A Low Power, 144 MHz, Earth-Moon-Earth Amateur Radio Station

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Amateur Earth-Moon-Earth (EME) communications is one of the most challenging projects that an amateur radio operator can attempt. The objective of this paper is to give the amateur radio enthusiast an idea of what is needed to successfully model, build, and operate a small EME station. The KC1HTT small, low power, 144 MHz, Earth-Moon-Earth amateur radio station is described in detail. Included are the physics of EME communications, site constraints, communication system analysis, design, and hardware implementation. In addition, the JT65B communication mode, waveforms, and signal processing are briefly described. Finally, EME operations are reported including QSO planning, safety considerations, EME support web sites, with examples of three successful QSOs and a signal-to-noise analysis of the QSOs based on the bistatic radar equation. Plans for the next generation KC1HTT EME radio station improvements are also discussed.

1. A Brief History of Earth-Moon-Earth Communications (EME)

On January 10, 1946 at 11:58 AM EST, the United States Army Signal Corps was first to successfully make radar measurements on the Moon. Project Diana used a modified World War II SCR- 271 surveillance radar. The radar operated with a power of 3000 Watts at 111.5 MHz and transmitted 250 msec pulses. The antenna consisted of an 8x8 dipole array with an antenna gain of 24 dB. Since the antenna could only move in azimuth, radar measurements were confined to Moon rise and Moon set, specifically during the time the Moon was no more than 15° above the horizon. This marked the beginning of radar astronomy and Earth-Moon-Earth communications. [1], [2] Figure 1 illustrates the idea of Earth-Moon Earth (EME) communications. [3]

The first EME amateur radio EME contact (QSO) was made on July 17, 1960 between the W6HB club in California and W1BU club in Boston. That QSO was made at 1296 MHz with each club using a 1000-Watt transmitter and a 5.5-meter parabolic dish. [2]

On May 9, 1962, researchers from Massachusetts Institute of Technology successfully used a high power, pulsed laser to range to the Moon. Project Luna See, which was supported by the United States Army Signal Corps, used a 50 joule/pulse ruby laser with a pulse duration of 0.5 msec and a transmitter telescope of 30 cm diameter. The laser receiver used a 1.2-meter telescope and a filter with a passband of 0.7 nm. Photon counting direct detection was used to measure the time of arrival of the very weak, reflected pulse of light. [4] [5]

Fifty years ago, in July 1969, after successfully landing on the Moon, NASA Apollo 11 Astronauts Neil Armstrong and Ed “Buzz” Aldrin deployed an array of 100 optical retroreflectors on the Moon to enhance laser lunar ranging measurements. [6] Many retroreflector-aided, lunar laser ranging measurements followed.

High speed, one-way optical communications to and from lunar orbit was first demonstrated by NASA and the Massachusetts Institute of Technology Lincoln Laboratory on October 17, 2013. Data rates of 622 Mbits/second were achieved in the Lunar Laser Communications Demonstration (LLCD) experiment. Once again, ultrasensitive single photon, detectors were used in the optical receiver. [7] [8] [9]

With the inspiring history of Project Apollo and the Moon landings, as well as radio frequency and optical experimental communications to and from the Moon, amateur radio enthusiasts have followed professional scientists and engineers in building radio stations capable of cw, phone, and more recently, digital modes of RF communications. [10] Amateur radio equipment manufacturers have designed transceivers, low noise preamplifiers, antennas, power combiners, and motorized tracking mounts suitable for EME communications. The real revolution in amateur EME communications has come with the development of special digital modulation formats by Dr. Joseph H. Taylor, **K1JT**. The software used to generate and decode weak lunar signals is freely available in the WSJT-X software suite at:

http://www.physics.princeton.edu/pulsar/K1JT/wsjtx.html

My effort to build a low power, Earth-Moon-Earth radio station began in July 2018 after doing FM satellite communications QSOs using two, BTECH 5-Watt handheld transceivers and an Arrow II dual band Yagi antenna. That led to the purchase of a book titled, Amsats and Hamsats Amateur Radio and Other Small Satellites, by Andrew Barron, **ZL3DW** where I read about amateur Earth-Moon-Earth communications. In addition to a basic review of some of the physics and technology of EME, the most important parameter that he described in his book was the average lunar reflectivity, 7%. [11] With the reflectivity, I could then estimate the performance of an EME link as if the EME link was a bistatic radar. In his book, Barron warned that,

"*I hope this chapter gives you a taste of the EME world. It is not for the faint-hearted. You need a great deal of skill and patience. Some days the signals are weak or there is too much distortion or fading and it just does not work, other days it is really exciting*". [11]

The examples of other hams, whom I saw operating small, low power EME stations on YouTube, provided the final motivation. With the 50th Anniversary of the Apollo 11 lunar landing fast approaching, in 2018, I set out to build and successfully demonstrate a low power Earth-Moon-Earth amateur radio station before the end of 2019 *because it was a challenge*.

In keeping with the tradition of naming space projects after the gods and goddesses of antiquity, my EME project was named *Project Selene* after the Greek goddess of the Moon.

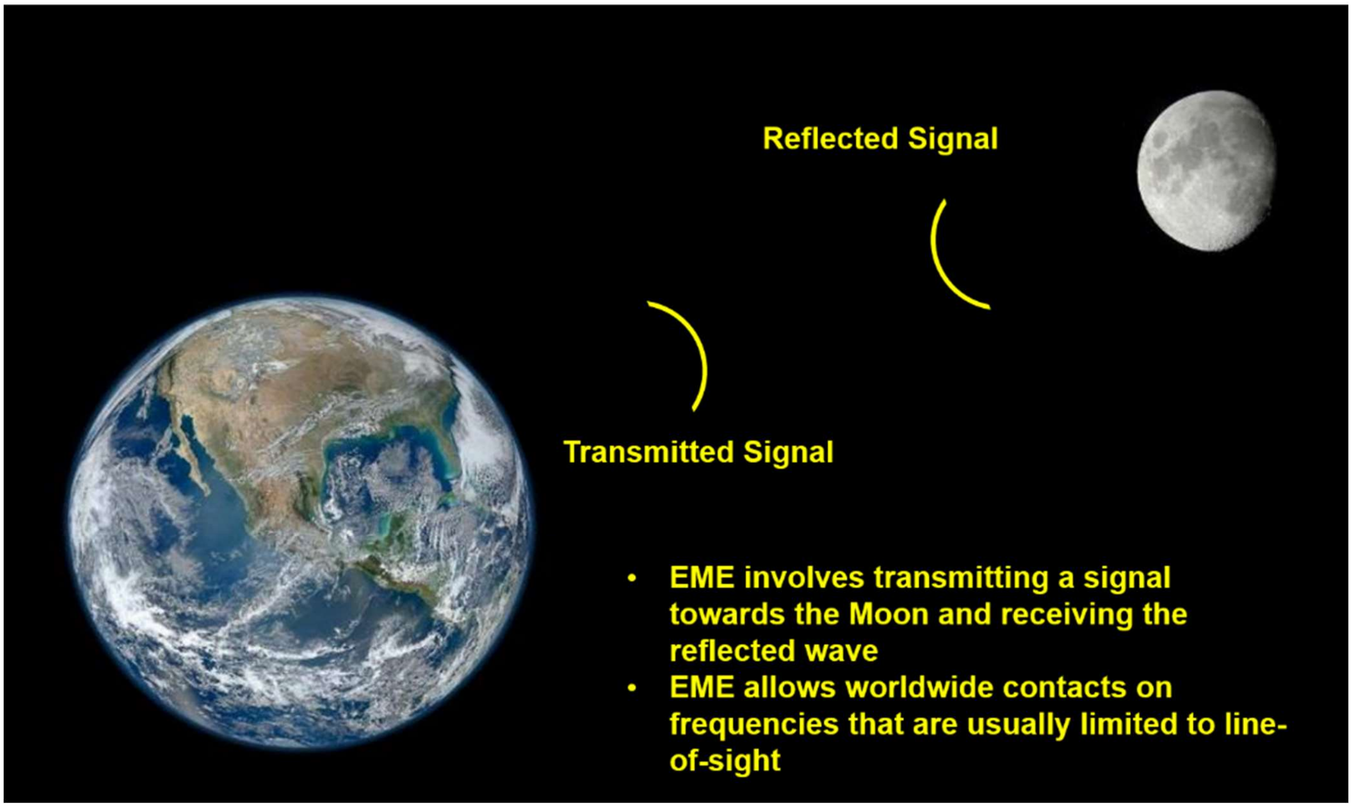


Figure 1. Earth-Moon-Earth (EME) Communications.

2. The Physics of Earth-Moon-Earth Communications

In order to do Earth-Moon-Earth communications, one has to understand some of the limitations imposed by physics on that communication link. When using the bistatic radar equation to calculate the performance of the EME link, several lunar parameters are needed. These include the range to the Moon, the physical size of the Moon to determine the apparent angular extent of the Moon, the mean radar cross section (RCS) of the Moon at VHF or UHF frequencies, the statistics of the lunar radar cross section, and how the motions of the Moon determine Doppler shifts and apparent angular rates. Table 1 lists some of these lunar characteristics.

Table 1. Important Lunar Characteristics

Range	3.844×10^8 m (3.631 to 4.057×10^8 m)
Lunar Diameter	1.736×10^6 m
Lunar Angular Subtense	~9.03 mrad or ~0.517°
Maximum Lunar Angular Rate	< ~15° per hour
Lunar Doppler Shifts at 144 MHz	< 350 Hz
Lunar Geometric Cross Section Area	9.47×10^{12} square meters
Lunar Reflectivity at VHF and UHF	~7.4%
Reflection is predominantly specular at VHF	
Median Lunar Radar cross section, σ_{Moon}	118.45 dBsm
The lunar radar cross section has a Rician probability distribution - one major scatterer ("smooth surface"), and many randomly-placed, minor, scatterers ("rough")	
Slow fading times - several seconds at 144 MHz caused by lunar libration	
Linear polarizations are not altered significantly by lunar reflection	

Measurements of the UHF cross section of the Moon were made in 1960. Because most radar target radar cross sections fluctuate, the RCS is best expressed in a probabilistic way. Figure 2 is the lunar RCS cumulative probability distribution at 425 MHz measured at Moon rise and during Moon transit. The measured median RCS ranges from +116 dBsm to +118.75 dBsm at 425 MHz. [12] It will be assumed that the magnitude of the lunar RCS at 144 MHz is essentially the same as that at 425 MHz.

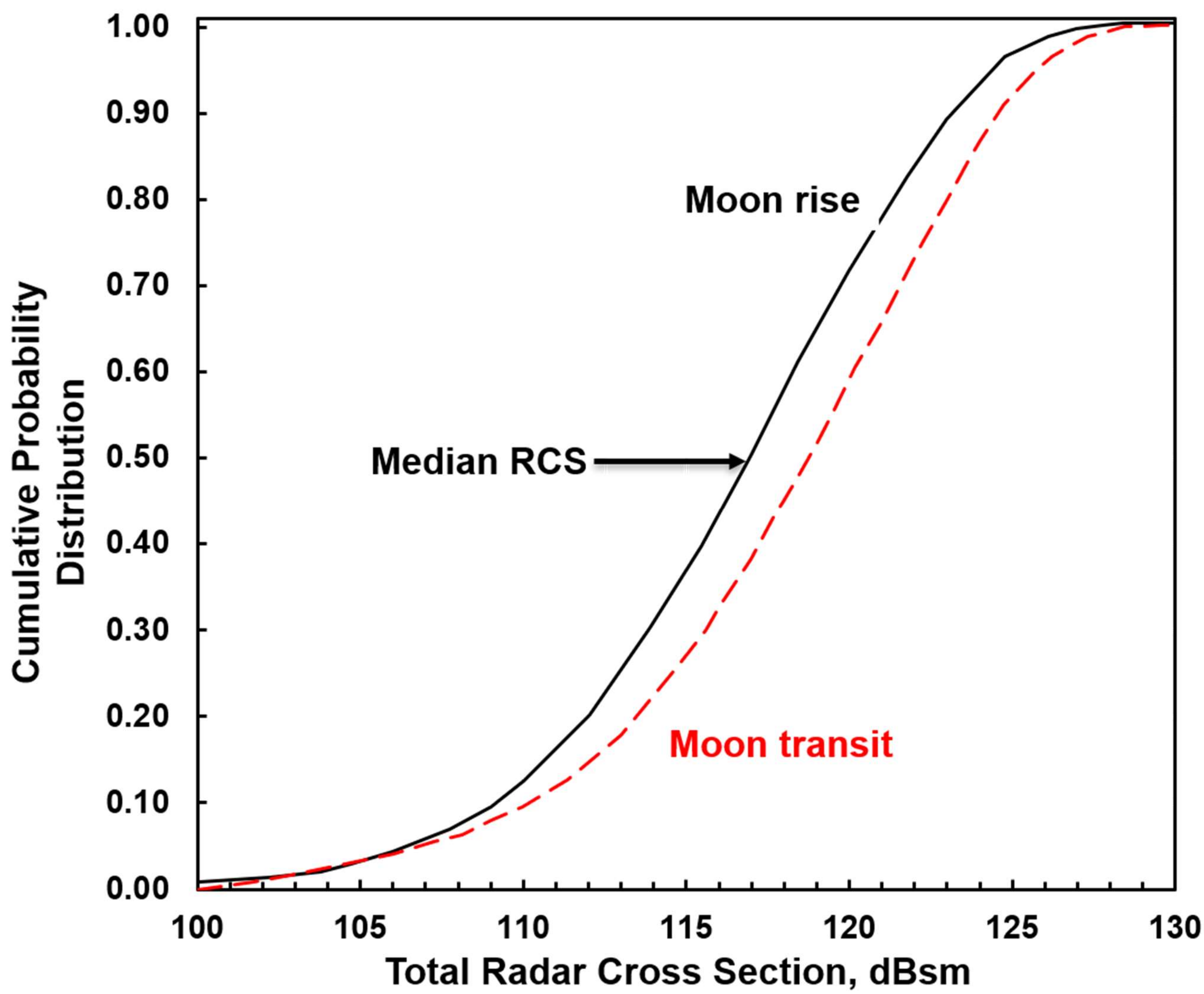
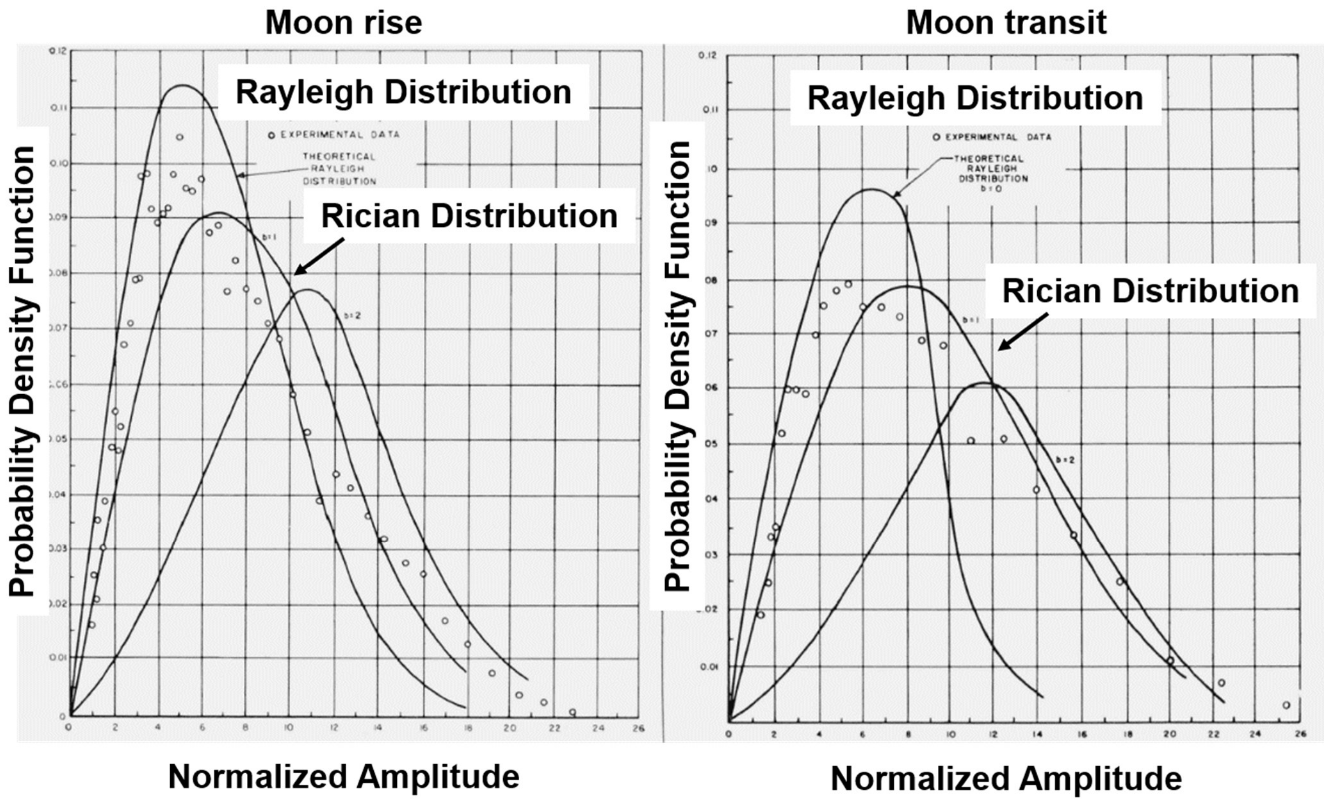


Figure 2. Cumulative probability distribution of the total radar cross section of the Moon at 425 MHz, February 8, 1960. [12]

The probability density function of the measured lunar RCS can indicate the type and character of the lunar return signal. Figure 3a and 3b are plots of the probability distribution function of the normalized return signal amplitude for Moon rise (3a) and Moon transit (3b). These plots indicate that the lunar reflection at 425 MHz is mainly specular, or mirror-like, with additional small scatters representing rough terrain features. The curve fit to a Rician distribution (Figure 3b Moon transit) indicates the preservation of the linear polarization of the incident radio signal. Figure 3a has a different Rician fit, indicating that the diffuse scatterers on the Moon were stronger than those during Moon transit. That is coupled to the lower median RCS shown in Figure 2 during Moon rise. The main conclusion that can be drawn is that the RCS is dominated by a strong specular reflection that will preserve the linear polarization of a signal incident on the Moon. This strong specular lunar reflection would change the sense of a circularly polarized signal, for example, right circular polarization incident on the Moon would be returned to the Earth as left circular polarization.



