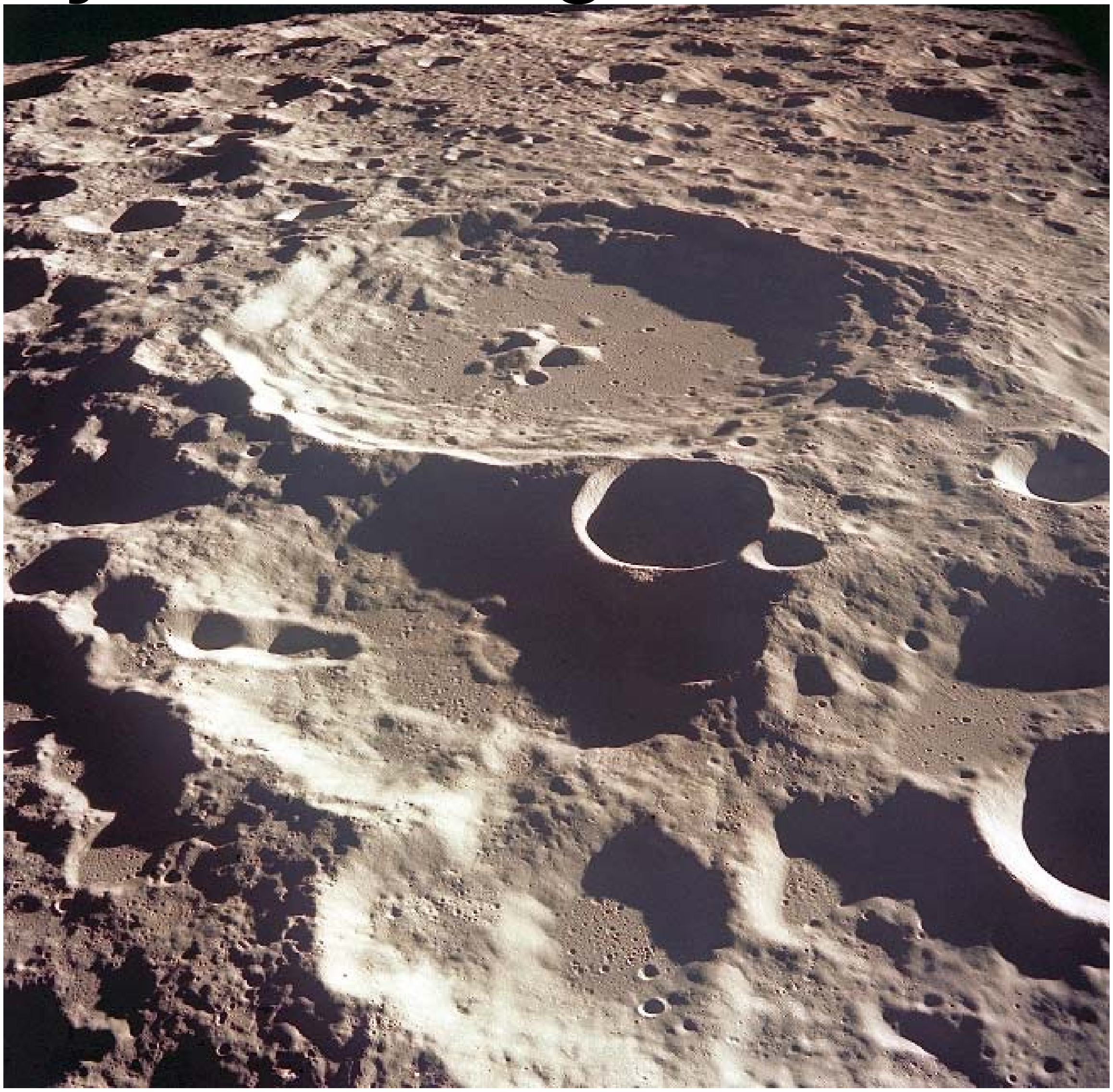
Lunar Radio Telescope System Design



Daedalus Crater, as seen from Apollo 11

Southard Applied Research Corporation
for the National Aeronautics and Space Administration
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Introduction

Traditionally, astronomy has confined itself to a tiny portion of the electromagnetic spectrum, the visible spectrum. However, a far more complete picture of the universe can be obtained by collecting data from alternate frequency bands, such as infrared, microwave, and radio-frequency. Collecting astronomical data from these bands is commonly known as radio astronomy.

