends of the path, as had been done at 10 GHz. Again, the signal strength dropped off to the sides; but the main feature observed was a shift in center frequency. An example of this is Fig 13, showing the signal at the southern end of the path.

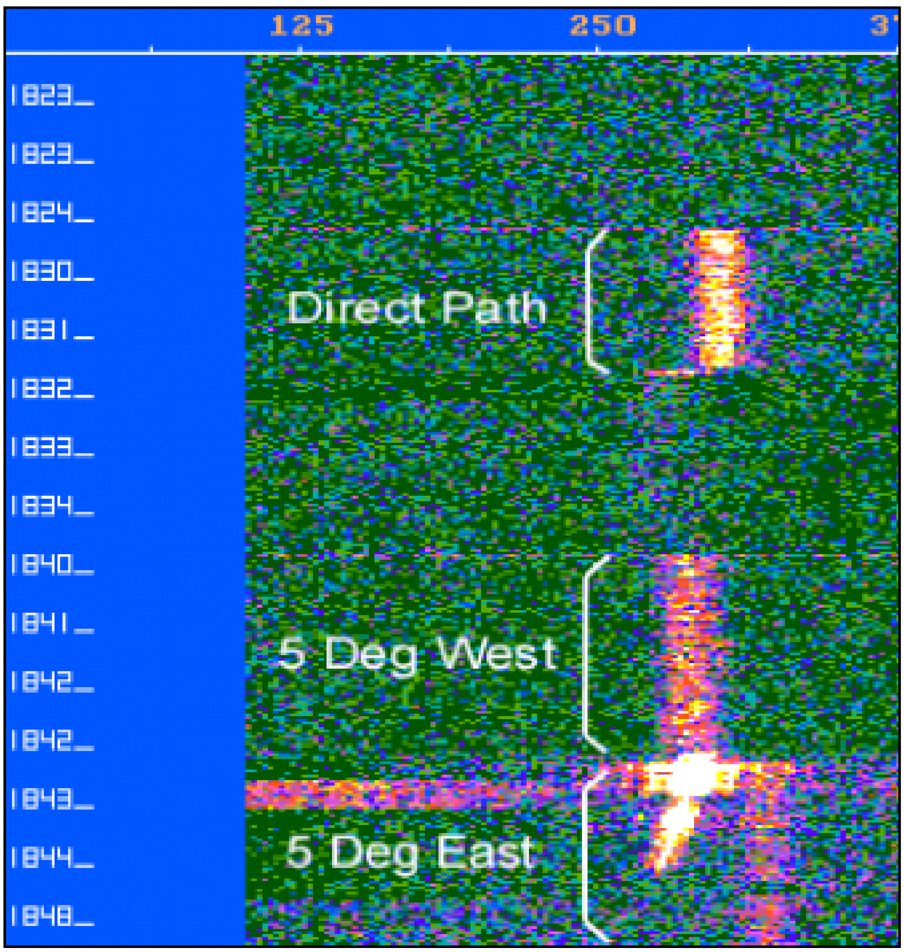

Fig 13—A spectral waterfall plot of the 1296-MHz signal being received at W7SZ, showing the variation in received frequency with azimuth angle. The frequency scale is at the top, and time (to the nearest minute) is on the left. The top segment marked "Direct Path" is for both antennas pointed at one another. This works out to be very close to a north-south path. The two lower segments correspond to azimuthal shifts of 5° east or west. The corresponding change in frequency is ±15 Hz. One probable explanation for this behavior is that the scattering media is in motion with these winds. The bright areas on the left at about 1843 are from an aircraft, and thus irrelevant.

Always in search of data correlation, we looked at the GOES-10 IR3 temperature that seemed to show correlation at 10 GHz. This was quite unsuccessful! Fig 14 is an example of the observed correlation. On that plot, both the strongest and weakest signals were found at a temperature of –30°C. The nine measurements show very little correlation. This agreed with the impressions that we gained from the many measurements. We explored correlation with other measures, generally with poor success. We looked at water-vapor content in the upper troposphere, wind speed and the product of wind speed and water-vapor content. The latter measure showed some correlation, but there were also contrary indications, so more data is needed to see if this is a valid measure of the propagation.

