

The Deep Space Network at Honeysuckle Creek Tracking Station

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The Honeysuckle Creek Antenna during the Apollo 11 Landing

1) About the Cover Image

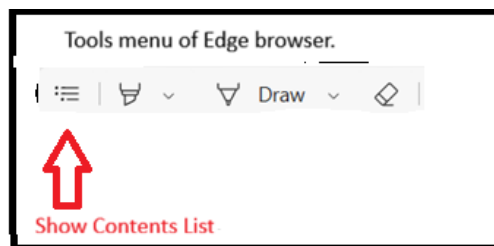
The cover photograph shows Honeysuckle Creek Tracking Station antenna during its unexpected moment of glory: receiving the television signal of Neil Armstrong and Buzz Aldrin descending the ladder of the Apollo 11 Lunar Module on 21 July 1969 (20 July in the United States). At this moment, the 26-metre antenna was pointed to the east, tracking the Lunar Lander on the Moon just before the first steps occurred. The X-Y mount of the antenna is clearly visible, as are the warning signs on the pedestal cautioning personnel about high-power radio emissions.

The main operations building, which housed the telemetry, command, and tracking equipment, lay to the right of the camera position. Five years later, in 1974, the station was reconfigured for Deep Space Network interplanetary support.

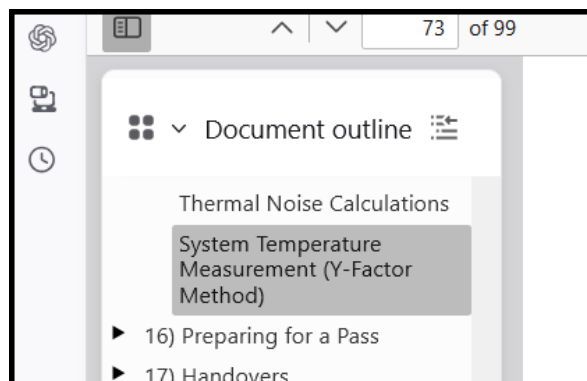
Photo: Hamish Lindsay.

2) Table of Contents

When using the Microsoft Edge browser to view the PDF file version, click on the leftmost icon of the browser (a list icon) as shown below to see the table of contents.



When using Firefox browser to view the PDF file version, click on the book shaped icon, then open the dotted square icon and select “Document outline”.



3) Overview

This document describes the technology used at Honeysuckle Creek Tracking Station during its Deep Space Network (DSN) era. During this time, it was known as Deep Space Station 44. The purpose of this document is:

- **To provide an explanation of DSN technology of the 1970s era.** The 1970s HSK configuration was technically simpler than modern DSN systems, yet conceptually similar. Understanding the HSK implementation provides a useful foundation for understanding today's more complex and refined versions.
- **To preserve technical details for posterity.** As time passes, it becomes increasingly difficult to reconstruct the details of HSK's DSN configuration. This document is a personal technical reconstruction based on the author's experience, supported by surviving documentation and engineering reasoning.

Honeysuckle Creek was originally built for the Apollo manned space flight network (MSFN) missions. After supporting Apollo, Skylab, and the Apollo-Soyuz Test Project, the station was converted in 1974-75 into a Deep Space Network (DSN) facility. It was then known as Deep Space Station (DSS) 44. Although it continued to use a version of the Unified S-Band (USB) system, the station was adapted to support DSN operations, which was tracking long-range interplanetary spacecraft.

Readers

This article is written for technically minded readers because the technical aspects of space communications are often skimmed over in historical accounts. Writers often focus on more widely interesting elements than engineering details, assuming they are fully covered elsewhere. The readers who could benefit from this article are students, technicians, and engineers wanting to learn a little about deep space communication systems, especially to get on track with the basics of long distance radio or with historical technology. A keen high school student with high school mathematics and some electrical/radio/physics knowledge should understand this article.

The article describes points of technical interest and explains what equipment was used and where this is known, why it was used. Keywords for technology like "phase locked loop" or "Viterbi decoding" are not discussed in depth because they can be explored further by online searching. This article offers basic explanations.

During the 1970s, many communication concepts now taken for granted were unfamiliar. The changes taking place involved Information theory, especially Shannon's theorem. Error correction usually meant automatically requesting a retransmission based on parity errors of characters. Forward error correction was not even effective with HF radio because it deals with random noise not obliterating interference like lightning and fading. Few understood how higher

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data rates could be achieved within less channel bandwidth than seems reasonable. Most thought that the bitrate was equivalent to the bandwidth and “going faster” was not possible. System design for reliable communication involved analogue systems where low distortion and high signal to noise were the means and definition of the performance. Nobody expected that errors could be reduced or even eliminated even when the signal-to-noise ratio was poor. During the 1970s people understood that broadband analogue frequency modulation (FM) had advantages in signal to noise above some threshold level that was called “the capture effect”. This is conceptually related to Spectrum spreading - later popularised by cordless phones and used in GPS and the DSN. It improved many of the analogue radio issues to do with resisting interference, fading, and noise.

Early History of the Deep Space Network

The Deep Space Network started from humble beginnings in January 1958. The Jet Propulsion Laboratory (JPL), managed by Caltech in California, deployed portable radio tracking stations in Nigeria, Singapore, and California. These caravans were to receive telemetry and plot the orbit of the U.S. Army's Explorer 1, the first successful U.S. satellite.

The separately developing space-exploration programs of the U.S. Army, Navy, and Air Force were consolidated into one civilian organization. This was NASA and thus JPL and the Deep Space Network (DSN), established in 1958. JPL eventually became a NASA research, development, and operations organisation with a focus on the Deep Space Network (DSN) and interplanetary research that it enabled.

The first DSN site outside the USA was Deep Space Instrumentation Facility (DSIF) 41 at Island Lagoon near Woomera in South Australia. The deep space stations were later known as DSS instead of DSIF. DSS 41 was operated by the Australian Department of Supply which ran the Woomera Rocket Range. It was completed in 1961. Some Honeysuckle Creek staff formerly worked at Island Lagoon DSS 41.

The DSN has three sites spaced around 120 degrees apart in longitude to provide continuous 24-hour coverage of spacecraft in solar orbit: Goldstone (California), Tidbinbilla (near Canberra), and Robledo de Chavela (near Madrid). Each complex originally operated 64-metre and 26-metre antennas, now upgraded to 70-metre and 34-metre antennas.

Following its original purpose of supporting Manned Space Flight Network (MSFN) missions, Honeysuckle Creek (DSS 44) operated as an auxiliary DSN station near Tidbinbilla and Canberra. It provided support to the Tidbinbilla DSN complex, supporting DSN tracking tasks within its capability.

There are few accessible detailed descriptions of the DSN-era HSK station, despite its role in tracking Pioneer 10 and 11, Helios 1 and 2, Viking 1 and 2, and the early phases of Voyager 1 and 2. Most online material focuses on the Apollo-era USB system, emphasising manned missions rather than telecommunications architecture.

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To illustrate the scale involving interplanetary spacecraft: light travels about 300 000 km in one second and just over one billion kilometres in an hour. From Earth, on average, it takes 1.3 light hours to reach Saturn, 5.5 light hours to reach Pluto and 14 hours from the Sun to the nearest point of the heliopause. That is where the influence of interstellar medium exceeds the influence of the sun.

A note on physical constants: in 1983 the speed of light was redefined from 300 000 000 m/s to 299 792 458 m/s.

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This article presents information for readers interested in the communications engineering of the DSN during the mid-to-late 1970s - sometimes called the Viking era. The author worked at HSK from early 1975 until early 1978.

HSK became DSS 44, a standard 26-metre DSN station, albeit with an X-Y antenna mount. It is easier to understand than today's complexes, which use multiple antennas and carriers across S-band, X-band, K and Ka-band, Cross-band links, Interferometry, and even optical systems.

Honeysuckle Creek became obsolescent when DSN upgrades for the Voyager era were completed in April 1978. It was expensive to operate as an isolated support station. These upgrades provided X-band capability (8.4 GHz) and telemetry rates up to 115 kb/s from Jupiter became possible for all three 64/70-metre antennas.



Figure 1: Apollo is gone, DSS 44 begins. [\[Attribution\]](#)

The photo above shows the equipment area at HSK with most of the Apollo era equipment removed. It is ready for the installation of the DSN era equipment. In the background the antenna servo console and its two cabinets remain. The window looks out on the antenna behind. This would have been late 1974 around the time the Author started work at Honeysuckle Creek.

“I remember pulling cables and connecting them to equipment racks”.

“There was a second period of reconfiguration to improve the station’s operation, around 1978”.

DSS 44 closed in 1981, but the antenna was moved to Tidbinbilla in 1986 and enjoyed an extended life as DSS 46. It ceased operations in 2009. In its modified form without the quadrupod it can still be seen at Tidbinbilla. At the Honeysuckle Creek site there remains the concrete antenna pad and some plaques added by the Local government later.

Surging Technology Change

The 1970s were a period of rapid technological change. Integrated circuits became accessible and transformed electronic systems, increasing reliability, reducing size, and reducing cost. In consequence digital computers became more widely available and used for control and monitoring systems where they had not been used before. The advent of the TTL (transistor-transistor-logic) series then CMOS (a low power integrated circuit technology) made computer chips with ever larger systems not just feasible, but available.

