Moonbounce at W2PU

Adaptive Polarization at 432 MHz

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We have built a highly capable 432 MHz EME station for the Princeton University Amateur Radio Club. Its dual-polarization ("X-pol") antenna is lightweight, modest in size, rugged, and easy to point in azimuth and elevation. An important station feature is its adaptive polarization capability, rendering moot the problems of Faraday lockout and one-way propagation often experienced by single-polarization EME stations on this band. With transmitter power of several hundred watts at the antenna, a station like ours is capable of working any comparably equipped station over the EME path whenever the moon is visible to both. We hope that some of our design ideas will be useful to others considering entry into the EME fraternity on the 70 cm band.

Why 432 MHz ?

The 222 and 902 MHz bands are not available world-wide, and EME antennas for 144 MHz are too large for our purpose. We have a 2.3 m dish equipped for an undergraduate advanced lab experiment observing galactic neutral hydrogen at 1420 MHz. In principle this dish could be outfitted for 1296 MHz EME; however, for a number of reasons we decided to develop EME capability at 432 MHz instead. As illustrated in Figure 1 and discussed in detail in reference [1], achievable system noise temperatures are nearly as low there as at 23 cm. Equipment for 70 cm is relatively easy to build and widely available off the shelf. It seems that in many ways 70 cm is the most under-utilized of all EME bands, and we hope to encourage a reversal of this trend.

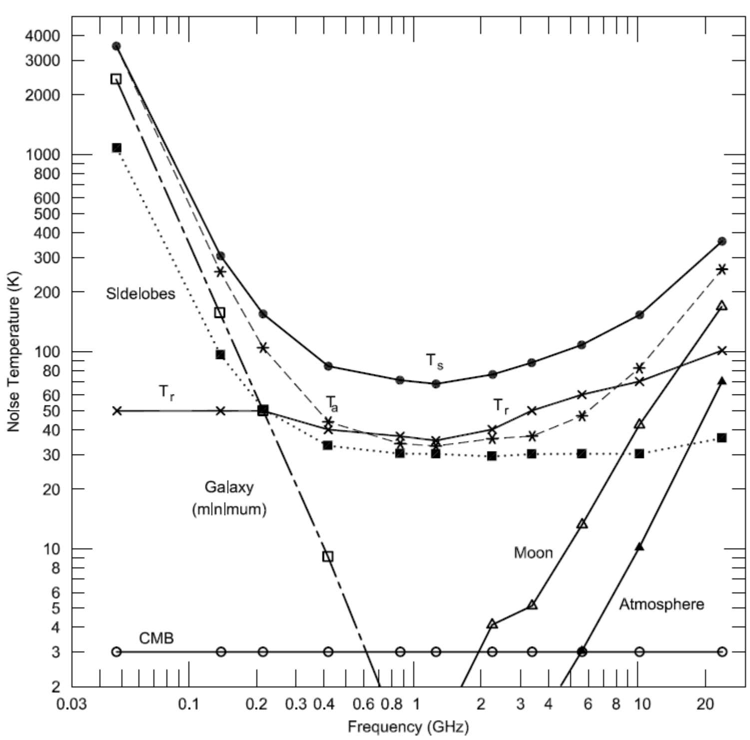

Fig 1 – Typical contributions to system noise temperature, T_s, from the cosmic microwave background (CMB), the Earth's atmosphere, the warm surface of the moon, galactic noise entering through the main antenna beam, and sky and ground noise from an antenna's side and rear lobes. Antenna temperature T_a is a combination of all these contributions, appropriately weighted by antenna pattern; T_s is the sum of T_a and receiver noise temperature T_r.

What sort of antenna?   How much power?

Linear polarization is the standard on 70 cm, so in principle dual-polarization (“X-pol”) antennas can provide the same well-known advantages that they do for 2 m EME. As described in reference [2], an adaptive-polarization receiver yields an average sensitivity improvement of 3 dB, and much more in extreme cases of polarization angle mismatch. However, X-pol Yagis with good performance are harder to build at 70 cm than at 2m, and they have not heretofore been widely used. The main problems are achieving accurate symmetry between the X and Y planes of Yagi elements and fitting the necessary feedlines, baluns, etc., into available space around the feedpoint.