Figures 3a and 3b. The measured probability density functions for the lunar echo amplitude at 425 MHz during Moon rise (2a) and Moon transit (2b), February 8 1960. Note the close fit to a Rician distribution for the Moon transit data. The Rician indicates a dominant specular reflector in the presence of weaker diffuse scatterers. This implies the preservation of the linear polarization in the radar return. [12]

The linear polarization preserving feature of the dominant, specular character of the UHF RCS was independently verified in time resolved reflected signal polarization measurements of lunar radar returns. [13] Figure 4 is a plot of the degree of polarization of the reflected lunar signal versus time. The short time delay indicates that the preserved linear polarization reflection is returned from the center "cap" of the Moon's surface closest to the Earth. This cap is most likely the lunar Mare.

The significance of the UHF radar cross section measurements of the Moon is that linear polarization is required for the transmitter since the Moon preserves that polarization in the return signal. With the measured median lunar RCS and RCS statistics available, the performance of a proposed EME communication system can be evaluated.

Although 144 MHz and higher frequencies are propagated through the atmosphere and ionosphere, the free electrons in the D, E, F1, and F2 layers of the ionosphere interact with the Earth's magnetic field and the linearly polarized radio signal. This is known as the Faraday Effect.

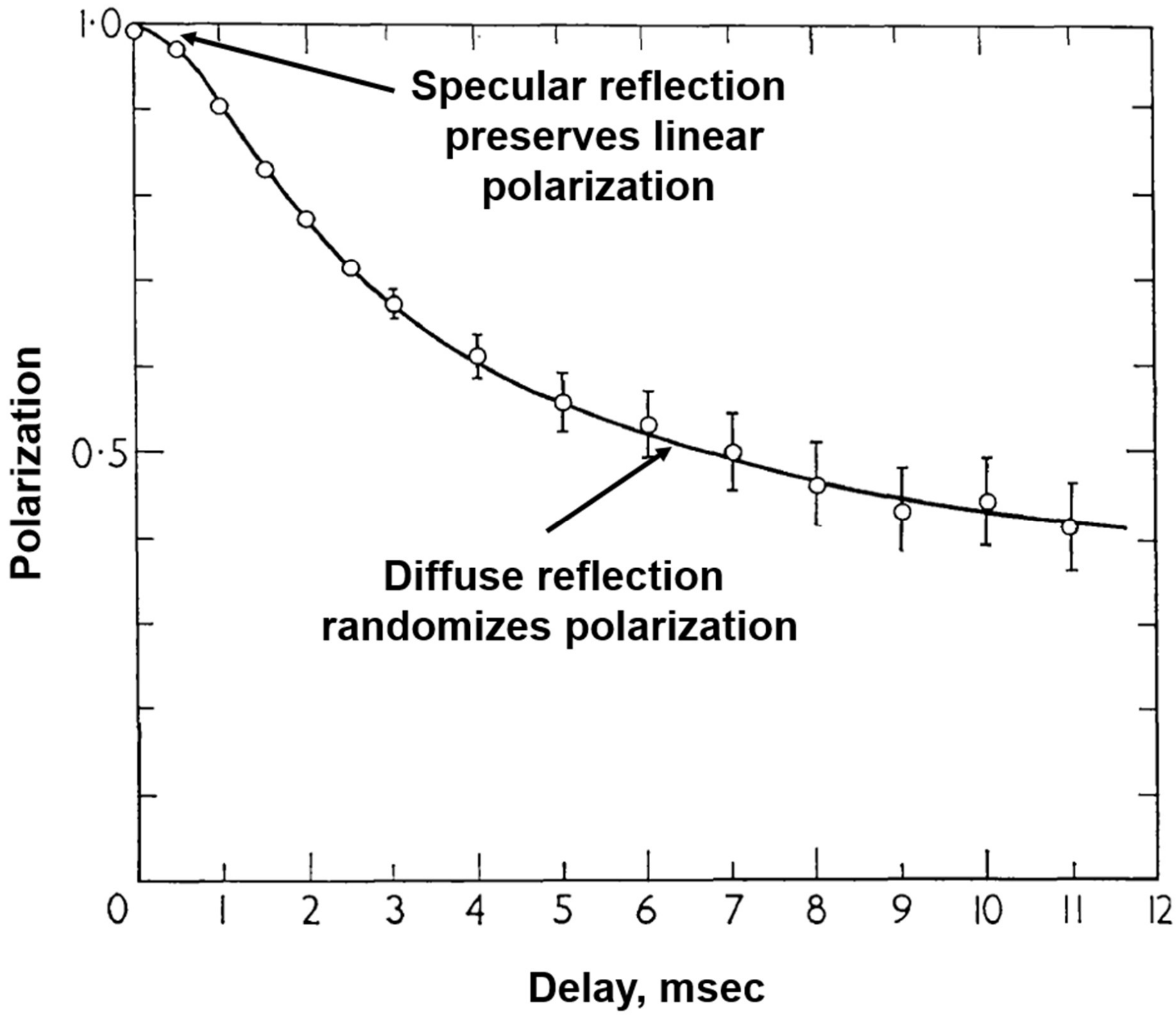


Figure 4. Measured polarization versus delay for lunar radar echos at 440 MHz August 17, 1960. [13]

The Faraday Effect is the rotation of a linearly polarized electromagnetic wave as illustrated in Figure 5. It is caused by a magnetically-induced birefringence in the Faraday medium, the ionosphere. The degree of rotation of the transmitted electric field vector is a function of the frequency, the electron density in the path of the electromagnetic wave, the total path length through the electron layer, and the alignment of the Earth's magnetic field and the propagation vector of the electromagnetic wave. If a reflected signal were to travel back on the exact path, the polarization rotation is doubled.

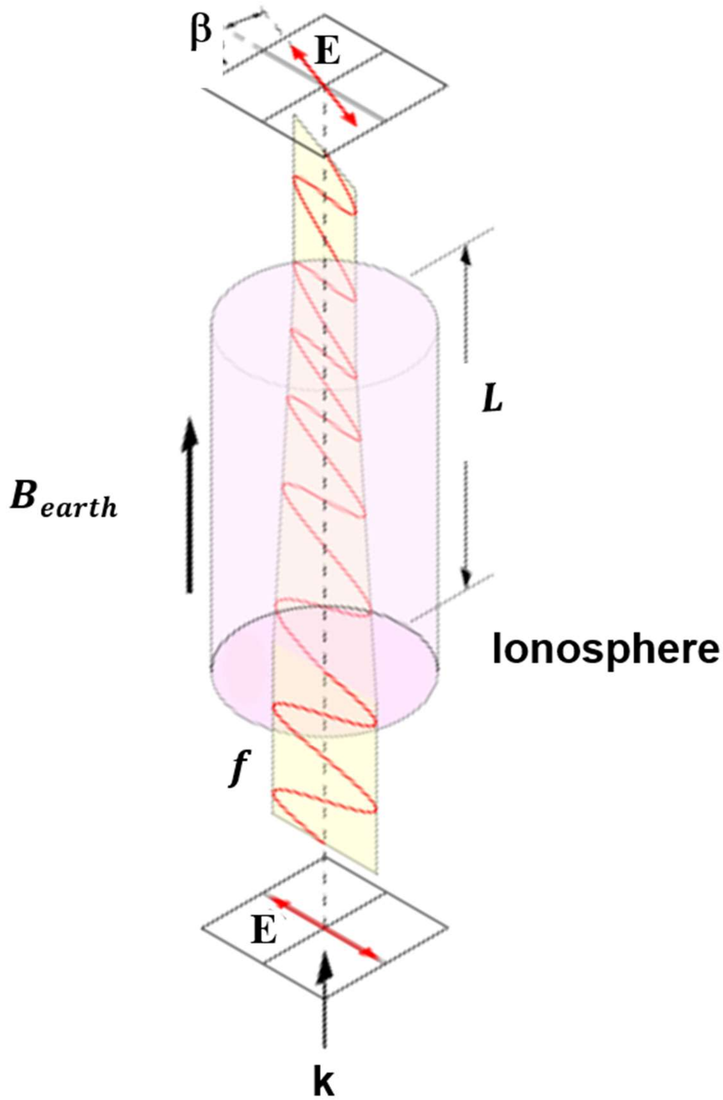


Figure 5. Faraday rotation. Under the right conditions, the combination of the free electrons present in the layered ionosphere (D, E, F1, and F2 layers) with the Earth's magnetic field rotates the polarization of a linearly polarized electromagnetic wave propagating though the ionosphere. Faraday rotation is caused by a magnetically-induced RF birefringence in the ionosphere. [14]

The equation describing the Faraday rotation, given the assumption of a uniform electron density in a contained volume, illustrates the magnitude of the effect. Equation 1 is a simplified description of the Faraday Effect, given these assumptions. [15]

The Faraday rotation, β, is:

$$\beta = (1.355 \times 10^{9} * N_{aver} * B_{earth} * L * \cos(\theta) * \sec(\varphi))/f^{2} \quad \text{degrees} \qquad (1)$$

where:

β = Faraday rotation, degrees

f = Frequency of electromagnetic wave, Hz

k = Electromagnetic wave propagation vector

φ = 0 degrees, angle between k and zenith

θ = 0 degrees, angle between k and B_{earth}

B_{earth} = 50 μT

L = 500 km

N_{aver} = 10^{12} electrons/m^2

The Faraday rotation can be calculated given the above assumptions. Table 2 illustrates the magnitude of Faraday rotation as a function of frequency for a single pass through an ionosphere having an average electron density of 10^{12} electrons/m^2, with the direction of signal propagation along the Earth's magnetic field lines.

Frequency	Maximum Estimated One-Way Faraday Rotation			
f MHz	β Degrees	β Radians	90 degree polarization shifts	Waves
50.19	10758.08	187.75	119.53	29.88
144.12	1304.73	22.77	14.50	3.62
432.07	145.17	2.53	1.61	0.40
1296.07	16.13	0.28	0.18	0.04

Table 2. Calculated ionospheric RF Faraday rotation as a function of frequency. Faraday rotation is most significant for the 6-meter, 2-meter, and 70 cm EME bands.

Table 2 shows that Faraday rotation can be very significant at both 50 MHz, 144 MHz, and 432 MHz. Note the strong dependence on frequency. The higher the frequency, the less the Faraday polarization rotation.

There is an additional, but predictable, geometric or spatial polarization rotation that depends on the position of the EME antennas on the Earth, and the elevation and azimuth angle of each antenna, which is determined by the position of the Moon as viewed at each EME site. However, the path the signal passes through has a variable ionospheric electron density that depends on solar illumination, which changes diurnally, with specific time zone, and with season. Therefore, the signal transmitted to the distant EME station has an unpredictable, random polarization. At 144 MHz, the random Faraday rotation completely dominates the predictable, geometric polarization rotation. [16]

Small EME stations typically have a single antenna with a single polarization. How important is the loss due to an unknown, random polarization arriving at a single polarization antenna? Assuming that any resultant polarization is equally likely, and knowing that the polarization loss is a function of the uniformly distributed random polarization, the expected value of polarization loss is 3 dB. That is, half of the time the loss is 3 dB or less and the other half of the time the loss is 3 dB or greater. The maximum loss is limited to the cross-polarization response of the small station's antenna, which might be between -20 dB and -30 dB. Figure 6 shows the polarization loss as a function of polarization mismatch between the single polarization antenna and the received signal.

How do the large, 144 MHz "big gun" EME stations correct for this polarization mismatch problem? Many have cross polarized antenna systems which can be used with special receivers that either select the best polarization or add the two vector components (V and H) to nearly completely fix the received signal. MAP65 is the software that can be used to process orthogonally polarized signals. How can the small EME station fix this received polarization problem? One possibility for overcoming this problem is for the 'big gun" station to transmit CQ or reply messages on alternate polarizations – temporally multiplexing the vertical and horizontal polarizations and assuming the Faraday rotation does not change very much minute to minute. The worst-case loss at the small EME station is then 3 dB. **I2FAK**, a "big gun" station with a cross polarized Yagi array, used this technique during my third QSO. Every other transmitted message was missing, but the QSO was successfully completed. Another technique would be for the "big gun" EME station to transmit circular polarization. A receiver with a single polarization antenna would be guaranteed to have 3 dB of polarization loss. This would be very unlikely to be used, since this requires additional phasing hardware. The best technique is for the small EME station to work "big gun" stations that have a large power aperture product – high transmit power and large arrays that have cross polarized Yagi antennas. It is likely that the small EME station will never be able to either hear his own lunar echo or work a similar small EME station.

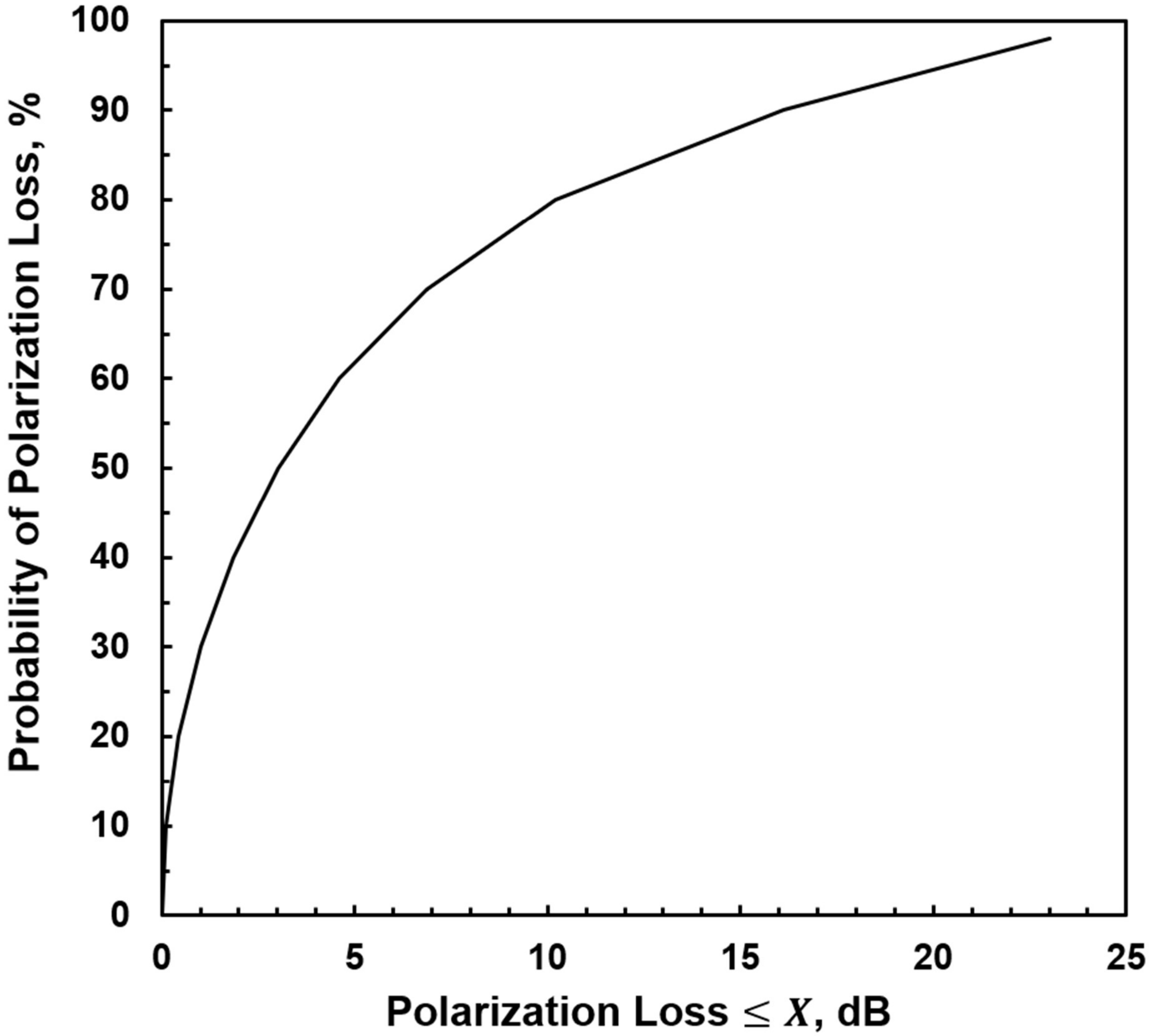


Figure 6. Cumulative probability of polarization loss due to mismatch between the single polarization receive antenna and the received signal. Since the polarization mismatch is a uniformly distributed random variable, (i.e., any polarization is equally likely), the expected value of the mismatch is 45° and thus half of the time the loss is 3 dB or less.