During the 1950s and 1960s, terrestrial broadband FM microwave links were being introduced worldwide. These used vacuum tubes to provide a base bandwidth of around 0 - 5 MHz. These systems used mountain top repeaters with around 40 km spacing to provide transcontinental links with good quality telephone channels. A notable and early system was across Canada. One of these links could carry up to 960 telephone channels using frequency division multiplexing (FDM) carrier systems with Single Side Band channels stacked across the baseband. The same systems could also carry one analogue TV channel. These broadband carrier systems were based on the older 12 channel open wire carrier systems. They became available with the advent of transistorised designs which could be much more compact. Broadband radio systems moved to using semiconductors. They replaced open-wire telephone trunk lines, providing widespread broadband connections that together with underwater coaxial cables between continents led to International Subscriber Dialling (ISD). While broadband digital radio systems were still being introduced during the early 1970s, they were soon overshadowed by Fibre-optic systems that were only just emerging.

During the 1970s, solar panels, LEDs, Lasers, Video Cassette Recorders, and electronic calculators appeared at the consumer level. Memory chips and ever more complex computer chips became available towards the end of the 1970’s. Systems using discrete components like transistors were being replaced. Entire technologies such as electromechanical telephone exchanges and telegraph systems disappeared. New networks appeared to the extent that nowadays the telephone system runs over the internet, whether using “cables” or mobile phones.

Audio cassette tapes and helical scan video cassette tape recorders became popular during the 1970s. Large digital tape recorders taking a half rack space were used for minicomputer mass storage, while early versions of floppy disks and

hard disk drives appeared. The first fly by wire aircraft appeared (F16), and GPS satellite navigation commenced operation in 1978. The first IBM PC appeared later, in 1981, but the HP 9830 “Calculator” was a desktop “personal computer” from the early 1970s that was capable and easily programmable with its own mathematics library though lacking in memory and expensive to own.

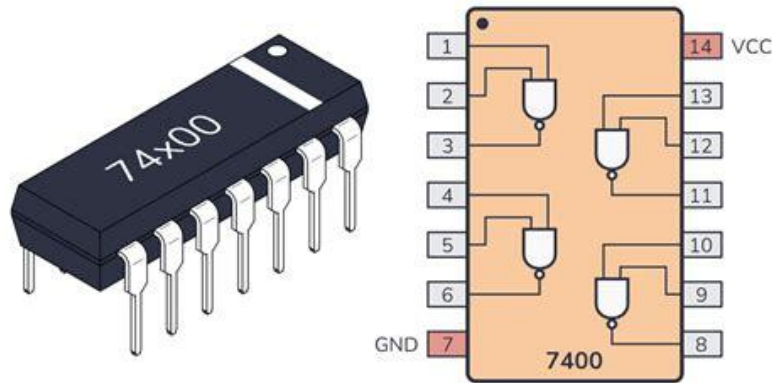


Figure 2: Example of a TTL logic series chip. [\[Attribution\]](#)

The TTL integrated circuits (example shown above) were reliable and low cost devices that could be used to build all parts of a computer in the 1970s, except the memory. This was the beginning of a major leap forward in availability of computers, even for onboard a spacecraft.

Digital memory chips finally relieved the cost and size bottleneck of computer memory late in the 1970s. The last of the necessary integrated circuit memory required to replace magnetic core memory on a spacecraft was non-volatile storage for firmware and software, which finally appeared as EPROM. These chips had a window for erasing them using UV light. You could see inside these chips, though there was always a sticker over the window to prevent light from getting in. The modern Flash memory is related. Magnetic tape, disk drives, and punched tape were used for storage on minicomputers of the 1970s.

Most people had never seen a computer of any kind during the early 1970s. though they did exist in larger Corporations for mundane tasks like payroll and inventory and booking systems. Right at the end of the 1970s some cheaper desktop computers appeared, using integrated circuits and memory chips. Some examples were Tandy, Commodore, and the earliest Apple computers. They could be programmed in the Basic Language just like the earlier HP Desktop “calculator”, and people wrote all sorts of programs. They were not connected to networks or time sharing in any way.

DSN Technology of the Era

The equipment used at DSN stations in the 1970s was highly specialised and sophisticated. Precision time and frequency references, push-button frequency synthesizers, large microwave Klystron Power amplifiers, ultra-low noise microwave masers were exotic at that time and still are. Minicomputers using TTL

logic chips were essential station components that had just become possible. NASA operated the first global network with telephone, data, and television capability. This was to allow spacecraft data to be moved around.

Many computer devices used at HSK – line printers, tape drives, disk drives, colour displays – were products of the “space race” era. In the DSN tracking stations sophisticated decoding of noisy signals became possible as digital computers became more accessible. These were the first computers the Author saw, at age 33.

Key Technologies in the USB System

The Unified S Band (USB) system at HSK incorporated several leading-edge technologies:

- High-reliability engineering.
- Phase modulation to allow coherent tracking including doppler and ranging and telemetry, while minimising the need for highly linear amplifiers, especially the transmitter power amplifier. Nevertheless, the system was capable of linear operation.
- Phase-locked loops for phase coherent tracking of Doppler.
- Atomic frequency standards for high precision time and frequency necessary for precision ranging and doppler measurements.
- Transistor-Transistor-Logic (TTL) chip based minicomputers that allowed cheaper computers to become available and practical.
- Microwave masers for ultra-low noise radio receiver front ends, essential for interplanetary range.
- Waveguide duplexers for simultaneous operation of high powered transmitter and sensitive receiver with a single antenna.
- Klystron for high power microwave transmitters.
- Early colour display terminals and other computer subsystems.
- The global data, voice, and television network run by NASA.

What is a Tracking Station

Tracking stations like DSS 44 were meant to track spacecraft at a great distance. The earlier development of such systems was to track missiles with precision. The obvious part of tracking is the position of the spacecraft in the sky, which is seen as where the antenna points. Less obvious is tracking the received signal level weakened by distance, tracking the received signal frequency which changes due to Doppler shift, tracking the ranging signal, and tracking the operational status of the spacecraft.

The goal of operations is to provide reliable and accurate navigation for determination of the spacecraft trajectory and to obtain scientific data for clients who plan missions. The science data (telemetry) includes results of measurements, images, and spacecraft engineering data. A tracking station is a specialised type of radar system which also transmits commands to the spacecraft and receives

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telemetry from the spacecraft. The spacecraft has a transponder which receives the uplink signal and retransmits it as the downlink signal.

Why Chose Microwave Radio

Why did the DSN move to using “S” band microwave in the 1960s, and since then, ever shorter wavelengths? The earliest satellites used HF radio and VHF radio for the required operations. These were the “long range” or “low noise” technologies of the post war era. However, there were issues with interference, galactic noise, bandwidth, congested spectrum availability, unreliable propagation, and the ionosphere. Clearly there needed to be a better system.

In a line of sight system, microwave offered stronger signals with less interference because of the potential gain in received signal level from larger dish antennas at each end of a link. Typical HF and VHF antenna gains were of the order of 10 dB (10 times), though a rhombic antenna could achieve around 27dB (500 times). A dish could provide 30-50 dB gain (one thousand to 100 thousand times the signal) or more at transmit and/or receive end due to focussing. The gain of the antenna increases with higher frequency bands if the dish surface is appropriate. This better link performance of microwave leads to more range and/or more bandwidth. Lightning and manmade interference are much less at the microwave frequencies.

The advent of semiconductor microwave designs (S-band 2100 - 2300 MHz) during the 1960s made the L band then the S band system attractive because a design with high frequency and phase stability became possible. This relied on atomic clocks that were an offshoot of masers. The cryogenically cooled maser was a low noise amplifier for the receiver with much less noise than previous systems. These two bands also have good penetration of the atmosphere including during weather events. The galactic noise was lower in these bands when compared with the HF bands where the Galactic noise limits receiving sensitivity. The USB concept was to include all the required facilities on one composite signal on the same link so that only one radio system was needed. This is a significant advantage to the spacecraft especially.

Spacecraft

The spacecraft of the 1970s started to increase in size and complexity. Viking and Voyager were among the first to have a proper computer on board, and transmitter powers increased from 0.5W to 20W. The antenna increased to ~4 meters diameter with Voyager. The power consumption was reduced. This allowed more power to be devoted to the science for a given payload. The instruments on board spacecraft were exotic, sometimes intended to measure what had not been measured before. One example was the GCMS on board Viking Landers, which was intended to analyse what was going on in the soil and atmosphere and the evidence for life on Mars. It was a Gas Chromatograph with a Mass Spectrometer attached. These instruments were commonly used in analytical laboratories, not on the surface of Mars. The spacecraft missions involve orbiting of planets, flybys and occultations. Remote sensing is used while the spacecraft are orbiting around the sun or planets

or moons. One of the desired capabilities is the transmission of all kinds of imaging. Some of the images that spacecraft have transmitted are magnetic fields, solar wind, plasma, infra-red, visible light, ultraviolet and gamma rays. The images of planets, moons, and closeups of surface features have been shown to the world.

All of this was under the Deep Space Network (DSN) operated by the Jet Propulsion Laboratory (JPL) for NASA and other clients in the USA and internationally.