One problem in finding correlation with tropospheric conditions is the scarcity of atmospheric data. The best sources of data are weather balloons. In our area, these are launched twice a day—at 0000 and 1200 UTC. The locations available for our area are Salem, Oregon, and Quillayute, Washington, which are not generally at the center of a propagation path. We are left trying to correlate with data measured at the wrong time or place! Fortunately, the upper-air features generally change slowly. Sometimes, features may change quite rapidly, and this alone could cause poor correlation. In contrast, the GOES IR-3 data are frequently updated, which is beneficial when those data can be used.

Signal Strengths

Although not strong, signals scattered from the upper regions of the troposphere are within the range of many amateur microwave stations. We wanted to try to quantify the losses for this type of propagation. Fortunately, the DSP-10 radio provides an estimate of the received power. (See the sidebar "Total Received Power.") The path between W7LHL and W7SZ will be used as an example, as illustrated in Fig 2.

The density of scattering material can be estimated by looking upon the measurements as a "bistatic" radar,[9] where the transmitter and receiver are geographically separated. The equation for the received power is:

$$P_r = \frac{P G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t^2 R_r^2} \qquad \text{(Eq 1)}$$

where

P_r = received power in watts

P = transmitted power in watts

G_t = transmitter antenna power gain as a ratio

G_r = receiver antenna power gain as a ratio

λ = wavelength in meters

σ = bistatic radar cross section in meters, discussed below

R_t = distance from the transmitter to the scattering particles in meters

R_r = distance from the receiver to the scattering particles in meters

Radar cross-section, σ, refers to the size of a hypothetical reflector that returns all the energy it intercepts. Jet aircraft cross sections are commonly 10 to 100 m^2. For the path from W7LHL to W7SZ, a received signal of –150 dBm at 10 GHz corresponds to a cross section of about 0.001 m^2. We will now try to put this into perspective.

It seems reasonable to assume that the scattering is coming from material distributed throughout the commonly visible volume. Some layering might occur that would produce more scattering at one height than at another; however, it is informative to estimate the density of scattering material and for this purpose, we will assume the density is uniform. One might envision that the first particles encountered would shadow those further away. As we will see, the densities are so low that this would be most unlikely.

The volume of the two intersecting beams is approximately the area of the smaller beam times the width of the larger beam divided by the sine of A, the angle between the beams. For the W7LHL/W7SZ case, the smaller beam is from W7LHL, as the common volume is closer to that station. For short paths, this angle is the sum of the elevation angles of the two stations, or in our case, about 13.5°. Thus the common volume is about

$$\textit{Common Volume} \approx \frac{\pi (B_t R_t)^2 B_r R_r}{4 \sin A} \qquad \text{(Eq 2)}$$

where B_t and B_r are the transmit and receive beamwidths in radians (degrees $\times \pi / 180$). This assumes that the transmit path has a smaller beam area; else the transmit and receive subscripts should be reversed.

For the W7LHL/W7SZ case, the common volume at 10 GHz is about 1.7 km^3 or 1,700,000,000 m^3. This is the volume required to provide a scattering cross section of about 0.001 m^2 (about 1.5 $inch^2$). In terms of scattering signals, it is obviously a sparsely occupied volume!

If the scattering is nearly uniform throughout the common volume, it suggests that smaller antennas may result in only modest decreases in signals. If both stations were to cut their antenna size by half, the antenna gain would drop by 6 dB at each end—or 12 dB over the total path. The common volume would increase by $2^3 = 8$, or 9 dB, and make up for all but 3 dB of the antenna's reduced gain. We have not experimentally measured this scaling, but it should encourage those with smaller antennas to explore these scattering mechanisms.