Summarizing, the lunar radar cross section has a statistical description with a median RCS value and a Rician probability density function and the Moon largely preserves incident RF linear polarization. Faraday rotation at 144 MHz is unpredictable and can be represented by a uniformly distributed, random polarization which produces an expected loss of 3 dB on receive for as single, fixed polarization, antenna.

Environmental noise can create problems for a very sensitive EME receiver. Other than local noise sources which might be controlled, there is a predictable source of receiver noise that can be avoided, the in-band radio noise from the Sun or other solar system and intragalactic radio noise sources in the main beam or sidelobes of the antenna. Fortunately, free software is available to predict the in-band radio sky temperature as a function of EME QSO parameters. The software is Moon Sked by **GM4JJJ** [17] and is available at:

http://www.gm4jjj.co.uk/MoonSked/moonsked.htm

Moon Sked helps you decide if it is worthwhile attempting an EME QSO based on sky temperature. An example of a Moon Sked radio sky map with color-coded equivalent sky temperature for my January 19, 2019 QSO is shown in Figure 7. [17]

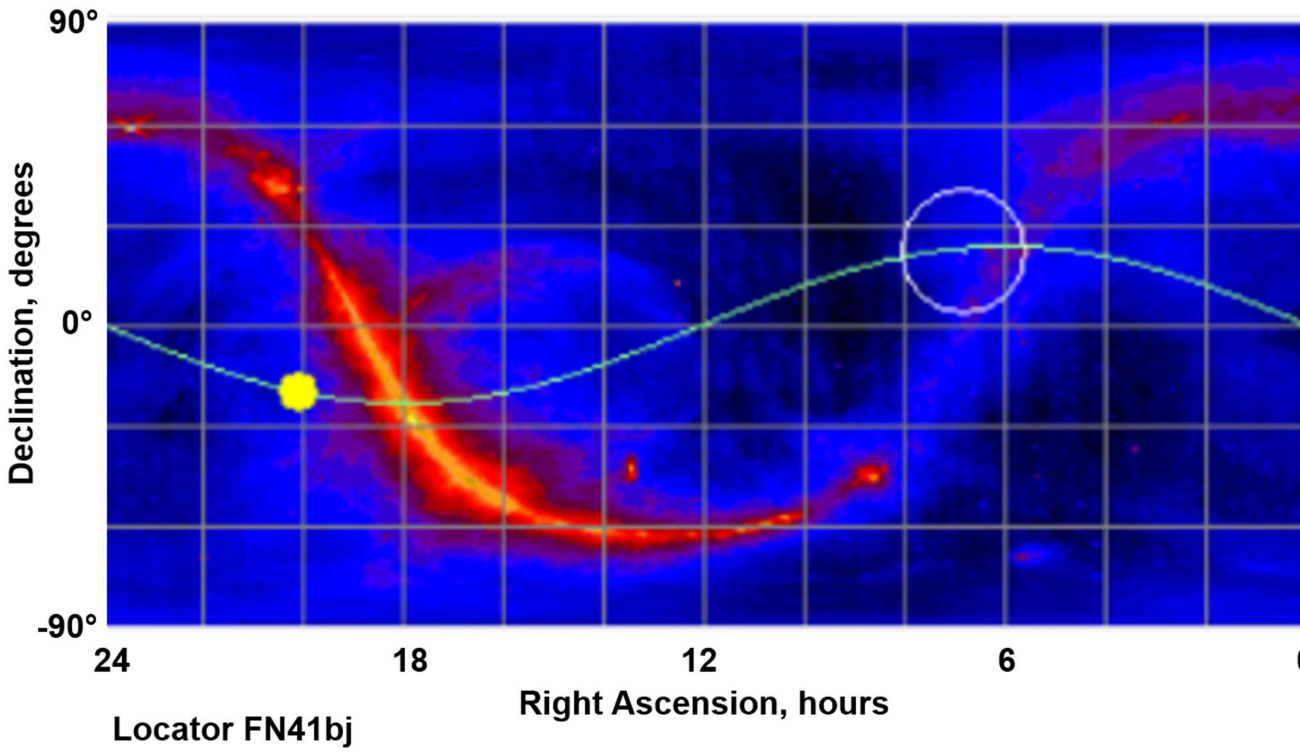


Figure 7. A color-coded equivalent sky temperature map for the conditions present during the first EME QSO, January 19, 2019, as viewed from the KC1HTT location (FN41bj). The sky temperature was 387 K. [17]

All celestial objects can be placed on the sky map in Figure 7. Solar system objects move across the sky map while the stars and other extra-solar system objects are almost in a fixed position. The position of the Sun on the ecliptic plane is indicated. The Milky Way Galaxy is also a source of radio noise and is indicated by the orange-red region on the sky map. The **KC1HTT** EME station antenna beamwidth is over the position of the Moon. The dark blue regions of the sky are "cold" and therefore best for EME. High sky temperature regions which raise the noise level of the VHF receiver have been avoided. Moon Sked calculates the equivalent sky temperature as a function of beamwidth and location of the beam on the sky map. This topic will be discussed further in section 6.

3. Modeling of the Small EME Station Link Performance

Before investing any significant amount of money in an Earth-Moon-Earth Amateur Radio Station, it is important to determine if what is planned, will work. Because EME is an unconventional form of communications, the best mathematical model for an EME communications system evaluation is the bistatic radar equation. The received signal, as measured at the antenna output, is given by:

$$\boldsymbol{S} = \frac{\boldsymbol{P} * \boldsymbol{G_T} * \boldsymbol{G_R} * \boldsymbol{\sigma_M} * \boldsymbol{L_D} * \boldsymbol{L_p} * \boldsymbol{\lambda^2}}{\boldsymbol{R^4} * (\boldsymbol{4} * \boldsymbol{\pi})^3} \quad \textbf{(2)}$$

where:

$\boldsymbol{S}$ = received signal, Watts

$\boldsymbol{P}$ = transmitted signal, Watts

$\boldsymbol{G_T}$ = transmitter antenna gain with respect to an isotropic antenna

$\boldsymbol{G_R}$ = receiver antenna gain with respect to an isotropic antenna

$\boldsymbol{\sigma_M}$ = lunar radar cross section, meters^2

$\boldsymbol{L_D}$= Doppler spread loss

$\boldsymbol{L_p}$= polarization loss

λ = radar wavelength, meters

$\boldsymbol{R}$ = one-way range to the Moon, meters

The receiver noise, including the external sky temperature, referred to the antenna output is:

$$\boldsymbol{N} = \boldsymbol{k} * \boldsymbol{B} * ((\boldsymbol{F} * \boldsymbol{T_R}) + \boldsymbol{T_{sky}}) \quad \textbf{(3)}$$

where:

$\boldsymbol{N}$ = total system noise, Watts

$\boldsymbol{k}$ = Boltzmann constant, 1.3806 x 10^{-23} $(m^2 * kg)/(\, s^2 * K)$

$\boldsymbol{B}$ = radio receiver bandwidth, 2500 Hz

$\boldsymbol{F}$ = receiver noise figure including cable losses ahead of the low noise amplifier

$\boldsymbol{T_R}$ = receiver temperature, 290 K

$\boldsymbol{T_{sky}}$ = equivalent sky temperature, K

These equations have been included in an Excel 2016 spreadsheet for quick evaluation of system performance. Typical parameters for a small EME station and a "big gun" station operating at 144 MHz are input (yellow highlight) into the spreadsheet and are shown in Table 3. The SNR at the small station has a greater probability of having a higher SNR at the input to its receiver than the "big gun" station has. This is because the small EME station has a 180-Watt transmitter versus the "big gun station having a 1000-Watt transmitter. This is an advantage of +7.5 dB for the small EME station receiving the signal from a "big gun" station.

	MKS Units	dB
Common Parameters		
Frequency, Hz	144,125,000	81.59
Wavelength, m	2.080	3.18
Range, m	3.84E+08	85.85
Mean Lunar Cross Section, m2		118.45
kTB, watts	1.00094E-17	-170.00
Tsky, K	350	25.44
Sky noise, kTB, watts	1.20803E-17	-169.18
$(4 * \pi)^3$	1984.40	32.98
Small EME Station		
Transmitter Power, P1 (watts)	180	22.55
Antenna Gain, G1		14.20
Receiver Noise Figure, F1	1.417	1.51
Receiver Noise, N1 (watts)	2.62635E-17	-165.81
Receive Polarization Loss, LP1		3.00
Receive Doppler Spreading Loss, LD1		0.10
Received signal, S1 (watts)	1.27175E-19	-188.96
SNR at Small EME Receiver		-23.15
Big Gun EME Station		
Transmitter Power, P2 (watts)	1000	30.00
Antenna Gain, G2		21.50
Receiver Noise Figure, F2	1.12	0.49
Receiver Noise, N2 (watts)	2.32907E-17	-166.33
Receive Polarization Loss, LP2		0.10
Receive Doppler Spreading Loss, LD2		0.10
Received signal, S2, (watts)	4.46348E-20	-193.50
SNR at Big Gun Receiver		-27.18

Table 3. Calculation of the mean signal to noise ratio (SNR) which will be processed by the JT65B decoder for both the small 2 m EME station (#1) and the "big gun" 2 m EME station (#2). Inputs are highlighted in yellow.

This small EME station advantage is somewhat offset by the “big gun” station having a cross polarized antenna and MAP65 adaptive polarization compensation. Since the SNR evaluation was based on an expected value of polarization loss of 3 dB for the small EME station, there is a 50% chance that Faraday rotation of the polarization will increase the polarization loss and reduce the small EME station advantage.

The sky temperature, 350K, reduces the receiver sensitivity. This effect depends on where the antenna is pointing and how large the antenna beamwidth and sidelobes are. If the sky temperature is high enough, this can eliminate the advantage of a mast mounted, low noise preamplifier. This translates to avoiding EME QSO operations during the New Moon or when the Moon transits the Milky Way Galaxy. Moon Sked software sky temperature predictions indicate when the best time is for an EME QSO.

It is important to note the SNR, and hence the signal level, that can be processed by the WSJT-X JT65B signal processor/digital decoder software. While SNR requirements will be discussed in detail later, JT65B requires an SNR of from -30 dB to -27 dB, measured in a 2500 Hz receiver bandwidth, to decode messages. In the example in Table 3, the signal level producing an SNR = -27.18 dB at input to the “big gun” station receiver is about 4.46 x 10^{-20} Watts or 44.6 zW, that is, 44.6 zeptoWatts!

Why choose a 2 m EME system versus a 70 cm EME system? Since the received signal is proportional to wavelength squared, all other things being equal, a 144 MHz EME system has a 9.5 dB advantage over a 432 MHz EME system. However, all other things are not equal. Higher gain antennas are available as well as other components to help make up for the difference. Perhaps the deciding factor is the greater popularity of 2 m EME over all other EME bands. There are more opportunities for a “big gun” QSO with a small 2 m station. Considering all factors, 2 m was the choice.

4. KC1HTT: A Low Power, Earth-Moon-Earth Radio Station

Financial and space constraints for an Earth-Moon-Earth amateur radio station have led to the conclusion that EME operation will only be possible if a “big gun” EME station is available at the other end of the link. The performance model described above was “verified” after viewing several brief YouTube videos of small EME stations working “big gun” systems. The requirements for a small EME station were taken from Table 3. After collecting performance and price information on specific subsystems and components, a decision to build a small EME station was made. This information was used to develop the block diagram of the EME radio station that is shown in Figure 8. The heart of the EME station is the ICOM IC-9100 which was designed for EME as well as other, more conventional amateur radio operations. The ICOM IC-9100, is a HF/VHF/UHF full duplex, double-conversion, transceiver with a DSP baseband processor that operates in the 160, 80, 60, 40, 30, 17, 15, 12, 10, 6, 2, 0.70-meter bands. The output power is 2 to 100 Watts from 160 meters through 2 meters and 2 to 75 Watts at 70 cm. The transceiver can be easily interfaced with a personal computer using a USB cable to support long duty cycle digital modes, such as FT8 and JT65B. It can be tuned by WSJT-X JT65B software so the Doppler shifts associated with lunar orbital motion can be compensated. In addition, the IC-9100 has an internal 12 VDC power supply rated at 200 mA that is automatically switched on during receive and fed through the antenna coaxial cable to power a low noise preamplifier. (Figure 9) This feature was added to power the weatherproof, mast mounted ICOM AG-25 (144MHz), AG-35 (430MHz), or AG-1200 (1240 MHz) low noise preamplifiers. Unfortunately, the ICOM AG-25 was discontinued and is only rarely available.

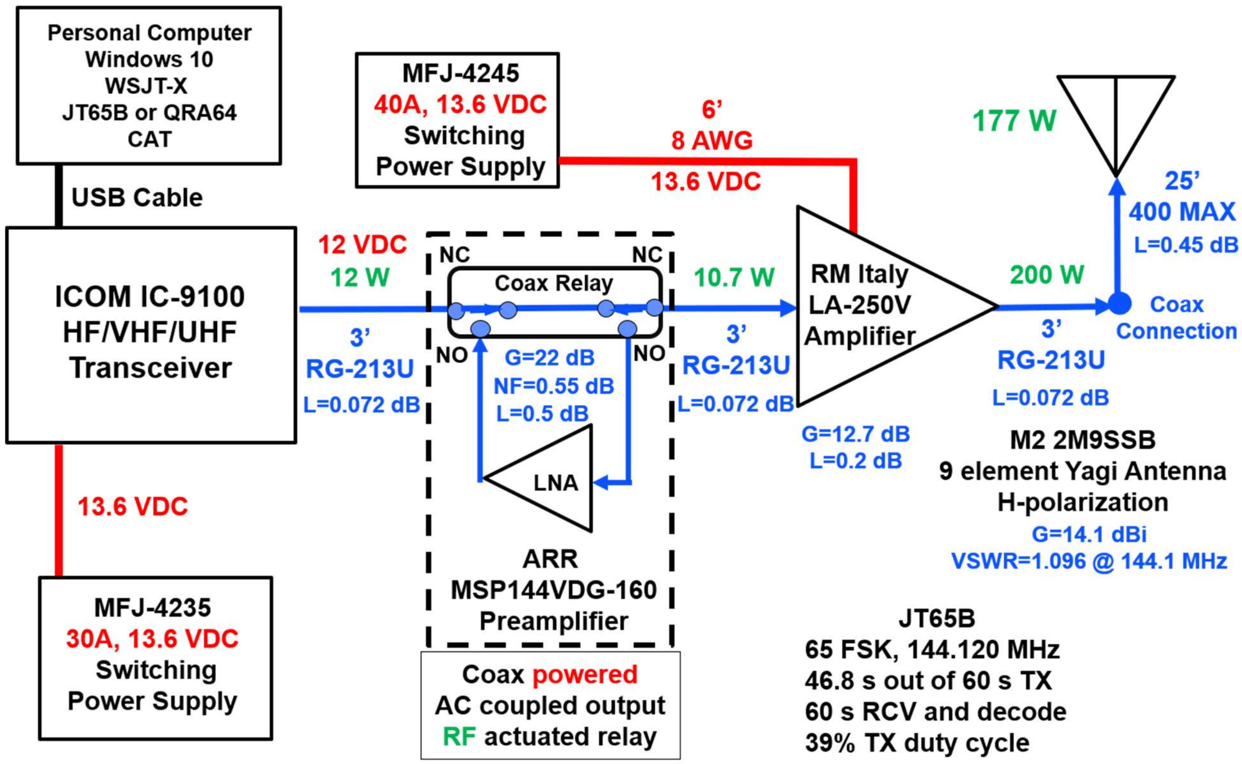


Figure 8. Block diagram of the KC1HTT Earth-Moon-Earth amateur radio station. Major subsystems and parameters are shown. Red connections and notes refer to DC power, blue connections and notes are coaxial cables and green indicates RF levels. The heart of the station is the ICOM IC-9100 100-Watt transceiver, which was designed for EME operation.