During the 1970s the performance improvement can be shown as data rate. It increased rapidly from 8.33 bits per second to 116 kb/s at the distance of Planet Jupiter. Data rate increased from around 1 Mb a day to 1 Mb in around 9 seconds. An engineering goal for the DSN was to calculate margins by adding the error bands of the components. This led to a reserve capacity that became extended missions for each spacecraft.

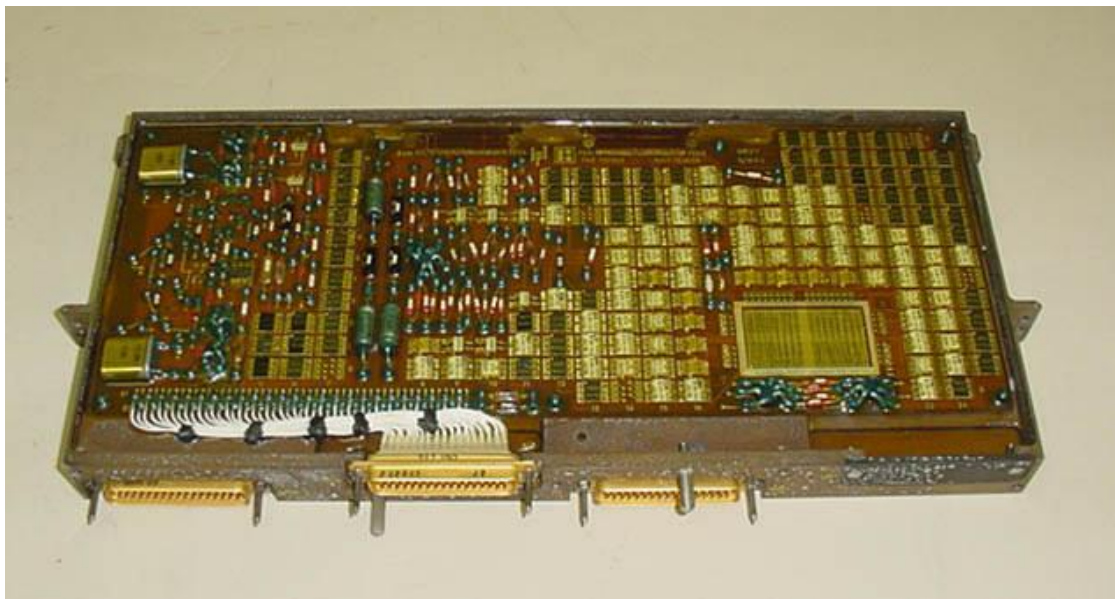


Figure 3: A computer board from one of Voyager's 3 computers. [\[Attribution\]](#)

The image above shows a circuit board from the first computer used for a planetary flyby (Voyager 1 and 2). It is part of the AACS subsystem. The Voyager Attitude and Articulation Control Subsystem (AACS) is the guidance-and-control system responsible for keeping this spacecraft properly oriented in space and correctly pointing its instruments and high-gain antenna. Voyager did not use spin stabilisation. It had a gyroscopic system because many of its instruments would have been hampered by the spin.

Most of the integrated circuits you can see in the image (lighter coloured rectangles on the right) are premium TTL chips in a hermetically sealed ceramic package. Back on earth most designs used the cheaper plastic package which was not hermetically sealed.

Other interplanetary spacecraft to use a computer at the end of the 1970s were the Viking 1 and 2 landers and orbiters. The computers on these two spacecraft series were similar designs. These computers allowed extended missions to take

place. Various problems were solved by reprogramming the spacecraft computers remotely.

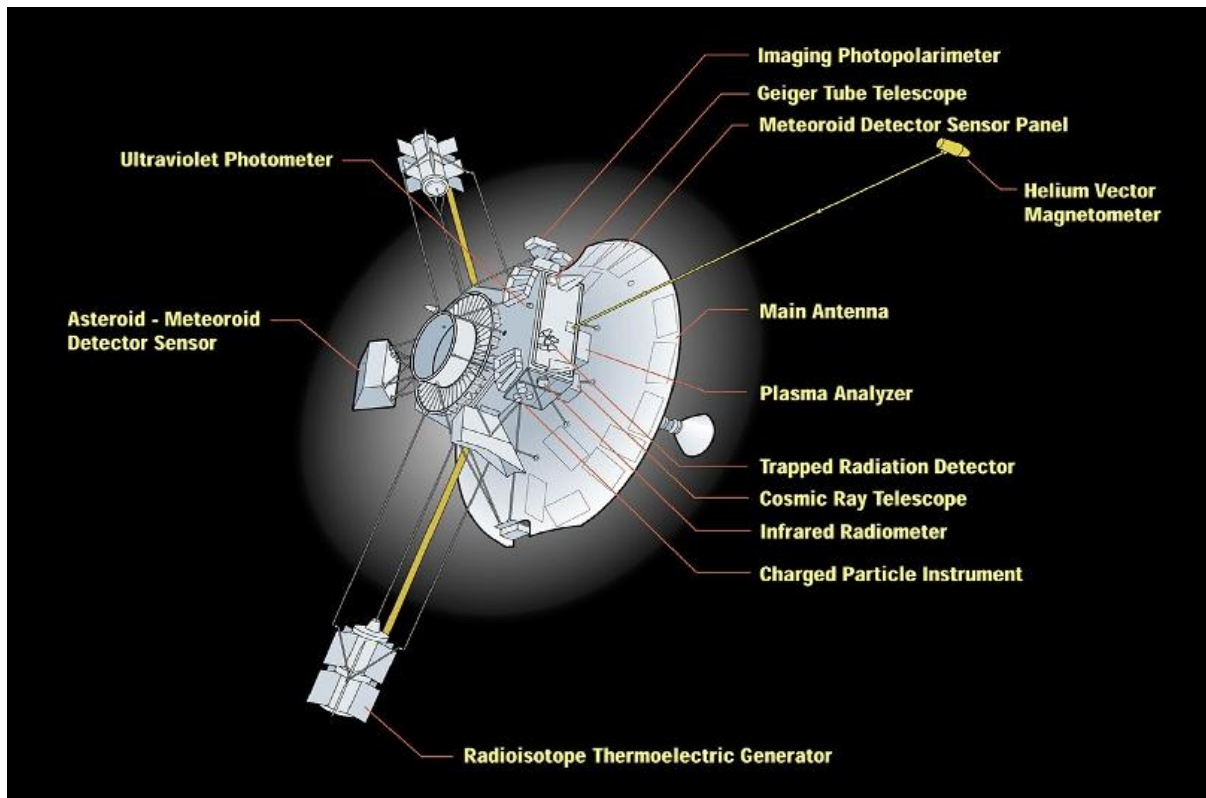


Figure 4: Sketch of Pioneer Spacecraft showing instruments. [\[Attribution\]](#)

Pioneers 10 and 11 (from 1972 and 1973) were the first spacecraft to go past Mars. They travelled on to the outer solar system. Pioneer 10 was the first spacecraft to traverse the asteroid belt and fly by Jupiter. Pioneer 11 was the first probe to do a flyby of Saturn. Pioneer 11's mission ended in 1995. Pioneer 10 sent its last signal to Earth in 2003. These were the last interplanetary spacecraft to have no proper computer. They did have some memory though, and a digital state machine or sequencer controlled by ground commands.

4) Using Decibels

Decibels (dB) are used throughout radio engineering and telecommunications. They are used for some basic radio engineering calculation examples in this article. The decibel expresses a ratio on a logarithmic scale, simplifying calculations involving larger or smaller numbers. When adding two logarithmic numbers the result is multiplication. When multiplying a logarithmic number the result is “power of n”. Dividing is “root of n”.

The logarithm used is base 10, and the decibel is always a power ratio unless otherwise stated.

Basic Formulas

$$\text{dB} = 10\log_{10}(\text{ratio}) \quad [\text{using log}]$$

$$\text{ratio} = 10^{(\text{dB}/10)} \quad [\text{using antilog}]$$

Some reference units are used with dB in this article. They are:

- dBm = dB referenced to one milliwatt.
- dBW = dB referenced to one watt.
- dBi = dB referenced to an isotropic antenna gain of 1.
- dBV = dB referenced to one volt.

Amplitude vs Power

Power ratios use $10 \log_{10}$. Amplitude ratios use $20 \log_{10}$ because power is proportional to amplitude squared.

In telecommunication systems, amplitude-based dB values depend on impedance; power-based values do not. Thus, gains and losses use power levels unless the input and output impedances are specified and defined properly.

Examples

- +30 dBm = 1000 mW = 1 W
- -30 dBm = 0.001 mW = 1 μ W (microwatt)
- 2:1 power ratio = +3 dB
- 1:2 power ratio = -3dB
- 2:1 amplitude ratio = 6 dB
- 1:1 ratio = 0 dB
- 20 dB + 10 dB = 30dB = 1000 times (100 x 10)
- 10 dB x 3 = 30 dB = 10^3 = 1000 times

Examples from Radio Systems

A receiver sensitivity of 1 μ V for a specified output signal to noise ratio (SNR):

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In dBV:

$$20\log_{10}(1 \times 10^{-6}) = -120 \text{ dBV}$$

If the input impedance is $50 \Omega \rightarrow -107 \text{ dBm}$.

