**Joseph H. Taylor, K1JT**

272 Hartley Ave, Princeton, NJ 08540: **k1jt@arrl.net**

# High-Accuracy Prediction and Measurement of Lunar Echoes

*K1JT describes a series of recent lunar echo measurements at 144 and 432 MHz, and tests his new* EMEcho *software to predict and measure Doppler shift, frequency spread, and polarization of EME signals using amateur equipment.*

## 1. Introduction

For me, one of the fascinations of amateur Earth-Moon-Earth (EME) communication is the range of interesting physics that accompanies it. Motivated in part by a need to test a new software program called *EMEcho*, and also by a desire to see how well I could predict and measure the phenomena of Doppler shift, frequency spread, and polarization of EME signals using amateur equipment, I recently made an extensive series of lunar echo measurements at 144 and 432 MHz. This paper describes how the measurements were made and presents a selection of results.

Doppler shifts of EME signals are caused by continuous changes in the total line-of-sight distance between a transmitter, reflecting or scattering spots on the lunar surface, and a receiver. The relevant rates of change are usually dominated by Earth rotation, which at the equator amounts to about 460 m/s. As a consequence, two-way Doppler shifts can be as large as ± 440 Hz at 144 MHz, ± 4 kHz at 1296 MHz, and ± 30 kHz at 10 GHz. Different reflection points on the lunar surface produce slightly different Doppler shifts, so the echo of a monochromatic signal is spread out over a small and predictable frequency range. The full range of spread can be as large as 4 Hz at 144 MHz and 300 Hz at 10 GHz. However, at VHF and UHF a majority of reflected power is returned from a region near the center of the lunar disk, so the observed half-power Doppler spread is always considerably less than the full limb-to-limb amount.

A smooth moon would produce a specular reflection that preserves linear polarization and reverses the sense of circular polarization. A rough moon (on the scale of one wavelength) would produce diffuse echoes and significant depolarization; cross-polarized return echoes might be just a few dB weaker than the dominant polarization. At VHF and UHF frequencies the circumstances are closer to the specular limit. Received echoes should be almost fully polarized, and with linear polarization they should have a polarization angle that depends on geographic locations of the transmitter and receiver and the amount of ionospheric Faraday rotation.

Together with our knowledge of solar-system dynamics, the relevant physics is such that EME Doppler shifts can be calculated with high accuracy (parts in $10^{10}$, or better) for any time and any terrestrial location. Maximum Doppler spread across the full lunar disk is also predictable. Faraday rotation depends on latitude, moon elevation, time of day, solar activity, and ionospheric "weather"; the resulting effects are generally not predictable in detail. For optimum efficiency, EME operators must know about and take account of this full range of phenomena, both predictable and otherwise.

## 2. Equipment Setup

I used single-station echo tests to measure Doppler shift, frequency spread, and polarization during the moon pass of January 2-3, 2015. My equipment was that of the 144 MHz EME station at K1JT and the 432 MHz station at W2PU, the Princeton University Amateur Radio Club. The two stations are configured in a similar way. Both have four dual-polarization Yagis — 4×2Mxp28's at 144 MHz[1] and 4×15LFA-JT's at 432 MHz.[2] Both stations use a single low-loss feed line for transmitting and separate LNAs and receive feed lines for each polarization. The receivers use dual-channel down-converters to produce four baseband signals, *I* and *Q* (in-phase and quadrature) for each polarization. WSE converters by SM5BSZ[3] were used at 144 MHz, and the IQ+ receiver by HB9DRI[4] at 432 MHz. Four-channel sound cards (M-Audio Delta44) digitize the *I/Q* signals at 96000 samples per second, and in normal EME operation all further processing takes place in the computer programs *Linrad*[5] and *MAP65*[6]. For this echo experiment my new program *EMEcho* was used in place of *MAP65*. Transmitter power was about 500 W at the antenna, at each station.

