By Dr H. Paul Shuch, N6TX

A Moonbounce Odyssey 2001

To fill an obscure yet important niche formerly filled by space probe Pioneer 10, radio amateurs built an EME calibration beacon that serves professional and Amateur Radio astronomers worldwide. As these hams discovered, calibrating ultra-high-gain receiving systems requires a special signal source.

On many occasions during the past four decades, several of the world's largest radio telescopes have been used to reflect interesting microwave signals off the Lunar surface, introducing hundreds of the world's Amateur Radio operators to the exotic world of EME (Earth-Moon-Earth) communications, or moonbounce. Operating under club call sign W2ETI, radio amateurs at the nonprofit, grassroots SETI League recently had an opportunity to return the favor, by providing astronomers at the Arecibo Observatory with a highly stable, precisely calibrated moonbounce signal with which to test their equipment. In the design, construction and operation of the Lunar Reflective Calibration Beacon for radio astronomy and SETI (funded in part by a NASA small equipment grant administered by the American Astronomical Society), these hams have demonstrated that the difference between amateur and professional is primarily fiscal.

Moonbounce

Radio amateurs have been exploiting the Earth-Moon-Earth (EME, or moonbounce) communications path for 40 years, using the Lunar surface as a passive reflector to extend the range of VHF, UHF and microwave signals. As a communications satellite (affectionately known as OSCAR 0), our Moon represents a low-gain transponder with only about 6 percent surface reflectivity. Its distance from the Earth is about 10 times greater than that of satellites in the Clarke geosynchronous orbital belt. The resulting high free-space isotropic path loss, coupled with various fading mechanisms, makes EME communications a challenge for the advanced amateur. Nevertheless, the ease of visually tracking this satellite makes the Moon a popular target.

The first successful amateur EME communications occurred in the 23-cm ham band at 1296 MHz, which is still a popular frequency for contemporary moonbounce activity. A significant portion of amateur and professional radio astronomical research is conducted in the adjacent 21-cm spectrum, at the 1420.40575-MHz emission frequency of neutral interstellar hydrogen. The typical hydrogen-line radio telescope (Figure 1) strongly resembles the low-power, low-cost (receive) half of a 23-cm EME station. Thus, many radio astronomers are

Figure 1—A typical hydrogen-line radio telescope.

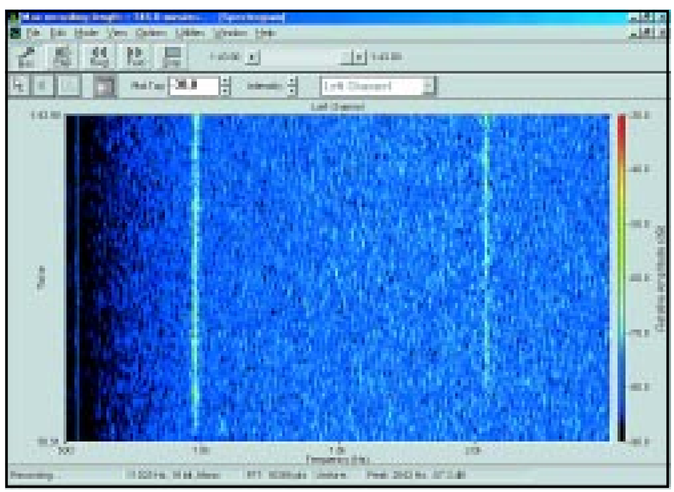

Figure 2—Amateur 1296-MHz EME signals received on an amateur 1420-MHz radio telescope (after digital signal processing).

able to receive amateur 23-cm EME emissions merely by tuning their receivers slightly lower in frequency (see Figure 2). In fact, members of the SETI League (who have collectively put 107 small radio telescopes on the air worldwide) frequently use weak amateur moonbounce signals to verify the proper operation of their equipment.

