EME with Adaptive Polarization at 432 MHz

Joe Taylor, K1JT, and Justin Johnson, G0KSC

Linear polarization is standard for both terrestrial and EME communication on the 70 cm band. For EME this convention ensures that ionospheric Faraday rotation and spatial polarization offsets often combine to cause "Faraday lockout" and apparent one-way propagation. On the 2-meter band, dual-polarization ("X-pol") Yagis and software-based adaptive-polarization receivers are widely used to solve this problem. As described in reference [1], such a receiver yields an average sensitivity improvement of 3 dB, and much more in extreme cases of polarization mismatch. However, up to now these techniques have not been much used at 70 cm because X-pol Yagis with good performance are considerably harder to build at UHF. The main problems are achieving accurate symmetry between the X and Y element planes and fitting the necessary feedlines, baluns, etc., into available space around the feedpoint.

In this paper we describe development and implementation of an excellent dual-polarization EME antenna for 70 cm using four mid-sized LFA Yagis. The array built at W2PU (the Princeton University Amateur Radio Club station) is shown in Figure 1. By EME standards it is small, lightweight, rugged, and easy to point in azimuth and elevation. The antenna is suitable and practical for nearly any QTH where EME is feasible. As outlined below, two stations using these antennas should be able to work each other by EME at nearly any time the moon is visible to both. We hope that some of our design ideas will be useful to others considering entry into the EME community on the 70 cm band.

Fig. 1. – Four-Yagi dual-polarization 432 MHz array at W2PU. The Yagis are rear-mounted; boom length is 3.5 m, and stacking distance is 1.2 m in each direction.

Antenna Gain Requirements

Of all propagation modes used by amateurs, EME is one of the few that allow accurate and reliable predictions of signal strength. The link budget for the Earth-Moon-Earth path is well understood, and described in detail in reference [2]. It can be summarized in the following equation for SNR, the received signal-to-noise ratio in dB:

$$SNR = P_r - P_n = P_t - L + G_t + G_r - P_n. \tag{1}$$

Here P_r and P_t are the received and transmitted powers expressed in dBW (dB above 1 W); 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

$$L = 261.6 + 20\log(f/432). \tag{2}$$

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,

$$P_n = 10\log(kT_sB) = -228.6 + 10\log(T_sB). \tag{3}$$

Let's assume equal gains $G_t = G_r = G$ for the transmitting and receiving antennas, as would be the case for a station communicating with its "twin". We can then rearrange equation (1) to solve for the antenna gain required for communication with any specified signal-to-noise ratio, path loss, system noise temperature, bandwidth, and transmitter power:

$$G = (SNR + L + 10\log(kT_sB) - P_t)/2\ . \tag{4}$$

Communication in the JT65 digital mode is nearly 100% reliable [3, 4] if $SNR > -24$ dB in bandwidth $B = 2500$ Hz. For $SNR = -24$ dB, $L = 261.6$ dB, $T_s = 100$ K, and $B = 2500$ Hz equation (4) reduces to

$$G = 31.5 - P_t/2\ . \tag{5}$$

For convenience this relation is plotted in Figure 2. It's clear that for transmitter powers around 100 W, antenna gains of 22 dBi should be sufficient. With a few hundred watts at the antenna, two stations equipped in this way will have several extra dB in hand — that is, they 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.

