Analyzing EME Path Loss at 77 GHz

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Abstract

Having successfully communicated via the moon on 47GHz, our interests now turn towards 77 GHz. Sergei RW3BP has successfully heard and recorded his echoes using a 2.4 m dish and a pulse rated 60 watt TWT. Sergei documented his success in a paper that he presented at the 2013 EME conference held in Orebro, Sweden in May of 2013[1]. Congratulations to Sergei for this fine accomplishment! In June of 2013, W5LUA successfully detected Sergei's weak CW signal using the MMCW decoder program which does averaging over several minutes time. The next step is to make a QSO but a second source of power is still needed. Barry VE4MA acquired an EIK which is rated for 80 watts but the tube may be gassy. I was given an opportunity by Jeff Kruth WA3ZKR to come to Kentucky and use the 21 m prime focus dish shown in Figure 1 at Morehead State University. The dish is rated for full performance through 25 GHz so we thought it might have some performance still at 77 GHz.

Figure 1. 21 m Prime focus dish at Morehead State University in Morehead, Kentucky

Through the generosity and connections of Tom Williams WA1MBA, we were able to borrow a 1 watt amplifier which according to some preliminary calculations using VK3UM's program we thought there might be an outside chance of hearing echoes. Considering that we were both under-illuminating the moon, meant that we would have a significantly better chance of detecting our own echoes than we would of aiming at the same point on the moon that Sergei was pointing to. However as amateurs, we decided to put the dish on 77 GHz and see what happens. As they say nothing ventured, nothing gained.

Well, we had no success on hearing Sergei and only detected very small amounts of signal that may have been our echoes. As a result of our initial failure, I decided to do some research into why and the results and questions are presented in this paper.

The Basic Path Loss Equation

I decided to start at the beginning and first understand how the basic path loss numbers that can be found in the literature were calculated.

The path loss to the moon can be calculated by the following formula.

Path Loss = $(4\pi R)^2/\lambda^2$

Where R is the distance to the moon and λ is the wavelength. Based on a nominal distance to the moon of 238,000 miles, the 1 way path loss at 1296 MHz is 206.4 dB. A round trip path would be double the 206.4 dB or 412.8 dB. Fortunately, the moon acts as a gigantic reflector of 2160 miles in diameter, although not a very good one as it is convex and very rough. The literature suggests the reflectivity of the moon to be .065 or 6.5% through roughly 3cm. So that would suggest that the moon as a reflector is only down 11.87 dB from a perfect reflector or roughly the equivalent gain of a 550 mile diameter reflector.

We calculate the gain of a parabolic reflector as Gain = $(\pi d)^2/\lambda^2$

Substituting in the 2160 mile diameter of the moon, the moon has a gain of 153.5 dB. If we subtract the reflectivity loss of 11.87 dB we arrive at an effective gain of 141.63 dB.

Therefore path loss at 1296 MHz to the moon and back is

Path Loss = Path loss to the moon (dB) - Moon Gain (dB) + Path loss back to earth (dB)

Path Loss = 206.4 dB - 141.63 dB +206.4 dB = 271.2 dB at 1296 MHz which agrees with reference [2]

We can also express path loss in ratios instead of dBs which provides the following equation

$$\text{Path loss} = 10 \log \frac{\frac{(4\pi R)^2}{\lambda^2} \frac{(4\pi R)^2}{\lambda^2}}{\frac{(\pi d)^2}{\lambda^2} * \sigma_m}$$

Simplifying we arrive at

$$\text{Path loss} = 10 \log \frac{(16\pi)^2 R^4}{\lambda^2 d^2 * \sigma_m}$$

Substituting in R=238,000 miles, d=2160 miles and converting units as necessary we arrive at

Path Loss = $10 \log (F(GHz)^2 / (2\times10^{-26} * \sigma m))$

Substituting in for 1296 MHz we calculate 271.1 dB path loss to the moon and back based on 6.5% reflectivity.

I generated an excel spreadsheet to help me with further calculations. Table 1 shows path loss versus frequency. Of course this is all based on the entire moon being fully illuminated by our transmit antenna which we know is not the case for higher frequencies where the 3dB beamwidth of the antenna is less than the 0.5 degree subtended angle of the moon. However, it confirms the path loss numbers as presented by Al Katz and Dick Turren in reference [2]. It also confirms that the equation in the original article should have had two of the quantities squared. Based on additional information, I have also included an additional column for path loss based on a reflectivity of 3.3% for the bands above 3cm based on lunar measurements at 35 GHz [3].