Possible Scattering Media

Part of the fun of these experiments has been postulation about scattering media. The RF signal strength and spectrum measurements provide only indirect indications of the nature of

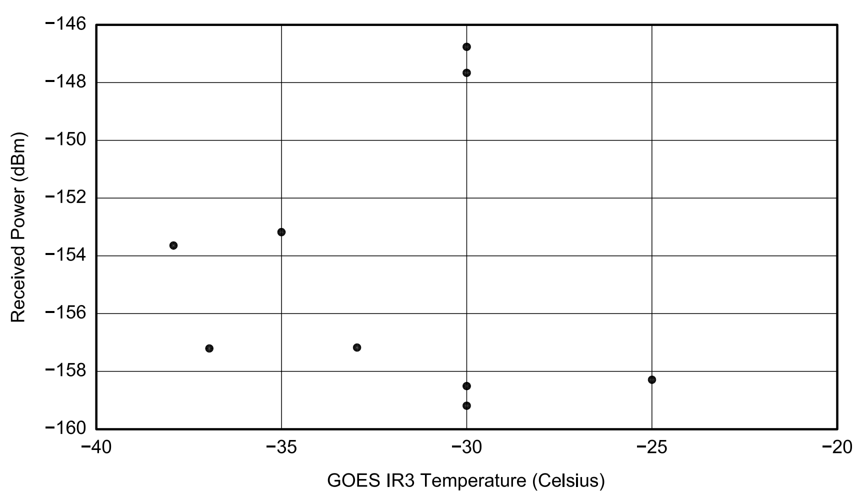

Fig 14—1296-MHz signal strength of W7LHL received at W7SZ is plotted here as a function of the observed GOES10 IR3 temperature. The correlation at this lower frequency is much less than observed at 10 GHz. That is seen here as randomness in the positions of the data points.

the media. Likewise, only limited data are available for the amount and character of the water vapor in the upper troposphere. One must search for an explanation that is consistent with both types of observations. In the following, we will explore several possibilities. Any scattering that occurs in the troposphere might be included in the term "tropospheric scattering," and so we are attempting here to be more specific about the media involved.

The location of the scattering media in the upper troposphere seems highly probable. If earthbound features such as mountains or sharp rocky edges were involved, there should not be a Doppler shift. Yet, Doppler measurements show a net movement of the scattering media that correlates with weather-balloon measurements of the winds in the common scattering volume. The Doppler shift consistently varies with the antenna direction. Pointing the antennas towards the wind source causes positive Doppler shifts while pointing away from the source causes negative shifts.

Rain scatter is precluded for two reasons: The signals are present on many occasions when no rain exists, either as observed by the station operators or as would be expected from the weather conditions. In addition, on paths where rain scatter is observed (never on the W7LHL/W7SZ path), the spectrum is much broader—often by hundreds of Hertz—than has been observed for upper-tropospheric scattering. This spectral broadening is associated with the noisy sound that operators report on rain scatter, sometimes making these signals difficult to copy with the ear. A net incoming (positive) Doppler shift is observed as a result of falling rain.

Aircraft scatter produces strong signals that are readily identified on the spectral display from the Doppler changes. Aircraft following a straight course will always start with a positive Doppler shift and end with a negative shift. These signals have often been observed on the paths such as W7LHL to W7SZ or W7SZ to W7PUA. For situations where aircraft are frequently present and where the changing Doppler shift is tolerable, these reflectors can be a major aid to communication. They were not our objects of primary interest, though, and we have consistently selected data where aircraft were not present.

This leaves the upper troposphere as our scattering material. Two possibilities have been identified: ice particles and water-vapor boundaries.[10]

Under certain conditions in the upper troposphere, water vapor can produce ice. Ice particles would be small compared to either of our wavelengths. This type of scattering object, called Rayleigh scattering, produces a scattering cross section that varies inversely with the fourth power of the wavelength. On a per-particle basis, the 1296-MHz signals would be about 36 dB below those at 10 GHz.[11] The larger beamwidths of the lower frequency would, however, have a larger number of particles in the common volume, making up most of the difference. Ice particles can have sufficient mass and volume to cause them to fall vertically. This could be responsible for some of the Doppler shifts observed.