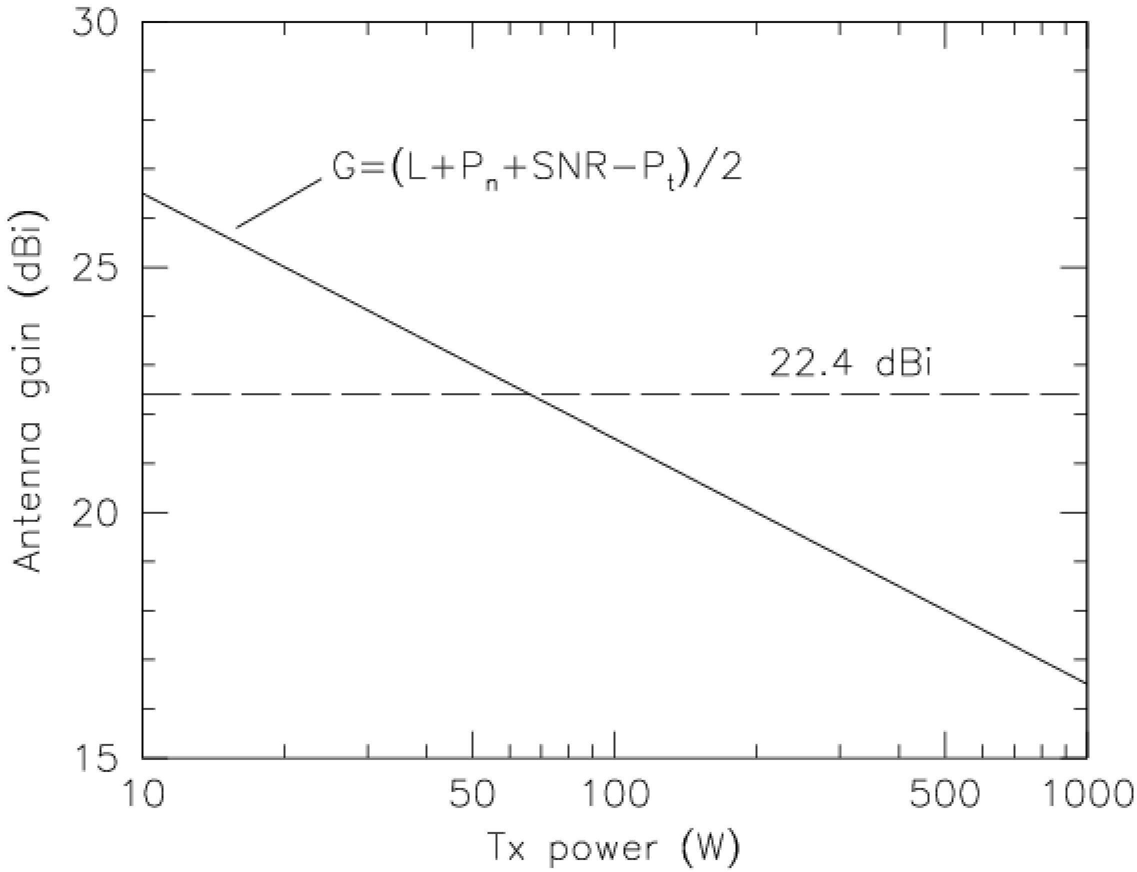

Fig. 2. – Minimum antenna gain for EME communication between twin EME stations using JT65 at 432 MHz, as a function of transmitter power. The dashed line corresponds to the four-Yagi array at W2PU.

Model 15LFA-JT Yagi

Forward gain is not everything. Clean antenna patterns with low side and rear lobes in elevation as well as azimuth are very important for achieving the low system noise temperatures required for EME, especially on the UHF and higher bands. One of the biggest challenges when building Yagis for 70 cm is a mechanical one. Matching devices, folded dipoles, etc., are much larger in terms of wavelength than at lower frequencies. For a single-plane antenna the consequences may be minimal — minor pattern distortions, for example. However, when two orthogonal Yagis are placed on the same boom more undesirable interactions will occur, as shown in Figure 3. To avoid such effects the centers of all elements must fall in a single straight line. Ideally, no part of either antenna should extend into the plane of the orthogonal polarization.

With these considerations in mind, after a few iterations we settled on a basic antenna design that we call 15LFA-JT: a 15-element, dual polarization, LFA-fed Yagi 3.5 m long, rear-mounted and built on a one-inch square hollow fiberglass boom. Simulation with antenna modeling software *EZNEC v5 Pro/4* and *4NEC2* (both using the latest NEC4.2 calculation engine) shows that an array of four such Yagis should provide 22.4 dBi in each of two orthogonal linear polarizations, with extremely low side- and rear-lobe responses (Figure 3, left).

