Optimized Small-Station EME

X-pol at 432 MHz

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Introduction

This paper describes the design and construction of a modest 432 MHz EME station for W2PU, the Princeton University Amateur Radio Club. The antenna and receiver front end will also be used for radio astronomy instructional purposes in the university's physics department. For this project my departmental colleagues Dan Marlow (K2QM), Norman Jarosik, and I have adopted a pedagogical approach characteristic of academic physicists: our planning and construction has proceeded one step at a time, with frequent tests and detailed measurements being made at each stage. As I write these words in June 2014, we have not yet made EME QSOs. But construction of the station is well along toward completion, and the station's eventual EME capabilities are already well established. We hope to have W2PU active on the moon in the near future.

Starting with a blank slate provided us a good opportunity to set goals, make design choices consistent with those goals, and carry out a number of minor optimizations. We hope that our design criteria and choices will be useful to others considering entry into the EME fraternity on the 70 cm band. We have aimed to satisfy the following goals:

- System noise temperature approaching the state of the art, at room temperature.
- Tx power < 1 kW, and preferably much less. (No special licenses, no QRO++ !)
- Antenna: small, lightweight, rugged, and easy to point in azimuth and elevation.
- No "Faraday lockout," no one-way propagation.
- Moderate cost, easy to build and maintain.
- Station capable of EME QSOs with its own "twin," anywhere in the world, whenever the moon is available.

Anyone who has done EME knows that it's not trivial to satisfy the first five of these requirements, while also meeting the last one. We expect to achieve all six goals reasonably well, and we can heartily recommend a similar approach to others planning an EME station.

Which band ?

144 MHz EME antennas are too big 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 good reasons we decided to develop EME capability at 432 MHz instead. As illustrated in Figure 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 would like to help reverse this trend.

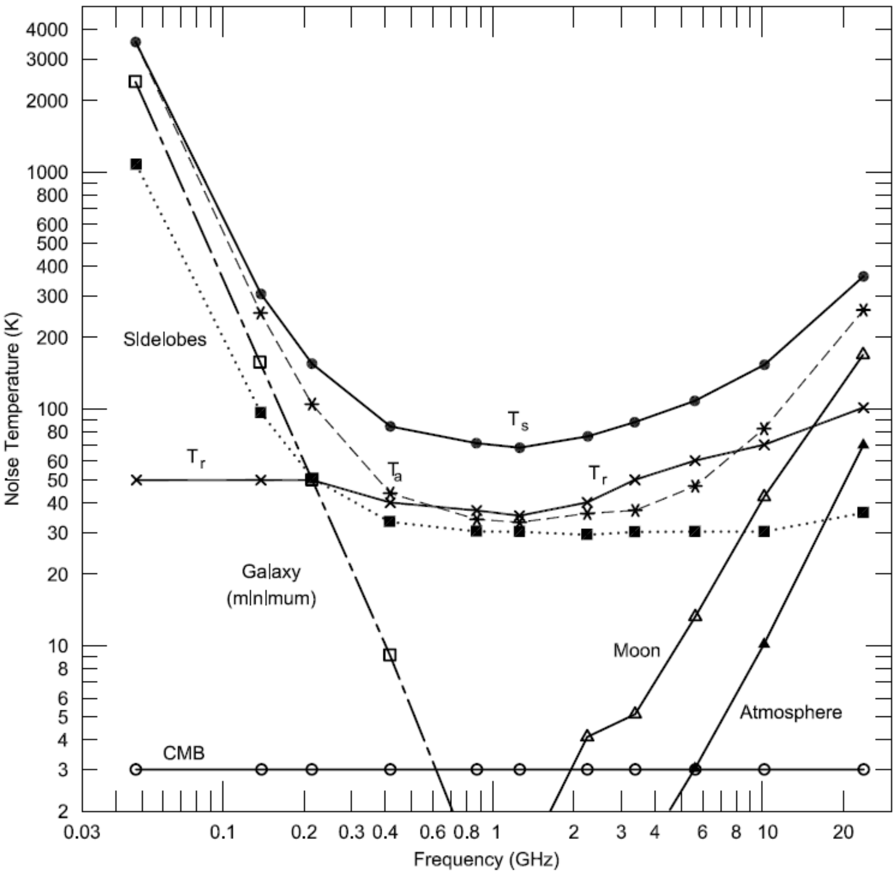

Fig 1 – Typical contributions to system noise temperature, T_s, from the cosmic microwave background (CMB), the Earth's atmosphere, the warm surface of the moon, galactic noise entering through the main antenna beam, and sky and ground noise from an antenna's side and rear lobes. Antenna temperature 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. For details see Reference 1.