Searching for a Pioneer

Professional radio astronomers also require stable, weak extra-terrestrial signals to calibrate their much more sensitive receiving systems. For the past quarter century, a popular calibration source has been the weak microwave telemetry beacon aboard NASA's Pioneer 10 interplanetary space probe (Figure 3). Even over distances exceeding the radius of our solar system, this weak beacon has been detectable in waterfall spectrograph displays (Figure 4) using sensitive receivers on the world's great radio telescopes, such as the famed Arecibo observatory in Puerto Rico (Figure 5).

In March 2000, SETI League President Richard Factor, WA2IKL (Figure 6), chanced to be visiting colleagues at Arecibo as they were conducting observations in the SETI Institute's Project Phoenix targeted search for intelligently generated signals of extraterrestrial origin. For the first time, those radio astronomers found themselves unable to receive the trusty old Pioneer 10 beacon. The spacecraft was now at a distance of about 11.5 billion km from Earth. Link analysis (Table 1) revealed the Pioneer 10 downlink signal to be about 1 dB weaker than the detection threshold of the Project Phoenix digital signal processors.

Remembering the numerous occasions on which Arecibo and other giant radio telescopes had been activated for EME DXpeditions over the years, Factor suggested that radio amateurs might be in a position to return the favor by developing an amateur EME beacon to provide a weak, stable calibration signal for the use of amateur and professional radio astronomers alike. The resulting system received modest NASA funding through the American Astronomical Society's small equipment grant program, and went on the air just one year later. With the exception of minor outages for maintenance and redesign, the beacon has been on the air ever since, illuminating the Moon at 1296.000 MHz any time it is above the horizon from Factor's New Jersey QTH.

Beacon Basic Blocks

A block diagram of the W2ETI 23-cm EME beacon is shown in Figure 7. To prove useful as a calibrator for radio telescopes, the utmost in frequency accuracy and stability is required. This is accomplished by locking all frequency-determining stages to a Thunderbolt GPS-disciplined reference oscillator (Figure 8) generously provided by Trimble Navigation (through the good offices of member Art Lange, W6RXQ). This drives a Hewlett-Packard synthesized signal generator with its own frequency counter for cross-verification (Figure 9), both obtained at pennies on the dollar through the eBay internet auction site. A cascade of linear solid-state amplifier stages from Steve Kostro, N2CEI at Down East Microwave (seen in Figure 10 atop a dc power supply) bring the transmit level up to 20 W. After feed line losses, half of the output signal reaches the antenna.

The antenna (Figure 11) consists of an array of four 15-turn RHCP helices (for transmitting), courtesy of SETI League member David Clingerman, W6OAL, of Olde Antenna Labs. A second quad helix array, this one LHCP, allows for reception of the mirror-reversed EME echoes. Each

Table 1
Link Analysis of Pioneer 10 Beacon (March 2001)

Transmitter Output	= 8 W (+39 dBm)
Transmitter Freq	= 2320 MHz
Antenna Gain	= +33 dBi
EIRP	= +72 dBm
Path Loss	= 301 dB
Incident Power	= –229 dBm

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Figure 4—Pioneer 10 beacon as received at Arecibo, displayed on the Project Phoenix spectrograph (faint trace on right side of screen).

SETI LEAGUE

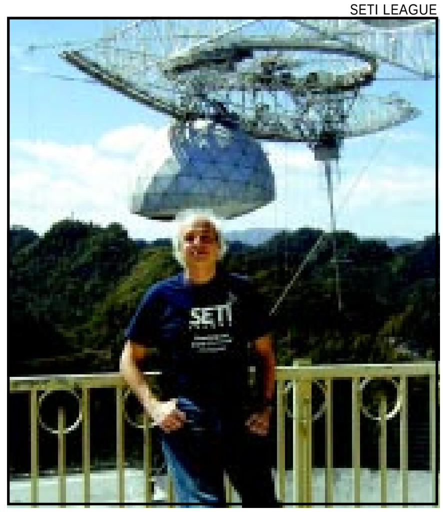

Figure 6—SETI League President Richard Factor, WA2IKL, visiting the Arecibo Radio Observatory.