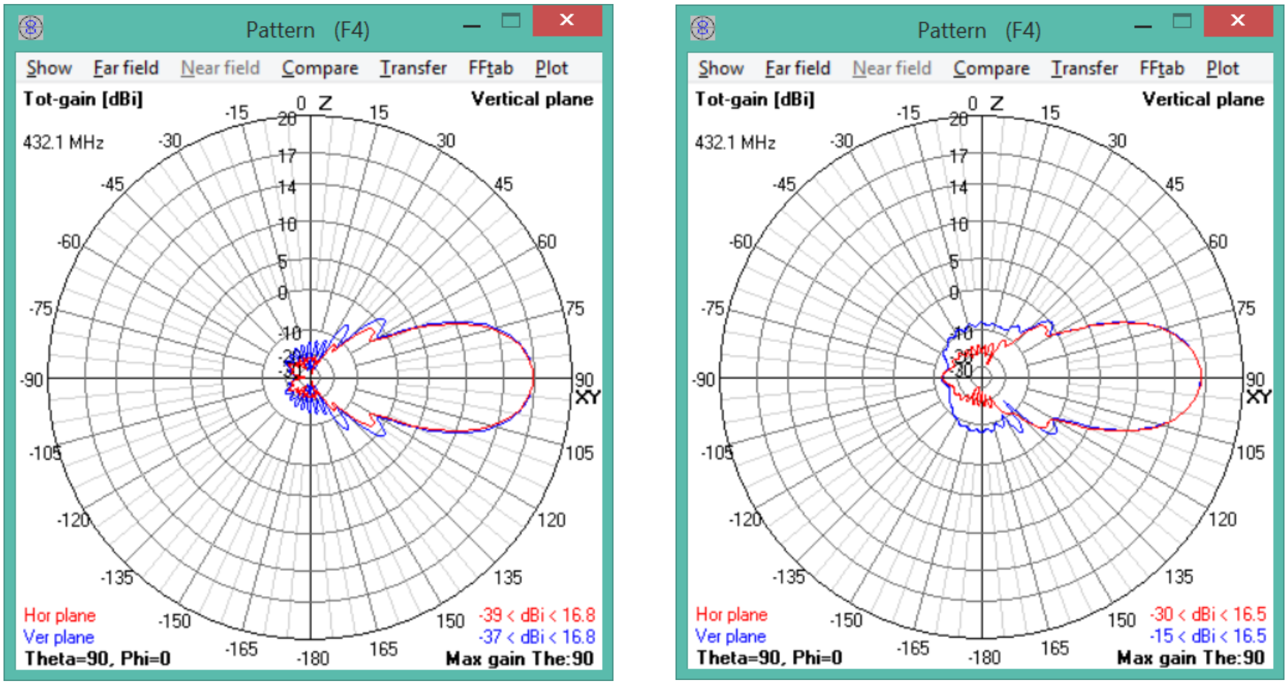

Fig. 3 – Simulated single antenna patterns for the 15LFA-JT in both E and H planes. Left: all elements are perfectly aligned. Right: elements are offset as though mounted above and to one side of a 1'' (25mm) square boom.

The LFA Yagi (Loop Fed Array) is a traditional style Yagi with an extended folded-dipole type feed laid flat on the boom. Thus, both sides of the driven loop are in line with the parasitic elements, rather than extending above or below the boom. Unlike a traditional folded dipole, even the feedpoint is in line. This leads to a perfectly symmetrical pattern in both E and H planes. However, this mechanical arrangement adds certain construction complications. With all elements in line the feedpoints lie inside the boom, centered on its axis. Workable construction options include using a metallic boom, although for optimum long-term performance the elements must be welded to the boom. Insulated elements passing through a metallic boom are another option, but this practice can lead to eddy currents in the boom, detuning the antenna and causing deterioration of both pattern and system temperature. With these problems in mind, we decided to use a hollow fiberglass boom for these antennas.