### 2.1 EMEcho Software

*EMEcho* is a new program designed to make reliable tests of lunar echoes from an amateur EME station. It goes beyond the Echo mode available in *WSJT* in two important ways. Doppler calculations are done with state-of-the-art accuracy, based on the Jet Propulsion Laboratory's DE405 planetary ephemeris.[7] In addition, *EMEcho* takes full advantage of a dual-polarization system by measuring the polarization as well as the frequency and strength of echo signals.

The basic echo-testing cycle is similar

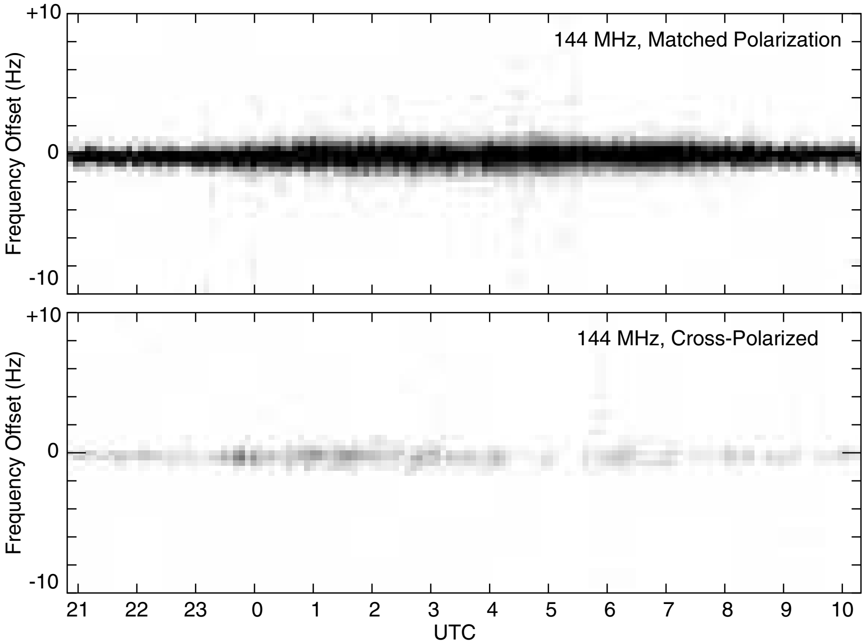


**Figure 1 — Measured echo power at 144 MHz as a function of frequency offset and time. Upper: linear polarization angle matched to that of the echo. Lower: orthogonal linear polarization.**