A low noise, "VOX" operated, 144 MHz preamplifier Model MSP144VDG-160 was purchased from Advanced Receiver Research (ARR) in Burlington, Connecticut (Figure 10). This low noise preamplifier can use the 12 VDC provided by the IC-9100 through the coaxial cable. DC power for the VHF preamplifier must be selected at the transceiver. The ICOM manual states that the preamp must immediately follow the ICOM 9100.

Transmitter
- **Transmit power 2 to 100 watts (all modes)**
- **Tunes for predicted lunar Doppler shift**

Power supply requirement
13.8 VDC, +/- 15%, 24 A

Receiver
- **Noise Figure = 4 dB @ 144 MHz**
- **Selectivity 2.4kHz/-6dB**
- **Double conversion, full duplex, superheterodyne receiver, DSP baseband**
- **Frequency stability < 0.5 ppm (0C to +50C)**
- **Tunes for predicted Doppler shift**
- **Operate in SSB USB mode**

Figure 9. The ICOM IC-9100 full duplex transceiver. [18] **This multiband, full duplex, transceiver can be controlled by a computer and was designed for EME operations.**

The low noise amplifier (LNA) subsystem can operate with 160 Watts at its output, that is, the coaxial cable relays can handle 160 Watts with a 0.5 dB insertion loss. The LNA is placed immediately after the ICOM 9100 transmitter and before the final amplifier, so the LNA will only see about 12 Watts from the ICOM 9100. Because of the LNA location, the additional ICOM 9100 receiver NF performance penalty is about 0.5 dB for the LNA.

The LNA subsystem has a GaAs FET RF preamp, and RF power sensing (VOX) and coaxial relay control circuits (Figure 11 schematic). If the ICOM 9100 DC power is off or if the ICOM 9100 automatically switches the 12 VDC power off, the coaxial relays in the LNA subsystem bypass the GaAsFET preamp (RL1 and RL2 COAX RELAYS ARE OFF).

The RF power sensing and relay control circuit in the LNA is powered on when the 12 VDC is on. When 12 VDC is present and RF power < 5 Watts is present in the coax, the GaAs FET is powered on (RECEIVE – RL1 and RL2 COAX RELAYS ON). When RF power > 5 Watts enters the LNA subsystem from the ICOM 9100 during transmit, two relays quickly switch the GaAs FET out of the coaxial cable circuit (TRANSMIT – RL1 and RL2 COAX RELAYS OFF). The RF power sensing circuit has an RF choke and an RF bypass capacitor to limit the RF sensing power which is rectified and voltage limited by a Zener diode to provide a control signal to the transistor that turns the coaxial relays OFF and powers down the GaAs FET amplifier. The power loss due to the LNA subsystem insertion has no effect on the final amplifier output. About 10 to 12 Watts from the ICOM 9100 drives the final amplifier to 200 Watts. The preamp will only see a maximum of about 12 Watts which is well below the 160 Watt limit on the coax relays.

- **MSP144VDG-160**
- **Frequency Range 144-148 MHz**
- **GaAs FET**
- **Noise Figure 0.55 dB**
- **Gain 22 dB**
- **1 dB Compression 12 dBm**
- **1 dB bandwidth 7 MHz**
- **Through mode VSWR 1.25**
- **Through mode attenuation 0.5 dB**
- **Maximum RF Power 160 watts**
- **Minimum RF power to switch 5 watts**
- **DC Supply 10 to 16 VDC, 200 mA via coax from transceiver**

Figure 10. The Advanced Radio Research MSP144VDG-160. This LNA features a GaAs FET amplifier with a very low noise figure and is powered by the IC-9100 transceiver via the coaxial cable. [19]

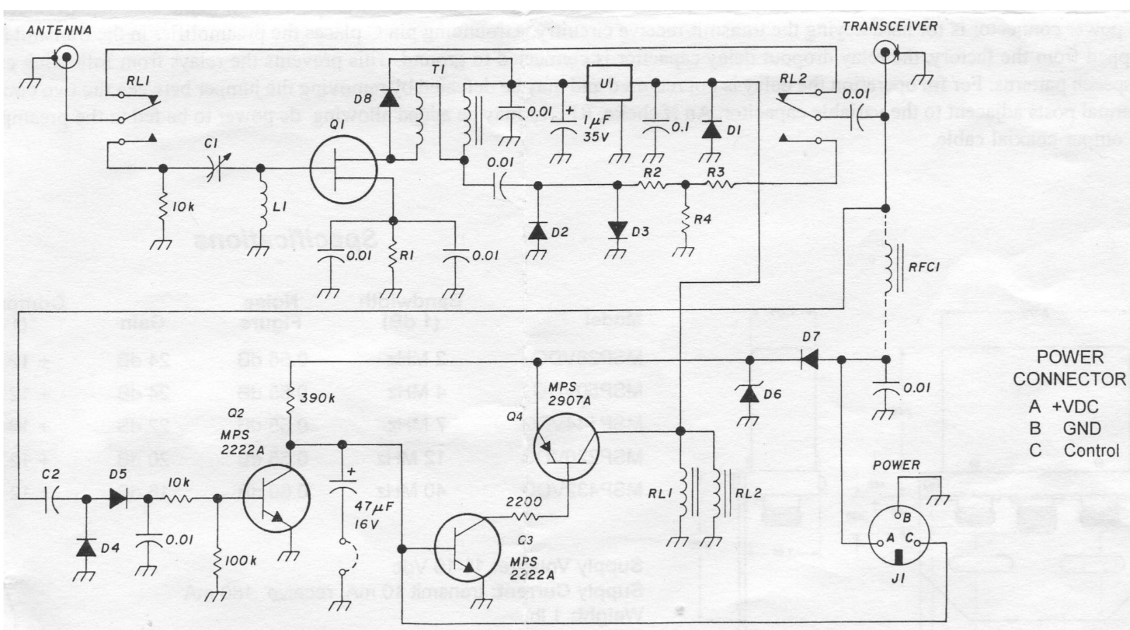


Figure 11. Schematic of the Advanced Radio Research LNA, Model MSP144VDG-160. Coax relays RL1 and RL2 can handle 160 Watts. [19]

The EME link analysis indicated that about 200 Watts was required for successful EME communications with a "big gun" station. With a 100-Watt maximum power out of the IC-9100 and coaxial line losses further reducing the transmitter power, a long duty cycle, linear VHF amplifier was required. Searching for a suitable linear amplifier, led to the RM Italy 250V, 200-Watt VHF amplifier (shown in Figure 12).

Figure 12. The RM Italy 250V long duty cycle, linear 200-Watt VHF amplifier.

The RM-250V is especially suited for long duty cycle waveforms at peak power. It operates from 140 to 150 MHz and generates 200 Watts with only 10 to 12 Watts input. It requires 13.6 VDC at 35 A.

Typical output power versus input power are shown in Figure 13. The 1 dB compression point is reached at 11.5 Watts input. The RM 250V did not heat up significantly during long duty cycle operation at 180 watts.

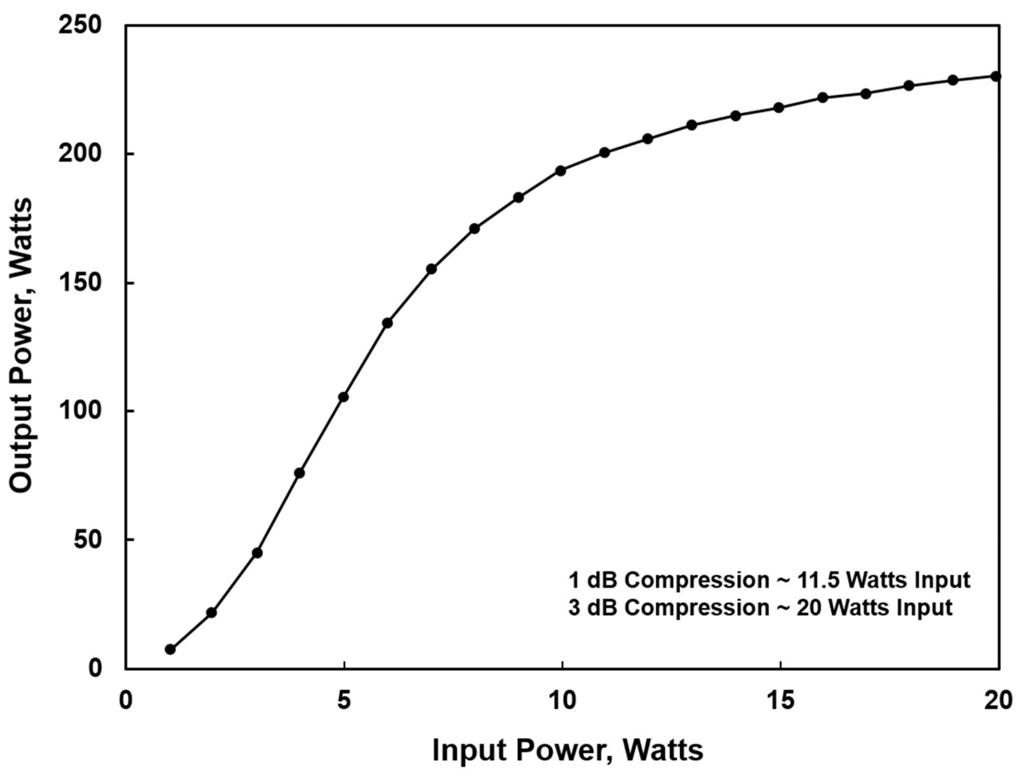


Figure 13. RM 250V Linear VHF Amplifier output power versus input power. [20]

The final major component in the small EME station is the 2-meter Yagi-Uda antenna. Home site constraints and cost limited the physical size, and therefore the gain, to a single antenna that could be broken down simply and easily stored on the wall of a garage. The optimum choice was the M^2 Antenna Systems 2M9SSBFM 9 element, Yagi antenna. The antenna has a free space gain of 14.1 dBi and is 2.125 wavelengths or 4.423 meters (14.5) feet long. In the 2M9SSB configuration, the bandwidth is 144 to 146 MHz and it can handle 2.5 kW. The horizontal polarization, free space beamwidth is horizontal 35°H x 38°V. A photo of the M^2 2M9SSB mounted on an MFJ-1918EX tripod is shown in Figure 14. An antenna-mount adapter made from PVC pipe is used for manual azimuth and elevation pointing.

Figure 14. M^2 2M9SSB horizontally polarized Yagi-Uda antenna mounted on an MFJ-1918EX tripod at the KC1HTT EME site. [21]

In situ measurements of the Yagi antenna VSWR as a function of frequency were made with an Accuracy Agility Series N1201SA 137.5 MHz to 2700 MHz vector impedance analyzer. The results of the measurement are shown in Figure 15.

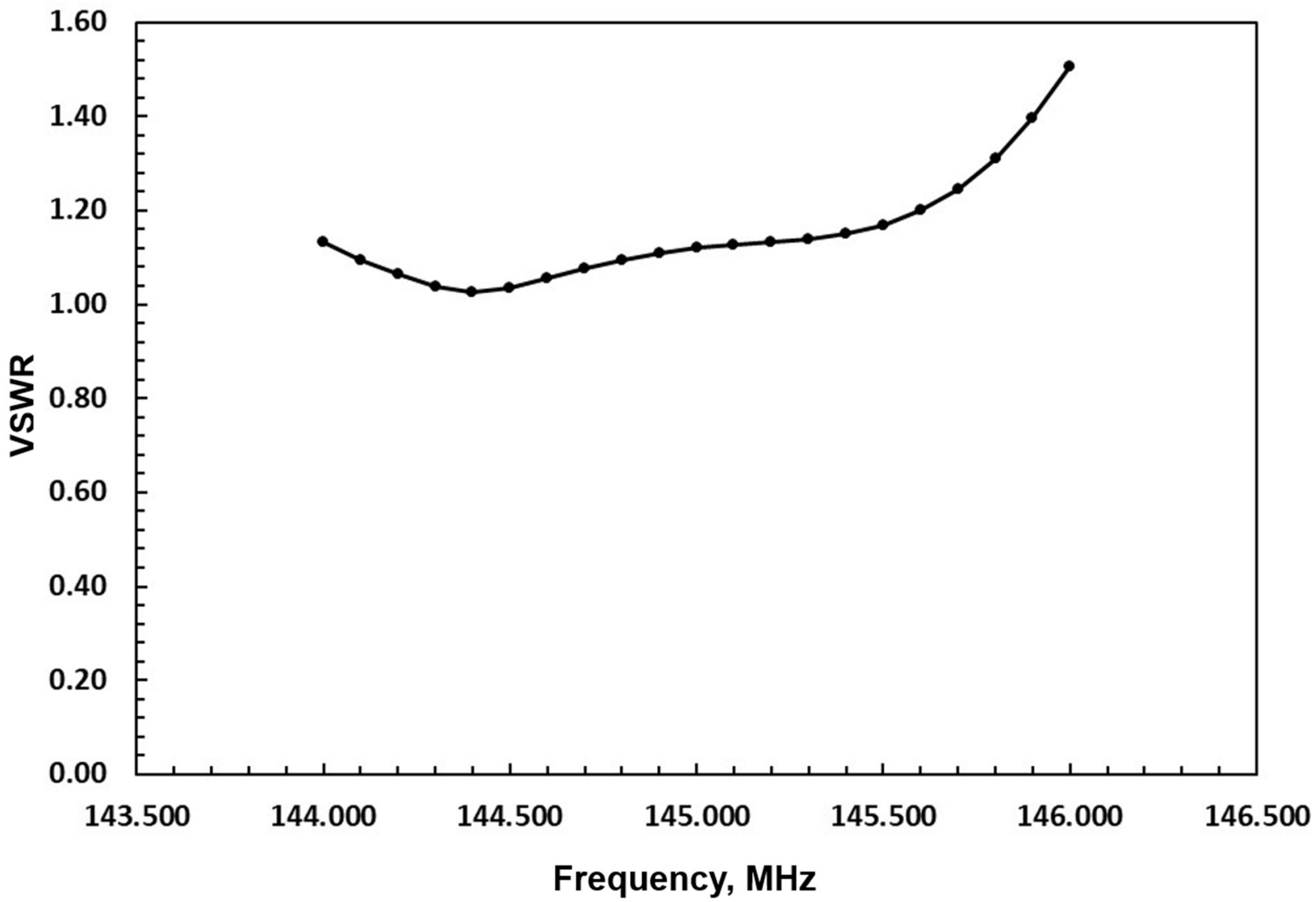


Figure 15. In situ VSWR measurements of the horizontally polarized, M^2 2M9SSB Yagi-Uda antenna located about 1 wavelength above the ground. The measurements were made with an Accuracy Agility Series N1201SA 137.5 MHz to 2700 MHz vector impedance analyzer.

Antenna modeling calculations were performed by **KC1HTT** using EZNEC+ V6 antenna modeling software [22] to determine the difference in antenna gain and VSWR as influenced by the choice of Yagi antenna polarization and the height above the ground. The antenna used in the model was a nine element Yagi very similar in gain and beamwidth to the M^2 2M9SSB Yagi antenna. The EZNEC+ V6 "Ground Type" was "Real/Accuracy" and the "Ground Description" was "1 Medium (0.005, 13)". That is, the ground conductivity was 0.005 S/m and the dielectric constant was 13. The significance of beam pointing was that the beam touches the ground at a one wavelength height with a zero-degree elevation angle (horizontal pointing). The calculated VSWR in both cases was about equal to 1.1:1. Figures 16 and 17 are antenna beamwidth and gain calculations for nine element Yagis located one wavelength above ground pointing horizontally. Figure 16 depicts results for vertical polarization and Figure 17 depicts results for horizontal polarization. Both cases illustrate the difficulty of getting the beam to propagate near the ground. This indicates EME QSOs should begin only after the Moon has risen to about 10 degrees in elevation.