As shown in Figure 4, simulations of the 15LFA-JT show that its gain and pattern are well maintained over a bandwidth of at least 5 MHz. As a result, we expect the antenna's performance to remain good even in the presence of un-modeled external influences such as rain or ice loading.

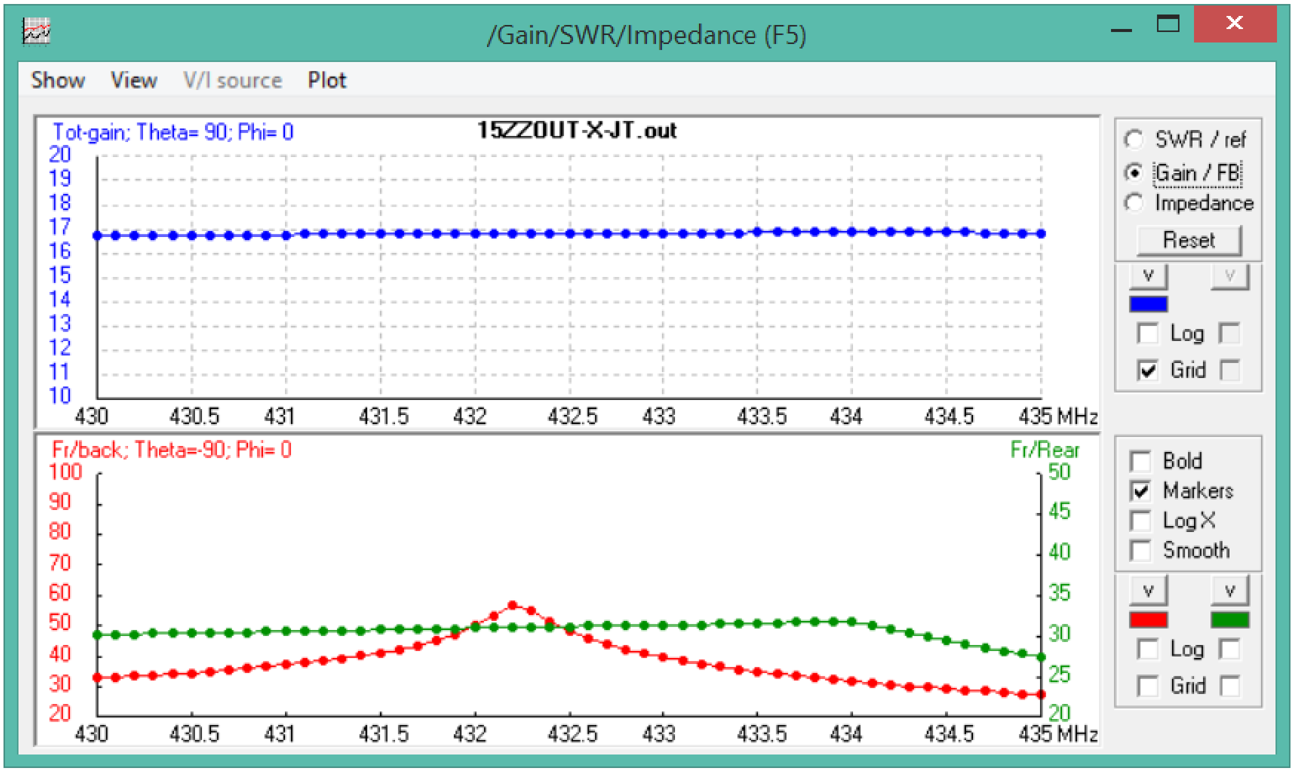

Fig. 4 – Simulated gain (blue), front to back ratio (red), and front-to-rear (green) plotted as functions of frequency.

Important construction details of the individual Yagis can be gleaned by studying Figure 5. Reflectors and directors are made from 1/4-inch aluminum rod, each one passing through the boom center to maintain full polarization symmetry. 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. Element positions for the two orthogonal polarizations are offset by 30 mm along the boom.