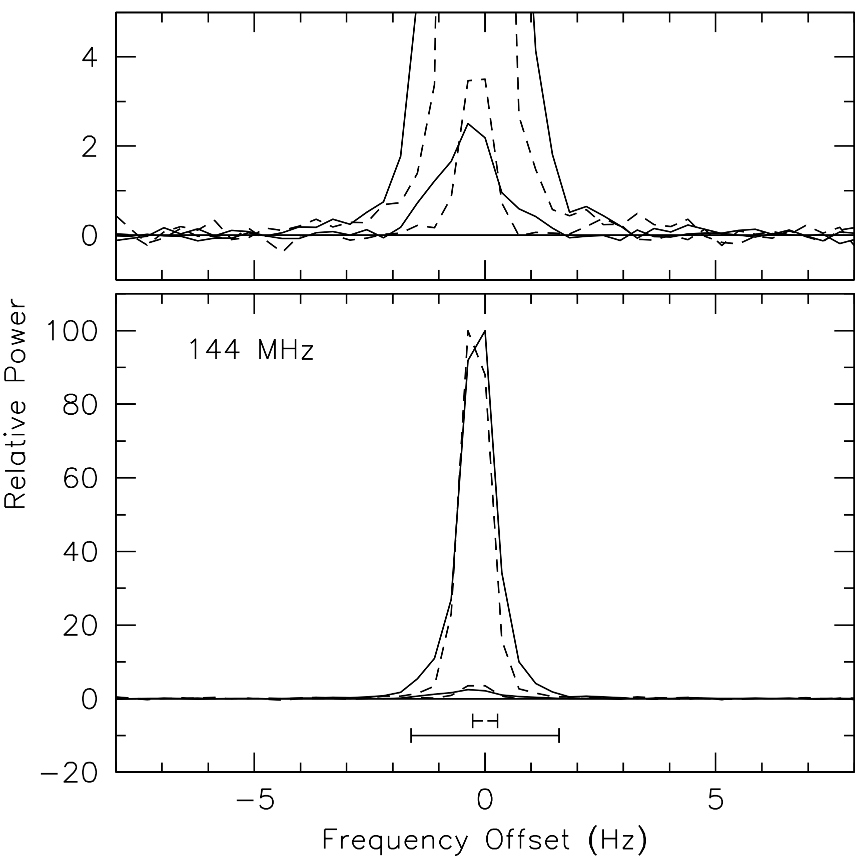


**Figure 2 — Frequency structure of echoes at 144 MHz near meridian transit (solid line) and near 2130 UTC, a time of minimum libration rate (dashed line). The upper panel uses an expanded vertical scale to show the weakest spectral features. Horizontal bars in the lower panel indicate the full range of predicted Doppler spread. The pair of curves with intensity a few percent of maximum show the measured cross-polarized power, which in this case may be mostly a result of minor alignment imperfections in the K1JT antenna. Horizontal bars in the lower panel indicate the full limb-to-limb ranges of predicted Doppler spread.**

to that used in program *WSJT*. The cycle repeats every six seconds, starting at 0, 6, 12, ... seconds of a UTC minute. A fixed-frequency tone is transmitted for 2.3 s, the echo is received and recorded about 2.5 s later, and the spectrum is computed, displayed, and (if desired) recorded in a disk file. In a dual-polarization *MAP65*-compatible system, spectra can be displayed for both the matched linear polarization and the orthogonal polarization.

## 3. Measurements

A six-second measurement cycle means that some 8400 2.3-second pulses were transmitted at each station over the full moon pass. A few of the return echoes were rejected for failing a simple interference test; the remainder were averaged in groups of 10 to produce about 800 sets of polarized spectra. Measurements are reported here for both 144 and 432 MHz. They include frequency profiles of the echoes with bin spacing 0.37 Hz, Doppler shifts accurate to around 0.1 Hz, and polarization angles accurate to a few degrees.

### 3.1 Doppler Shift and Doppler Spread

Figure 1 is a grayscale plot showing matched-polarization and cross-polarized echo strengths as a function of frequency and time. No *ad hoc* frequency adjustments have been made; the plotted "Frequency Offset" is that of the received spectrum relative to the predicted Doppler shift. The Doppler shift, in turn, is based on station location, UTC according to the internet-synchronized computer clock, and the JPL DE405 planetary ephemeris. The grayscale chosen for Figure 1 is logarithmic, so as to emphasize the weakest features.

It's easy to see that the frequency width of return echoes is greater in the middle of the run than near either end. These differences are consistent with the predicted dependence of Doppler spread during the course of a moon pass. Further details of this effect can be seen in Figure 2, where spectra have been averaged over about an hour near the times of minimum and maximum libration rate. Dashed curves represent the echo profile around 2130 UTC, shortly after moonrise, while solid curves are the average spectral profile around 0330 UTC, near lunar culmination.

Figures 3 and 4 display the corresponding results obtained at 432 MHz. Again the measured frequency offsets are essentially zero (within the measurement uncertainties). Doppler spreads are rather more than 3 times larger than at 144 MHz, owing to the higher frequency and the somewhat larger size of the lunar reflecting region. Cross-polarized echo signals are essentially undetectable in the grayscale plot and only barely visible in the expanded view (upper panel) of Figure 4. It is interesting to see that at both frequencies the weak wings of the spectral profile extend out to the full calculated limb-to-limb Doppler spread — as they should, with adequate sensitivity. These effects have been noted before by EME operators.[8,9]

I consider the Doppler calculations used in this paper to be the best achievable with today's knowledge of solar system dynamics. The JPL DE405 ephemeris represents a numerically integrated model of the solar system based on several hundred years of astronomical observations, radar observations of planets out as far as Saturn, and tracking observations of many interplanetary spacecraft. Positions and velocities of the Earth and Moon (and many other solar system objects) are tabulated in a data file suitable for numerical interpolation. Doppler calculations in *EMEcho* include the following steps:

1. Convert geodetic coordinates of the antenna to geocentric coordinates, accounting for the Earth's oblateness.
2. Convert UTC to UT1 and to LAST (local apparent sidereal time). Note that UTC runs at an essentially constant rate defined by the average of many atomic clocks, plus occasional leap seconds. UT1 represents the actual measured rotation of the Earth. UTC and UT1 can differ by up to ± 0.9 s.
3. Compute 3-dimensional position and velocity of the antenna with respect to center of Earth.
4. Convert UTC to ET (Ephemeris Time), accounting for all leap seconds up to the present.
5. Interpolate the DE405 ephemeris to obtain the 3-dimensional position and velocity of center of moon relative to center of Earth.
6. Combine results of items 3 and 5 to get position and velocity of antenna with respect to moon.
7. Calculate Doppler shift from the line-of-sight component of velocity obtained in item 6.

Achieving the accuracies required to produce the results presented in Figures 1 through 4 requires knowledge of antenna coordinates to better than one km and clock accuracy better than one second. The transmitter frequency in the antenna's reference frame must also be specified accurately: for example, 144.118 MHz rather than 144 MHz. The Doppler calculations must avoid certain shortcuts and approximations that have typically been used in amateur EME-related software, including my own programs *WSJT* and *MAP65*.

Figure 5 illustrates some potential consequences of ignoring one or more of the

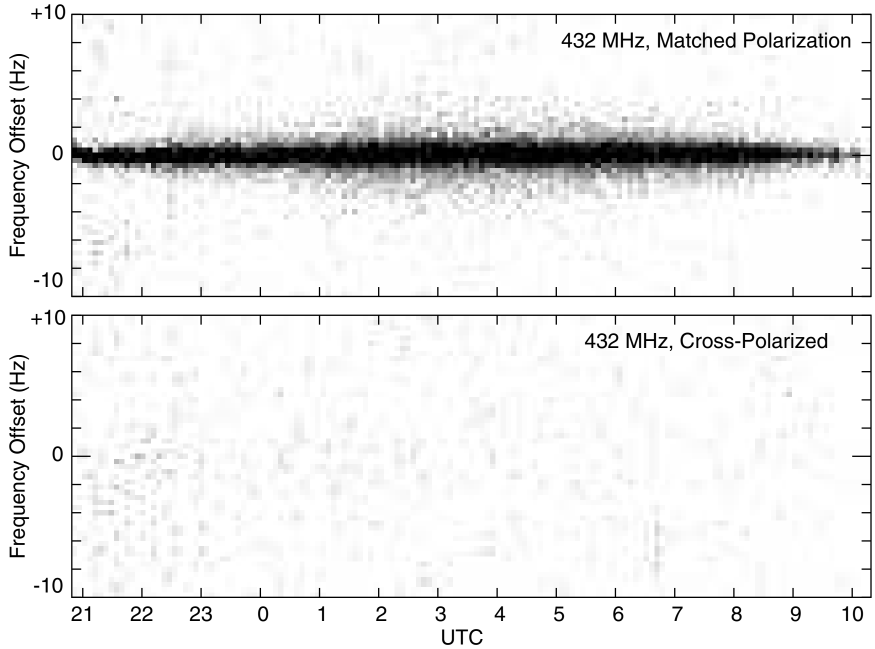


**Figure 3 — Measured echo power at 432 MHz as a function of frequency offset and time. Upper: linear polarization angle matched to that of the echo signal. Lower: the orthogonal linear polarization.**