Water-vapor irregularities produce boundaries of changing dielectric constant. These boundaries are continually altered by turbulence in the troposphere. This effect has generally been considered the dominant cause of tropospheric scatter.[12] Gannaway published a summary of this propagation mechanism, along with a model for the expected signal strengths.[13] This model gives poor results for the paths that we have been exploring, underestimating the signal strengths of the W7LHL/W7SZ path by 50-70 dB and overestimating the W7SZ/W7PUA path by 20-30 dB. The fading rates reported by Gannaway are in general agreement with our observations, though.

One would expect the water-vapor boundaries to be swept along with the winds, much as a cloud travels across the sky. The average movement causes fixed Doppler shift while the turbulence around the boundaries causes broadening of the spectrum. This is all consistent with the observations.

Our observations of two separate signal spectra suggest that two different scattering materials might be involved. Our current speculation is that these are ice particles and turbulent water-vapor boundaries.

Further Exploration

Amateur Radio allows one to explore areas such as propagation at will. Our experiments over the last year and a half have led to more questions than answers! There are many opportunities

Doppler Shift from Moving Media

The upper levels of the troposphere are windy. Wind speeds are seldom less than 50 km/hr. At times, jet-stream speeds over 150 km/hr are common and they can sometimes be twice that value. When the scattering media are moving with this wind, there will be Doppler frequency shifts on the received signals, depending on the details of the geometry.

The propagation paths that we have used are essentially north-and-south. The prevailing winds are at right angles to these paths, or west-to-east, as shown in Fig A. For this geometry, the Doppler shift is zero when the two stations point directly at one another. With the antennas shifted to either side of the direct path, however, there is a Doppler shift that is proportional to the beam angle, as shown in the figure. Comparisons between this Doppler shift and the radiosonde balloon wind-velocity data is good confirmation that the scattering is from the moving medium. [For θ from 1° to 58°, sin θ ≈ θ in radians —*Ed.*]

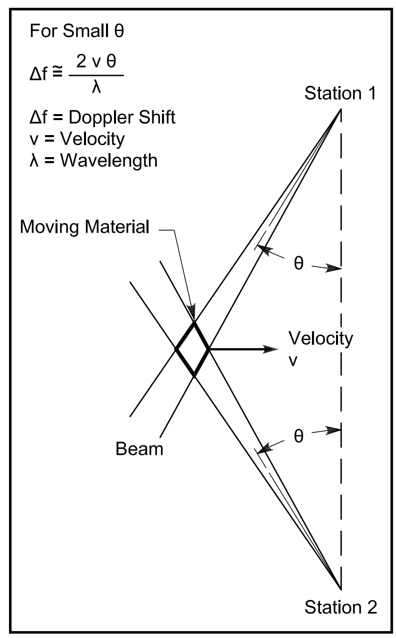

Fig A—Geometry for observing the Doppler shift on a signal that has been scattered by a moving media. The antenna beams have been shifted off the direct path. Angles are in radians, which are about 0.01745 times the angle in degrees. The distance units for velocity and wavelength should be the same and the velocity should be in distance units per second. Then the Doppler frequency shift will be in hertz. This geometry is specific to a path at right angles to the moving media.

for others to add to our knowledge of tropospheric propagation.

For instance, all of our work has been done in the maritime climate of the US Pacific Northwest. Other regions may exhibit different properties. We have had very little opportunity for working with cumulonimbus thunderstorm systems. Those should be interesting sources of scattering.

Multiple types of scattering have been observed, but we feel these are not fully understood. What is the role of ice particles and turbulent water-vapor boundaries? Are other factors, such as dust or insects involved? Our experiments have only involved the two frequencies of 1296 and 10,368 MHz. Further work at other frequencies is likely to show interesting results. The common-volume concept suggests diminishing returns for increasing antenna sizes. This area could lend itself to considerable exploration.

Besides what we have listed here, there must be many more interesting areas of exploration in the troposphere. Every answer found seems to suggest a new list of questions!

Conclusion

Microwave signals have been exchanged over several obstructed paths in the US Pacific Northwest. This includes the 159-km path between W7LHL and W7SZ that would seem to be so obstructed as to preclude any sort of knife-edge refraction or reflection from mountains. The local horizons for this path are about 9.5° and 4°. The lowest mutually visible volume is in the troposphere at about 28,000 feet above the Earth's surface.