Earth-based radio astronomy is hampered by the high noise floor on the Earth from countless electronic devices, from Wi-Fi hardware to GPS satellites to high-speed processors. All these devices steadily raise the noise floor in many of the frequencies of interest in radio astronomy, severely limiting the sensitivity of Earth-based radio astronomy facilities.

There is hope on the horizon for radio astronomy, however. At the time of this writing, NASA has established a moon base in the Daedalus crater on the far side of Earth's Moon. This base is shielded from the Earth's interference by the Moon itself, leading to much higher sensitivities than are obtainable on the earth. NASA has begun construction of a dish that will receive radio-frequency data in the 1-4 GHz range. The specifications for the dish can be seen in Table 1.

Diameter	300	meters
Aperture Efficiency	0.9	
Gain at 2.5 GHz	106.8	dBi
Noise Temperature	20	K

Table 1. Radio telescope specifications.

Problem Statement

The data generated by the radio telescope must be transferred back to Earth for processing, as NASA's scientific and computing facilities at the Daedalus base are severely limited. There are several unusual problems in this situation, which demand consideration above and beyond the standard satellite link. First, because of the broadband, high-fidelity nature of the Daedalus telescope, a massive amount of data is generated, requiring a large bandwidth and elaborate encoding of the data. In addition, the two ends of the link are blocked by the moon, necessitating a multi-step communications network.

Technical Approach

Southard Applied Research Corporation has developed a comprehensive plan for the communications network that will transfer the data from Daedalus telescope back to the Deep Space Network sites on the Earth. The network will consist of a Moon ground station and two satellites, and will use the Deep Space Network for its Earth-based receiver. The system will utilize the Ka-band, from 18 GHz to 41.5 GHz.

Radio Telescope Receiver

The receiver design for the Daedalus telescope is shown in Figure 1. The raw signal from the telescope is filtered and amplified before being passed through a high-speed 8-bit analog-to-digital converter. This ADC actually consists

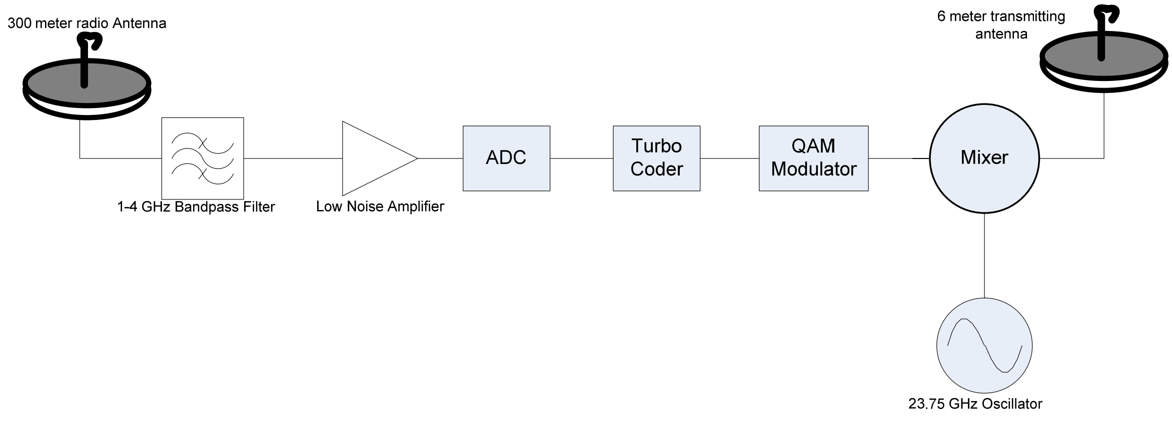

Figure 1. Block diagram for the Daedalus radio telescope.

of 6 individual 1.5 Gsps ADCs, all of which are synchronized to enable a higher sampling rate than any one converter could operate at. This technique is similar to that used by high-speed time domain instrumentation. The 8-bit resolution gives the quantizer a 48 dB dynamic range. This means that the telescope is capable of viewing both very powerful signals and very small signals, without having to change the RF front end.