A lunchtime conversation with Justin Johnson, G0KSC, at the 2012 EME Conference in Cambridge persuaded us that with sufficient care, excellent X-pol Yagis could be built and deployed for 432 MHz. With the help of Justin’s company, InnovAntennas, we decided to proceed in that direction. After a few iterations we settled on a basic antenna design that we call 15LFA-JT: a 15-element, dual polarization Yagi about 3.5 m (11.5 ft) long, rear-mounted and built on a one-inch square hollow fiberglass boom. Simulation with the antenna modeling software NEC4 shows that an array of four such Yagis should provide 22.4 dBi gain in each of two orthogonal linear polarizations, with extremely low side- and rear-lobe responses. Clean patterns are very important for achieving the low system noise temperatures required for EME on the UHF and higher bands.

Among all of the propagation modes used by amateurs, the Earth-Moon-Earth path is one of the very few that allow accurate and reliable predictions of signal strength. The link budget for EME communication was described in detail in reference [1]. It can be summarized in the following equation for SNR, the received signal-to-noise ratio in dB:

$$SNR = P_r - P_n = P_t - L + G_t + G_r - P_n. \qquad (1)$$

Here P_r and P_t are the received and transmitted powers expressed in dBW (dB above one watt); L is the Earth-Moon-Earth path loss in dB, assuming isotropic antennas; G_t and G_r are gains of the transmitting and receiving antennas in dBi; and P_n is the received noise power in dBW. For average moon distance the path loss L can be written as

$$L = 261.6 + 20\log(f/432). \qquad (2)$$

Received noise power is equal to kT_sB, where $k = 1.38 \times 10^{-23}$ Joules/K is Boltzmann’s constant, T_s is the system noise temperature in Kelvins, and B the received bandwidth in Hz. Thus, in units of dBW,

$$P_n = 10\log(kT_sB) = -228.6 + 10\log(T_sB). \qquad (3)$$

Let’s assume equal gains $G_t = G_r = G$ for the transmitting and receiving antennas, as would be the case for our station communicating with its “twin”. We can then calculate the transmitter power required for any specified system noise temperature, bandwidth, and SNR, using the equation

$$P_t = SNR + L + 10\log(kT_sB) - 2G. \quad (4)$$

Communication in the JT65 digital mode is nearly 100% reliable [3, 4] if $SNR > -24$ dB in bandwidth $B = 2500$ Hz. For $G = 22.4$ dBi and typical system noise temperature $T_s = 100$ K, the required transmitter power for $SNR = -24$ dB is then

$$P_t = -24 + 261.6 - 174.6 - 2 \times 22.4 = 18.2 \text{ dBW}, \quad (5)$$

or 66 watts.

With transmitters producing at least several hundred watts at the antenna, two stations equipped in this way will have several extra dB in hand, and should nearly always be able to work each other by EME. Audible self-echoes and CW communication with a twin station will require something like $SNR > 3$ dB in 50 Hz bandwidth, and thus about 10 dB more transmitter power — say 700 W at the antenna.

Model 15LFA-JT Yagi

To allow us to verify the antenna design and make initial test measurements, G0KSC sent us materials for a pair of 15LFA-JT Yagis following his design. Some important construction details can be made out by studying Figures 2 through 4. Reflectors and directors are made from 1/4-inch aluminum rod, each one passing through the boom center to maintain full polarization symmetry. Element positions for the two orthogonal polarizations are offset by 30 mm along the boom. Long sides of the LFA driven elements are made from 10 mm brass tubing with 1 mm wall thickness; the U-shaped end pieces are made from 8-mm brass tuning, cut to 45-degree angles and hard-soldered at the 90-degree corners. These end pieces fit snugly into the long straight sides, and are soldered in place after final tuning. The forward side of each LFA loop is split with a 6 mm gap filled with a nylon insulator. We drilled all the way through the brass and nylon and tapped the holes for 4-40 machine screws. Ends of the RG142 feedlines are stripped, fitted with eye lugs, treated with liquid rubber sealant, and secured to the feedpoints with 4-40 screws. The screws are accessible through 6-mm holes drilled through one side of the boom, immediately above the feedpoints. Full details of element lengths and spacings will be published soon.

Fig 2. – A pair of 15LFA-JT rear-mounted Yagis on a simple mount with azimuth and elevation control. Light-duty Dacron ropes serve as forward guys, to prevent boom sag.

Fig 3. – Separate feedlines carry signals for horizontal and vertical linear polarization from each Yagi to the power splitters.