F (GHz)	100%	6.50%	3.30%
0.144	240.2	252.0	
0.432	249.7	261.6	
0.902	256.1	268.0	
1.296	259.2	271.1	
2.3	264.2	276.1	
3.4	267.6	279.5	
5.76	272.2	284.1	
10.368	277.3	289.2	
24.048	284.6	296.5	299.4
47.088	290.4	302.3	305.3
77.184	294.7	306.6	309.6

Table 1. EME path loss (dB) with 100% and 6.5% and 3.3% reflectivity versus frequency in GHz

These path loss numbers also agree well with VK3UM's program version 9.10 when using the 6.5% moon reflectivity factor. As mentioned before, the literature may suggest that the reflectivity of the moon at frequencies higher than 10 GHz may be less than 6.5 % and closer to 3.3%. More research is required.

At the higher frequencies, where we are not fully illuminating the moon, we have an additional factor that we must include in the calculations. The additional loss brought about by not fully illuminating the moon is as follows.

Cross Sectional Loss = 10 log $\frac{0.5^{2}}{(3dB\ beamwidth)^2}$

Sergei RW3BP mentioned this in his paper from the 2013 Swedish EME conference [1]. The 3 dB beamwidth of the antenna is expressed in degrees and the 0.5 deg is the subtended angle of the moon as viewed from earth. If the 3 dB beamwidth of the antenna is equivalent to the 0.5 degree subtended angle of the moon, then there is no additional path loss. If the beamwidth of the antenna is half the subtended angle of the moon, then there is an additional 6 dB of path loss due to under illuminating the moon. VK3UM's program also has an option to include a "Sergei" factor which is based on illuminating a smaller portion of the moon. The program includes a suggested scaling factor for 24, 47 and 77 GHz. Sergei chose a .77 factor for the moon at 77 GHz. I believe Sergei is suggesting that only 75% of the moon is a reasonable reflector at 77 GHz. In a paper by DF5AI [4] Volker suggests that the moon looks like a small 200 km disc where a majority of the reflection occurs at 3 cm and longer wavelengths. At visible wavelengths we know that we see nearly 100% of the moon due to light reflecting off of the various rough surfaces of the moon. It then may make sense that even though the reflectivity of the moon could be worse above 10 GHz, the effective area that reflects back to earth is larger, maybe 75% of the moon diameter? More research is definitely required in this area.

Table 2 shows the theoretical gain at 50% efficiency and the associated 3 dB beamwidth and the resultant cross sectional ratio for the moon versus dish diameter. The beamwidth is calculated by using 41253 / gain factor at 100% efficiency. The cross sectional factor is also shown in dB versus dish diameter. The last column represents Echo Loss. The Echo Loss is calculated by taking the path loss at 77 GHz as shown in Table 1 and adding on the additional cross sectional factor and then adding on the antenna gain for transmit and the antenna gain for receive.

Echo Loss (dB) = Path loss (dB)+ Cross-sectional Factor (dB) - Transmit Antenna Gain (dB) - Receive Antenna Gain (dB).

Of course for echo testing, the transmit and receive gains are the same. It is clear for echo testing with a larger antenna with increased cross sectional loss, that the increase in antenna gain more than offsets the increased cross sectional loss. This is clearly shown in Table 2.

Dia (M)	Gain(dBi) 50% eff	Beamwidth degrees	Cross-sectional Ratio	Factor (dB)	Echo Loss (dB)
0.5	49.1	0.503	1.010444164	0.0	208.4
1	55.2	0.251	0.252611041	6.0	202.3
2.4	62.0	0.105	0.043856084	13.6	196.3
5	69.1	0.050	0.010104442	20.0	188.3
21	81.6	0.012	0.000572814	32.4	175.8

Table 2 Dish diameter vs cross sectional loss factor and echo loss at 77 GHz

Calculating received signal strength

Having the echo loss in dB for various dish sizes, we can calculate some signal levels. System sensitivity can be calculated using the following formula.

Sensitivity (dBm) = -174 dBm/Hz + 10 log (BW)Hz + 10 log (Ta/To + NF -1)

Where Ta is the effective antenna temperature, To = 290K, and NF is the noise factor expressed as a ratio

In our case the antenna is seeing only moon noise so we will assume Ta = 210K

Our noise figure is 4.3 dB which expressed as a ratio = 2.69

Our post detection bandwidth will be 1 kHz

Substituting into the formula we have

Sensitivity (dBm) = -174 dBm + 10 log 1000 + 10 log (210/290 + 2.69 – 1)

= -174 dBm + 30 dB + 3.83 dB

= -140.2 dBm in a 1 kHz bandwidth

If we increase our bandwidth to 2.5 kHz, the noise floor rises by 4 dB to -136.2 dBm.