What antennas, how much transmitter power ?

Linear polarization is the standard on 70 cm, so dual-polarization ("X-pol") antennas should provide the same major advantages that they do for 2 m EME. With random polarization angles of incoming signals, adaptive polarization yields an average 3 dB improvement in receive sensitivity, and much more in cases of large polarization mismatch[2]. However, X-pol Yagis with good performance are much harder to build at 70 cm than at 2m, and they have not heretofore been widely used. The main problems are achieving accurate symmetry in the X and Y planes of Yagi elements, and fitting the necessary feedlines, baluns, etc., into the available volume 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 long, rear-mounted and built on a 25 X 25 mm hollow fiberglass boom. Simulation with 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.

The link budget for EME communication[1] can be summarized in the following equation for SNR, the received signal-to-noise ratio in dB:

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

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

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

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,

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

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] when $SNR > -24$ dB in bandwidth $B = 2500$ Hz. For a typical system noise temperature $T_s = 100$ K, the required transmitter power for $SNR = -24$ dB is

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

or 66 Watts. Audible self-echoes and CW communication with a twin station require something like $SNR > 3$ dB in 50 Hz bandwidth — and thus about 10 dB more transmitter power, or 660 W at the antenna. These numbers are fully consistent with the goals outlined in the introduction.

Model 15LFA-JT Yagi

To allow us to verify the antenna design and make some 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 in Figures 2 and 3. Reflectors and directors are 1/4-inch aluminum rod, each one passing through the boom center to maintain full polarization symmetry. Element positions for the two 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.

Fig 2. – A pair of 15LFA-JT rear-mounted Yagis on a simple mount with azimuth and elevation control. Separate feedlines carry signals for horizontal and vertical linear polarization from each Yagi to a power splitter. Light-duty dacron ropes serve as forward guys, to prevent boom sag.

Fig. 3. – Rear view of a single Yagi showing construction details around the driven elements. The brass loops are fed at the center 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 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. Adjustments to both were made 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 – 437 MHz, in excellent agreement with the simulations. Compared with some designs, these Yagis are relatively wideband antennas.

We are well aware that measurements of angular power patterns are difficult without a professional antenna range, but nevertheless we attempted such a measurement using purely amateur-radio techniques. The test signal was an amateur beacon transmitter 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 in a soundcard at 48 kHz, squared, and averaged over 1-second intervals. The averages were recorded along with the readout azimuths. Plots in Figure 4 show the simulated and measured azimuth patterns for our phased pair of 15LFA-JT Yagis, for horizontal polarization.