Fig. 4. – Rear view of a single Yagi showing construction details around the driven elements. The brass loops are fed at the split centers of their forward sides, inside the hollow boom. RG142 coaxial feedlines pass out to the rear. All elements are held in place with tight-fitting holes and a few drops of fiberglass resin.

Antenna tests

One of the most sensitive indicators of how closely a real antenna resembles its computer model is a plot of return-loss versus frequency. Therefore, after assembling each Yagi we made a number of swept-frequency return-loss measurements, following advice from G0KSC to take advantage of two "tuning controls" for each polarization: the telescoping ends of the driven loops, and the length of the first director. We adjusted both in steps as small as 0.5 mm; in practice, this required us to cut several extra D1 elements with slightly different lengths, to find the best match. We checked carefully for evidence of feedline radiation possibly caused by connecting coax directly to the driven loop. We found none. With optimum tuning we obtained return losses better than 25 dB over the range 427 to 437 MHz, in excellent agreement with the simulations. Compared with some designs, these Yagis are relatively wideband antennas.

Measurements of angular power patterns are difficult without a professional antenna range. Nevertheless, we attempted such a measurement using purely amateur-radio techniques. Our test signal was the W3CCX/B beacon located in Philadelphia, 42 miles away. We drove the antenna at constant rate over a full 360 degrees in azimuth, and then repeated in the opposite direction. With the receiver AGC turned off and the upper-sideband bandwidth set to 5 kHz, audio output from the station's TS-2000X transceiver was sampled by a computer soundcard at 48 kHz, squared, and averaged over 1-second intervals. The averages were recorded along with readout azimuths. Plots in Figure 5 show the simulated and measured azimuth patterns for our phased pair of 15LFA-JT Yagis, for horizontal polarization.

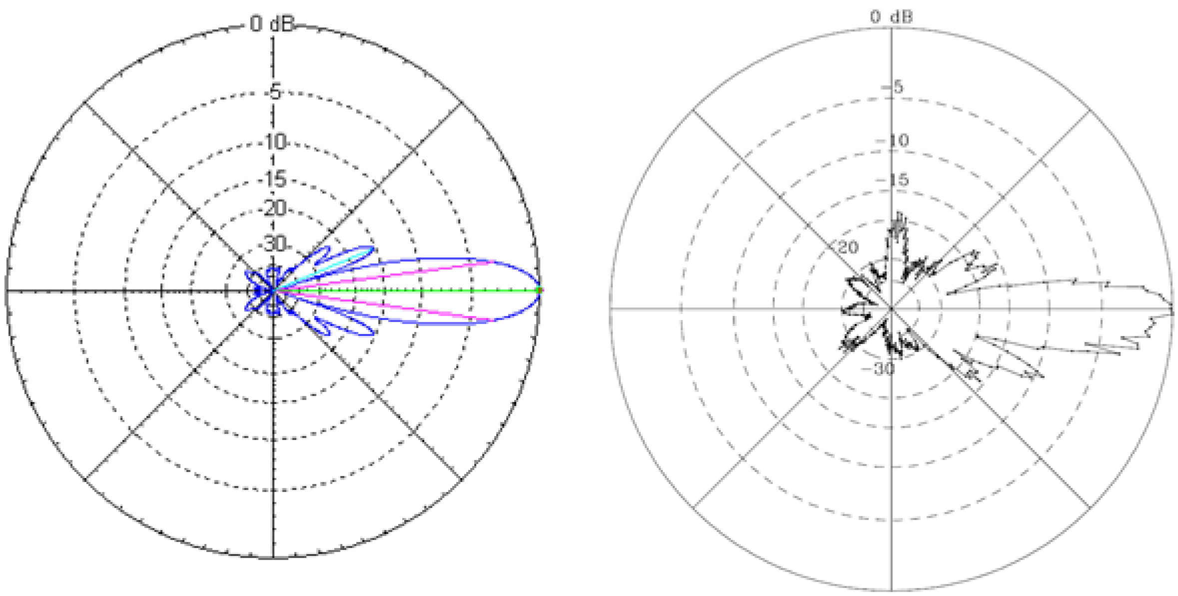

Fig 5. – Simulated (left) and measured (right) azimuth patterns of a pair of 15LFA-JT Yagis stacked horizontally, in horizontal polarization. The stacking distance was 1.2 m.