The NEC electromagnetic calculation engine assumes zero-length, “tail-less” connections to the feedline. The forward side of each LFA loop is split with a 6 mm gap filled with a nylon insulator, and very short pigtails on the coax are compensated by adjusting the “trombone” end pieces of the driven loops. For the initial antennas we opted to drill all the way through the brass and nylon and tap the holes for 4-40 machine screws. Ends of the RG142 feedlines were stripped, fitted with eye lugs on very short tails, 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. Soldering the feedline to the driven element would be an even better option, ensuring minimal resistive losses and a long service life. Soldering would require somewhat larger holes in the boom.

Rear-mounting the Yagis ensures that coax feedlines between each feed point and the 3/2-wavelength power dividers can be as short as possible. Rear-mounting also means having no H-frame or other un-modeled metal parts (including the elevation positioning mechanism) inside the active regions of the Yagis. Such conductive parts could detune the antennas and degrade both gain and system noise temperature.

Fig. 5. – Rear view of a single LFA15-JT 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.

For the benefit of home constructors, element lengths and spacings for the 15LFA-JT Yagi are presented in Table 1. For best results you should use a fully insulated boom or a metallic boom with welded elements. The specified element lengths assume a non-conducting boom. Corrections must be applied for a metallic boom: for example, a ¾-inch square boom with electrically connected elements requires 11.5 mm added to each element length. Offset between elements in the two polarizations is 30 mm along the boom. High accuracy is required to replicate the simulated antenna at 70 cm. Use a quality caliper to measure the elements.

Table 1. – Element lengths and spacings for the 15LFA-JT Yagi.

Element	Spacing (mm)	Length (mm) uncorrected
R	0.0	338.5
DE1	48	299*
DE2	120	299**
D1	179.5	314
D2	310.5	300.5
D3	454.5	292
D4	648.5	290.5
D5	891	287
D6	1157.5	283.5
D7	1442	279
D8	1738.5	276
D9	2037	275
D10	2330	273
D11	2617.5	268
D12	2918	257
D13	3183	238.5

*Total length of loop. The long straight sections should be reduced in size to allow for the telescoping end sections.

** The forward section of the loop has the feed point at its center. Loop size is based on 10 mm brass tube with 8 mm end sections. Adjustments will be required for changes in these dimensions.

Initial 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. After assembling each Yagi we made swept-frequency return loss measurements as a tuning aid, adjusting the telescoping ends of the driven loops and the length of the first director for best match. We used length steps as small as 0.5 mm; in practice, this required us to cut several extra first-director elements with slightly different lengths, to find the best (and flattest) return-loss curve. We checked carefully for evidence of feedline radiation potentially caused by connecting coax directly to the driven loop. We found none, but nevertheless we installed two UHF-rated ferrite cores (Laird Technologies 28A0593-0A2) on each feedline where they exit the boom. 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.

We built a temporary two-Yagi array and mounted it with full azimuth and elevation control in the planned location atop the Princeton University Physics building. With this array we made measurements of return loss, angular pattern, and sun noise; we also did a bit of successful SWL-only EME operation. Satisfied with the performance of the temporary two-Yagi array, we proceeded to build two more Yagis and configure them in the 2 × 2 array shown in Figure 1.

Optimum use 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 6, 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 at the receive port, when transmitting.