Table 3 shows the level of the received echo for both 1 watt and 60 watt transmissions versus dish diameter. The corresponding echo S/N is shown in dB for both 2.5 kHz and 1 kHz IF bandwidths. The predicted signal to noise ratio of -12.3 dB correlates within a couple of dB of Sergei's prediction before atmospheric loss and libration signal width loss are taken into consideration. The calculations also predict that our echoes at the 21 m dish with 250 milliwatts at the feed and a similar 2.5 kHz bandwidth would have been -9.6 – 6dB (for our ¼ W) = -15.6 dB S/N ratio so it is not too much of a surprise that we did not see them on Spectran. It also shows that our echoes with 250 milliwatts would be approximately 3 plus dB worse than Sergei's echo level based on his tests earlier in 2013 when he first saw his echoes on 77 GHz. Once again, the effect of atmospheric absorption and libration signal spreading are not included in these calculations. There has also been considerable discussion regarding increasing antenna gain and narrowing beamwidth and can it actually cause an increase in echo signal to noise ratio? More work needed in this area.

						Transmit Power = 1 Watt			Transmit Power = 60 Watts		
						Echo	Echo	Echo	Echo	Echo	Echo
	Gain(dBi)	Beamwidth	Cross-sectional	Factor	Echo Loss	Power	S/N	S/N	Power	S/N	1 kHz
Dia (M)	50% eff	degrees	Ratio	(dB)	(dB)	Received	2.5kHz BW	1 kHz BW	Received	2.5 kHz BW	Echo (dB)
0.5	49.1	0.503	1.010444164	0.0	208.4	-178.4	-42.2	-38.2	-160.6	-24.4	-20.4
1	55.2	0.251	0.252611041	6.0	202.3	-172.3	-36.1	-32.1	-154.5	-18.3	-14.3
2.4	62.0	0.105	0.043856084	13.6	196.3	-166.3	-30.1	-26.1	-148.5	-12.3	-8.3
5	69.1	0.050	0.010104442	20.0	188.3	-158.3	-22.1	-18.1	-140.5	-4.3	-0.3
21	81.6	0.012	0.000572814	32.4	175.8	-145.8	-9.6	-5.6	-128.0	8.2	12.2

Table 3 Echo Signal to Noise Ratio vs antenna diameter for 1W and 60W and 1 kHz and 2.5 kHz BW

At this point, I decided to take another look at DJ7FJ's paper [5]. The emphasis on DJ7FJ's paper was to show how larger dishes on 10 GHz with beamwidths smaller than the subtended angle of the moon show less improvement in both echo strength and the strength of a station being worked than one might have originally hoped for.

DJ7FJ states that "The power reflected by the moon cannot be increased by more antenna gain. The losses of reflection are assumed to be the same, whether the diameter of the spot is 1000km or 100km. The reflections on the moon surface are diffuse. When the same antenna is used for transmitting and receiving always the same spot is illuminated or observed. Using bigger dishes, the received power increases only with the single gain factor. Now more gain can only be made on the receiving side. The moon always reflects the same sum of energy. If the surface of the receiving antenna increases, this will have an effect on the power level." DJ7FJ produced a Figure 8 in his paper that shows the relationship between antenna diameter to path loss compared to a 4 m dish. His plot shows a flattening of his echo strength that increases with the "single gain factor" of the dish used for both transmitting and receiving.

I decided to generate a similar graph based on numbers at 77 GHz. I took my data in Table 3 and generated a plot similar to his Figure 8 which is shown in Table 4.

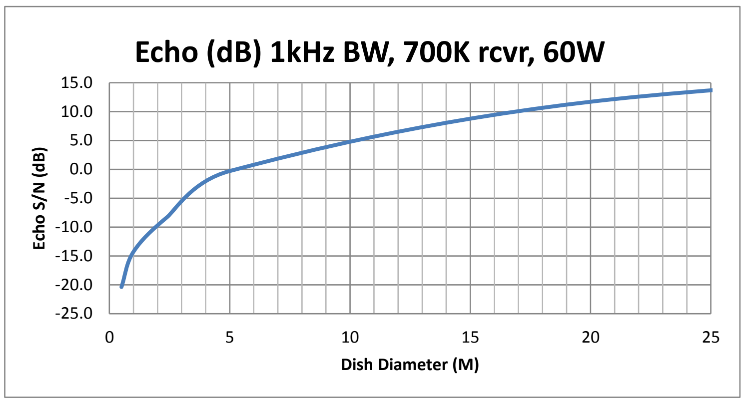

Table 4. Echo strength at 77 GHz versus dish diameter.