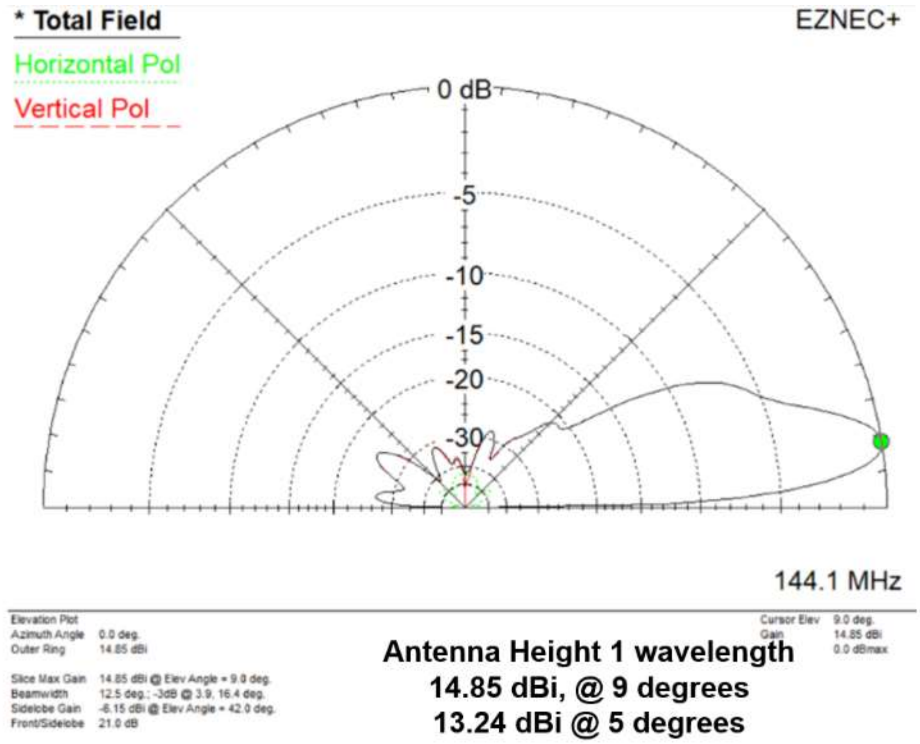


Figure 16. Nine element Yagi, one wavelength above ground, vertical polarization, zero-degree antenna elevation. The ground was modeled with the ground conductivity = 0.005 S/m, and the ground dielectric constant = 13. EZNEC+ V6 model results.

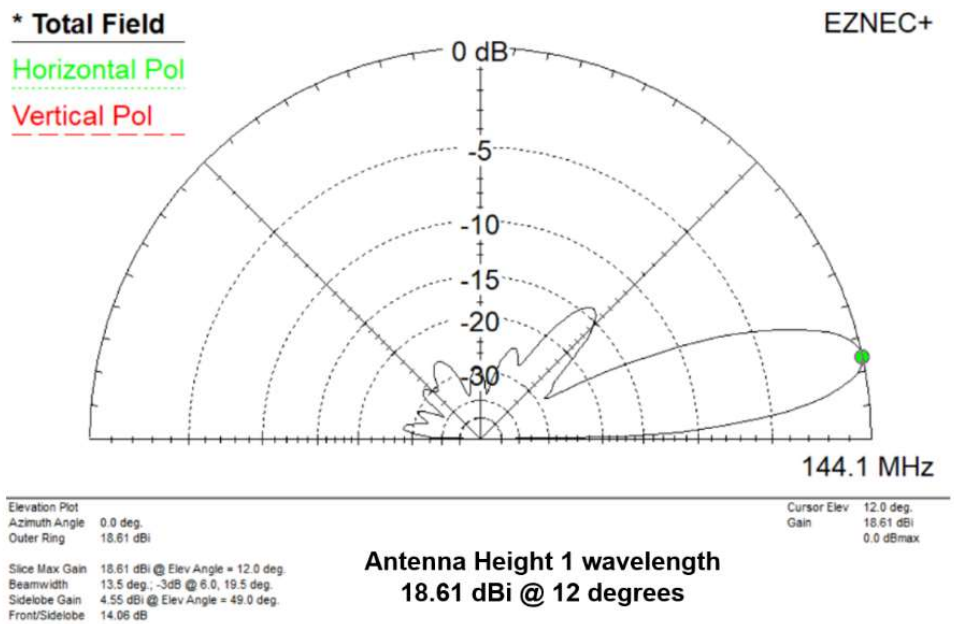


Figure 17. Nine element Yagi, one wavelength above ground, horizontal, polarization, zero-degree antenna elevation. The ground was modeled with the ground conductivity = 0.005 S/m, and the ground dielectric constant = 13. EZNEC+ V6 model results.

The model calculations indicate that the horizontally polarized antenna exhibits significant "ground gain" (+3.76 dB) at low elevation angles, while the vertically polarized antenna does not. Thus, horizontal polarization is employed by the **KC1HTT** EME station.

Low loss cable should be used to maximize the transmitter signal as well as the received signal. The longest cable run for the **KC1HTT** EME station is 7.62 meters (25 feet) of DXE-400MAX 50 ohm coaxial cable and it connects the antenna with all of the station equipment inside the garage. That cable introduces a loss of 0.45 dB, thus reducing the transmit power by 10% and increasing the system noise figure by 0.45 dB. A 0.914 m (3 feet) section of RG-213U between the window panel and amplifier introduces 0.072 dB of loss so that the 200-Watt transmitter power at the antenna input is about 177 Watts. The LNA is at the input of the RM Italy 250V linear amplifier which is unconventional. It suffers an additional loss of about 0.272 dB. The reason for placing the preamplifier between the transceiver and the linear amplifier is fourfold, first the preamplifier can only handle 160 Watts at its input and the amplifier provides 200 Watts, second, the transceiver must provide DC power in the proper transmit receive sequence via the coaxial cable to the LNA, third, the analysis in Table 3 shows that the real difficulty is the small EME station being '"heard" and not "hearing" the "big gun" EME station, and fourth, the sky noise at 144 MHz could possibly determine the over receiver performance. This especially true for a large antenna beamwidth.

5. JT65 Waveforms and Performance

Now that the **KC1HTT** EME station has been described in the above example as having received a signal that is -23 dB below the kTB receiver noise, where B = 2500 Hz and T = 290K, or about 260 zeptoWatts, what type of waveform, forward error correction, interleaving and decoding can be used to extract information from that very weak signal? Dr. Joseph H. Taylor, Jr., **K1JT**, a physicist who is a professor at Princeton University and who won the Nobel Prize in Physics in 1993, developed the waveform and signal processing necessary to extract the key information in amateur radio QSOs reflecting off of the Moon. The EME software that controls the transceiver, generates the properly encoded digital signal for transmission and also decodes the digital signal is known as JT65B. JT65B comes in a package of programs known as WSJT-X and WSJT v10.0 and is distributed for free.

WSJT-X is at:

http://www.physics.princeton.edu/pulsar/K1JT/wsjtx.html

and WSJT v10.0 is at:

http://www.physics.princeton.edu/pulsar/K1JT/wsjt.html

Each web site has user manuals available. [23] Each version of WSJT JT65B has its proponents. Since I have used several software programs in WSJT-X, including FT8, JT9, and JT65 for HF, I use JT65B, which is the 2-meter version of JT65 within WSJT-X. Other software programs, including QRA64 and MAP65, have certain advantages over JT65B for Earth-Moon-Earth communications, but will not be described in this paper.

JT65B uses continuous-phase frequency shift keying, FSK, to convey 72 data bits. Specifically, 65 distinct tones are employed, hence, FSK65. Messages bits are transmitted using 64 different tones (64-ary alphabet) as symbols plus one synchronizing tone at 1270.5 Hz. Each message symbol in the 64 tone FSK alphabet occupies 2.62 Hz and carries 6 bits. The transmission time for each message symbol is 0.372 seconds which allows for a processing resolution of 2.7 Hz. Each transmitted message tone, or symbol contains 6 bits. An encoded 72 data bit message is distributed in six Reed Solomon [63,12] blocks with each RS block containing 12 data bits and 51 error correction bits out of 63 RS message bits. The total of 378 message bits is transmitted in 63 FSK symbols interleaved with 63 synchronization tones. The interleaving is determined by a pseudorandom sequence for a total message transmission time of 46.811 seconds every other minute. This is a transmission duty cycle of 39%. The total message signal, including the sync tone at 1270.5 Hz, occupies a bandwidth of about 177.6 Hz. Shorthand (SH) message tones have a different time and frequency structure and are alternately repeated with sync tones. Decoding begins immediately after receiving the message. [24]

At 144 MHz, the Doppler spreading of each tone (echo width caused by lunar libration) [25] can be range up to 4 Hz, so the FSK tones are spaced by about 5.4 Hz. The total spectral width used by all of the 64 message tones and the sync tone is about 350 Hz as viewed on the “waterfall” display. Lunar libration induced Doppler spread reduces the message signal to noise ratio because a fraction of the signal power is outside of the 2.7 Hz signal processing bin.

JT65B messages contain synchronization tones at 1270.5 Hz that are interleaved with both the long messages and the shorthand messages. The shorthand messages include “RO”, “RRR”, and “73”. An example of a JT65B QSO is shown in Figure 18.

Transmitted JT65B Message	Meaning
00:01:01 – 00:01:48 CQ KC1HTT FN41 *	KC1HTT in grid square FN41 calls to anyone listening
00:02:01 – 00:02:48 KC1HTT RX1AS KO59 *	RX1AS in grid square KO59 responds to KC1HTT
00:03:01 – 00:03:48 RX1AS KC1HTT FN41 OOO *	KC1HTT Reports sufficient SNR
00:04:01 – 00:04:48 RO ...	RX1AS “Roger, sufficient SNR”
00:05:01 – 00:05:48 RRR ...	KC1HTT “Roger, roger, roger”
00:06:01 – 00:06:48 73 ...	RX1AS “Best regards”
00:07:01 – 00:07:48 73 …	KC1HTT “Best regards”

* 72 bit message encoded in 378 bits and sent only once using 63 FSK tones + 63x sync tone
(…) Indicates repeated shorthand (SH) message tones + interleaved sync tone

Figure 18. An example of a JT65B QSO. Note the transmission time. [26]

The SNR required to successfully decode the long JT65B messages is shown in Figure 19. These long messages are decoded using the Franke-Taylor soft decision algorithm which can employ the "Deep Search" algorithm. "Deep Search" uses a database of all active EME amateur radio operators known as CALL3.TXT which will be described in section 6. This greatly limits the number of possibilities for different messages. In communication theory terms, it reduces the entropy in the message, thus minimizing the required energy for message decoding. The required SNR for successful JT65B synchronization and decoding shorthand messages is shown in Figure 20.

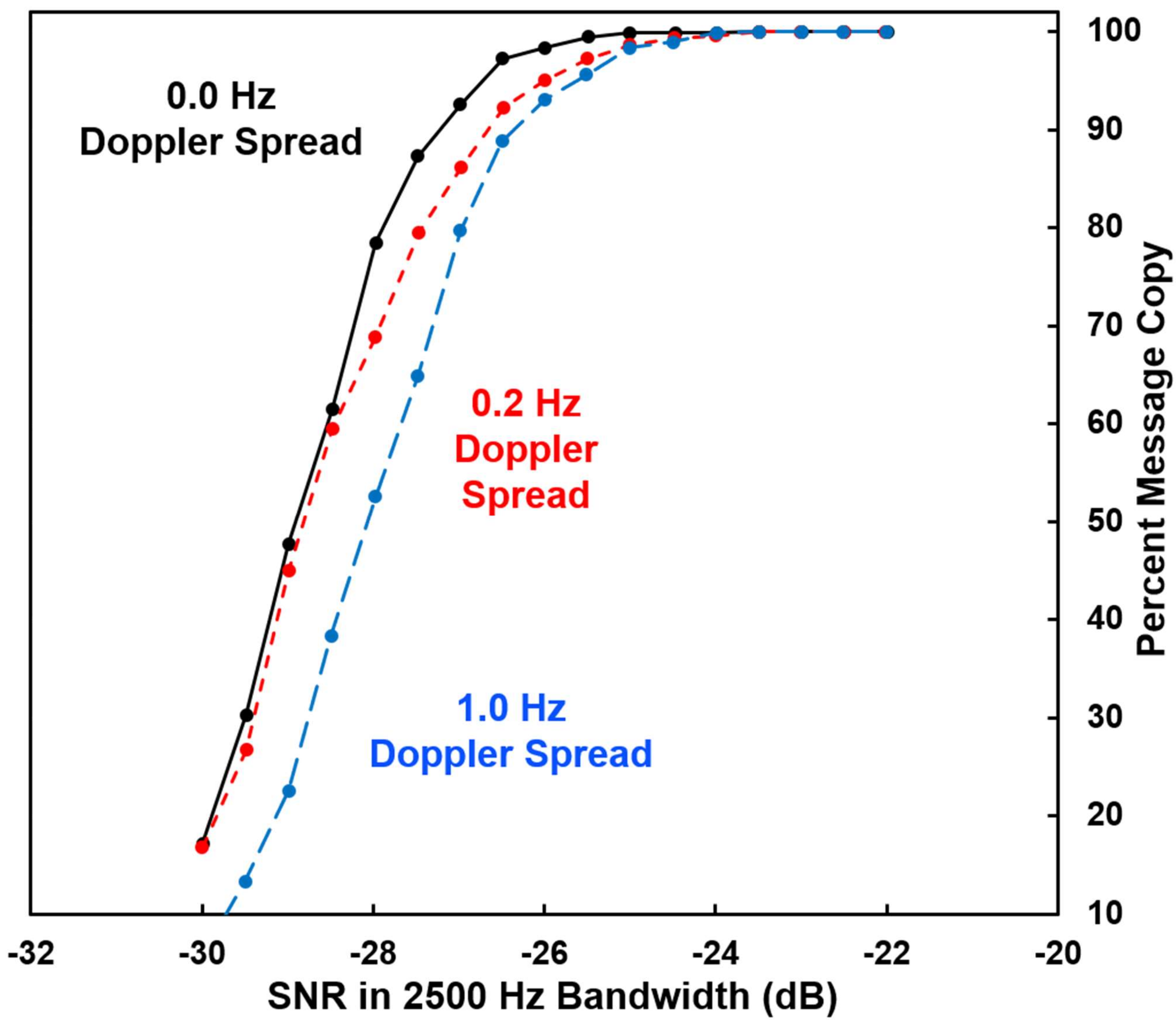


Figure 19. JT65B simulation results of percent long message copy with Deep Search algorithm as a function of lunar libration induced Doppler spread (Hz) and SNR. [27]

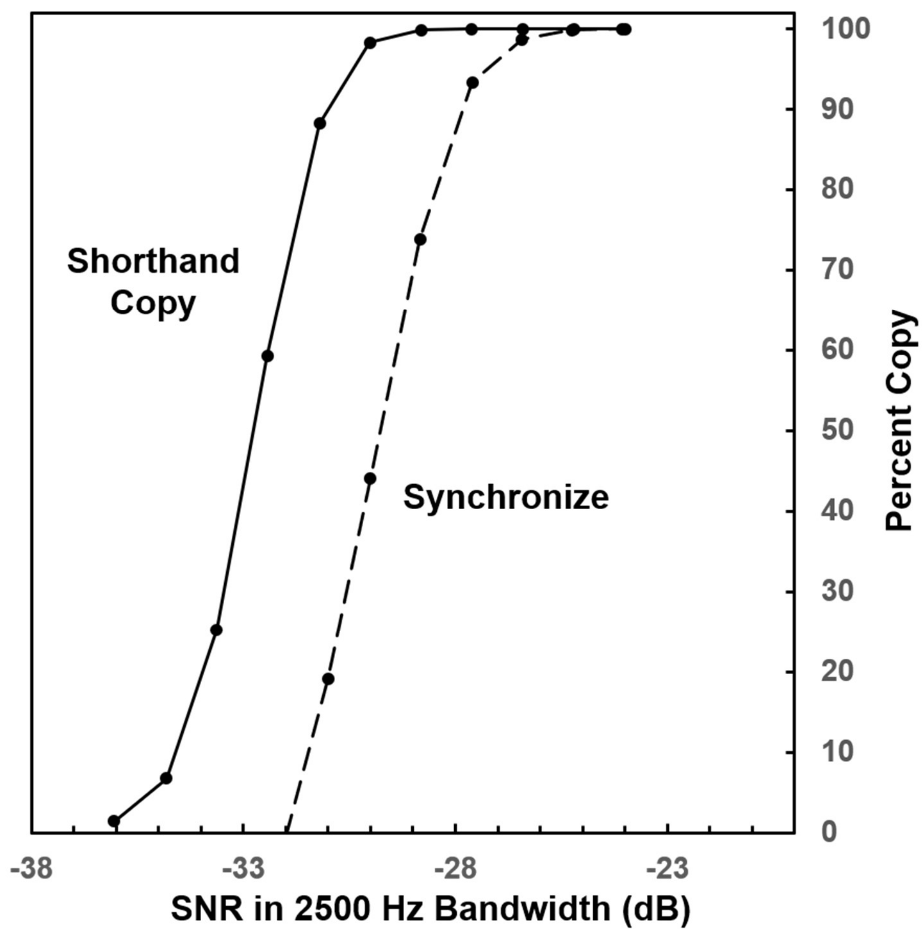


Figure 20. JT65B simulation results of percent copy of shorthand (SH) messages and probability of synchronization as a function of SNR. [27]

To summarize, long messages can be decoded at an SNR of -29 dB as measured in a 2500 Hz bandwidth about 50% of the time. Synchronization and the short hand messages require roughly -30 dB and -32 dB respectively for a probability or 50% decoding. Successful QSOs have occurred with SNRs equal to -30 dB.