Using DSP-10 radios, along with phase-locked transverters for 1296 MHz and 10,368 MHz, it was possible to measure the Doppler shift on the path and from this, to determine that the scattering media were moving. By movement of the parabolic dish antennas to either side of the shortest path, it was possible to make rough estimates of the scattering-object speed and direction. This was found to correlate reasonably well with the velocity vectors at this height above the Earth, as determined by radiosonde balloon measurements.

In addition, it was found at 10 GHz that the signal-strength level increased with the height of the top of any cloud layer. GOES-10 IR3 infrared data was used to estimate the height of the cloud top. This effect was so strong on 10 GHz that signals often became too weak to measure when the top of the cloud layer was below the height of the commonly viewable volume. At 1296 MHz, the variations in signal strength were not as great and signals were found on most days, regardless of the cloud top height.

It is reasonable to associate this signal propagation with scattering from some suitable medium. Scattering stands in contrast to refraction. Refraction bends an RF wave in layers of varying dielectric constants. Scattering refers to re-radiation from some medium that is being excited by an incident wave. With antennas at both ends of the path off the direct heading, the ability to propagate signals is associated with scattering.

For the paths we explored, signals were being propagated by scattering in the upper levels of the troposphere from about 4.5 km (15,000 feet) to 9 km (30,000 ft), or higher. We tried to deduce the details of the scattering medium. The cirrus clouds associated with the stronger signals were typically at –40°C. Any condensed water vapor would be in the form of ice. A second possible scattering medium would be rapid changes in water-vapor content, such as small vortices that have been claimed to be responsible for some tropospheric scattering. Frequently on 10 GHz—and rarely on 1296 MHz—there is Doppler evidence that two different scattering media are involved, each moving with a different velocity. We have been unable to be specific about the scattering media.

In summary, we have been able to communicate over some difficult microwave paths between home stations. Scattering in the upper troposphere has been successful for this purpose. The signals are not strong, but this propagation mode has allowed us to communicate over paths when other modes were not available. We are still learning about the scattering media involved. We encourage others to join us in this endeavor. The study of propagation can be a fun and rewarding activity that extends beyond the making of conventional contacts. In addition, the signals being exchanged are sufficient for making contacts and represent a challenge for the better-equipped stations.

This has been a learn-as-you-go experience for us. We received assistance in understanding the multiple disciplines involved in this project from many helpful individuals. We would especially like to thank Don Hillger, WDØGCK, of Colorado State University for help with the GOES IR3 data and Mike Reed, KD7TS, for important measurements as well as leads to many useful weather data sources; and Matt Reilly, KB1VC, for supplying the path-profile plots. Thanks to Beb Larkin, W7SLB, for help with coordination of the measurements.

Notes

[1]See, for example, E. Pocock, W3EP, "Chapter 3, UHF and Microwave Propagation," *The ARRL UHF/Microwave Experimenter's Manual,* (Newington, Connecticut: ARRL, 1990).

[2]T. Williams, WA1MBA, "10 GHz—A Nice Band for a Rainy Day," *CQ VHF*, Feb 1997.

Total Received Power

The spectral display of the DSP-10 is an estimate of the signal-plus-noise (S+N) power at each of many frequency bands. These bands are narrow and have selectable spacings of 2.3, 4.7 or 9.4 Hz. At microwave frequencies, the signals' total spectral width is often wider than a single band, because of the propagation-path modulation. The total received power, measured across all the spectral signal bands, is often the quantity of interest. This quantity is calculated as follows.

First, the noise power in each band is found and referenced to the antenna input. This is the sum of the noise powers from the receiver and external noise sources. For the experiments described here, the latter quantity is dominated by Earth noise when the antenna beam is along the horizon. If the total receiver noise power were expressed in kelvins as the system noise temperature,* T_s, the noise power in a band of B Hz would be $n = K\ T_s\ B$ W, where K is Boltzmann's constant or 1.38×10^{-23} joule/kelvin.

By observing the average spectrum at frequencies where signals are absent, the receiver power response for noise, n, can be found. If the $S+N$ power response were divided by this noise power, we would have $(S+N)/N$.