The slightly asymmetric sidelobes are almost certainly the result of reflections from nearby structures — in particular, a permanent steel ladder the top of which is only about 1 m away from the forward ends of the (temporarily mounted) Yagis when pointed toward the horizon, close to the direction of W3CCX. This near-field distortion should disappear when the antennas are elevated, and especially after the array is raised to its final position at the top of its mast (see Figure 2). Other than this (presumably temporary) distortion, the measured array pattern closely approximates the very low side- and rear-lobe responses of the computer model, especially when allowance is made for likely multi-path propagation at very low signal levels. We concluded that the completed array should have excellent performance.

Our next test of the temporary two-Yagi array was a measurement of Sun noise. Software was written to control the azimuth rotor in a repetitive Off-On-Off pattern, centered on the Sun's current position. The offset positions were set at $\Delta Az = \pm 16/\cos(El)$ degrees. Once again, we recorded 1-second averages of the receiver output power. Results after normalization to the mean off-source power level are plotted in Figure 6. The On- to-Off-source power ratio was found to be $Y_{Sun} = 7.2 \pm 0.1$ dB, very close to the expected value 7.4 dB calculated for that day's solar flux at 432 MHz and our measured system noise temperature (44 SFU and 118 K, respectively). Essentially identical results were obtained for each of the two polarizations.

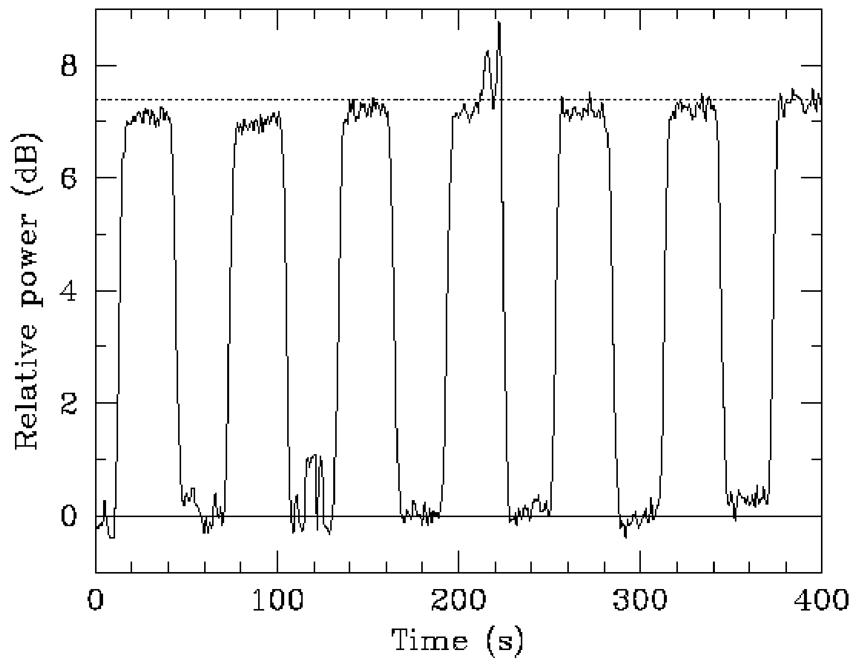

Fig. 6. – Measurements of Sun noise with a phased pair of 15LFA-JT Yagis. The dotted line represents the expected Y_{Sun} on the day of measurement.

Final Station Configuration at W2PU

Satisfied with the performance of our temporary two-Yagi array, we proceeded to build two more Yagis and configure them in the 2 × 2 array shown in Figure 7. The completed array is very compact, with stacking distance only 1.2 m (47 inches) in each plane.

Fig. 7. – The four-Yagi 432 MHz array at W2PU.

Optimum configuration of a dual-polarization EME system requires independent preamplifiers for each polarization mounted at the antenna and feeding separate Rx feedlines. A separate low-loss feedline is used for the Tx side. As illustrated in Figure 8, the front-end configuration at W2PU uses three coaxial relays: K1 and K3 accomplish the necessary T/R switching, while K2 selects horizontal or vertical polarization for transmitting. All three relays must handle the full transmitter power. In order to protect the preamplifiers, K1 and K3 must have better than 60 dB isolation on their “off” port.