6. Earth-Moon-Earth Operations

Earth -Moon-Earth QSOs require detailed planning. In order to effectively use the software for amateur radio Earth-Moon-Earth communications, you must register your station with Make More Miles on VHF (MMMONVHF) [28] at:

http://www.mmmonvhf.de/

This web site is not secure so there may be problems registering or during LOGIN depending on the security setting of your web browser. Once registration is approved, your call sign and station details are placed in the CALL3.TXT data base. You can then download the database for use both before and during EME QSOs. The CALL3.TXT database is used with the Moon Sked software for planning an EME and with JT65B software to enable the Deep Search algorithm in JT65B during an EME QSO. CALL3.TXT has 6,749 VHF stations registered as of January 19, 2019. Not all stations in the list participate in EME. The latest CALL3.TXT file must be placed in the WSJT-X folder.

Now that the home station data is in CALL3.TXT and is available for JT65B, the first question to be answered is when to attempt an EME QSO. Fortunately, MoonSked software provides all of the information needed to determine when and how the EME QSO should take place. Earlier, MoonSked software was used to calculate the radio sky temperature by determining where the Moon would be relative to the major radio noise sources such as the Sun and Milky Way. MoonSked produces a monthly Moon Graph that summarizes some of the effects that affect EME communications. This a very useful tool to begin planning EMQ QSOs. Minimal SNR degradation is the best time for an EME QSO. My first EME QSO will illustrate an EME operation. Figure 21 is the Moon Graph for the month I made my first successful EME QSO.

MoonSked also produces a detailed table of information absolutely necessary to complete an EME QSO. The Sked Maker table for my first EME QSO is shown in Figure 22.

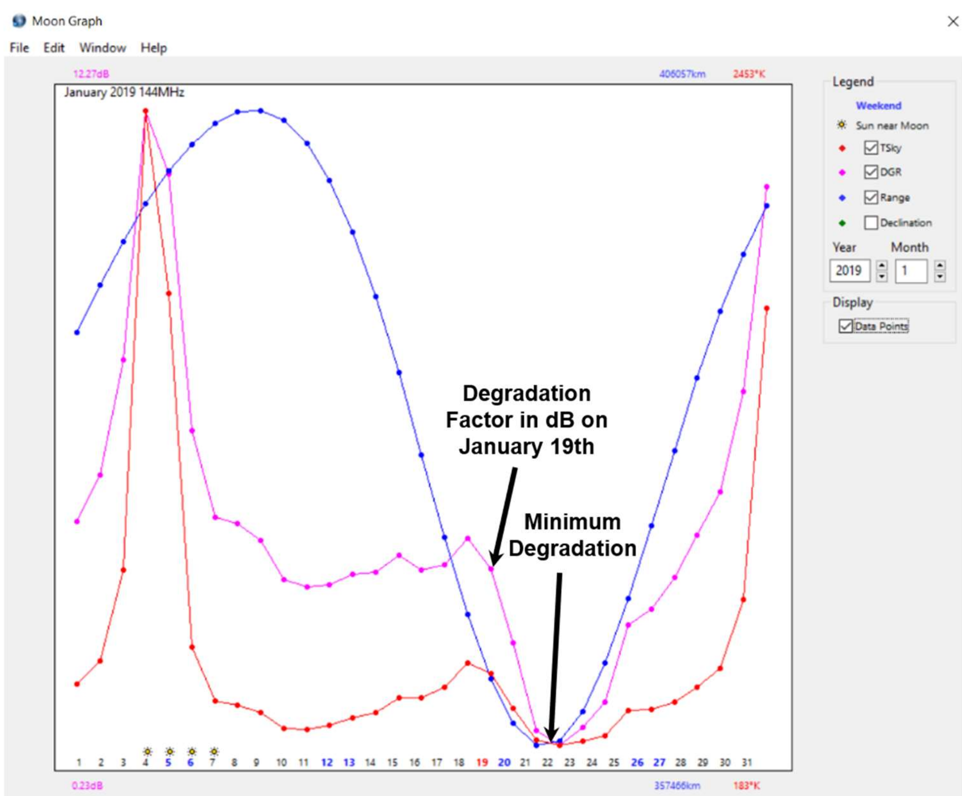
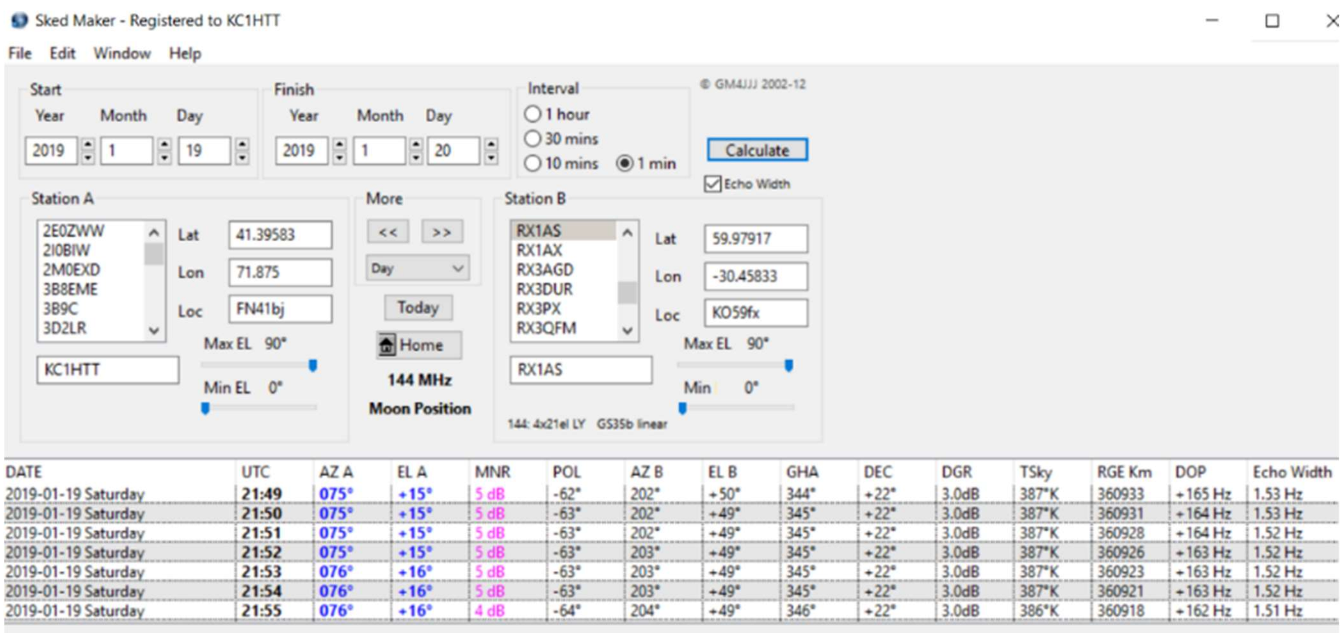


Figure 21. MoonSked Moon Graph of the predicted conditions for January, 2019. Range is color coded in blue, degradation factor in purple and sky temperature in red. [17]

The table in Figure 22 lists the UTC date and UTC time, the azimuth and elevation of the Moon as viewed by **KC1HTT** (station “A”), an estimate of the maximum transmit and receive antenna polarization loss due to geometrically determined polarization mismatch (MNR), the geometric or spatial signal polarization rotation (POL), the azimuth and elevation of the Moon as seen at **RX1AS** (Station “B”), the position of the Moon on the radio sky map as expressed as lunar Greenwich Hour angle (GHA) and lunar declination (DEC), the SNR degradation (DGR) with respect to lunar perigee and a minimal sky temperature of 60K, the range to the Moon, the Doppler shift of the **KC1HTT** signal echo, and the lunar libration Doppler spread. Since random Faraday rotation at 144 MHz can dominate the total rotation of the signal polarization, MNR due to the geometric or spatial polarization mismatch is not useful at VHF frequencies. Faraday rotation is unpredictable, but it can be modeled as a uniformly distributed polarization variable (zero to 90 degrees) whose expected value is 45 degrees. It is best dealt with statistically as shown in Figure 6. The expected value of polarization loss is 3 dB.



DATE	UTC	AZ A	EL A	MNR	POL	AZ B	EL B	GHA	DEC	DGR	TSky	RGE Km	DOP	Echo Width
2019-01-19 Saturday	21:49	075°	+15°	5 dB	-62°	202°	+50°	344°	+22°	3.0dB	387°K	360933	+165 Hz	1.53 Hz
2019-01-19 Saturday	21:50	075°	+15°	5 dB	-63°	202°	+49°	345°	+22°	3.0dB	387°K	360931	+164 Hz	1.53 Hz
2019-01-19 Saturday	21:51	075°	+15°	5 dB	-63°	202°	+49°	345°	+22°	3.0dB	387°K	360928	+164 Hz	1.52 Hz
2019-01-19 Saturday	21:52	075°	+15°	5 dB	-63°	203°	+49°	345°	+22°	3.0dB	387°K	360926	+163 Hz	1.52 Hz
2019-01-19 Saturday	21:53	076°	+16°	5 dB	-63°	203°	+49°	345°	+22°	3.0dB	387°K	360923	+163 Hz	1.52 Hz
2019-01-19 Saturday	21:54	076°	+16°	5 dB	-63°	203°	+49°	345°	+22°	3.0dB	387°K	360921	+163 Hz	1.52 Hz
2019-01-19 Saturday	21:55	076°	+16°	4 dB	-64°	204°	+49°	346°	+22°	3.0dB	386°K	360918	+162 Hz	1.51 Hz

Figure 22. The MoonSked “Sked Maker” window contains detailed information necessary to initiate and analyze an EME QSO. The Sked Maker details are for the KC1HTT – RX1AS QSO on January 19, 2019 from 21:49 to 21:55 UTC. [17]

The **KC1HTT- RX1AS** EME QSO details illustrate what happens during a successful EME session. As part of the preparation for an EME, all LED and CFL lights were turned off in the radio shack (garage), both the wireless phone and cell phone were turned off, and the clock on the computer used for the QSO was set to within 0.1 seconds of UTC time. Accurate computer time is required because all EME QSOs start 1 second after the minute. Most western stations transmit on odd minutes and stations to the east transmit on even minutes. This minimizes man-made interference (QRM). In addition, the JT65B software must be set to SH mode for the messages, and Doppler tracking is set to maintain a constant signal frequency at the Moon. The “B” submode, JT65B, must be selected for 144 MHz EME operation since the JT65B waveform tone frequency spacings are designed to cope with the lunar induced

Doppler shift. When operating shortly after Moon rise, **KC1HTT** is likely to contact a "big gun" station like **RX1AS** to the east. When selecting a frequency to use for an EME transmission, it is best to monitor an EME bulletin board site to announce to all stations monitoring the board that **KC1HTT** will be operating at, say, 144.115 MHz. The bulletin board used by many EME station operators is **WSJT 1 EME by N0UK**. [29] The web site is:

> **https://www.chris.org/cgi-bin/jt65emeA**

N0UK, runs the Board and warns, *"Exchanging any contact details on here before you're complete, invalidates the contact, and, if it's not WSJT via Moonbounce it doesn't belong here!"*. [29]

It must be remembered that JT65B operates in a semi-automatic mode, that is, the operator has to click on the received signal as in the FT8 mode, but, unlike FT8, must also click on the latest message received in order to transmit the next message. After announcing the KC1HTT frequency, the following EME QSO message exchange occurred as recorded in a JT65B screenshot in Figure 23.

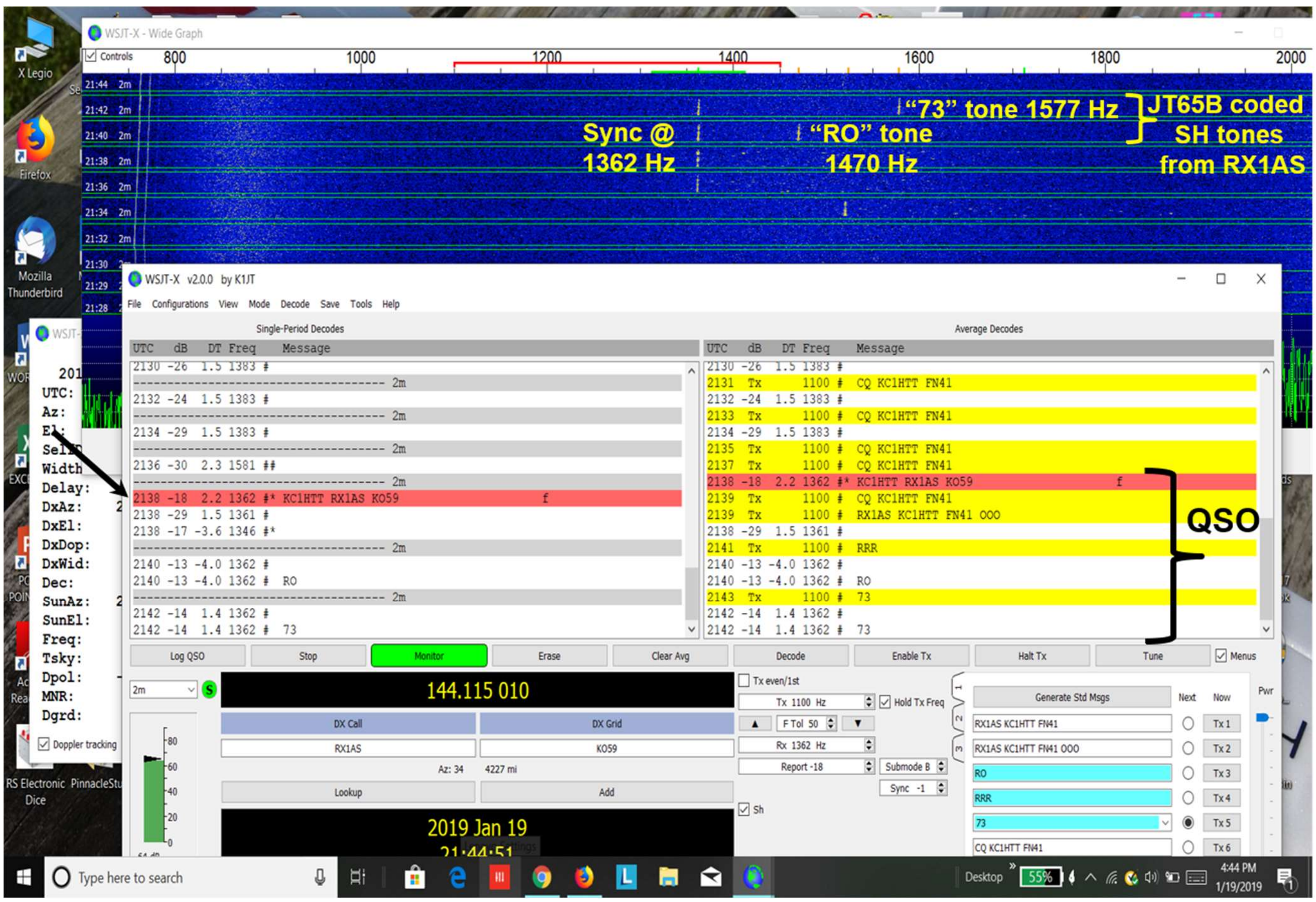


Figure 23. JT65B screenshot of the KC1HTT – RX1AS EME QSO. Note the yellow highlighted messages from KC1HTT and the red highlighted message from RX1AS.

RX1AS sync tones are at 1362 Hz and are clearly visible in the waterfall display. The **RX1AS** shorthand "RO" tone at 1470 Hz and "73" tone at 1577 Hz are also visible. Red fiducial markers are at the top of the JT65B waterfall display as frequency markers for each of the shorthand tones. This can help an operator observe the successful progression of an EME QSO.

An analysis of he SNR during the **KC1HTT** – **RX1AS** QSO is shown in Figure 24. The SNR varied during the QSO and roughly corresponds to the message content in each part of the message from **RX1AS**. Seventeen characters were transmitted at 2138 with an SNR = -24 dB. Two characters each were transmitted as short hand messages "RO" at 2140 and "73" at 2142 with SNRs of -13 dB and -14 dB respectively, which is an average difference of about 10.5 dB compared to the long message. This difference is at least partially accounted for by the ratio of the number of characters in the long message to the number of characters in the short hand messages, 9.3 dB, and the degree of uncertainty in each of the three messages.

2137	**CQ KC1HTT FN41**		**KC1HTT calls CQ**
2138	**KC1HTT RX1AS KO59**	**SNR = - 18 dB**	**RX1AS calls KC1HTT, 2.2 second delay**
2139	**RX1AS KC1HTT FN41 OOO**	**SNR = - 24 dB**	**KC1HTT reports sufficient SNR**
2140	**RO**	**SNR = - 13 dB**	**RX1AS "Roger, sufficient SNR"**
2141	**RRR**		**KC1HTT "Roger, Roger, Roger"**
2142	**73**	**SNR = - 14 dB**	**RX1AS "Best regards"**
2143	**73**		**KC1HTT "Best regards"**

Figure 24. Analysis of the SNR during the KC1HTT – RX1AS QSO. The SNR varied during the QSO and roughly corresponds to the number of characters in each part of the message from RX1AS. The UTC time order is preserved in the recorded transmission times.