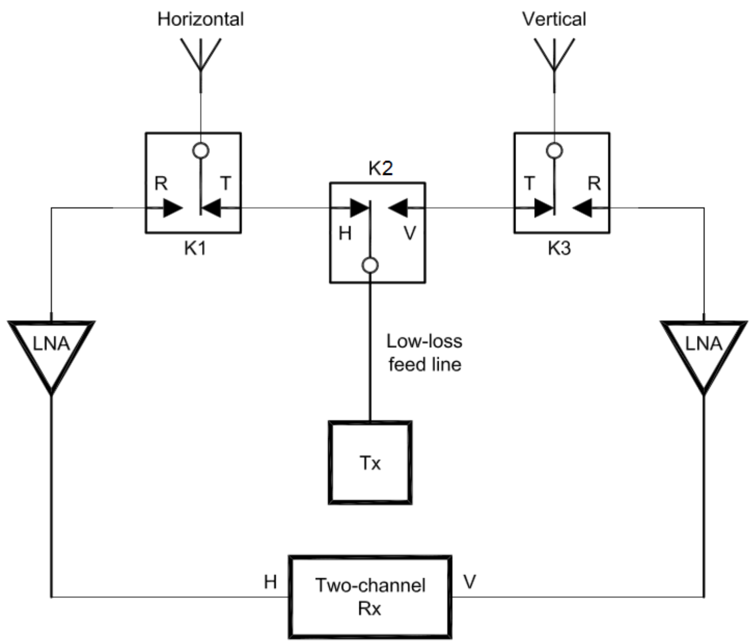

Fig. 6 – Front-end switching arrangement used at W2PU.

Major components of our two-channel receiver are summarized in the block diagram of Figure 7. The indicated combination of hardware and software provides adaptive-polarization reception of all modes and a highly sensitive band-scope covering a 90 kHz portion of the 70 cm band. The IQ+ receiver hardware (manufactured by LinkRF, see ref. [5]) converts incoming signals to in-phase and quadrature (I/Q) baseband pairs for each polarization. The 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 [1]. For transmitting we use a Kenwood TS-2000X followed by a Beko HLV-1100 solid-state power amplifier.

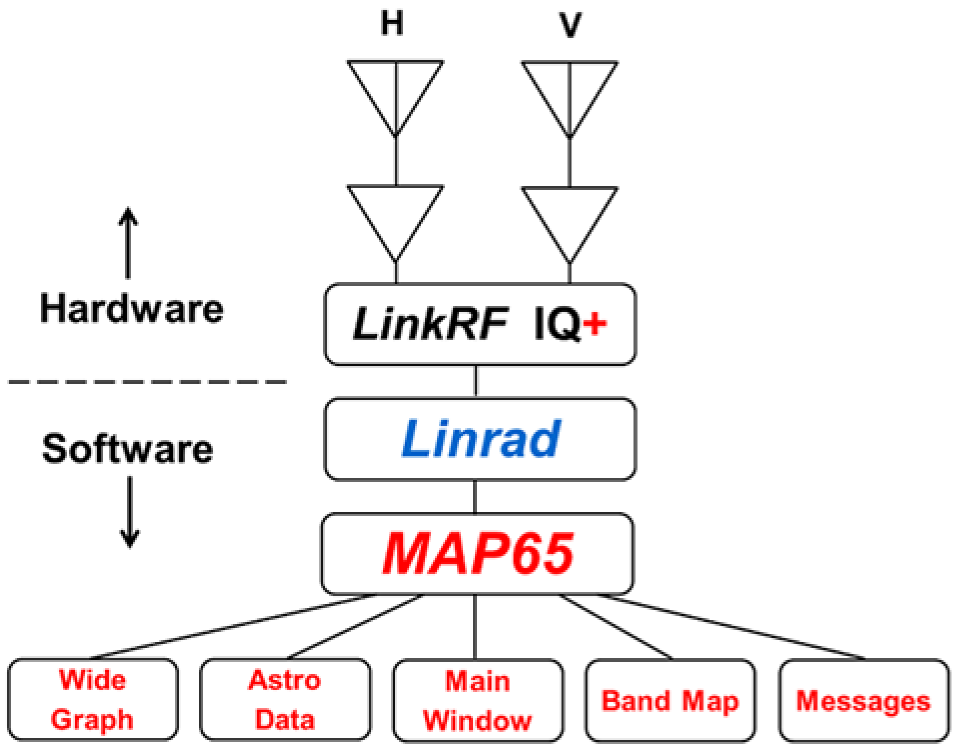

Fig. 7 – Block diagram of the 432 MHz receiving setup at W2PU.