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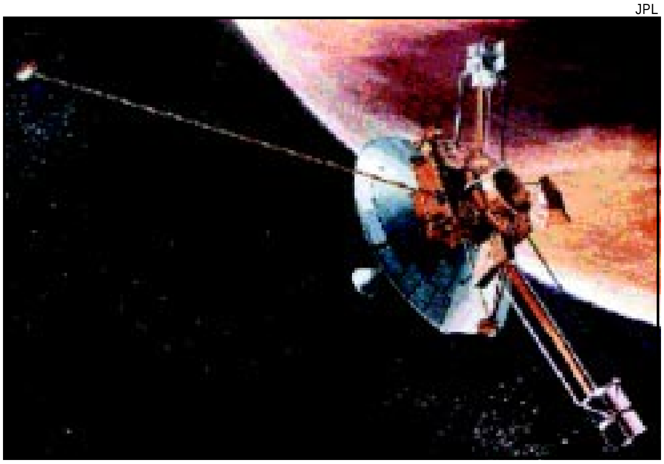

Figure 3—NASA Pioneer 10 interplanetary probe.

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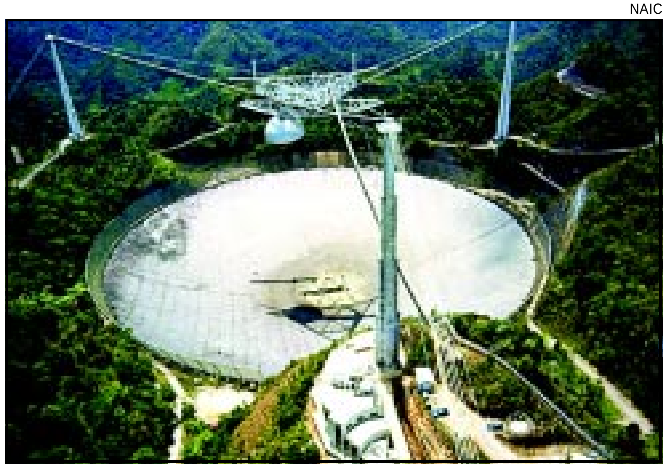

Figure 5—The impressive Arecibo Radio Observatory.

quad array produces +24 dBic of gain. A parabolic reflector of even modest size would produce higher gain and stronger echoes. Because of the resulting narrow beamwidth, however, this approach would require precise Lunar tracking. By using more modest antennas, tracking precision is reduced—an important consideration for the continuous, unattended operation that this beacon requires.

The antennas do, in fact, track the Moon in real time, rotated in azimuth and elevation by a set of Yaesu G-5600B rotators under computer control via an L. L. Grace Kansas City Tracker board obtained through AMSAT. The *Nova* software suite contributed by Mike Owen, W9IP, locates the moon and does much more, as we'll see

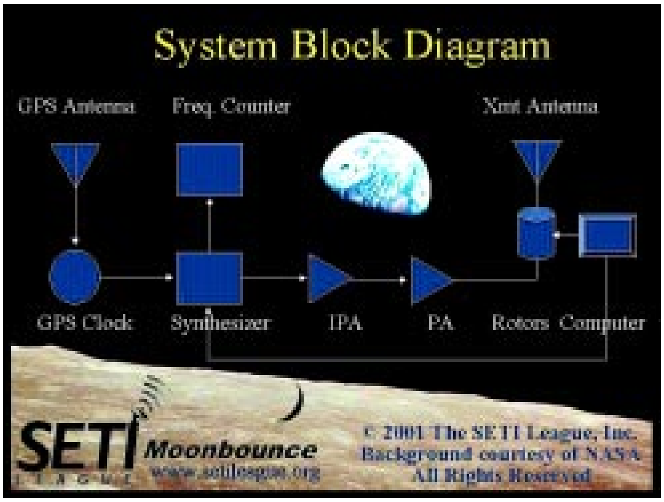

Figure 7—A block diagram of W2ETI's 1296-MHz EME beacon.