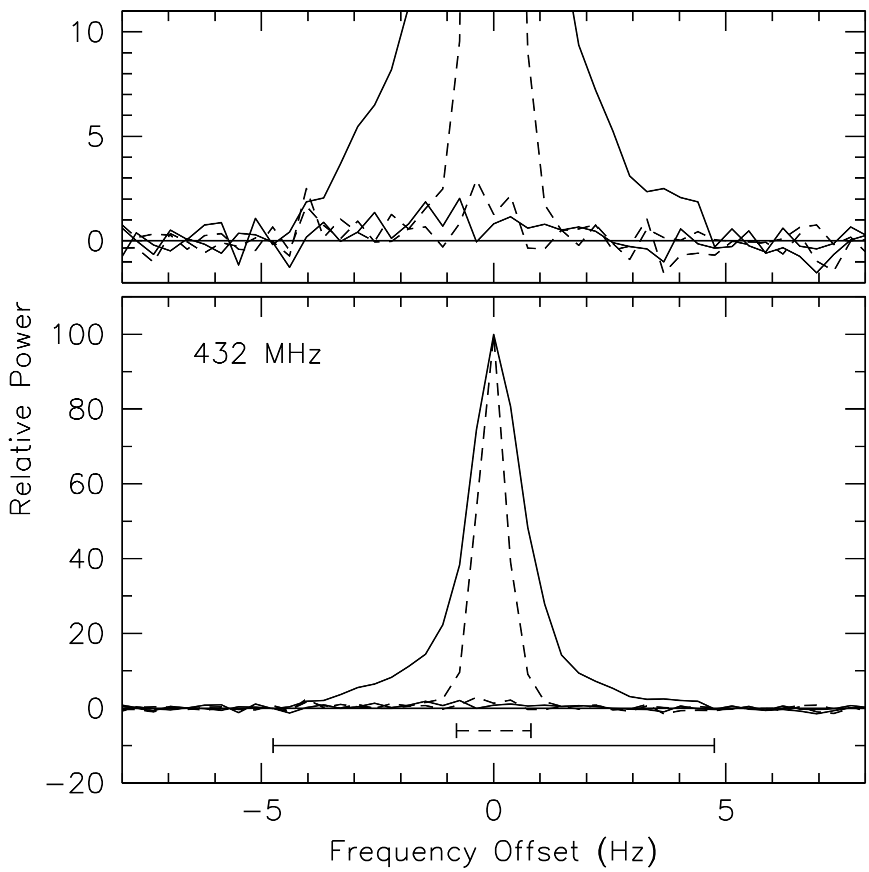


**Figure 4 — Frequency structure of echoes at 432 MHz near meridian transit (solid line) and near 2130 UTC, a time of minimum libration rate (dashed line). The upper panel uses an expanded vertical scale to show the weakest features. Horizontal bars in the lower panel indicate the full limb-to-limb ranges of predicted Doppler spread.**