Worksheet for System Noise Temperature

Optimizing the receive performance of an EME station at UHF and above 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 with a Yagi array necessarily has a number of lossy, ambient-temperature items in front of the first preamplifier. We highly recommend the use of VK3UM's *EME Calculator* software [8], or alternatively a simple spreadsheet like the one shown below 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 current 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 30 cm, 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 worksheet 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 Capability

The Tsys worksheet can provide good estimates of station capability, but many of the numbers shown in the example 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 8 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 nearly 10 dB, close to the predicted value.

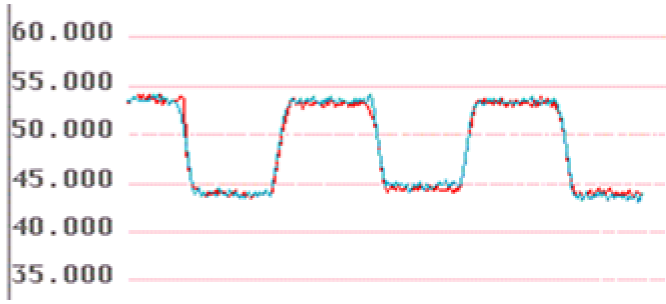

Fig. 8 – Measurement of Sun noise with the W2PU four-Yagi array using *Linrad*'s calibrated, recording S-meter. Blue and red curves correspond to horizontal and vertical polarizations, respectively.

We also made measurements of the astronomical radio 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 the latitude of Princeton, 40°, this elevation corresponds to celestial declination −29°. 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 in a soundcard at 48 kHz, squared, and averaged over 1-second intervals. We recorded these relative power measurements 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 9 shows the observed power levels (expressed as equivalent noise temperatures) after further averaging into 5-minute intervals. We expected a maximum of about 160 K additional noise temperature from Sagittarius A, very close to the amount observed.

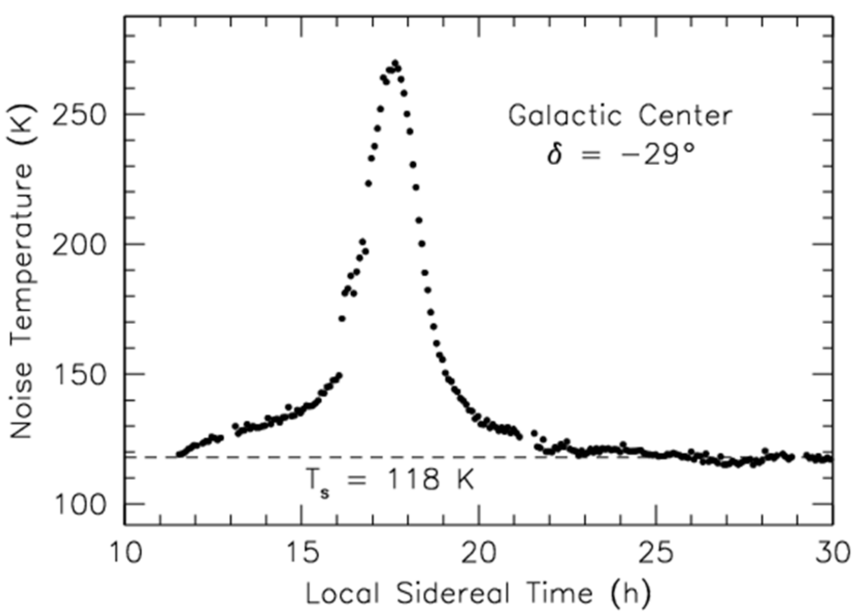

Fig. 9 – Measurement of excess antenna noise from Sagittarius A, at the center of our Galaxy.

Arguably the most important tests of a station's EME capability are quantitative measurements of its own lunar echoes. The freely available open-source program *WSJT* [ref. 11] includes a feature for making automated echo measurements. Measured echo returns from the W2PU station, around –24 dB for Tx power 100 W, are consistent with the strengths predicted by the Tsys worksheet.