Figure 8—Trimble Thunderbolt GPS-disciplined clock.

Figure 9—EME beacon exciter (see text).

Figure 10—EME beacon intermediate power amplifiers (see text).

Figure 11—EME beacon antennas: four RHCP and four LHCP helices.

Figure 12—W2ETI station computers (see text).

Table 2
Link Analysis, W2ETI EME Beacon (March 2001)

Transmitter Output = 10 W (+40 dBm)
Transmitter Freq = 1296 MHz
Antenna Gain = +24 dBi
EIRP = +64 dBm
Path Loss = 271 dB
Incident Power = –207 dBm

below. Figure 12 shows the station computers, yet another eBay acquisition.

Note the power amplifier indicated in Figure 7, a stage not implemented in the EME beacon's initial configuration (but to be discussed later). Without it, the SETI League 23-cm EME beacon achieves an effective isotropic radiated power of +64 dBm, and its echoes illuminate the Earth at an isotropic power level of –207 dBm, as indicated in Table 2. Compared to the Pioneer 10 beacon specifications in Table 1, this is a signal about 22 dB stronger than the calibrator previously used at Arecibo.

First Light

Project Phoenix, which purchases dish time at Arecibo, had scheduled a four-week-long observing run to begin in early March 2001. Because the EME propagation path varies widely over time, it was desired to schedule First Light (initial testing of the EME beacon) for a date and time that would maximize our success potential. Fortunately, *Nova* facilitated such optimization, as shown in Figures 13 through 18.

Because the Moon's orbit is elliptical, its distance from Earth varies over the course of a moonth—er, month. Figure 13 is a *Nova* plot of how this distance varied during March 2001. It indicated Lunar perigee (closest approach to Earth) for March 8 to March 9, and apogee (greatest distance) for the 20th. Because greater distance translates into increased free-space isotropic path loss, an operating period about one week into the month appeared optimum.

The 23-degree inclination of the Lunar orbit also influences EME scheduling. Because the 305-meter-diameter cylindrical reflector at the Arecibo observatory is fixed and looks straight up, the antenna's steering is limited and Lunar passes directly overhead are favored. This suggests operating when the Moon is near its maximum northern declination, which Figure 14 suggests was to occur March 5. Perigee and maximum Lunar declination coincide only occasionally, and this time we seem to have gotten lucky.

Figure 15 shows the combined effects of declination and Earth-Moon distance. It allowed us to select March 8 as the optimum date for running EME tests with Arecibo. In fact, we did not achieve success until March 9, as the 8th saw the US Northeast gripped firmly in the arms of a blizzard, which encased the helix antennas in a coating of ice. There are some things that *Nova* cannot predict!

Because striking the Lunar surface with a grazing blow causes polarization scattering of the reflected signal, EME success is maximized when both stations view the Moon straight-on. That would occur at Lunar zenith if both transmitting and receiving stations were situated on the same meridian of longitude. Such is not the case for Arecibo and New Jersey. Fortunately, *Nova* calculates polarization scattering loss over time (Figure 16). Adding all of these temporal considerations (Figure 17), we see that for March 9, success