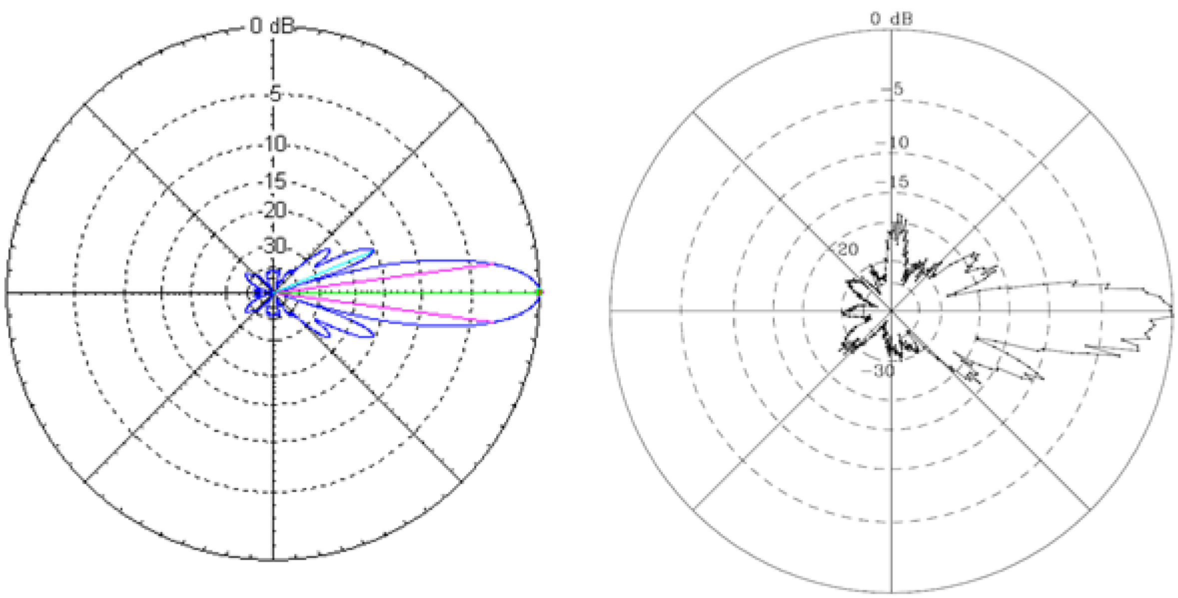

Fig 4. – Simulated (left) and measured (right) azimuth patterns of a pair of 15LFA-JT Yagis stacked horizontally, in horizontal polarization. The stacking distance was 1.2 m.

We believe the measured asymmetric sidelobes are likely the result of a permanent steel ladder, the top of which is only about 1 m away from the forward ends of the Yagis when they are pointed toward the horizon and close to the direction of the beacon. This near-field distortion should disappear when the antennas are elevated, especially after the array is raised to its final position at the top of its mast (see Figure 2, at left). Other than this (presumably temporary) distortion, the measured array pattern closely approximates the very low side- and rear-lobe responses of the simulation, especially when allowance is made for likely multi-path propagation (reflections from nearby structures) at low signal levels. 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 and elevation positioners in an Off-On-Off pattern in azimuth, centered on the Sun's 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 5. Expressed in dB, the on-to-off-source power ratio was found to be

$$Y_{Sun} = 7.2 \pm 0.1 \text{ dB} \quad (6)$$

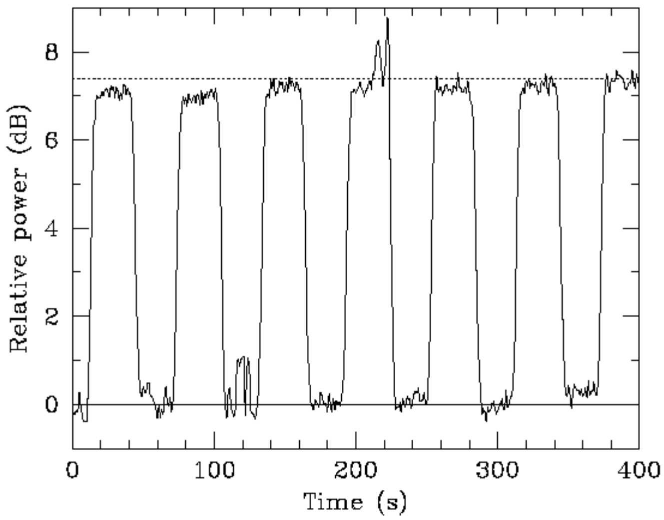

Fig. 5. – Measurements of Sun noise with a pair of 15LFA-JT Yagis. The dotted line represents the expected value for Y_{Sun} with 432 MHz solar flux $S = 44$ SFU and system noise temperature $T_s = 119$ K.

EME receiving setup

On several occasions we have operated the W2PU station in SWL mode, with the antenna pointed at the moon. We find EME receiving performance to be consistent with expectations. The first such measurements were made with the TS-2000X receiver and a single polarization — that is, without benefit of adaptive polarization. Some results are shown in the *WSJT* waterfall spectrogram of Figure 6. Note that K5DOG (at DF=900 Hz) was using a modest array of four M2 model 432-12EME antennas and about 400 W transmitter power. His signal was easy to copy ($SNR \approx -22$ dB) with our temporary two-Yagi setup.