If the input impedance is $1 \text{ M}\Omega \rightarrow -150 \text{ dBm}$.

This illustrates why amplitude-based dB values depend on impedance, while power-based values do not. Amplitudes such as dBV might be used at the input and output of an amplifier where the impedance is the same (like 50 ohms). There are situations where the input impedance is high and the output impedance is low though both are not well defined. In these cases, voltage gain (amplitude) is the desired value.



5) History of Early Radio

Early radio transmitters used a stream of sparks to generate the sharp changes in flow of charge (electric current) which emitted a broad frequency range of “hash” because the transitions between spark to no spark is very rapid. The desired band was coarsely filtered by a resonant transformer coupling to the antenna, or just the resonance of the antenna itself. This was a low coherence signal. The band selected was broad and random in phase, amplitude, and frequency. It sounded like a buzzing noise but that depended on the spark rate. The significant radio pioneers were:

- 1864 - 1873. James Clerk Maxwell wrote definitive mathematical equations for electricity based on the observations of Michael Faraday and others. He predicted that electromagnetic waves (as radio waves) existed.
- 1885. Heinrich Hertz made the first spark transmitter. It used an Induction Coil to produce high voltage sparks from a battery. The transmit antenna was a dipole using 2 x 1 meter elements, so it worked in the VHF region. The wavelength would have been around 4 meters (75 MHz). He detected and so verified James Clerk Maxwell’s predicted electromagnetic waves using wavelength, polarisation and wave interference. The receiver was a metallic loop with a tiny spark gap. The range was a few meters, just enough to get out of the near field of the antenna.
- 1880 onwards. Oliver Heaviside made significant developments on the nature of electricity through Maxwell’s equations, developing the telegrapher’s equations, inventing coaxial cable and a method of improving long cable performance by adding series inductance. He predicted the Heaviside layer in the ionosphere, which was part of the radio propagation puzzle addressed by Marconi later. Heaviside led the way to modern theoretical understanding of electricity, cables, and propagation on wires or by electromagnetic waves. Heaviside coined many electrical and electromagnetic terms like susceptance and admittance that are still used today.
- 1894. Oliver Lodge published improvements to the Hertz transmitting and receiving methods. He recognised the importance of resonance effects on wires and got an improved radio range of up to 55 meters. He used and named a “coherer” using metal filings. When a signal was received, the filings cohered or clumped together. The power required to cause “cohering” was small (0.5 mW), but the voltage was quite high, around 20 Volts. Once cohered the resistance dropped to a few hundred ohms and that could operate a sensitive relay. This was the Branly coherer. He promoted the idea of radio wave transmission being possible over a distance. He invented “syntonic” tuning which are resonant circuits using inductors and capacitors. These can increase the voltage of signals significantly as

required by coherers, as well as separate the signals for transmitters and receivers from other transmitters and receivers. Each link could be on its own “channel”. Lodge also invented spark plugs, a loudspeaker, and an electrostatic precipitator for cleaning up smoke emissions.

- 1894-1899. Jagadish Chandra Bose made a short range millimetre wave microwave link building on Oliver Lodge’s ideas. It operated up to 60 GHz (5 mm wavelength now known as V-band in the millimetre-wave spectrum). With the wavelength around 5mm it was much easier to investigate than light waves (500 nm) or medium wave radio of 500 meters. He discovered the galena crystal and mercury “coherers” (both early semiconductors) and so diode envelope detectors and demonstrated a working Terahertz link for the first time. In the process he invented waveguide and a horn antenna and had them made by a local tin smith in India. Surely this qualifies him as “the father of microwaves”. He showed these millimetre wavelengths could penetrate human bodies and fog, and measured polarization, refraction, and diffraction effects. Today these wavelengths are used in airport security scanning. Bose left his legacy for all to use, by not patenting most of his ideas.
- 1897. Marconi commercialised his radio communication ideas with short radio links across marine channels. Eventually, with improvements like the Bose detectors he established commercial transatlantic communications in the lower medium wave band (perhaps 500kHz) in 1907. The envelope detectors he used could be much more sensitive than previous metal filings coherers. That is because the detected output could be a replica of a sound wave. By connecting the detector output to a sensitive telephone earpiece. This gave a receiver sensitivity increase like 40 dB (10,000 times). Marconi’s significant achievement was demonstrating how long range over the horizon propagation of radio waves was possible, and commercially viable. He developed the idea of marine radio systems when he realised that radio communication of the time was subject to serious competition with the undersea cable network.
- 1898. Nikola Tesla made a practical demonstration of a radio controlled electric boat with spark transmitters using coherers for the receivers. It did not use any resonant circuits at the receivers though other devices he made did. He made public demonstrations of radio principles using induction coils in 1893. He enlarged on Lodge’s work by inventing and demonstrating the Tesla coil where radio frequency resonant transformers were used to step up the receiver antenna voltage and match the spark transmitter to its transmit antenna. Tesla focussed on scientific principles, including high frequency alternators for radio transmission. He had already made his reputation with AC electric motors (induction motors).

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- 1898. Braun in Germany made spark transmitters and receivers. He also made discoveries related to asymmetric conduction of certain materials in 1874. This led to point contact diodes. He also invented antennas using phased arrays for directional gain. He developed the earlier Crookes cathode ray tube which led to an early oscilloscope in 1897 and eventually better understanding of thermionic vacuum tubes which led to a much improved cathode ray tube. He also invented antennas using phased arrays for directional gain.
- 1904. Ambrose Fleming was an electrical engineer who developed the vacuum tube (thermionic valve or diode) and designed Marconi's early operational spark transmitters. These transmitters were about 10 kW.
- While Lee DeForest invented a primitive triode vacuum tube amplifier in 1906, it did not have a sufficiently hard vacuum, so performance was erratic. It had to wait for people to recognise the issue, and hard vacuum techniques to evolve towards the end of WW1.

Human operators could transmit morse code using the spark transmitter “band of noise” by sending letters as in the telegraph system. Morse code forms letters using two different symbols - a long and a short pulse. The original Morse systems wrote the character on a paper tape, hence the marks and spaces. Then they moved to sound, the clack-clack of a sounder. Early radio with metal filing coherers had relay operated sounds too. The earphones with galena crystals were suitable for AM radio and made a buzzing sound related to the spark rate when receiving a spark transmitter.

Spark Transmitters were legislated out of existence after WW2 because they caused so much interference over Radio Frequency (RF) bands. This is called spectrum pollution. The simple on-off modulation of a laser is still used in some fibre optic communications.

Radio Without Spark Transmitters

A single-frequency electrical source is a clean sine wave with stable phase and amplitude relationships. Information can be carried by modulating the amplitude, frequency, or phase of the “carrier” wave. This is the preferred way of using radio because the desired station can be received by selectively tuning the signals present using resonant filter circuits. The pathway to this was electron tubes which came of age at the end of World War 1. During the WW1 years naval vessels used “wireless receivers” with up to 100 valves. These had a small amount of gain in each stage because the triodes of that time were prone to oscillation if the gain or frequency was increased. This explained the focus on longer radio wavelengths at that time too. Oscillators and amplifiers using electron tubes with a hard vacuum allowed development of proper coherent radio systems with sine wave carriers. During the 1920s amplitude modulated (AM) broadcasts became commonplace. Edwin Armstrong demonstrated the superior superheterodyne radio in 1918 and developed the superior FM radio system in 1933. Further developments

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of radio and electronics were usually team or corporate achievements after this time.

Radio stations are usually separated as channels of different frequency. The unwanted “out of channel” interference is filtered out. Channels can be very narrow if the frequency and filter tuning is stable but narrow channels carry less information.



6) About Radio Waves

Radio waves are a form of electromagnetic radiation and can transmit power through “empty space”. They travel at the speed of light and behave like light waves, though much longer in wavelength. We use the term as if radio emissions are always waves, but they can be random and so emissions (not waves), just like light from a candle. They can still be random but filtered to a particular band of wavelengths like a sunlight through red or green glass. Radio waves are like light from a laser. That is a coherent beam. This is explained later.

About Electricity

An understanding of electricity helps with the explanation of radio waves which are a manifestation of electricity. Electricity is a form of energy associated with a flow of electric charge. The energy travels in the fields. Electric charges can be positive or negative in polarity. Like charges repel each other, while unlike charges attract each other. An electric field forms between charges. If two wires connect to a battery, there will be an electric field between the wires, and a force appears between the wires. This is the same force that holds matter together. It is charge that makes things “stick” together. Often this force is weak, but we can pick up a piece of paper with one finger. When we touch something, it is charge that makes it feel hard and resist being deformed.

A flow of charge requires a conductor to form a path between points of differing charge, and the flow is known as electric current. When charge flows, a magnetic field forms around the conductor. Magnetic fields also have polarity. It is known as North and South poles. Similarly to electric poles, like magnetic poles repel and unlike magnetic poles attract.

Charge is associated with particles known as charge carriers. Some examples are electrons, protons or ions with an excess or a shortage of electrons in the structure of a material. Electricity is more about the movement of fields, and less about the movement of charge carriers. Even so the disturbance to charged particles when electric current is flowing causes heating. Electric current is typically supported by a metal, which has a lot of free electrons floating around in its structure. The shininess of a polished metal is due to the visible effects of electrons around the surface. Electric current can be the flow of electrons in an electron beam (a vacuum tube). In a gas or a liquid, the charge carriers can be electrons or protons but are more likely to be due to positive or negative ions. Charge can even be carried by antimatter like positrons and antiprotons.