The shape of the graph has a very similar resemblance to Figure 8 in the DJ7FJ paper. Keep in mind that a 1m dish at 77 GHz has a 3 dB beamwidth of about a .5 degree so it pretty much illuminates the entire moon. Clearly when increasing the dish diameter from 5 m to 21 m, the curve shows a 12.2 – -.3 = 12.5 dB which is exactly the increase in antenna gain 81.6 – 69.1 = 12.5 dB which DJ7FJ calls the increase in the "single gain factor". DJ7FJ suggests that this "single gain factor" is only related to receive gain and not transmit. I suggest that it is a result of both an increase in receive and transmit antenna gain but it is offset by the ever increasing cross sectional loss factor. The effect is that the echoes only increase by the added gain of the antenna and not by the addition of increases to both receive and transmit gain as we would expect on the lower bands where we over illuminate the moon. The bottom line is that echoes should increase with increased antenna diameter which is an important piece of information regarding echoes only.

Hearing Sergei with the 21 m dish.

Since Sergei's 2.4 m dish is illuminating a bigger spot on the moon than we are, we must use the cross sectional factor of the larger dish to determine the effective path loss between our 2 stations.

Therefore the signal level received at the 21 m dish from Sergei would be

Received signal = Pout + Gt – Path Loss – Cross Sectional Loss Factor + Gr

Received signal = +47.8 dBm + 62 dB – 306.6 dB – 32.4 dB + 81.6 dB = -147.6 dBm or a S/N ratio of about -7.4 dB in a 1 kHz bandwidth.

Table 5 shows the predicted received S/N ratio of Sergei's signal from his 2.4 m dish in a 1 kHz bandwidth as received by various dish diameters. Note the compression once the dish size approaches 3 to 4 m. This clearly shows that the increased gain of the larger dish is offset by additional cross sectional loss. When calculating any EME link, the cross sectional loss is calculated based on the larger antenna.

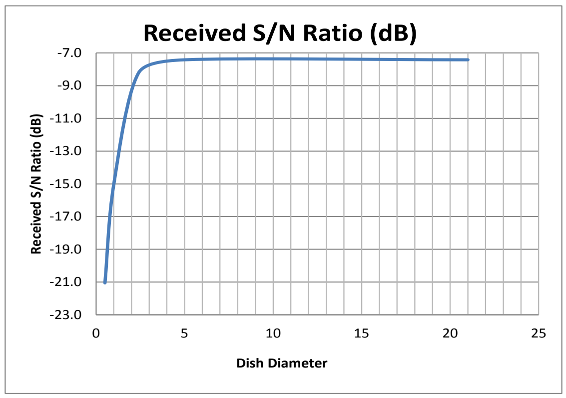

Table 5. Received S/N Ratio of RW3BP's 77 GHz Signal vs Receive antenna dish size in meters.

There is little doubt that the 21 m dish should not have been expected to receive a significantly stronger signal than would have been received with a 2.4 to 4 m dish.

Tests at Morehead State University using the 21 m dish.

This was my first experience in being able to be a part of a big dish operation. Through the generosity of Jeff Kruth and the entire staff at Morehead State University, we were given all the support we needed. I brought my 77 GHz transverter which I have been using at the home location with both 2.4 m and a 1 m offset fed dishes. The first couple of days were spent integrating the driver and PA borrowed from WA1MBA into my transverter. The PA provided 250 milliwatts at the waveguide relay. The receiver noise figure measured 4.0 dB. The completed assembly prior to installing at the feed of the 21 m dish is shown in Figure 2.

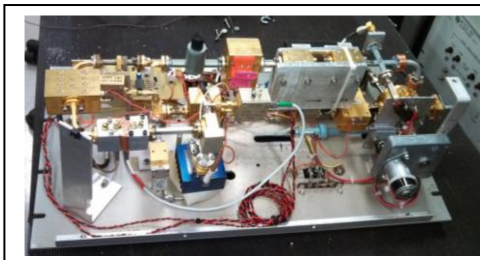

Figure 2. W5LUA 77 GHz Transverter with 250 mW PA installed. Note homebrew actuator for WR-15 waveguide switch on the right side.