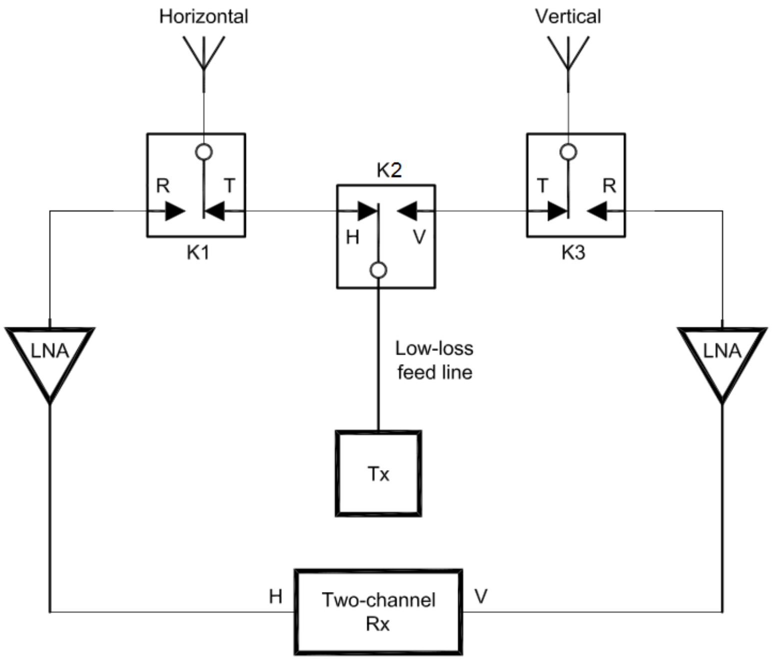

Fig. 8 – Front-end switching arrangement used at W2PU.

Major components of the two-channel receiver are summarized in the block diagram of Figure 9. The indicated combination of hardware and software provides adaptive-polarization reception of CW, SSB, and JT65 signals and a highly sensitive band-scope covering a 90 kHz portion of the band. The IQ+ receiver hardware (manufactured by LinkRF, see ref. [5]) converts incoming signals to an in-phase and quadrature (I/Q) baseband pair for each polarization. These two pairs are sampled at 96 kHz by a 4-channel sound card, in our case an M-Audio Delta44. All subsequent signal processing is done by computer, using the programs *Linrad* [6] and *MAP65* [7]. Many additional details concerning the receiver can be found in the documentation for these programs and in reference [2].

For transmitting we use a Kenwood TS-2000X followed by a Beko HLV-1100 solid-state power amplifier.

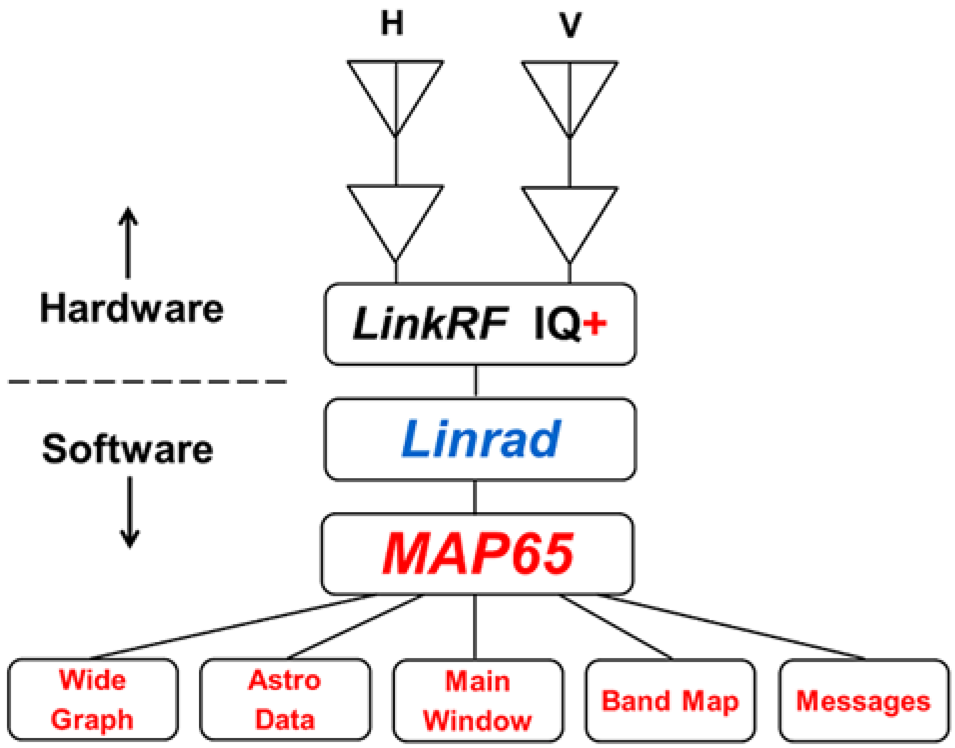

Fig. 9 – Block diagram of the 432 MHz receiving setup at W2PU.