After sampling and quantization, the data is digitally downconverted from the 1-4 GHz range to 0-3 GHz. The data is then turbo-coded at a ½ rate, to ensure error-free reception at low signal-to-noise ratios. The coded data is passed to a 1024-QAM modulator, which pulse-codes the signal according to a standard square QAM constellation. Although the QAM modulator would be similar to off-the-shelf models, a custom modulator would be necessary to accommodate the high data rate of this link. This large QAM constellation is chosen to increase the number of bits per symbol, which helps fit a high data rate into a manageable bandwidth, but increases the required signal-to-noise ratio. A

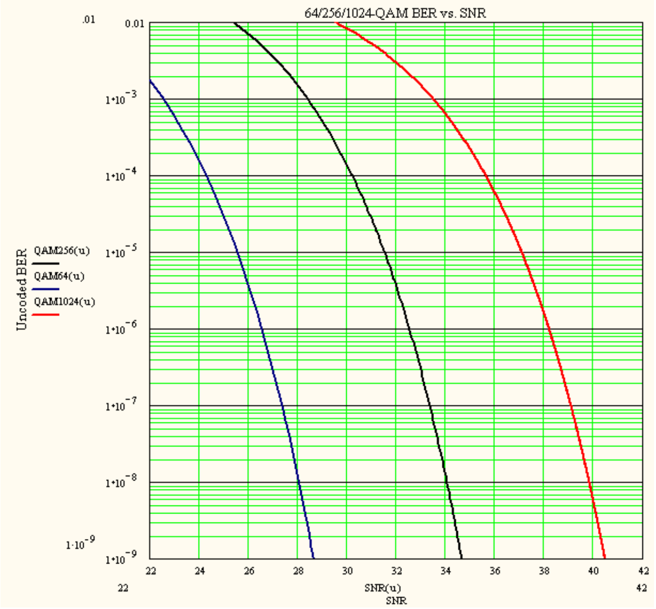

Figure 2. BER vs. SNR for various QAM constellations. From http://broadband.motorola.com/ips/pdf/QAM.pdf

plot of bit error rate vs. SNR for several different modulation schemes is shown in Figure 2.

The pulse-coded data is then mixed with a MMIC oscillator similar to the one designed by Professor John Cressler's lab at Georgia Tech, operating at 23.75 GHz, modulating the signal up to the Ka band. The modulated signal is amplified using a Ka-band power amplifier to 5 dBW and transmitted with a 6-meter dish to Satellite A. The total bandwidth of the uplink is 11.5 GHz, and the link from the Moon to Satellite A occupies the bandwidth from 18 GHz to 29.5 GHz.

Satellite Placement and Design

This design places two satellites in High Earth Orbit, one in each of the Lagrangian Points of the Earth-Moon system, which are shown in Figure 3. Satellite A will be located in the L2 point, on the far side of the moon, in the line of sight of the observatory. This satellite will have one dish antenna pointing down at the Moon surface and one antenna pointed at the second satellite. Because the L2 point is an unstable point, Satellite A will be provided with ample station-keeping propulsion systems.

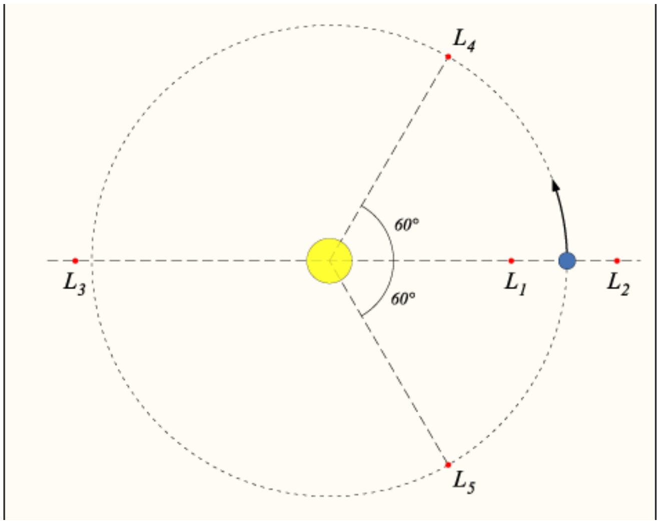

Figure 3. Lagrangian points of a two-body system. From http://en.wikipedia.org/wiki/Lagrangian_point

The second satellite, Satellite B, will be placed at the L4 point of the Earth-Moon system, which is at the same radius as the moon, but 60 degrees offset. Satellite B will have one six-meter dish antenna aimed at Satellite A and one aimed at the Earth. The L4 point is stable, so less station-keeping will be required for this satellite, although some will still be included.

The Satellite A-Satellite B link will operate from 30-41.5 GHz, so it will not interfere with the two other links in the system. This frequency band's susceptibility to atmospheric effects will not be a factor, as this link never enters the Earth's atmosphere.