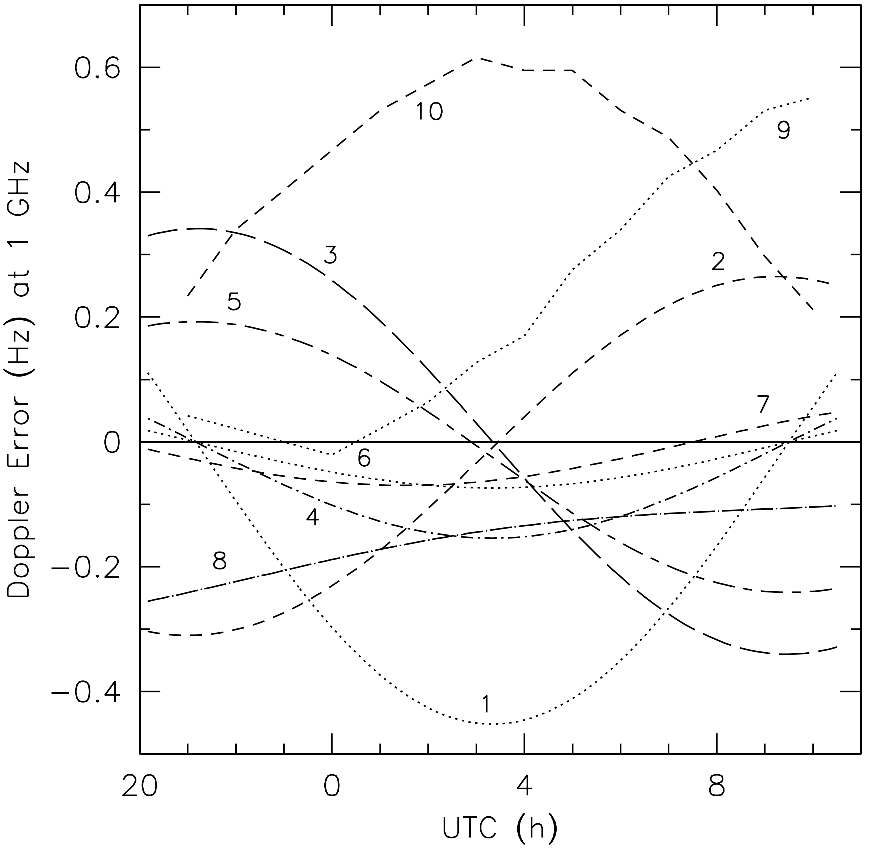


**Figure 5 — Examples of contributions that might affect the accuracy of computed Doppler shifts.**

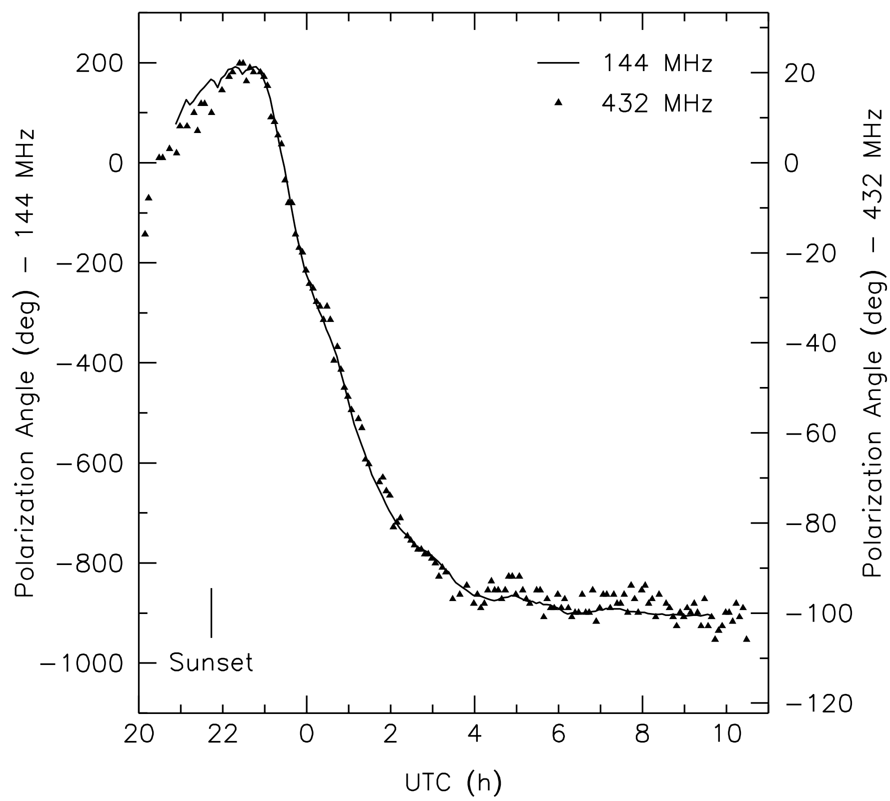


**Figure 6 — Measured polarization angles at 144 MHz (left scale) and 432 MHz (right scale).**

warnings mentioned above. To produce this graph I used GPS-measured coordinates of the W2PU antenna and calculated Doppler shifts at a nominal frequency of 1.0000 GHz, at frequent intervals from moonrise to moon set on January 2-3, 2015, the date of my echo-test observations. The horizontal straight line at zero represents my supposed state-of-the-art calculation. The ten numbered curves show the differential effects of various changes, omissions, or assumptions in the Doppler calculation, as follows:

1. Antenna moved 1 km East.
2. Antenna moved 1 km North.
3. Antenna moved to 1 km higher elevation.
4. UTC clock error +1 s.
5. Frequency changed to 1.0001 GHz.
6. Time difference UT1-UTC ignored.
7. Nutations ignored.
8. Calculation of moon position based on a closed-form series expansion rather than interpolation of the DE405 ephemeris.
9. Doppler calculation made by program *EME Planner*, by VK3UM.[12]
10. Doppler calculation made by program *EME System*, by F1EHN.[11]

I call particular attention to several points relating to Figure 5. First, the Doppler calculations in *EME Planner* and *EME System* are very good — in this example, accuracies better than 1 Hz at 1 GHz, through a full moon pass. Note that in order to obtain this accuracy you must start with very accurate station coordinates: a six-digit Maidenhead locator is not good enough. Your computer clock must be synchronized to UTC and your software must be updated with the latest leap seconds. And you must use the actual transmitter frequency, not just the frequency of the band edge, for example. Careful use of *EMEcho* should give Doppler predictions even better than those of *EME Planner* and *EME System*, accurate to about 1 Hz at 10 GHz.

### 3.2 Polarization

In addition to Doppler shift and Doppler spread, my experiment yielded polarization measurements at both 144 and 432 MHz. The polarized spectra recorded on disk were averaged over five-minute intervals. The resulting polarization angles are plotted in Figure 6. A solid line connects sequential measurements at 144 MHz. As shown by the scale at left, these angles increased gradually from about 60 degrees to 200 degrees in the two hours around local sunset. The angles then decreased through some 1080 degrees — three full turns — over the next five hours. Subsequent angles decreased only slightly more from 0400 UTC (an hour before local midnight) until moon set, about two hours before sunrise.

Polarization angles measured at 432 MHz

are plotted as filled triangles in Figure 6, using the scale at right. Note that the left and right scales are in the ratio of 9 to 1. The close tracking of the scaled results at the two frequencies is an excellent confirmation that Faraday rotation scales inversely as the square of frequency.

## 4 Conclusion

Program *EMEcho* requires a *MAP65*-compatible EME station and was written mainly for my personal use. However, all of its features except the dual-polarization capability have been incorporated into the *WSJT-X*, the latest program version in the *WSJT* project.[12] *WSJT-X* also offers a number of features such as automatic rig control and Doppler tracking, which make it especially attractive for amateur EME communication on any band.

*Joe Taylor was first licensed as KN2ITP in 1954, and has since held call signs K2ITP, WA1LXQ, W1HFV, VK2BJX and K1JT. He was Professor of Astronomy at the University of Massachusetts from 1969 to 1981 and since then Professor of Physics at Princeton University, serving there also as Dean of the Faculty for six years. He was awarded the Nobel Prize in Physics in 1993 for discovery of the first orbiting pulsar, leading to observations that established the existence of gravitational waves. After retirement he has been busy developing and enhancing digital protocols for weak-signal communication by Amateur Radio, including JT65 and WSPR. He chases DX from 160 meters through the microwave bands.*

## Notes

[1]**www.m2inc.com**.
[2]Joe Taylor, K1JT, and Justin Johnson, GØKSC. *Dubus*, 4/2014, p 53.
[3]**www.sm5bsz.com/linuxdsp/optrx.htm**.
[4]**www.linkrf.ch/**.
[5]**www.sm5bsz.com/linuxdsp/linrad.htm**.
[6]**physics.princeton.edu/pulsar/K1JT/map65.html**.
[7]**ftp://ssd.jpl.nasa.gov/pub/eph/planets/fortran/userguide.txt**.
[8]**www.sm5bsz.com/sm5frh/sm5frh.htm**.
[9]**physics.princeton.edu/pulsar/K1JT/EME2010_K1JT.pdf**.
[10]**www.vk3um.com/eme%20planner.html**.
[11]**www.f1ehn.org/**.
[12]**physics.princeton.edu/pulsar/K1JT/wsjtx.html**.