Worksheet for System Noise Temperature

Optimizing the receive performance of an EME station requires careful attention to every contribution to system noise temperature. Unlike the situation for a well-designed 23-cm station using a parabolic dish and circular polarization, a 70-cm setup using a Yagi array necessarily has a number of lossy, ambient-temperature items in front of the first preamplifier. I highly recommend the use of VK3UM's *EME Calculator* software [8], or alternatively a simple spreadsheet like the one shown on the next page as an aid to minimizing T_s in a step-by step manner. Reference [9] provides a link to the spreadsheet file, which is easily adaptable for your own use. Spreadsheet items highlighted in yellow are input by the user, while all remaining numbers are calculated from the input data. As displayed here, the spreadsheet reflects the 432 MHz EME setup at W2PU.

We have not yet done a particularly good job of minimizing before-the-preamp contributions to system noise. For example, the 22 K contribution from RG142 feedline segments could certainly be reduced; this small-diameter cable is needed only for about one foot, inside the hollow booms. On the other hand, the estimated 48 K contribution from antenna noise is likely to be overly pessimistic, especially at higher elevations. Overall, we believe the numbers are conservatively realistic for typical EME conditions. Two stations equipped similarly to W2PU, each with four X-Pol Yagis similar to the 15LFA-JT and Tx power of 100 W or more at the antenna, should be able to work each other by EME more-or-less any time the moon is available.

Tsys Worksheet	Gain	Noise Figure	Noise Contribution	
	(dB)	(dB)	(K)	% Total
4 ft RG-142	-0.32		22.2	18.7%
Power splitter	-0.05		3.6	3.1%
3 ft LDF 4-50A	-0.04		2.9	2.5%
T/R relay	-0.05		3.7	3.1%
LNA1 (DB6NT)	23.00	0.40	30.8	26.0%
10 ft LMR400	-0.27		0.1	0.1%
100 ft LMR240	-5.20		3.9	3.3%
10 ft RG58	-1.00		1.5	1.2%
LNA2 (ARR)	20.00	0.50	0.9	0.7%
LinkRF IQ+		9.00	0.5	0.4%
Tr at antenna feedpoint		**0.94**	**70.0**	59.2%
Antenna and feed losses	0.06		4.0	3.4%
Sky noise (main beam, on ecliptic)			20.0	16.9%
Side and rear lobes			25.0	21.1%
Total antenna noise, Ta			48.4	40.8%
System noise temperature, Ts			**118.4**	100.0%
Frequency (MHz)	432			
Lossless antenna gain (dBi)	22.40			
Solar Flux at 432 MHz (SFU)	44.0			
Tx power at antenna (W)	100			
EME path loss (dB)	261.6			
G/Ta (dB/K)	5.5			
G/Ts (dB/K)	**1.6**			
Y Sun (dB)	**9.9**			
EME S/N in B=2500 Hz (dB)	**-23.0**			
EME S/N in B=50 Hz (dB)	**-6.0**			

Quantitative Tests of Station Capabilities

The Tsys worksheet can provide good estimates of station capabilities, but many of the numbers shown in the example above are little more than estimates based on manufacturers' data sheets. In order to confirm the important bottom-line performance numbers, we conducted a number of astronomical measurements and EME echo tests.

As one example, the spreadsheet calculates a value for Y_{Sun}, the ratio (expressed in dB) of sun noise plus system noise to system noise alone. On one particular day of measurement the solar flux at 432 MHz was 44 SFU [see ref. 10] and the resulting calculated Y_{Sun} was 9.9 dB. Figure 10 shows a screen snapshot of the *Linrad* recording S-meter, calibrated in dB, during a series of Off-On-Off scans of the Sun. It's easy to see that the measured Y_{Sun} is close to the predicted value, nearly 10 dB.