With an insulating material, different charges can exist on the surface like clouds. They do not move readily. In a conductor the charge disperses and equalises immediately. There is a potential difference between charges, meaning an ability to move charge. If a conductor connects two charged objects, current will flow briefly until the charge is equalised.

Electricity is made useful when the difference in charge is maintained continuously so the current can flow continuously, as with a battery or a generator. Various forms of energy are used to maintain the potential difference of charge that causes electric current to flow via a conducting path known as a circuit. Thus, a mechanical generator moves a magnetic field near wires to maintain that potential difference even when charge is flowing.

A physical property of materials is the permittivity which is the ability to store energy when polarised by electric current. It is the ability of a material to act as a dielectric as in a capacitor. Dielectric materials can store more charge if they have a higher permittivity. There is a physical constant known as the permittivity of space, the minimum ability to store charge. Permittivity is important in insulators used as dielectrics like glass, plastic, ceramic, rubber and dry air or dry wood. Most insulators have different permittivity values.

“Capacitance is proportional to the area of the plates, the spacing, and the permittivity of the dielectric”.

Another physical property of materials is permeability, which is the ability of a material to store energy when magnetised by a magnetic field. Magnetic materials produce a stronger field if they have a higher permeability. However, most materials have the same permeability as space or air.

“Inductance is proportional to the number of turns, the area enclosed by the turns, the length of the coil and the permeability”.

In radio and electrical systems, the velocity of the fields moving along (around) a wire or in space depends on the materials near the wire. The magnetic field is affected by permeability, and electric field is affected by permittivity. A wire with solid plastic insulation might support a velocity of around 60% of the light speed in a vacuum. Open wires on good ceramic insulators on poles in dry air may support a velocity more like 99% of light in a vacuum. In the DSN, cable insulation degrades slightly over time, changing the dielectric effect of the insulation slightly and so the velocity of charge traveling along a cable. This needs to be compensated in the precision ranging system.

Most materials have the same magnetic permeability as space, so this effect can often be ignored. The magnetic permeability has been used to increase the range and signalling speed of long cables, by adding ferro-magnetic materials around the wire. Search for the “telegrapher's equations” for more about that. It took about 100 years to find a full understanding and solution to losses in bandwidth with long cables. One of the expected solutions was to use radio instead of cables, but the range was thought to be the horizon (line of sight like light beams). However light waves can be refracted, reflected, and show us mirages from over the horizon. So can radio waves. Radio waves of appropriate frequency can travel well over the horizon and sometimes right around the world by reflection from the ionosphere, ducting, and refraction due to humidity gradients. Undersea coaxial cables with broader bandwidth used a magnetically permeable material (mu-metal) wrapped

around the wire. This first appeared in submarine coaxial cables in 1956, making underwater transcontinental telephone calls possible.

Generating Radio Waves

In the radio context, electromagnetic radiation arises when electric current changes. As voltage rises or falls, so does the current in a normal circuit. If the current is steady there is no radiation. The current cannot rise or fall indefinitely, so a cycling current is used that is always changing. This corresponds with alternating current electricity. The purest emission involves a single frequency only, which is represented by a sine wave. This cyclic variation causes radio emissions to behave like waves.

“Changing electric fields and magnetic fields generate each other. This allows radio emissions to continue through space and time. Waves in free space are possible because it has finite permittivity and permeability”.

An antenna is designed to radiate and capture radiation efficiently. In practice antennas are designed to work with the electric or magnetic components of the radio wave. Radiators are based on plates or dipoles for electric field components and loops for magnetic field components. Practical antennas are inherently directional.

Velocity of Radio Waves

Radio waves travel at the velocity of light in a vacuum. The presence of other materials such as air causes slight changes in velocity because of the permittivity and permeability of materials the radiation is passing through. The DSN ranging system accounts for atmosphere, including weather patterns. Even in space there are “dispersive paths” with charged particles that change the velocity enough to need consideration. Space has its own weather too, caused by solar variations.

Waveguide

While an antenna radiates electromagnetic waves into space, these waves can also travel through a waveguide, which is something like a pipe. Because of size related to wavelength, waveguides are mostly used at microwave frequencies. In practice an antenna in the correct part of the waveguide is the source, or a beam can be projected into the waveguide, often using a tapered waveguide section called a horn. Optical fibre is the same concept for light waves. Waveguides are practical sizes at microwave frequencies and work better than a cable. There are many shapes of the waveguide, such as circular, elliptical, rectangular and square. The geometry and dimensions determine the range of frequencies that can be propagated. Waveguides are dimensioned to propagate in a particular mode that is stable. Modes can involve waves travelling in spirals or other rolling motions, so mode jumps are to be avoided. Waveguide devices include some unique devices. Some involve ferrite materials. Here are some examples:

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- Circulators (3 or 4 port coupler) using magnetised ferrite. The coupling is only to the nearby port in the direction of the arrow. There are coaxial versions too.
- Isolators 2 port device (one direction) using magnetised ferrite. Used to mask reflections in waveguide systems.
- Splitters. Usually not a waveguide component. The input is split with half the power in each port and isolation between the ports. For example, a radio frequency transformer with three windings.
- Hybrid couplers, e.g. a 4 port coupler with orthogonal right angle T junctions. These sometimes rely on a balance using a termination.
- Magic Tee. Waveguide coupler with 4 ports that can produce sum and difference outputs.
- Rat-race coupler. Alternative to a magic tee suitable for strip line, using a ring with 4 ports all dimensioned for the wavelength. It can also have sum and difference ports.
- Directional coupler. A straight through path and a pickoff path for sampling a signal as it passes by. The pickoff samples the forward or the reverse direction only. There is often a termination, and there are coaxial cable versions.
- Filters. Here combs and pegs are placed carefully in a waveguide to make bandpass or band stop filters.
- Phase modulators. A ferrite in the waveguide is magnetically modulated.
- Attenuators and delay lines. Vanes and slots provide a mechanical means to adjust loss or delay.
- Transducers to convert between waveguide and coaxial cable.

In modern systems, strip line and microstrip are so called planar methods, usually constructed on flat printed circuit board. These have superseded waveguides wherever the dimensions are practical. They can be much more compact and cheaper. The K and Ka-Bands still use waveguide. During the 1970s bulky waveguide was used for S-Band and X-band.

Noise

Natural radio emissions are highly random. If a receiver translates the radio noise to a sound, this noise has a hissing sound because of the wide range of frequencies present. Much of this “random white noise” is generated by the radio receiver itself.

The DSN Era at Honeysuckle Creek

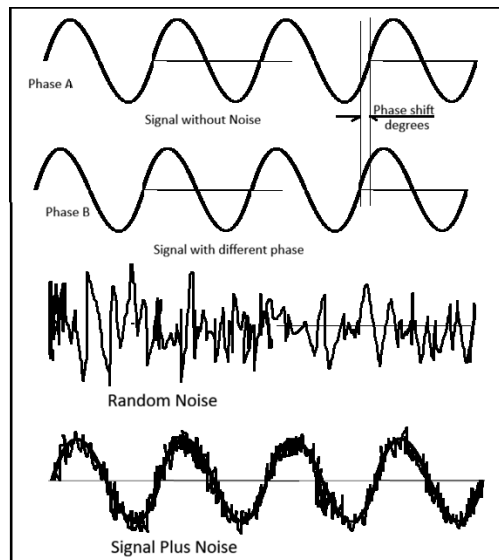


Figure 5: Signal and Noise. [\[Attribution\]](#)

The coherence of noise is extremely low. Crackling and buzzing sounds are caused by interference like lightning, electrical distribution, and electrical equipment. It is often associated with discharges or sparks. Whistles and garbled sounds come from intermodulation, like mixing of spurious signals with the desired signals. These types of interference are small at VHF and higher frequencies. Galactic noise and electrical interference including lightning are stronger at medium and high frequencies than at microwave frequencies.

The diagram above shows a sine wave at the top. Another sine wave of the same frequency but shifted in phase is shown next. This sine wave has a difference in phase around 45 degrees and a complete cycle is 360 degrees. Random noise contains a wide range of different frequencies, amplitudes and phase and is the opposite of the sine wave. The signal plus noise is how a noisy radio signal looks. In the example the signal to noise ratio is about 12 dB. This would be a noisy signal to a human ear, but speech would be just discernible. This signal to noise ratio has a low error rate with some forms of digital modulation. This SNR of 12 dB is near the working threshold with many kinds of analogue and digital modulation. As can be seen, the signal only crosses the zero region near the position of the sine wave zero crossings. With FM the threshold is more like 15dB. The error rate or intelligibility rapidly improves as the SNR increases.

Phase Coherence

Phase coherence indicates the phase difference between oscillators over time. High coherence means better stability. It has less phase drift, noise, and jitter. It is an indication of synchronization. Two aeroplane propellers are synchronised when rotating at the same speed exactly. There is no audible beat note. The relative position of the two propellers at any given instant will be the same, though they may be offset from each other. There is a phase difference between them, but this difference is constant if the coherence is high. If the rotational speed is slightly

different there is an audible beat note. This beat note in beats per second is the difference in revolutions (cycles) per second.