NOVA PLOTS

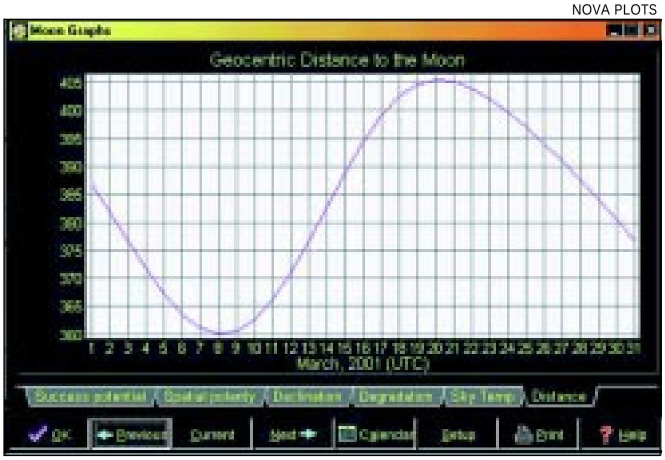

Figure 13—Earth-Moon distance for March 2001.

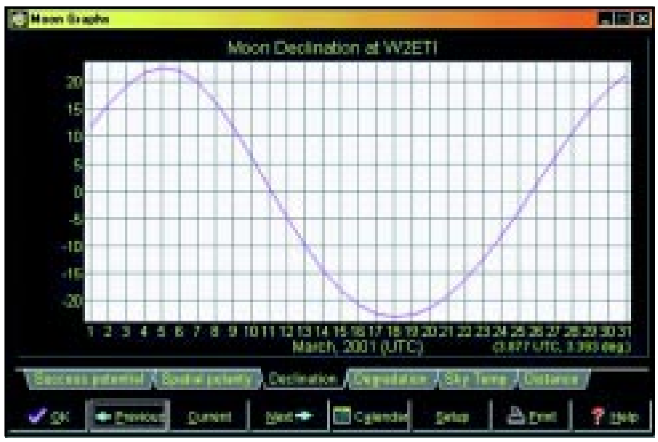

Figure 14—Lunar declination for March 2001.

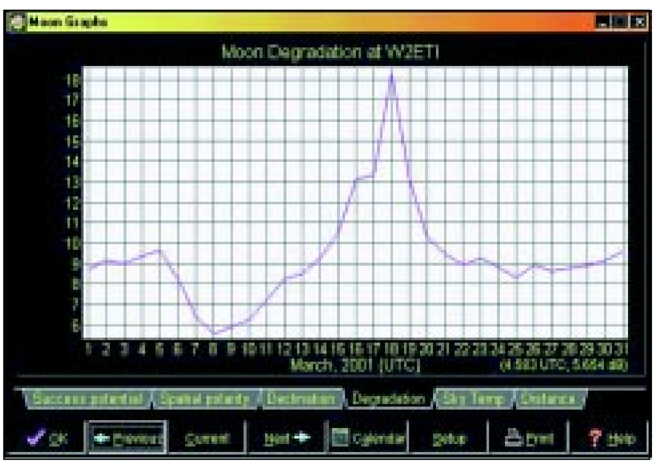

Figure 15—Moon path degradation for March 2001.

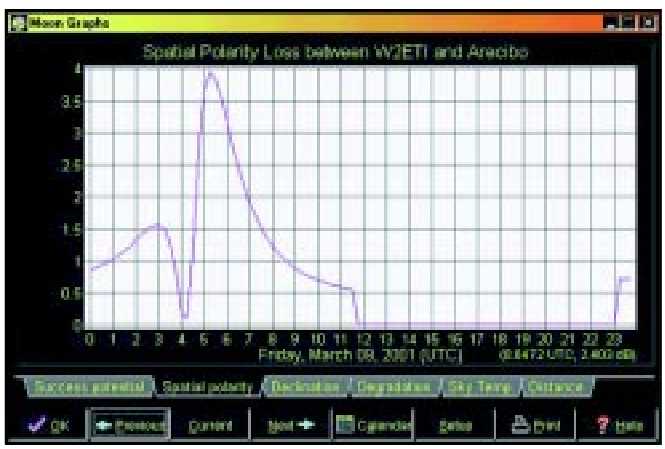

Figure 16—Spatial polarity loss for March 9, 2001.