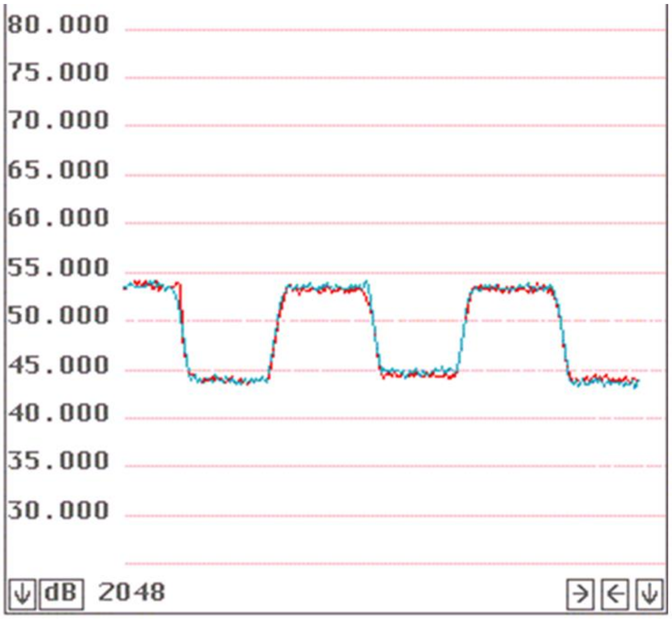

Fig. 10 – Measurement of Sun noise with the W2PU 4-Yagi array. Blue and red curves correspond to horizontal and vertical polarizations, respectively.

We also made measurements of the astronomical source known as Sagittarius A, located at the center of our Milky Way galaxy. The antenna was pointed to azimuth 180° (due south, on the local meridian) and elevation 21°. For our latitude of 40° this elevation corresponds to celestial declination −29°. Using the simple computer program described earlier, we sampled the receiver output and calculated relative power at 1-second intervals over a period of nearly 20 hours. Owing to Earth rotation, our antenna beam passed across the galactic center at about 17:45 local sidereal time. Figure 11 shows the observed power levels (expressed as equivalent noise temperatures) after further averaging into roughly 5-minute intervals. We expected a maximum of about 160 K additional noise temperature from Sagittarius A, very close to the amount observed.

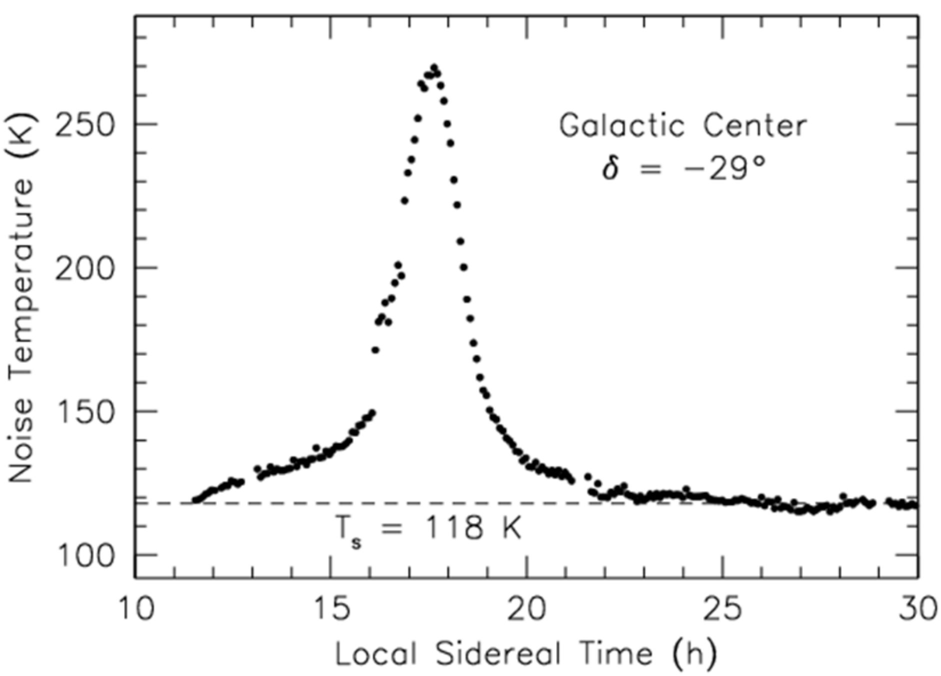

Fig. 11 – Measurement of excess antenna noise from the center of our Galaxy.

Arguably the most important tests of a station's EME capability are quantitative measurements of its own lunar echoes. My freely available open-source program *WSJT* [ref. 11] includes a feature for making automated echo measurements. The results of one such test are summarized in the screen shot below, showing a measured signal-to-noise ratio –19 dB for Tx power 450 W at the antenna.