The image of signal and noise above shows the phase difference between two sine waves that are coherent. That is, over the period involved they are within the same cycle relative to each other (the same frequency). A phase locked loop is a feedback system that keeps the two oscillators within the same frequency. As can be seen the difference in phase is relative to the two signals and occurs because one signal is delayed from the other by an amount less than a single cycle. They are the same frequency. During tracking of a signal, the oscillator might drift outside the bounds of one cycle, especially when there are changes to the frequency that are not exactly tracked. This is called a cycle slip in the context of phase modulation. When the signal is too noisy the cycle slips increase until the signal is not useful and the loop is likely to lose lock. Note that noise is spread widely across wavebands. It involves frequency, phase, and amplitude changes, so if the carrier is highly stable (coherent), the filtering can be very narrow and the noise reduced relative to the carrier.

Coherence is essential in DSN operations, particularly for precision navigation. By minimising frequency/time jitter and drift, the carriers and subcarriers can be passed through very narrow band filters which is a form of integration (averaging) that filters out the random component (noise) near the carrier or subcarrier. Narrow band pass filters reduce the noise without reducing the signal. The bandwidth required for a digital message depends on the rate of information being transmitted. In communications there is a trade-off between noise, bandwidth, data rate, and error rate. Digital messages can be corrected by digital processing.

Information is transferred by modulating the sine wave carrier frequency. Modulation forms sidebands with a shape and spectrum around the carrier that depends on the nature of the modulation. Phase locked loops can track the residual carrier frequency despite the modulation. This is because the instantaneous frequency crosses the carrier frequency periodically, so there is a percentage of time (and so power) that the signal is at the carrier frequency.

Spacecraft could not carry high-accuracy clocks which were too heavy at that time, so the uplink is locked to a precision reference from an atomic clock on earth. The spacecraft transponder locks to the uplink and returns a coherent downlink derived from the uplink.

The noisy signal shown in the diagram has a Signal to Noise Ratio (SNR) about 4 times the amplitude. That is about 12 dB power ratio. Looking at the diagram, this noisy signal has uncertainty about exactly when the wave crosses zero amplitude, and exactly what the amplitude of the wave is. Nevertheless, this signal is reliably converted to a digital on off signal using the zero crossing to activate a switch for high or low (mark or space).

This is why noisy digital signals need a signal to noise ratio like 10 dB to be decoded simply. If the signal is only twice the amplitude of the noise, the noise itself would cross the zero line, making it seem unreliable, and a more relevant

“slicer” is needed. Noise reduction usually involves integration so that the more robust trend line due to the state of a bit is detected towards the end of the bit. If the frequency is very stable the noise can be filtered by passing the signal through a narrow band that includes the signal but hardly any noise. The filtering and demodulation are often best achieved at a lower intermediate frequency, so radio receivers often down convert the signal frequency. This is because the bandwidth is the same when shifted to a lower frequency, so a much larger ratio with the frequency. The filters and other components are simpler to construct and more precise.

Integration for Decoding Noisy Data

After demodulation, digital signals with rectangular waveforms can be decoded using integration to improve the detection of the noisy signal state (logic 0 or logic 1). In the image below the data is the rectangular shaped black line. In this case it is encoded as NRZ. It could have noise superimposed (not shown for clarity). The integration process filters the higher frequencies (noise) to some extent.

Importantly the integrator extracts a trend line, a more robust indicator of the hi or lo state. The integrator is reset at the end of each bit, so that a new integration starts at the beginning of the next bit. At the end of each bit the integrator output (green line) is sampled and time stamped to help decide whether the data is hi or lo.

This method filters some of the noise by averaging and accentuates the trend of the data over the whole bit rather than determining the instantaneous value at the centre of the bit.

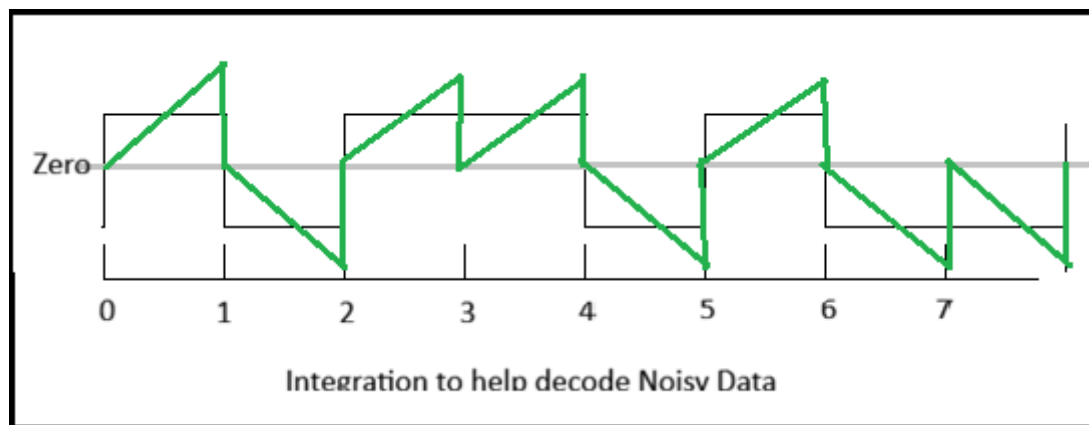


Figure 6: Decoding Noisy Data [\[Attribution\]](#)

The bit times of the data can be obtained by counting from a VCO frequency that is phase locked to the carrier/subcarrier, because the data crossings are related to the carriers in this system. The data bits are synchronised to the carrier and/or subcarrier. This system reduces errors by analogue methods but can be implemented by digital methods too.

Radio Beams and Antennas

A parabolic dish antenna is like an optical reflecting telescope, focusing power from the source into a narrow transmit beam, or capturing a cross section from a beam and focusing it onto the receiving aperture. Antennas are reciprocal, meaning they have the same characteristics for transmitting and receiving. Focusing increases the directional gain of the antenna. The total power is spread more densely in a narrow beam. Antenna gain is usually referred to a theoretical source that radiates equally in all directions, which is known as an isotropic radiator.

“Antenna gain is expressed as dBi which is the ratio with a theoretical isotropic antenna”.

Path loss calculations use steradians as a beam related to distance squared where distance is the radius of a sphere and the cross sectional area at the surface of the sphere is radius^2 . The actual beam has an area that forms a ratio with a steradian. This is due to focussing.

All real antennas have some directional effects. This can be enhanced by design which means focussing the beam. The antenna gain and the beam width are related.

“Light and radio emissions travel “forever” through space without loss unless there is absorptive material in the path”.

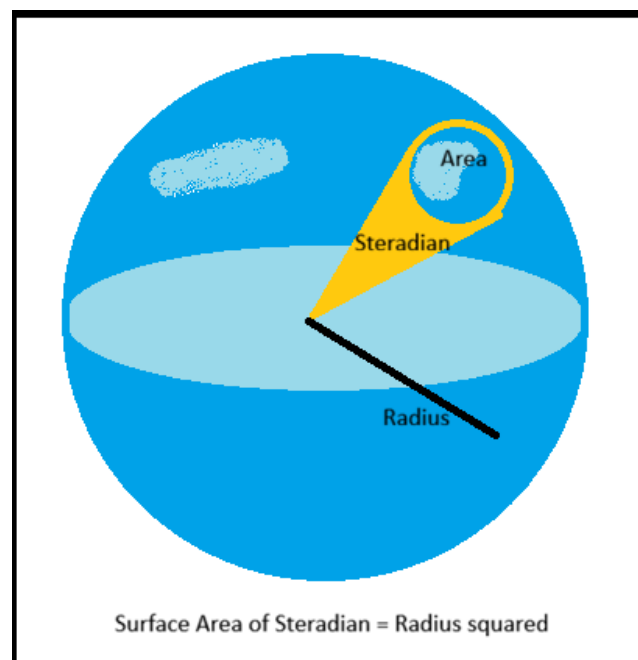


Figure 7: Steradian in a sphere [\[Attribution\]](#)

On transmitting, the power density (W/m^2) can be related to the radius with the source located in the middle of the sphere. The beam spreads with increasing distance, which accounts for the power density being reduced. The distance to the receiver is the radius of the sphere and the cross sectional area of a one steradian

beam is radius squared. A one steradian beam is equivalent to a solid geometry conical beam about 60 degrees wide. The beam is defined as having a spherical surface area of radius squared. It does not have to be a conical shape, though this is helpful to understand what is happening. There are $4 \times \pi$ steradians in a sphere. This is used in the formula for free space path loss (FSPL) for isotropic antennas:

$$\text{FSPL} = \left(\frac{4\pi d}{\lambda} \right)^2$$

Where:

FSPL = free space path loss.

d = distance between transmit and receive antennas in meters.

λ = wavelength of the signal in meters.

The power density in the beam can be found by geometry comparing the one steradian beam cross section to the actual beam cross section. Another approach is to compare the antenna gain ratio with the isotropic radiator which has 4π steradians. The precise gain can be determined by comparison with a known (calibrated) antenna like a dipole or measuring the power density in the beam. Think of a calorimeter or calibrated receiver to do that. Antennas can be characterised using field strength measurements but there are often practical issues. For example, a dish antenna performance may be determined as the side lobe performance. Formulas and dBi specifications are often used. The ability to calculate the expected power in the beam and the received power is important in radio. The antenna gain should always be verified because assembly mistakes can change everything. With phased arrays of dipoles, phase errors result in different directional response to that expected. Each dipole must be installed with the correct polarity.