Both satellites will operate on solar power. Both satellites will also contain lithium ion batteries, to ensure operation even when totally shadowed by the Earth or the Moon.

Satellite Receiver Design

Satellite A is a simple "bent-pipe" transponder, meaning than the signal will be shifted in frequency and transmitted without digitally regenerating the signal. Although this means that noise generated in this step will be passed

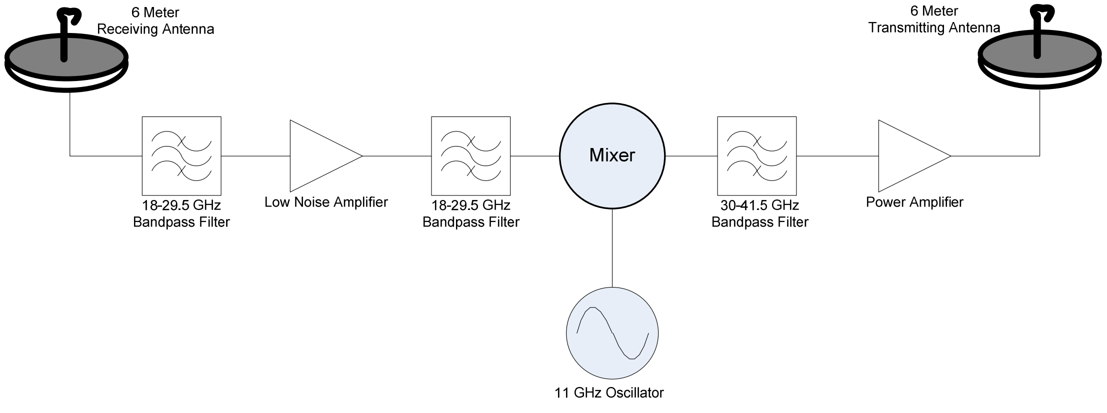

Figure 4. Satellite A block diagram.

through to the next satellite, the lack of digital processing circuitry in this step will reduce power consumption greatly. A block diagram for Satellite A is shown in Figure _. Note that the high power output from Satellite A will require a high power amplifier. In this and all the other receivers, Cavity microwave filters will be used for all the microwave and RF bandpass filters.

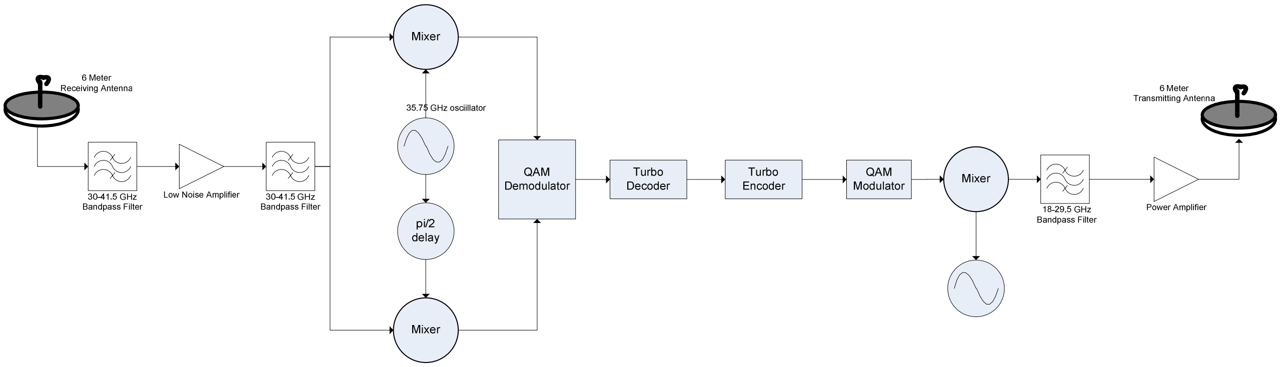

Figure 5. Satellite B block diagram.