The WSJT EME – 1 bulletin board [29] provides an initial confirmation of an EME QSO as well as information on the SNR received at each station. In Figure 25, a screenshot of the WSJT EME – 1 bulletin board indicates the initial request for an EME QSO at 21:37 UTC, the confirmation at 21:42 UTC with information on the SNR at RX1AS, **-24 dB**, relative lunar round trip time delay**, 2.1 seconds**, a measurement of the polarization rotation observed and compensated at RX1AS, -**272°**, and the confirmation of QSO, **RX1AS KC1HTT FN41 OOO**, and in the signature, **(RX1AS/4X15XP/1 Serge xx KO59xw)**, which indicates the operator's call sign, **RX1AS**, a quad array of 15-element cross polarized

Yagi antennas, **4X15XP**, a one kW transmitter power, **1**, the operator's name, **Serge**, and Maidenhead grid locator, **KO59xw**, near St. Petersburg, Russia.

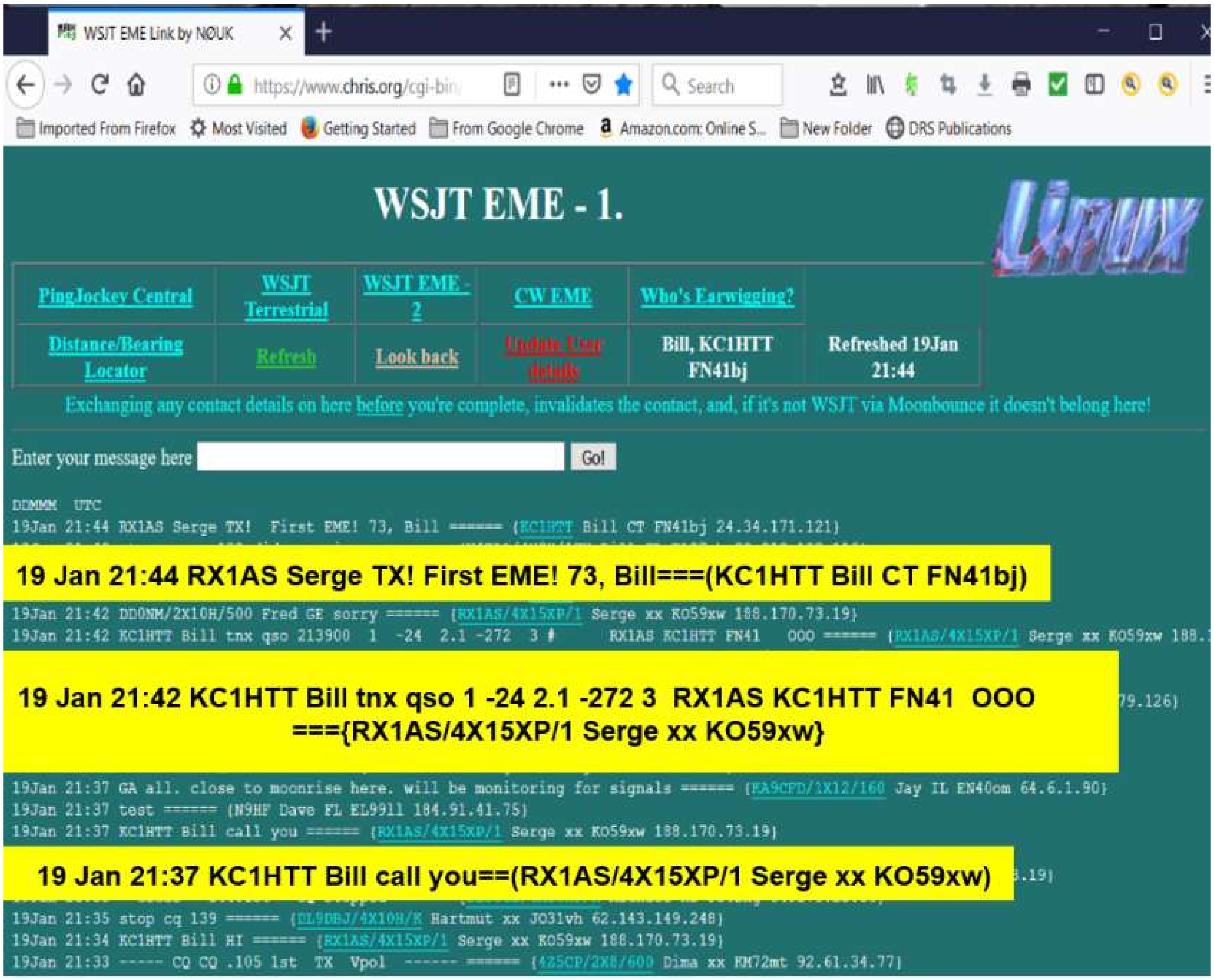


Figure 25. Screenshot of WSJT EME – 1 bulletin board taken after KC1HTT – RX1AS QSO. Note that at 21:42 RX1AS reports the best message SNR, -24 dB, the roundtrip time delay, 2.1 seconds, and the polarization correction, -272° as well as QSO confirmation, OOO. [29]

7. Earth-Moon-Earth Communication System Performance

In order to evaluate the EME link performance, the effect of the environment on the **KC1HTT** Yagi antenna gain and beamwidth must be determined. EZNEC+ V6 was used to estimate the antenna gain as affected by the ground and elevation angle. The **KC1HTT** 9 element, horizontally polarized, Yagi antenna was operated at a height of one wavelength above ground, and at an elevation angle of 15°. The ground was modeled with the ground conductivity = 0.005 S/m, and the ground dielectric constant = 13. The EZNEC+ model calculated that the gain is 16.66 dBi at 15°. When the EZNEC+ antenna gain calculations in Figure 17 (horizontally polarized Yagi antenna is at a zero-degree elevation angle) are compared to the antenna gain calculations in Figure 26 (horizontally polarized Yagi antenna pointing up at 15° elevation angle), the conclusion is that it would have been better to point the antenna at a zero-degree elevation during the QSO to maximize the total antenna gain. Since antenna pointing is done by hand and with a compass, this can be easily accommodated.

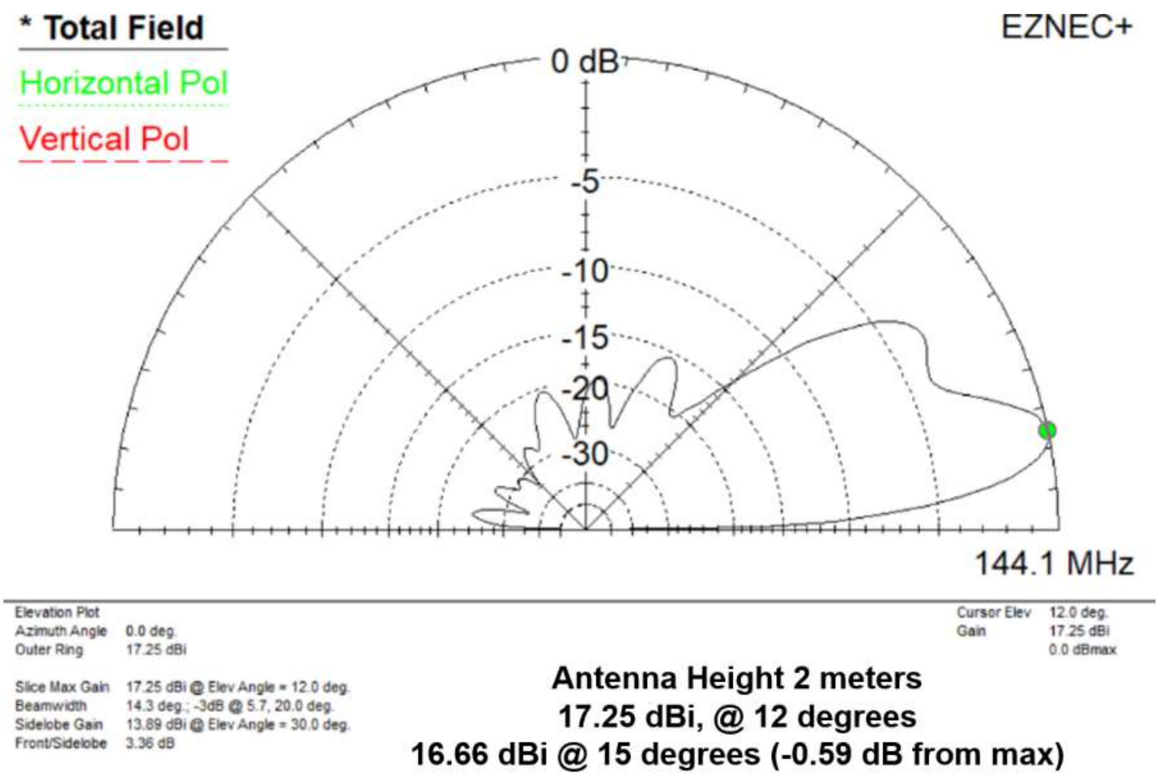


Figure 26. EZNEC+ V6 calculation of the KC1HTT 9 element, horizontally polarized, Yagi antenna at a height of one wavelength above ground, at an elevation angle of 15°. The antenna was pointed directly at the Moon, which was at 15°, during the KC1HTT – RX1AS QSO. The ground was modeled with the ground conductivity = 0.005 S/m, and the ground dielectric constant = 13. The EZNEC+ model indicates that the total gain is 16.66 dBi at 15°.

The **KC1HTT** amateur radio station parameters for the night of January 19, 2009 are shown in Figure 27. The power aperture product is +39.4 dBW, which is about as small as an amateur radio station can have and be successful with EME QSOs.

Operator	William Keicher
QTH	Pawcatuck, CT, USA
Grid	FN41bj
CQ Zone	5
ITU Zone	8
Receiver	H pol
Transmitter	177 W, H pol
Antenna Array	1 x 9 element 2M9SSB
Antenna Gain	14.2 dBi
Ground Gain @15°	2.46 dB
Total Antenna Gain	16.66 dBi
Power*Aperture	39.14 dBW
Mode	JT65B

Figure 27. The KC1HTT amateur radio station parameters the night of January 19, 2019. Total antenna gain was calculated to include the antenna height, one wavelength above the ground and with an elevation angle of 15°. Ground gain contributed 2.46 dB to the total antenna gain. The power aperture (P*A) of this small EME station is +39.14 dBW. (Photo from 10/2018)

The **RX1AS** amateur radio station parameters and antenna photo are shown in Figure 28. MAP 65 software is used with the cross polarized receiver antenna array to compensate for the Faraday and spatial polarization mismatch. The large power aperture product of +53.5 dBW defines a "big gun" EME station. A small EME station (+39 dBW) can only successfully communicate with a "big gun" EME station (> +50 dBW).

Operator	Sergey. A. Spiridonov
QTH	St Petersburg, Russia
Grid	KO59xw
CQ Zone	16
ITU Zone	29
Receiver	V and H pol
Transmitter	1000 W, V or H pol
Antenna Array	4 x 15 element XP
Antenna Gain	23.5 dBi (est.)
Power*Aperture	53.5 dBW
Mode	MAP 65

Figure 28. RX1AS amateur radio station parameters.

Evaluation of the EME radio link can now be performed using the information in the JT65B QSO, MoonSked, and the SNR and station information exchanged in the WSJT EME – 1 bulletin board.

KC1HTT - RX1AS EME QSO	MKS Units	dB
Common Parameters		
Frequency, Hz	144,115,000	81.59
Wavelength, m	2.080	3.18
Range, m	360,931,000.00	85.57
Mean Lunar Cross Section, m2		118.45
kTB, watts	1.00094E-17	-170.00
Tsky, K	388	25.89
Sky noise, kTB, watts	1.33918E-17	-168.73
$(4*\pi)^3$	1984.40	32.98
KC1HTT		
Transmitter Power, P1 (watts)	180	22.55
2M9SSB Antenna Gain, 14.2 dB + 2.46 dB GG		16.66
Receiver Noise Figure, F1	1.417	1.51
Receiver Noise, N1 (watts)	2.75751E-17	-165.59
Receive Polarization Loss, LP1		3.00
Receive Doppler Spreading Loss, LD1		1.00
Received signal, S1 (watts)	3.71448E-19	-184.30
SNR at KC1HTT Receiver		-18.71
RX1AS		
Transmitter Power, P2 (watts)	1000	30.00
Antenna Gain, G2		23.50
Receiver Noise Figure, F2	1.25	0.97
Receiver Noise, N2 (watts)	2.59035E-17	-165.87
Receive Polarization Loss, LP2		0.10
Receive Doppler Spreading Loss, LD2		1.00
Received signal, S2, (watts)	1.30368E-19	-188.85
SNR at RX1AS Receiver		-22.98

Table 4. Calculation of the KC1HTT – RX1AS EME QSO SNR during the evening of January 19, 2019.

The reported best long message SNR at **KC1HTT** was -18 dB versus the calculated SNR of -18.71 dB, a difference of +0.71 dB. The reported best long message SNR at **RX1AS** was -24 dB versus the calculated SNR of -22.98 dB, a difference of -1.02 dB. The model is in excellent agreement with the measured SNR in both cases.

A second EME QSO between **KC1HTT** and **S52LM**, a "big gun" station in Slovenia, was successfully completed shortly after the **KC1HTT** – **RX1AS** EME QSO. The reported best long message SNR at **KC1HTT** was -26 dB versus the calculated SNR of -21.07dB, a difference of -4.93 dB. The reported best long message SNR at **SM52LM** was -25 dB versus the calculated SNR of -25.34 dB, a difference of +0.34 dB.

A third EME QSO was successfully completed between **KC1HTT** and **I2FAK**, a "big gun" station in Italy, on February 10, 2019. The reported best long message SNR at **KC1HTT** was -30 dB versus the calculated SNR of -19.31 dB, a difference of 10.69 dB. The reported best long message SNR at **I2FAK** was -26 dB versus the calculated SNR of – 25.31 dB, a difference of -0.69 dB. Table 5 is a summary of all three EME QSOs.

EME DX Station	EME QSO Date	Time (UTC)	Modeled KC1HTT Received SNR, dB	Measured KC1HTT Received SNR, dB	KC1HTT Measured - Modeled Difference, dB	Modeled EME DX Station Received SNR, dB	Measured EME DX Station Received SNR, dB	DX Station Measured - Modeled Difference, dB
RX1AS	1/19/2019	2130	-18.71	-18	0.71	-22.98	-24	-1.02
S52LM	1/19/2019	2200	-21.07	-26	-4.93	-25.34	-25	0.34
I2FAK	2/10/2019	1800	-19.31	-30	-10.69	-25.31	-26	-0.69
Average					-4.97			-0.46

Table 5. Comparison of three EME QSOs. The measured SNR of QSO long messages is compared to the modeled SNR of QSO long messages. The difference between the measured and modeled SNR is calculated.

The best SNR model predictions are for the DX station received signal where the average error is -0.46 dB. This means that the model is reasonable for predicting the SNR. This is likely due to the use of cross polarized antennas, MAP 65 software, and polarization compensation at the DX station receiver. Polarization compensation eliminates the polarization loss variable for the "big gun" stations. The larger error in predicting the SNR at the **KC1HTT** receiver is likely due to the lack of knowledge of what the Faraday rotation polarization loss is. The SNR model uses a statistical approach for polarization loss, assigning the expected value of polarization loss equal to 3 dB to the modeled SNR calculation. Although the SNR at the **KC1HTT** receiver was adequate in each case, the lesson is that additional SNR margin may be likely to ensure an EME QSO. This can be obtained by adding a second antenna (+3dB), doubling **KC1HTT** transmitter power (+3 dB), and operating at Moon rise or Moon set to obtain "ground gain" as was done for the first two QSOs.

8. Summary and Future Work

The overall objective of *Project Selene* was to design, build and successfully use a small EME station during 2019, the year of the 50th Anniversary of the Apollo 11 Lunar landing. To this end, the physics of Earth-Moon-Earth communications has been described and used in a performance model of EME stations. The performance model uses the bistatic radar SNR equation. The model was used to set the design parameters for the small EME station. A small, low power, Earth-Moon Earth amateur radio station (P*A = +39 dBW) was constructed and its performance described along with the analyzed results of three successful EME QSOs. The objective of *Project Selene* was successfully achieved.

In addition to continuing to make and analyze EME QSOs, and testing the station with the French GRAVES Space Surveillance radar [30] , future plans for the KC1HTT EME station include building a 2 x 2M9SSB Yagi antenna array to improve performance, doing receive polarization tests with an SDRplay RSPduo dual channel, software defined receiver, using QRA64, and developing a better mathematical model for the effect on SNR of lunar libration induced Doppler shift. Other possibilities include adding a second RM Italy 250V VHF linear amplifier to double the transmit power.