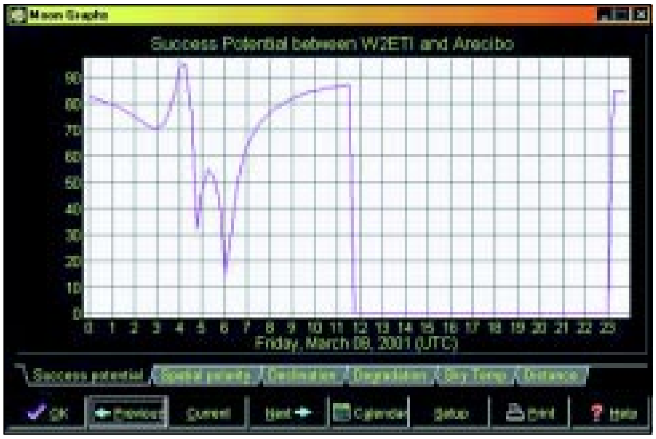

Figure 17—EME success potential for March 9, 2001.

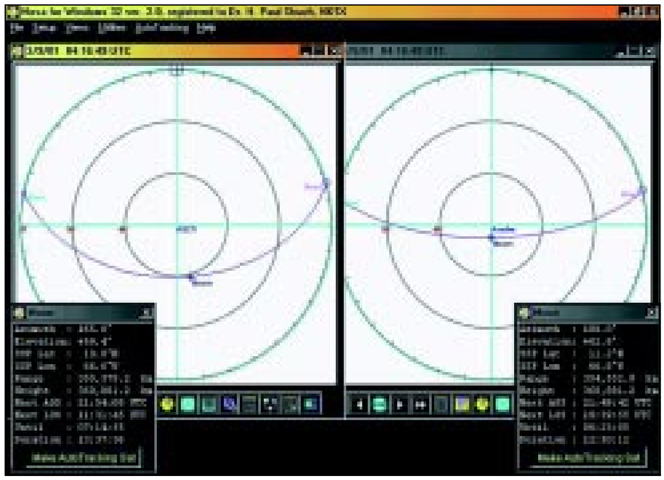

Figure 18—Lunar position during first detection of beacon.

potential was maximum at 0400 UTC, and that's when we set up our EME sked.

Persistent blizzard conditions in the US Northeast nearly scuttled the tests. For days WA2IKL was snowed in at work, and I was snowed in at my northern Pennsylvania home. Neither of us was able to reach the location of the W2ETI beacon. Fortunately, all of the beacon equipment was wired for IEEE-488 bus control, and Richard was able to operate the beacon remotely, via the Internet. I was able to coordinate the experiment from home, monitoring the position of the Moon at both locations (Figure 18) in real time and, using a Webcam (Figure 19), to follow Arecibo's progress.

At 0400 UTC on March 9, 2001, precisely as predicted in software, a slowly Doppler-shifted carrier representing the weak W2ETI beacon appeared on Arecibo's spectrographic display (see Figure 20). First detection was achieved by astronomer Seth Shostak, N6UDK. Two weeks later at the California Academy of Sciences, I presented Seth with the very first W2ETI EME beacon QSL card (Figure 21).

Under-Illumination Loss

Interestingly, although the software predictions were accurate and the equipment worked well, the signal shown in Figure 20 was scarcely discernible and hardly stronger than the former Pioneer 10 beacon signals shown in Figure 4. How could this be, considering that Tables 1 and 2 predicted that our beacon should have nearly 4 S-unit advantage?

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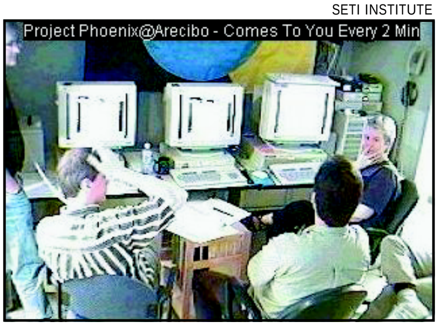

Figure 19—This Webcam image shows the action at Arecibo. Left to right: Dr Seth Shostak, N6UDK (at edge of frame), software scientists Gerry Harp and Rob Ackermann, astronomer Dr Jill Tarter, and Congressman Lamar Smith (just off camera with only his leg visible).