At this point, we would have removed the effect of the receiver gain, since we would be using the same signal path for both $S+N$ and N. The signal-to-noise ratio could now be found: $(S+N)/N = 1+(S/N)$. Knowing N, we could calculate S. So the process of finding signal power involves starting with $(S+N)/N$ (as a power ratio, not in decibels), subtracting 1 and multiplying by the noise power, in watts.

*Bob Atkins, KA1GT, "Estimating Microwave System Performance," in Chapter 7 of *The ARRL UHF/Microwave Experimenter's Manual,* (ARRL, 1990).

[3]E. B. Shera, W5OJM, "A GPS-Based Frequency Standard," *QST*, July 1998, pp 37-44.

[4]The DSP-10 transceiver project was originally described in a three-part article by Bob Larkin, W7PUA, "The DSP-10: An All-Mode 2-Meter Transceiver Using a DSP IF and PC-Controlled Front Panel," *QST*, Sep, Oct and Nov 1999. See also **www.proaxis.com/~boblark/dsp10.htm**.

[5]P. Martinez, G3PLX, "Narrow-Band Doppler Spectrum Techniques for Propagation Study," *QEX*, Sep/Oct 1999, pp 45-51. This paper demonstrates the use of Doppler-spectrum measurements to imply changes in the propagation media at HF. Although the media are different from that explored in this paper, the measurement principles are the same.

[6]See Note 1.

[7]See **www.cira.colostate.edu/ramm/rmsdsol/ROLZIP.HTML** with links from there to specific images. The temperature at the upper levels of the clouds is indicated by the IR3 wavelength as viewed by the GOES satellites.

[8]For North America, information about the atmosphere can be obtained from the weather-balloon data linked from the Web site **www.rap.ucar.edu/weather/upper/**. The balloons measure dry and wet bulb temperatures and barometric pressure.

[9]The conventional radar "range equation" is for a co-located transmitter and receiver. A similar equation exists for a separated transmitter and receiver. See, for example, David K. Barton, *Radar System Analysis*, (Englewood Cliffs, New Jersey: Prentice-Hall, 1964) Section 4.3.

[10]Insects and dust are sometimes offered as scattering material. Because of both the height of the common volumes and having the prevailing winds from the Pacific Ocean, we suspect that insects are unlikely. We have been unable to quantify the possibilities of dust scattering, but we should have a relatively poor area of the Earth for such material.

[11]Assuming that the antenna sizes, receiver sensitivities and transmitter powers are kept constant.

[12]A summary of tropospheric scattering is in "Radio Transmission by Ionospheric and Tropospheric Scatter," *Proceedings of the IRE*, Jan 1960, pp 5-44.

[13]J. N. Gannaway, G3YGF, "Tropospheric Scatter Propagation," *QST*, Nov 1983, pp 43-48. Essentially the same material was first published under the same title in the RSGB *Radio Communications,* Aug 1981. It is also in M. W. Dixon, G3PFR, Editor, *Microwave Handbook,* Vol 1, (Radio Society of Great Britain, 1989), section 3.2.4.

Bob Larkin, W7PUA, has been active in Amateur Radio since he was first licensed in 1951 as WN7PUA. He received a BS in EE from the University of Washington and an MSEE from New York University. He is a consulting engineer for communications companies. His current interests are VHF through microwave propagation and weak signal techniques using DSP.

Larry Liljequist, W7SZ, has been a licensed for 46 years, previously holding calls WF8C, G4BIR and W7EKI. He has a BSME from Oregon State University (1959), and is retired from Caterpillar Inc.

Ernie Manly, W7LHL, was licensed in 1947. He is no stranger to the pages of ARRL publications. His article, "A Two-Meter Transverter," appears in the Sep 1963 QST. *He co-authored "Crystal Control on 10,000 Megacycles" with L. F. Garrett, W7JIP (*QST, *Nov 1963). He and W7JIP set world distance records on 10 GHz in 1959 and 1960. For a history of 10-GHz activity, browse to* **www.g3pho.free-online.co.uk/microwaves/history.htm**. □□