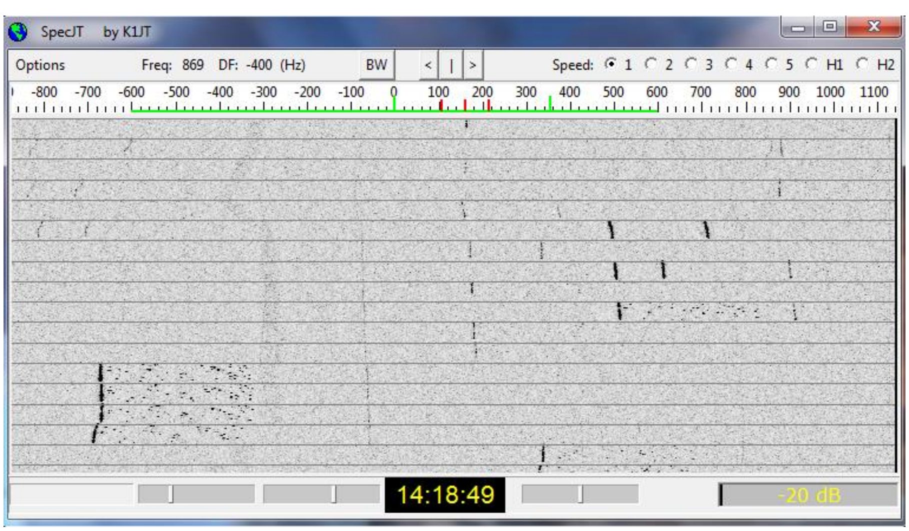

Fig. 6. – Waterfall spectral display for a sequence of 15 two-minute intervals during the 2013 ARRL EME contest. One can see decodable EME signals from an unidentified station at upper left, near DF = –800 Hz; OH2PO, –700 Hz; LZ1DX, +150 Hz; K5QE, +500 Hz; and K5DOG, +900 Hz.

As another test we operated the W2PU station remotely over the April 26-27, 2014 weekend. This time we used the LinkRF IQ+ receiver[5] together with *Linrad* and *MAP65* software, as will be our norm — but again without enabling adaptive polarization, because only one of the Rx preamplifiers was installed at the time. Despite moderately poor conditions (degradation –0.9 dB, moon 28 degrees from Sun, high libration rate), we easily copied EME signals from additional stations in Europe, North America, and Japan.

Worksheet for System Noise Temperature

Optimizing the receive performance of an EME station requires careful attention to all contributions 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 units in front of the first preamplifier. I highly recommend the use of VK3UM's *EME Calculator* software, or alternatively a simple spreadsheet[6] like the one copied below, as an aid to minimizing T_S in a step-by step manner.

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**			

Spreadsheet items highlighted in yellow are input by the user; all remaining numbers are calculated from the input data. As displayed above, the spreadsheet properly reflects our present setup except that it lists antenna gain $G = 22.4$ dB, the value for our planned four-Yagi array.

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 can certainly be reduced; this small-diameter cable is needed only for about 0.3 m, 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. Two stations equipped similarly to W2PU, using four X-Pol Yagis similar to the 15LFA-JT and power 100 W or more, should be able to work each other by EME more-or-less any time the moon is available.

References

1. J H Taylor, K1JT, "Earth-Moon-Earth (EME) Communication." *ARRL Handbook for Radio Communications*, Chapter 30 (2010); http://physics.princeton.edu/pulsar/K1JT/Hbk_2010_Ch30_EME.pdf
2. 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.
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 Furure Evolution." *Proceedings of the 12th International EME Conference, Wurzburg* (2006); http://physics.princeton.edu/pulsar/K1JT/K1JT_eme2006.pdf.
5. See the LinkRF web site, http://www.linkrf.ch/IQ+.html.
6. The Excel spreadsheet is available at http://physics.princeton.edu/pulsar/K1JT/W2PU_432.xlsx.