Satellite B is a regenerative transponder, meaning that it demodulates and decodes the received signal, then encodes and modulates it for transmission. This effectively removes all the noise from the signal, which reduces the required CNR at Satellite B's receive antenna. This reduces the power that is required to be transmitted from Satellite A considerably. A system block diagram is shown in

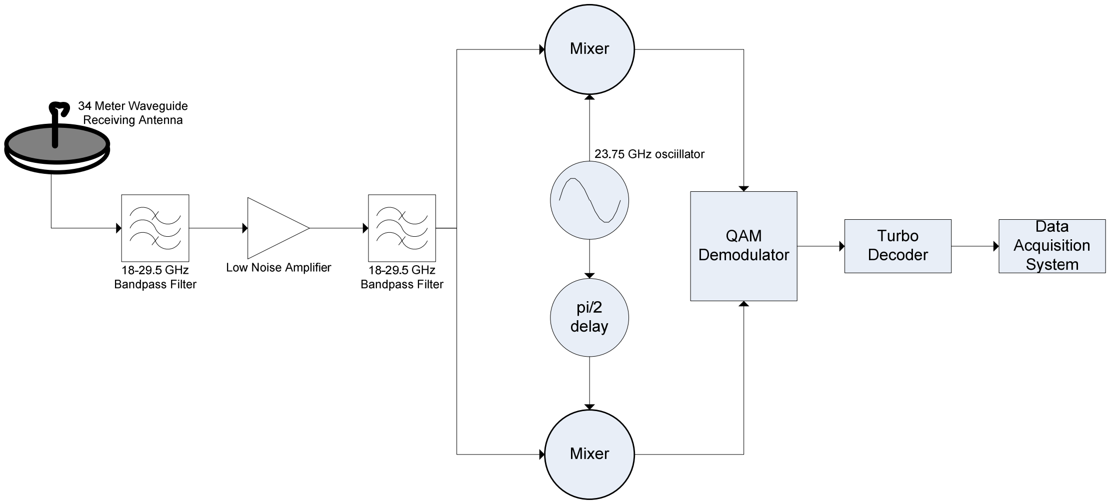

Figure 6. Earth receiver block diagram.

Figure 5.

The link from Satellite B to the Earth will be received by one of the Deep Space Network's 34 meter waveguide antennas, then fed to a ground-based demodulation, decoding, and data acquisition system. There are three DSN stations on the Earth, and one should be visible from Satellite B at any given time. This link will operate at the same frequency as the Moon-Satellite A link, but is shielded by the Moon from any interference. The block diagram of the Earth-based receiver is shown in Figure 6.

Antenna Design

To reduce the necessary power transmitted, the satellites are equipped with 6-meter radius transmit and receive dishes. The antenna efficiency is approximated to be 0.8, leading to a total antenna gain of 68.5 dBi for the moon-Satellite A and Satellite B-Earth links, and 72 dBi for the Satellite A-Satellite B link.

Link Budget

The link budget is shown in Table 2. The parameters in this link budget were calculated in MATLAB using the script in Appendix A.

Estimated Cost

Using a rough estimate of $150 million per satellite put in orbit and $1 million per transmitted watt of power, the communications system will cost approximately $336 million.

Conclusion

A communications system has been developed to receive and collect radio telescope data from a high-fidelity broadband radio telescope operating in the RF region. The unique challenges of this design included an unprecedented volume of data, as well as an transmitter point completely occluded from the receiver, and separated by an entire planet.

Table 2: Link Budgets

Moon-Satellite A Link Budget		
Transmitted Power	5	dBW
Transmitting Antenna Gain	68.532	dBi
Path Loss	-215.7362	dB
Receiving Antenna Gain	68.532	dBi
Total Received Power	-73.6722	dBW
Total Receiver Noise	-105.6606	dBW
Carrier-to-Noise Ratio	31.9884	dB
Satellite A - Satellite B Link Budget		
Transmitted Power	15	dBW
Transmitting Antenna Gain	71.9657	dBi
Path Loss	-235.5564	dB
Receiving Antenna Gain	71.9657	dBi
Total Received Power	-76.625	dBW
Transmitted Noise	-16.9884	dBW
Total pass-through noise	-108.6134	dBW
Linear pass-through noise	1.3761E-11	W
Receiver B noise	-105.66	dBW
Linear Receiver B noise	2.7164E-11	W
Total Noise	4.0926E-11	W
Total Noise in dB	-103.88004	dBW
Carrier-to-Noise Ratio	27.2550378	dBW
Satellite B-Earth Link Budget		
Transmitted Power	-1	dBW
Transmitting Antenna Gain	68.532	dBi
Path Loss	-232.1227	dB
Receiving Antenna Gain	83.5986	dBi
Total Received Power	-80.9921	dBW
Total Receiver Noise	-110.1738	dBW
Carrier-to-Noise Ratio	29.1817	dB
Power Transmitted Link 1	3.16227766	W
Power Transmitted Link 2	31.6227766	W
Power Transmitted Link 3	0.79432823	W
Total Power Transmitted	35.5793825	W