EME Operation with Adaptive Polarization

As outlined above, *MAP65* works together with a two-channel SDR-style receiver that mixes RF signals to baseband. Conversion from analog signals to digital data takes place at the hardware-to-software boundary indicated by the horizontal dashed line in Figure 7. We use *Linrad* as a "front end" for *MAP65*, mainly because of its superb noise blanker and flexible capabilities for CW operation. We normally set the Rx center frequency to 432.045 MHz, and the displayed passband (for both *Linrad* and *MAP65*) to the range 432.000 – 432.090. *Linrad* and *MAP65* can run in the same computer; however, both programs display a lot of information, so a separate video screen for each is essentially a requirement. We actually use two separate computers, with *Linrad* running under Linux and *MAP65* under Windows 7.

MAP65 uses the so-called "timf2" network data forwarded from *Linrad* to locate and decode all JT65 signals in its displayed passband. In practice this allows us to locate CW signals in the lower portion of the frequency range and JT65 signals in the upper portion. For every JT65 signal, *MAP65* makes an optimized linear combination of the two receiver channels so as to match the signal's actual polarization angle, whatever that might be. If the decoded JT65 message includes the transmitting station's grid locator, the program calculates and recommends the transmitted polarization (H or V) that will produce the closest approximation to the polarization that was used for transmitting at the DX location. In practice, we usually respond to a CQ by using the recommended Tx polarization. If we get no answer, we call again using the opposite polarization. When calling CQ we generally alternate between H and V in subsequent transmissions.

Conclusions

By now we have made many EME QSOs with the system described. 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 array, thereby preserving the excellent angular patterns of the model simulations. We note that rear-mounting requires suitable counterweights extending behind the antennas, thereby complicating the structure mechanically. A possible alternative would be to build an H-frame of fiberglass or other non-conducting material, attaching the individual Yagis near their balance points. Such an arrangement could be much lighter and particularly attractive for portable or DXpedition use — especially if the simple "armstrong" method is used for tracking the moon. It should be obvious that 8- or 16-bay arrays of these Yagis would make even more capable EME antennas. Further information on the 15LFA-JT can be found at reference [12].

Acknowledgments

We thank Princeton University Physics Department colleagues Dan Marlow (K2QM), Norm Jarosik, and Geoff Gettelfinger for their essential help throughout the course of this project.

References

1. J H Taylor, K1JT, "MAP65 Version 2: A Panoramic, Polarization-Matching Receiver for JT65." *Proceedings of the 15th International EME Conference*, Cambridge, pp. 101-108 (2012); http://physics.princeton.edu/pulsar/K1JT/K1JT_EME2012.pdf.
2. J H Taylor, K1JT, "Earth-Moon-Earth (EME) Communication." *ARRL Handbook for Radio Communications*, Chapter 30 (2010); also available online at http://physics.princeton.edu/pulsar/K1JT/Hbk_2010_Ch30_EME.pdf .
3. J H Taylor, K1JT, "The JT65 Communications Protocol." *QEX* (September-October 2005); http://physics.princeton.edu/pulsar/K1JT/JT65.pdf.
4. J H Taylor, K1JT, "Open Source WSJT: Status, Capabilities, and Future Evolution." *Proceedings of the 12th International EME Conference, Wurzburg* (2006); http://physics.princeton.edu/pulsar/K1JT/K1JT_eme2006.pdf.
5. LinkRF web site: http://www.linkrf.ch/IQ+.html.
6. *Linrad*, by SM5BSZ: http://www.sm5bsz.com/linuxdsp/linrad.htm.
7. *MAP65*: http://physics.princeton.edu/pulsar/K1JT/map65.html.
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. Current data and other details can be found at http://www.swpc.noaa.gov/ftpmenu/lists/radio.html, and archival data at http://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-radio/noontime-flux/.
11. *WSJT*: http://physics.princeton.edu/pulsar/K1JT/wsjt.html.
12. The 15LFA-JT antenna: http://g0ksc.co.uk.