A Flex-1500 was used as the IF and the waterfall from WSJT was used to look for echoes. Our best sun noise with the 21 m dish measured 7.5 dB. Best moon noise was 0.8 dB. At home with the same transverter and a 2.4 m offset fed dish, I obtained 5.5 dB sun noise and 0.4 dB of moon noise. The improvement in performance at the Morehead dish was most likely due to much better surface accuracy and possibly better atmospheric conditions. We attempted to map the sun but our .05 degree increments were too large to really get a good idea as to the real slope of the drop-off as we moved off the sun. Next time we will scan the sun in .01 degree increments. We will probably need better resolution than the Power SDR software for the Flex-1500 will provide. We also had rain during our initial tests so time was limited. Figures 3 and 4 show plots of sun noise in both azimuth and elevation planes. The plots show that we had a small offset in azimuth due to small mounting errors. When we scan the sun in smaller increments next time, we should be able to determine the precise offset which in hind sight is what we needed to know when we went looking for Jupiter and stars.

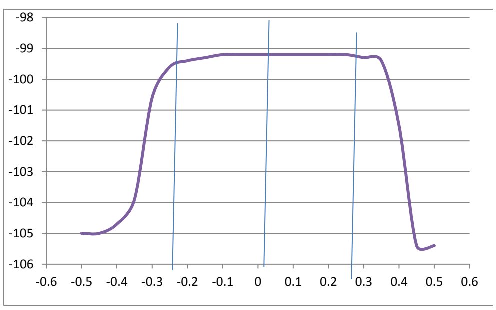

Figure 3. Azimuth scan showing slight .05 degree offset

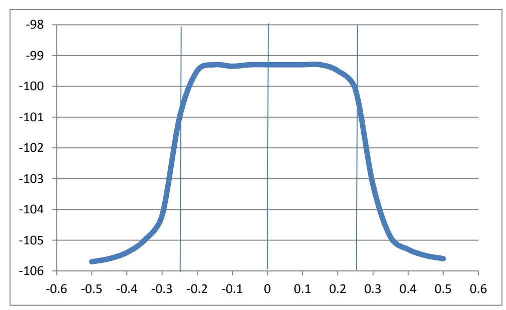

Figure 4. Elevation scan showing pretty good symmetry

Figure 5 shows our attempt at seeing our echoes. We kept the transmit frequency constant and looked for echoes as the self Doppler changed with time. There was some evidence that we observed echoes but not very conclusive. We were also panning the moon looking for hot spots in echo returns. However, we have since reminded ourselves that is an additional plus or minus offset in self Doppler as we get closer to the limb of the moon. This is something to consider the next time we try for echoes.

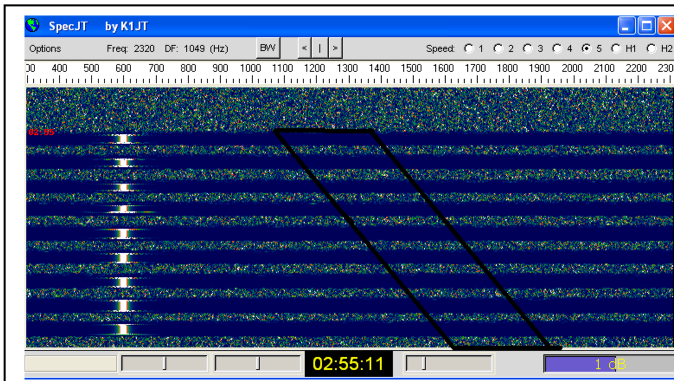

Figure 5. 77 GHz Echo attempt at 21 m Dish. Box shows approximate expected receive echo frequency. White area shows transmit frequency tone. Tilt of echo box shows extent of Doppler change with time

Summary

This was my first opportunity to operate EME at a very large dish and to try it at 77 GHz was an even bigger challenge. Although my optimism is high we still have some work to do to hear our echoes. Most notably is more power. Having a watt would give us another big 6 dB in power and would be a good short term goal. The results predict that the large 21 m dish should allow us to hear our echoes once we get our power up several dB.

Although RW3BP has already seen his echoes at 77 GHz with a 2.4 m dish and 60 watts power, the next goal would be to make 2 way contact with Sergei. The results predict that the large 21 m dish offers very little receive advantage over a 3 or 4 m dish due to the increased dish gain being unable to offset the additional cross sectional loss of the larger dish.

I would like to plan a second visit to the 21 m dish for additional tests.

I wish to thank the following individuals who provided support at the Morehead State University dish, Jeff Kruth WA3ZKR, Ben Malphrus, and Bob Kroll. I also wish to thank VE4MA, K5GW, WA1MBA, WA1ZMS, WA8RJF, and WA3ZKR for their continued discussion on this fascinating subject and thanks to Barry VE4MA for his comments on the conference paper.

Your comments are appreciated.

Best 73 Al W5LUA June 26, 2014

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