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Appendix A. RF Safety

Average Power at the Antenna	200 watts
Antenna Gain in dBi	14.2 dBi
Distance to the Area of Interest	100 feet 30.48 metres
Frequency of Operation	144.1 MHz
Are Ground Reflections Calculated?	Yes
Estimated RF Power Density	0.1154 mW/cm^2

	Controlled Environment	**Uncontrolled Environment**
Maximum Permissible Exposure (MPE)	1.005 mW/cm^2	0.205 mW/cm^2
Distance to Compliance From Centre of Antenna	34.0137 feet 10.3674 metres	75.9952 feet 23.1633 metres
Does the Area of Interest Appear to be in Compliance?	yes	yes

Table A1. Calculation of safe distance from antenna main lobe illumination. The safe distance is about 25 meters (80 feet) or greater from the front of the antenna. [31]

Average Power at the Antenna	200 watts
Antenna Gain in dBi	1.2 dBi
Distance to the Area of Interest	25 feet 7.62 metres
Frequency of Operation	144.1 MHz
Are Ground Reflections Calculated?	Yes
Estimated RF Power Density	0.0926 mW/cm^2

	Controlled Environment	**Uncontrolled Environment**
Maximum Permissible Exposure (MPE)	1.005 mW/cm^2	0.205 mW/cm^2
Distance to Compliance From Centre of Antenna	7.6535 feet 2.3328 metres	17.052 feet 5.1975 metres
Does the Area of Interest Appear to be in Compliance?	yes	yes

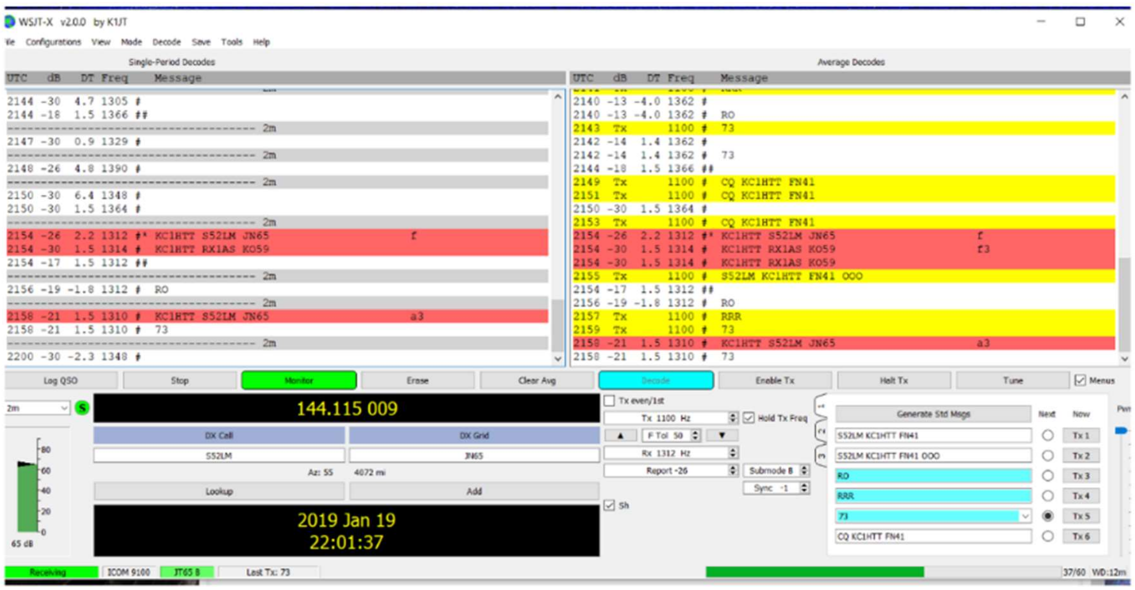
Table A2. Calculation of safe distance from antenna sidelobes illumination. The safe distance is about 6 meters (20 feet) or greater from the antenna. [31]

Appendix B. KC1HTT – S52LM QSO, January 19, 2019

• Operator	Milos Leban
• QTH	Solkan, Slovenia
• Grid	JN65tx
• CQ Zone	15
• ITU Zone	28
• Receiver	V and H
• Receiver NF	0.2 dB
• Transmitter	V or H, 1000 W
• Antenna Array	4 x 2M28XP Yagi
• Antenna Gain	21.14 dBi
• Power*Aperture Product	+51.14 dBW
• Mode: MAP 65	

Figure B1. S52LM Earth-Moon-Earth Station

Roundtrip time delay 2.4 seconds, -0.2 second error



2153	CQ KC1HTT FN41		KC1HTT calls CQ
2154	KC1HTT S52LM JN65	SNR = - 26 dB	S52LM calls KC1HTT, 2.2 sec delay
2155	S52LM KC1HTT FN41 OOO	SNR = - 25 dB	KC1HTT reports sufficient SNR
2156	RO	SNR = - 19 dB	S52LM “Roger, sufficient SNR”
2157	RRR		KC1HTT “Roger, Roger, Roger”
2158	73	SNR = - 21 dB	S52LM “Best regards”
2159	73		KC1HTT “Best regards”

Figure B2. KC1HTT – S52LM QSO Analysis

KC1HTT - S52LM EME QSO	MKS Units	dB
Common Parameters		
Frequency, Hz	144,115,000	81.59
Wavelength, m	2.080	3.18
Range, m	360,931,000.00	85.57
Mean Lunar Cross Section, m2		118.45
kTB, watts	1.00094E-17	-170.00
Tsky, K	388	25.89
Sky noise, kTB, watts	1.33918E-17	-168.73
$(4 * \pi)^3$	1984.40	32.98
KC1HTT		
Transmitter Power, P1 (watts)	180	22.55
2M9SSB Antenna Gain, 14.2 dB + 2.46 dB GG		16.66
Receiver Noise Figure, F1	1.417	1.51
Receiver Noise, N1 (watts)	2.75751E-17	-165.59
Receive Polarization Loss, LP1		3.00
Receive Doppler Spreading Loss, LD1		1.00
Received signal, S1 (watts)	2.15724E-19	-186.66
SNR at KC1HTT Receiver		-21.07
S52LM		
Transmitter Power, P2 (watts)	1000	30.00
2 x Antenna Gain, G2		21.14
Receiver Noise Figure, F2	1.25	0.97
Receiver Noise, N2 (watts)	2.59035E-17	-165.87
Receive Polarization Loss, LP2		0.10
Receive Doppler Spreading Loss, LD2		1.00
Received signal, S2, (watts)	7.5713E-20	-191.21
SNR at S52LM Receiver		-25.34

Table B1. Calculation of the KC1HTT – S52LM EME QSO SNR during the evening of January 19, 2019.

Appendix C. KC1HTT – I2FAK QSO, February 10, 2019

- **Operator** **Franco Giorgi**
- **QTH** **Broni, Italy**
- **Grid** **JN45ob**
- **CQ Zone** **15**
- **ITU Zone** **28**
- **Receiver** **V and H**
- **Receiver NF** **0.2 dB**
- **Transmitter** **V or H, 1500 W**
- **H Antenna Array** **16 x 19 LLY**
- **V Antenna Array** **16 x 6 el Yagi**
- **LLY H-pol Ant Gain** **25.7 dBi**
- **Yagi V-pol Ant Gain** **23.5 dBi**
- **Power*Aperture Product**
  +55.2 dBW or +57.4 dBW
- **Mode: MAP 65**

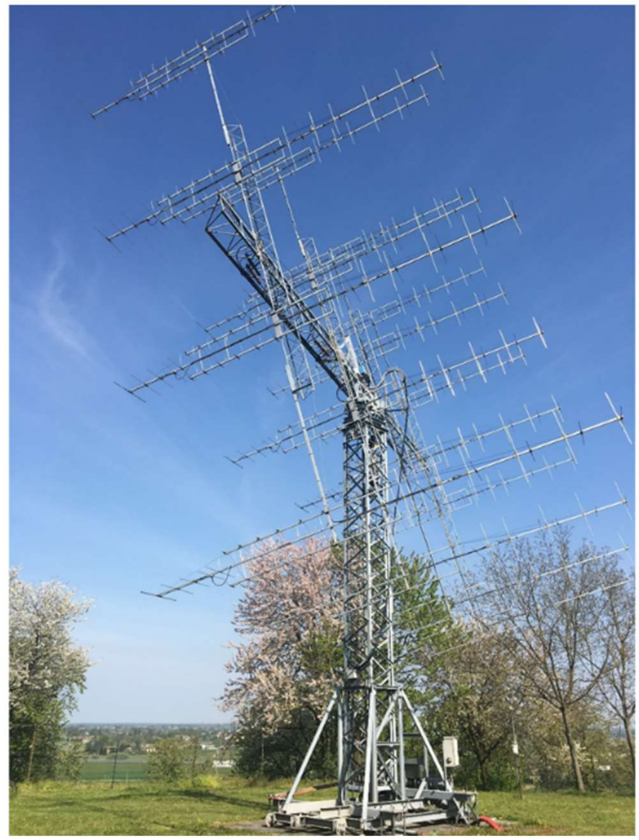
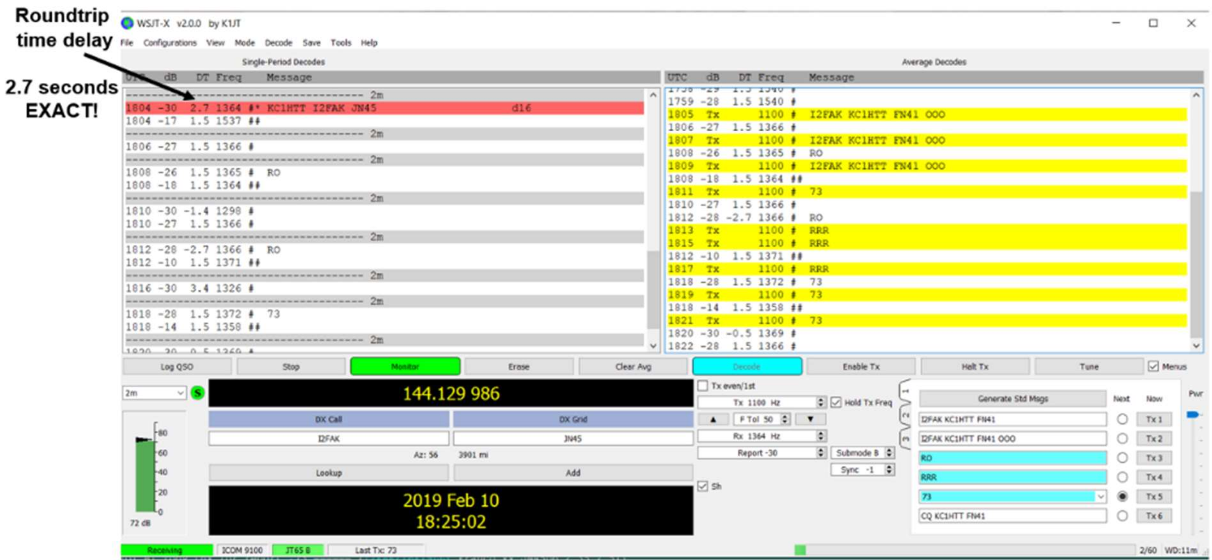


Figure C1. I2FAK Earth-Moon-Earth Station



1804 KC1HTT I2FAK JN45 — SNR = - 30 dB — I2FAK calls KC1HTT, 2.7 second delay

1807 I2FAK KC1HTT FN41 OOO — SNR = - 26 dB — KC1HTT reports sufficient SNR

1812 RO — SNR = - 28 dB — I2FAK "Roger, sufficient SNR"

1817 RRR — KC1HTT "Roger, Roger, Roger"

1818 73 — SNR = - 28 dB — I2FAK "Best regards"

1819 73 — KC1HTT "Best regards"

Undecoded calls occurred at 1805 1806, 1808, 1809, 1810, 1811, 1813, 1814, 1815, 1816. Undecoded even time (red) I2FAK calls were caused by I2FAK alternating TX polarizations.

Figure C2. KC1HTT – I2FAK QSO Analysis

KC1HTT - I2FAK EME QSO	MKS Units	dB
Common Parameters		
Frequency, Hz	144,129,986	81.59
Wavelength, m	2.080	3.18
Range, m	395,942,000	85.98
Mean Lunar Cross Section, m2		118.45
kTB, watts	1.00094E-17	-170.00
Tsky, K	300	24.77
Sky noise, kTB, watts	1.03545E-17	-169.85
$(4 * \pi)^3$	1984.40	32.98
KC1HTT		
Transmitter Power, P1 (watts)	180	22.55
2M9SSB Antenna Gain		14.20
Receiver Noise Figure, F1	1.417	1.51
Receiver Noise, N1 (watts)	2.45377E-17	-166.10
Receive Polarization Loss, LP1		3.00
Receive Doppler Spreading Loss, LD1		2.00
Received signal, S1 (watts)	2.87786E-19	-185.41
SNR at KC1HTT Receiver		-19.31
I2FAK		
Transmitter Power, P2 (watts)	1500	31.76
16 x 19LLY Yagi Antenna Gain, G2		25.70
Receiver Noise Figure, F2	1.25	0.97
Receiver Noise, N2 (watts)	2.28662E-17	-166.41
Receive Polarization Loss, LP2		0.10
Receive Doppler Spreading Loss, LD2		2.00
Received signal, S2, (watts)	6.73365E-20	-191.72
SNR at I2FAK Receiver		-25.31

Table C1. Calculation of the KC1HTT – I2FAK EME QSO SNR during the evening of February 10, 2019.

Appendix D. QSL Cards

EUROPEAN RUSSIA

RX1AS

WAZ: 16 ITU: 29 LOC: KO59XW

TO RADIO: KC1HTT VIA:

DAY	MONTH	YEAR	UTC	RST	MHz	MODE 2X	QSO VIA
19	01	2019	21.38	"O"	144 UP: DW:	❑ TROPO ❑ AUR ❑ MS ❑ ES ☑ EME ❑ FAI ❑ ION ❑ AUE	JT65B

Serge A. Spiridonov
Ryabowskoe sh.117 korp.3 - 73
St-Petersburg 195043
Russia

PSE QSL TNX

REMARKS:

UA1OMS QSLprint http://www.quadrat.ru/qsl

Figure D1. QSL Card received from RX1AS.

Figure D2. QSL Card received from S52LM.

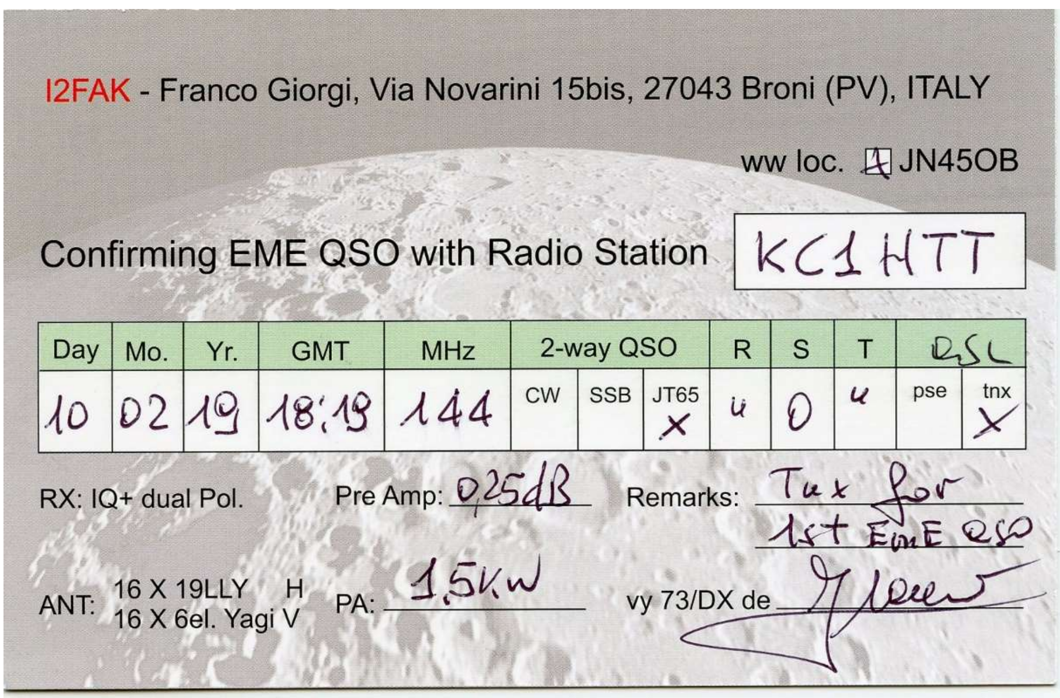


Figure D3. eQSL card received from I2FAK