On receiving, an antenna can be seen as having a capture area (effective aperture) which is its equivalent cross section that intercepts the incoming beam. The receiving antenna captures radiated power from its capture area to received electrical power with a typical efficiency of 0.55 for dish antennas. The receiver is presumed to be in the centre of the transmitted beam. If the receiving antenna is big enough, it captures all the energy radiated in the beam from the transmitter. This is rare because the size of the antennas at each end is prohibitive, but it does show there is no power lost in the transmission. The weaker received signal is all because of the directional geometry of the antenna beams.

Polarisation of the radiated signal must match between transmitter and receiver; spacecraft typically use circular polarisation because the relative motions make linear polarisation change over a pass. Nevertheless, Helios 1 and 2 had linear polarisation, which was adjusted manually during the pass at the tracking station.



7) Information Theory

According to the Shannon Theory of Channel Capacity (part of Information Theory) there is a hard limit to what errors can be recovered, which depends on average signal to noise ratio and channel bandwidth. It is based on statistics of randomness. It assumes the noise is random in the bandwidth. It does not consider effects like lightning crackle or fading which can wipe out complete sequences. It is about the noise on a tape or compact disc or long cable or radio in the UHF and microwave spectrum where thermal noise and low level crosstalk is the main contributor to errors.

About Channel Capacity

Here is Shannon's Channel Capacity formula, which provides a simple understanding of theoretical channel capacity:

$$C = B \log_2(1 + S/N)$$

Where:

C = Capacity in bits per second.

B = Bandwidth in Hz.

S/N is signal to noise ratio.

Log is log base 2.

Here is an example for a low noise telephone channel which shows the capacity with SNR = 56 dB (398107/1 ratio) and bandwidth 3 kHz (bandwidth of a 4 kHz spaced channel is 3.4 kHz).

$$C = 3000 \times \log_2(1 + 398107)$$

$$C = 56 \text{ kilobits per second (kb/s)}$$

This example shows that dial up telephone modems can achieve 56 kb/s with a quiet line. It shows that dial up modems can still achieve 6.95 kb/s with a very noisy line (SNR = 6 dB). Such a speech channel would be so noisy that it would be difficult for a human to catch any words. It does not show how to achieve this. This caused people to doubt the Shannon theorem. It was counter intuitive because it applied to digital signals, not the more familiar noisy analogue signals of radio as people knew it. People did understand that morse code (known as CW for continuous wave) was the most robust format for radio. That was because a receiver could have very narrow filters, and the human brain helped decode the remaining signal. The big step forward, apart from analogue SNR improvements, was forward error correction (FEC).

The Shannon Channel Capacity theory showed the theoretical capacity (bitrate) that could be achieved for a given bandwidth. It relates to bitrate not error rate. It applies to digital systems. Multiplexing usually allows many channels over one path but does not conserve bandwidth. It just stacks the channels side by side for example. Radio systems already used frequency separation to have many channels side by side. Frequency Division Multiplex (FDM) Carrier systems used in

telecommunications were a strong example using SSB channels stacked side by side. There were simple examples in the digital world. It just needed people to think in digital ways.

How to Improve Channel Capacity

The basic analogue improvements involve getting a stronger signal with less noise, and the narrowest possible bandwidth as the starting point. This leads to less processing and less residual errors or faster overall data. The higher the bits per symbol, the more precise the channel needs to be when considering noise, frequency response, and channel distortions like amplitude linearity, phase linearity, and group delay.

Definitions

In the context of digital communications, computing and electrical engineering, a mark and a space are states, originating in the concept from Samuel Morse where the code was written to a paper tape, so a mark state causes a mark on the paper, and a space leaves no mark. As time went on different forms of telegraph used different means to indicate the mark and space state, especially sounds. These were all intended to be used by human operators. Most people would recognise the teleprinter as the arrival of digital communications with multibit characters.

Here are some definitions to do with digital communications. They started in the context of telegraphic communications and electrical/radio engineering, then became relevant to digital communications, networking, and computing:

- A mark and a space are electrical states, originating in the original Morse concept where the code was written to a paper tape, so a mark caused a mark on the paper and when there is no mark there is a space. In the electrical sense these are represented by various means such as current/no current, forward/reverse current, and two frequencies or phases or amplitudes of a modulated carrier. Morse characters were made of longs and shorts and different spacings designed for a human interface. The combinations of long and short marks and spaces made up symbols called characters. In undersea cables the marks and spaces were wiggles on the paper tape made by a syphon recorder, a kind of oscillograph. They represented the distortions due to the cable (group delay). The telegraphic terms like mark and space and words per minute are now obsolete.
- A bit is the most basic unit of information. The name is derived from binary digit. A bit can be represented by a mark and space, 1 and 0, on/off, +/-, true/false, yes/no and other combinations. Bits can be combined to form numbers as in a digital computer or communications codes.
- A byte is made up of 8 bits. It represents the numeric values from 0-255 using binary digits. Computers are commonly organised in bytes because bytes stacked side by side correspond to larger binary numbers too.

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- A word in the computer context is the fixed width of the data path used for processing. It is to do with the architecture of the computer. Nowadays a word is usually 16, 32 or 64 bits (2, 4 or 8 bytes). The word length is qualified as “bits or bytes”, especially in specifications. In telegraphy the term for signalling speed was words per minute. This was measured using an average of 5 characters per text word. However, characters were variable length. An accurate speed of 30 words per minute was “good” for human operators.
- A symbol is “the smallest amount of data transmitted at a time”. Significantly this can contain more than one bit. While telegraph and semaphore were very much about visual or audible symbols the definition above is not in context for morse code, but for binary codes. It certainly applies to a teleprinter code where each character can be seen as a 5 bit binary number punched on a paper tape, though the code was often a group of 5 bits sent serially. This code was known as the Baudot code. Symbols are sent in a stream, with a symbol period allocated that guarantees the symbol can be read properly.
- A baud is the unit for symbol rate in symbols per second. If a symbol is one bit, the baud rate is also the bit rate.
- The bit rate is the symbol rate times the number of bits per symbol. The unit is bits per second.
- Characters use a binary number assigned to a character. In telegraphic codes for nonstandard character sets (US Morse was the standard usually), the codes for decimal digits to form a character number or code were transmitted. US Morse was the standard usually. Thus, characters like Greek, Cyrillic or Chinese. There were special code books for large character sets like Chinese. Nowadays a character code up to 4 bytes long is used for “all the characters in the world”. It is called Unicode. Telegraph systems with early teleprinters used a shorter Baudot code with 5 bits. Teleprinters with a 7 bit code were used for English/U.S. characters and named the ASCII character set. An 8 bit code could extend a character set with another 128 special characters.
- Packets, blocks, or frames consist of coded numbers and bits packed into a single block of data that is a standalone complete formatted section of a message. It is part of a message. Packets contain information in slots like Recipient and Sender address, length, type, message ID, packet ID, start and stop synchronisation and extra bits of data to help with error correction. Modern communication such as the internet uses streams of packets. Packets may be switched as they pass through routers where they are directed along the way to the recipient.

Encoding Symbols

A binary encoder allows numbers to be represented by bits. Thus 16 numbers (0 to 15) can be represented by 4 bits ($2^4 = 16$). A binary decoder allows the 4 bit code to be decoded into one of 16 numbers. The encoded signal can be sent on 4 wires (and a return wire) simultaneously. That coded entity of four bits is a symbol. Each symbol must last long enough to transmit the code. The symbol rate leads to the bit rate once the number of bits per symbol are defined. To send 16 digits without this encoding would need 16 wires (and a return). But with the encoding only 4 wires (4 bits) can send any one of 16 numbers per symbol.

How is that done with radio? What is an equivalent of “parallel wires” with encoder/decoder. The answer is to use a digital modulation scheme that can have multiple phases and/or amplitudes of the carrier. There is an extra step. A matrix of 4 phases and 4 amplitudes can be used to represent any one of 16 numbers ($4 \times 4 = 16$). These 16 numbers are equivalent to 4 bits of information ($2^4 = 16$). The symbols are streamed at a steady rate. This can be expanded in practice to about 12 bits, limited by the presence of phase and amplitude noise and channel distortions. This modulation technique is often a kind of combined amplitude (Double Sideband or DSB) and phase modulation known as Quadrature Amplitude Modulation (QAM).

“Some methods have more than two states in the digital modulation, so the bit rate is higher than the symbol rate”.