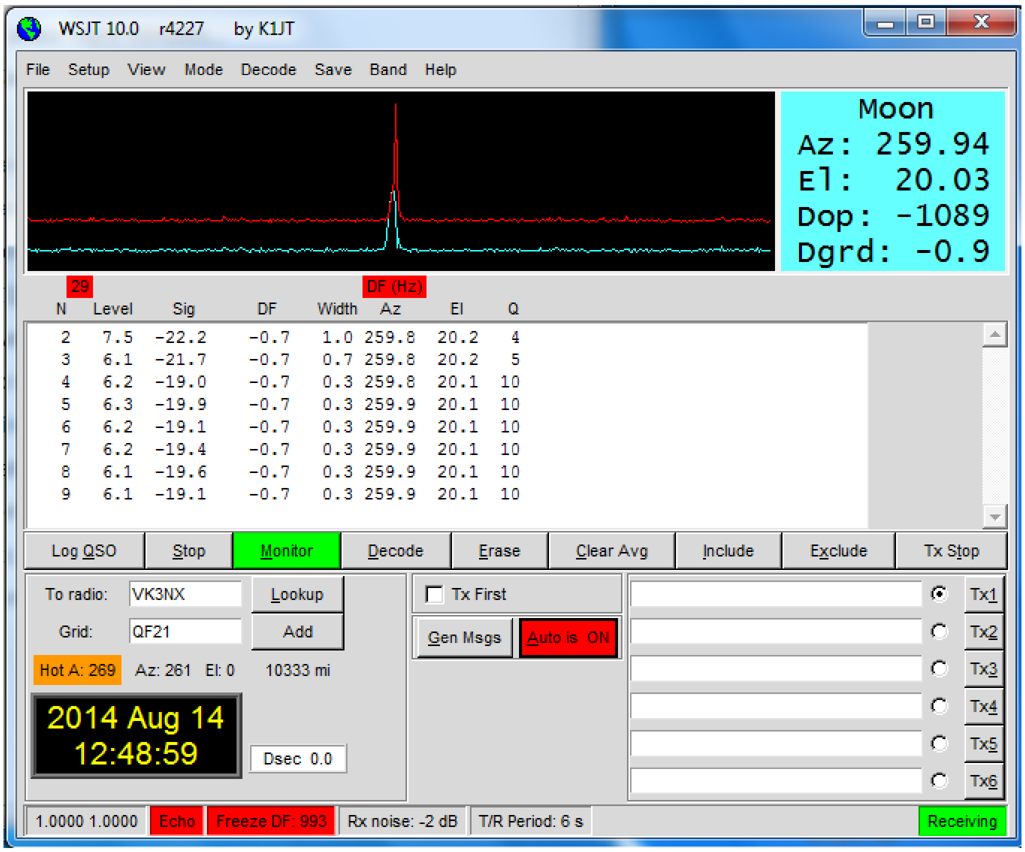

Fig. 12 – Measurement of lunar echoes from the W2PU station. The blue curve is corrected for the expected Doppler shift at the start of the run; the red curve also includes corrections for changes in Doppler shift over the full measurement interval, about 1 minute.

Conclusions

By now we have now made many EME QSOs with the system described herein. We find it to be every bit as capable as we had hoped.

Our decision to rear-mount the 15LFA-JT Yagis has the distinct advantage of keeping all extraneous metal out of the active region of the antenna, thereby preserving the excellent angular patterns of the model simulations. However, rear-mounting requires suitable counterweights extending to the rear, complicating the structure mechanically. A possible alternative would be to build the necessary H-frame of fiberglass or other non-conducting material, attaching the individual Yagis to the H-frame near their balance points. Such an arrangement would be much lighter and could be particularly attractive for portable or DXpedition use — especially if the "armstrong" method is used for tracking the moon.

Acknowledgments

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8. VK3UM EME Calculator, http://www.vk3um.com/eme%20calculator.html
9. The Excel spreadsheet is available at http://physics.princeton.edu/pulsar/K1JT/W2PU_432.xlsx.
10. Solar flux measurements are made by the US Air Force every day at a number of frequencies and at four sites around the world. Details can be found at http://www.swpc.noaa.gov/ftpmenu/lists/radio.html.
11. *WSJT*: http://physics.princeton.edu/pulsar/K1JT/wsjt.html.