It turns out that Arecibo's greatest advantage—its huge size and impressive gain—worked to our detriment. Like jam on a soda cracker, our broad uplink beamwidth spread the W2ETI signal smoothly across the 1/2-degree Lunar disk. But Arecibo, with its 0.05-degree beamwidth, was only able to lick up about 1 percent of that jam (see Table 3). The rest of the jam ended up missing Arecibo completely, merely sticking to the tablecloth. Now if we factor in Arecibo's 20 dB of under-illumination loss, we see in Table 4 that our beacon signal, as available to Arecibo, was only 2 dB stronger than Pioneer 10. Because that transmitter was estimated at 1 dB below Arecibo's threshold, it's no wonder that our EME echo was received a scant 3 dB above mental telepathy!

N6UDK

Figure 20—EME beacon first light at Arecibo.

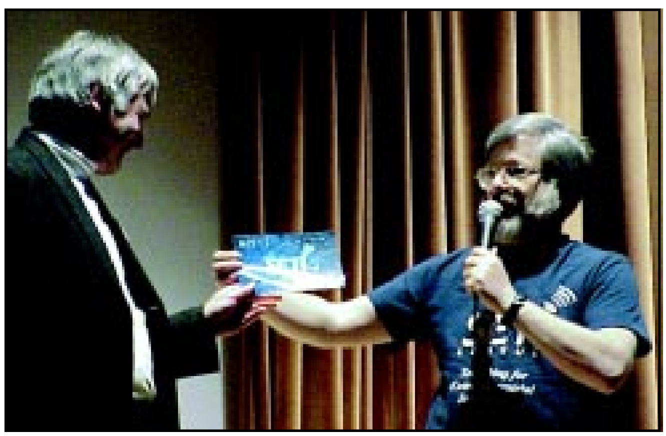

Figure 21—The author (right) presents Dr Seth Shostak, N6UDK, with the very first W2ETI EME beacon QSL card.

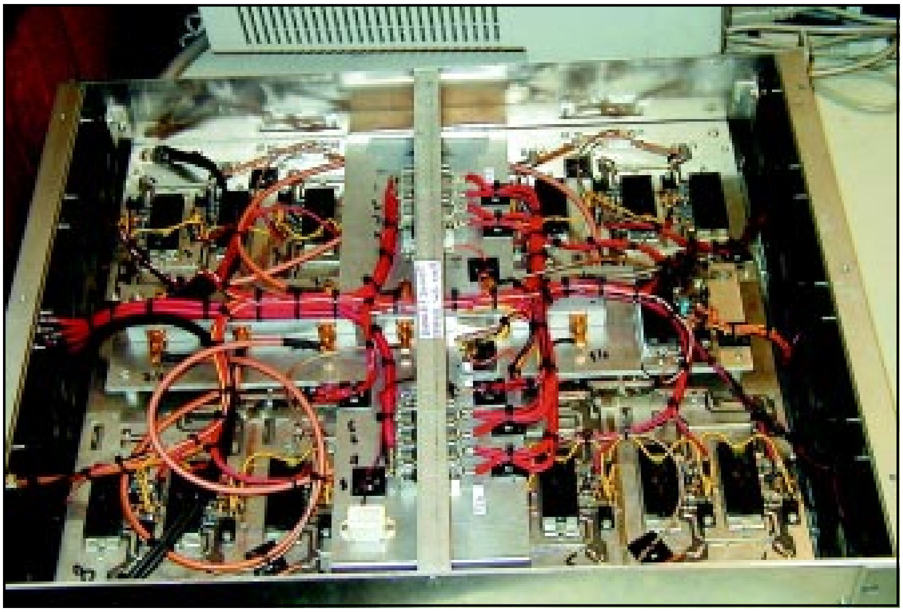

Figure 22—K3AX's 225-W solid-state power amplifier (see text).

Table 3
Under-illumination Loss

Moon Subtends: 0.5 degree
Arecibo's Beamwidth $\simeq$ 0.05 degree
Loss = $10 * \log_{10} (\theta 1/\theta 2)^2 \simeq 20$ dB

Table 4
Comparison of Effective Isotropic Incident Power for Pioneer 10 vs W2ETI EME Beacon, as Received at Arecibo

Pioneer 10 = –229 dBm
W2ETI Beacon = –227 dBm

Well, we had promised Arecibo a *weak* calibration signal, and that's what we delivered. The 250-foot-diameter Lovell Telescope at Jodrell Bank in the UK received us somewhat better; at four times the beamwidth of Arecibo, it actually had about a 12 dB advantage. And Jay Liebman, K5JL, with his 30-foot homebrew dish, fared better than either of these monster radio telescopes. With a beamwidth, slightly wider than the lunar disk, he recovered the lion's share of our feeble roar.

Going QRO

Still, not everyone has access to a 30-foot dish. If our objective was to provide a calibration signal that could be received by the average Amateur Radio astronomer, we were going to have to go QRO. Harry Price, K3AX, came to the rescue with the 225-W, solid-state linear amplifier shown in Figure 22 (one standard brick driving four bricks driving eight), with which he had made dozens of 1296-EME contacts years earlier. Back to eBay, and WA2IKL acquired an 80-A, 14-V dc power supply to feed this amplifier's voracious appetite.

After nearly five months of continuous operation, the W2ETI beacon was taken off the air in late July 2001 for total refurbishment. (At this writing it is still off the air.) With the K3AX power amplifier derated to a modest 100 W for continuous operation, we anticipate continuously illuminating the moon at +74 dBm of EIRP, for an isotropic power on Earth of better than –200 dBm. This should put reception of The SETI League's EME Beacon well within the grasp of our members.

Conclusion

At 17:27:30 UTC on Saturday, April 28, 2001 (seven weeks after the Arecibo tests described here), the signal from Pioneer 10 was received at NASA Deep Space Tracking Station 63 in Madrid, the first contact with the spacecraft in nearly a year. It appears that Pioneer 10 has life, albeit in another mode (only in a two-way, coherent mode). NASA and Project Phoenix had been listening for the Pioneer 10 signal in a one-way, non-coherent transmission mode with no success. Apparently, in order for Pioneer 10 to talk to Earth, Earth needs to talk to it. Pioneer 10 may well have outlived its usefulness. Thus, the W2ETI EME beacon will continue to serve as an invaluable calibration aid for the world's radio observatories, proving the dedication and professionalism for which radio amateurs have long been noted.

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[2]H. Paul Shuch, N6TX, "SETI sensitivity: calibrating on a Wow! Signal," *Proceedings of the AMSAT-NA Fourteenth Space* Symposium, pp 130-141, American Radio Relay League, 1996.

Paul Shuch, who serves as executive director of the SETI League, is a retired engineering professor credited with designing the first commercial home-satellite TV receiver. A Fellow of the British Interplanetary Society, he is the author of nearly 300 articles and other publications, has received numerous honors and awards and (as N6TX) has operated in all 20 ham bands between 1.8 MHz and 24 GHz. Paul served as director, technical director and chairman of the board of Project Oscar Inc, predecessors to AMSAT. He lives on a radio-quiet hilltop in northern Pennsylvania with his biologist wife, five of their seven recombinant DNA experiments, 10 networked computers, three motorcycles, two radio telescopes and an antique MG-TD. You can reach the author c/o The SETI League, Inc, PO Box 555, Little Ferry, NJ 07643; **n6tx@arrl.net**.