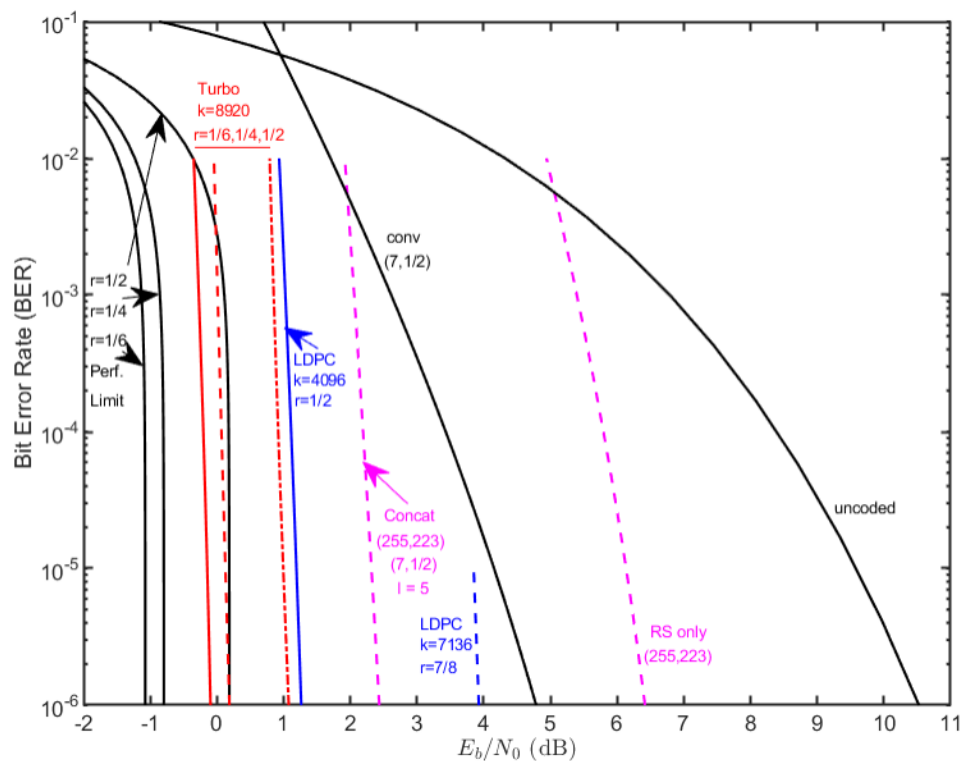


Figure 8: Forward Error Codes (FEC) Performance [\[Attribution\]](#)

This explanation shows that a channel can transmit more data than its bandwidth suggests, because each symbol can transmit many bits. It shows how to apply

Shannon's theorem. Examples of systems using this are dial up modems, ADSL and VDSL, Digital terrestrial television, and Wi-Fi. These systems may also use FDM to have many channels on one radio channel. The purpose of that is to slow the symbol rate further, so dealing with reflections. Readers can study Orthogonal Frequency Division Multiplex (OFDM) to get a deeper understanding of these systems.

There are also disk drives, compact disks, and memory. In practice, convolutional/trellis/Viterbi methods are applied so that parity bits can be used more effectively for forward error correction (FEC) at the receiving/reading end. These methods were used in the late 1970s, but trellis coding did not become widely known till the 1980s.

It was the combination of error correction and multibit symbol modulation and multiple channels that finally allowed the channel capacity to approach the Shannon theory limit. Multichannel helps deal with multipath reflections in terrestrial systems. This is because the symbol rate can be reduced so that reflections/echos are not relevant. Channel capacity improvements with modems on telephone lines started out modestly by allowing 9600 b/s with QAM modulation. This was a hard limit because of errors due to telephone line noise.

Analogue phone networks were designed around a Signal to Noise Ratio (SNR) of 45 dB which has a modest hiss and garbled crosstalk in the background. This quickly improved to 14.4 kb/s then 28.8 kb/s and eventually 56 kb/s with trellis encoding. Instead of "fixing the phone network" the digital network (internet) eventually became the carrier for telephone calls, even with mobile phones.

The diagram above shows the Bit Error Rate (BER) for various FEC methods according to E_b/N_0 . That is energy per bit versus spectral noise density. Think of that as being like "SNR per bit" or "normalised SNR". This diagram shows the DSN capability at the end of the 1970s as "conv" for convolutional + Viterbi.

The diagram above shows the effect of noise on bit errors for various encoding systems. For Binary Phase Shift Keying (BPSK) the normalized SNR should be around 11 dB to achieve 1 error in a million bits without any encoding or FEC.

Convolutional encoding with Viterbi decoding as used on Voyager gave this BER with a 5 dB normalized SNR. Turbo codes gave this BER with 0 dB normalized SNR. Modern codes (not shown) offer this performance with -10 dB normalized SNR, where the noise is 10 times stronger than the bit. Here are some points about modern FEC methods:

- In the 1970s DSN, convolutional codes + Viterbi got about 4-6 dB coding gain. That is the error rate could be maintained with 5dB more noise.
- Reed-Solomon codes add robustness but not huge gains.
- Turbo codes (1993) got within 0.5 dB of the Shannon theorem. This is seen in dial up modems working at 56 kb/s in a 3.4 kHz bandwidth as illustrated in the calculation above. It is seen that some Turbo Codes can give a BER of 1 per million with a normalized SNR of 0 dB.

- Low-density parity-check (LDPC) codes (rediscovered in the 1990s) got even closer to the Shannon limit. The decoding is different to Viterbi.
- Artificial Intelligence (AI) systems work on a different principle but can outperform other decoders.
- The AI system needs a powerful computer system. A desktop PC is too slow and lacks latency. Forward Error Correction processing using AI requires ASICs or GPUs to get 1 microsecond latency.

In the 21st century Artificial Intelligence (AI) is being used for superior error correction on long distance or high capacity systems such as fibre optic cables. There is debate about whether it exceeds the Shannon theoretical limit. In practice AI error correction still has a hard limit like the Shannon theory. It is just that modern AI systems can exploit structure in the data that classical theory treats as “random”. This structure is to do with biases in the use of bits. For example, in plain text the capitals, figures and symbols are less likely than the lower case letters. Certain characters are more frequently used. The author remembers being told 50 years ago that one day the limit to channel capacity would be computer power.

“Computer power is now the dominant factor in channel capacity”.



8) Antenna System

The Honeysuckle Creek 26-metre antenna was a Cassegrain-type microwave reflector. The main dish was 26 metres (85 feet) in diameter. Its surface consisted of individually adjustable panels aligned using laser metrology to achieve the required accuracy at S-band (≈ 2.2 GHz). At this wavelength, the antenna had:

- Beamwidth: $\sim 0.5^\circ$.
- S band Gain: ~ 52 dBi.

S-band was chosen partly for its excellent atmospheric transparency.

Antenna Mount

HSK used an X-Y mount, unlike the more common Azimuth-Elevation (Az-El) or Hour Angle/Declination mounts used elsewhere in the DSN. An X-Y mount has the two axes one above the other and at right angles.



Figure 9: Example of an XY antenna mount showing the two large gears.

[\[Attribution\]](#)

The X-Y mount avoids the zenith blind-spot (zone of confusion) problem of Azimuth-Elevation (Az-El) mounts. Near the zenith, an Az-El antenna may need to rotate almost 360° in azimuth for a slight change in pointing; the X-Y mount does not suffer from this, though it does have keyholes which are areas that it cannot reach, as do all mounts. The downside of this antenna mount is that it needs large counterweights so has a centre of gravity high above the ground. This is not ideal for shipboard mounting.

Antenna Drive System

The lower (primary) axis was driven by two 75-horsepower (56 kW) hydraulic motors, arranged in opposition to eliminate backlash. The upper axis was driven by

The DSN Era at Honeysuckle Creek

smaller motors. This provided a maximum slew rate of 3° per second, allowing rapid repositioning.

The hydraulic motors were able to operate at a slow creep rate. They had a set of pistons arranged radially with a common crankshaft. They were known as constant volume motors. The hydraulic motors were servo controlled for acceleration, speed, and position.

The antenna servo could be driven by several input sources, but during deep-space operations it was normally controlled by the antenna pointing computer, which received pre-calculated predicts. These guided the antenna smoothly across the sky as the spacecraft appeared to move in a path like the Sun.

Cassegrain Antenna

The DSN stations used a Cassegrain antenna, which is like the optical reflecting telescope of the same name. The feed is through a hole in the middle of the main reflector, with a feed cone housing waveguide and components inside. At the outer end of the feed cone is a sealed window transparent to microwave signals so the waveguide and launcher horn can be pressurised with dry nitrogen gas.



Figure 10: Showing the Antenna with Cassegrain feed system [\[Attribution\]](#)

The advantage of the sub reflector when compared to a launcher at the focal point is that the sub reflector is closer than the focal point, so a shorter quadrupod or tripod is needed. The feed point being at the focal point may not have been practical with a 26 meter antenna considering the mass of the components and the extended leverage. The hyperbolic sub reflector is mounted inside the apex of the quadrupod. It reflects the transmitted signal onto the main dish which focuses the

signal into a beam. The smaller acquisition dish is mounted at the apex but outside the quadrupod. On receiving, the signal is captured by the capture area of the main dish and reflected to the sub-reflector. It is reflected into the aperture of the horn antenna which is matched to the waveguide system.

Mono-pulse Tracking (Launch Phase Acquisition)

During launch and early mission phases, the spacecraft ephemerides were not yet precise enough for pure predictive tracking. In these cases, the antenna used mono pulse auto-tracking with the main antenna or a smaller acquisition antenna that had a wider beam. The main antenna is shown here. The dotted lines show the feed horn. The four sections of the feed horn are shown passing through to the orthogonal mode junction.

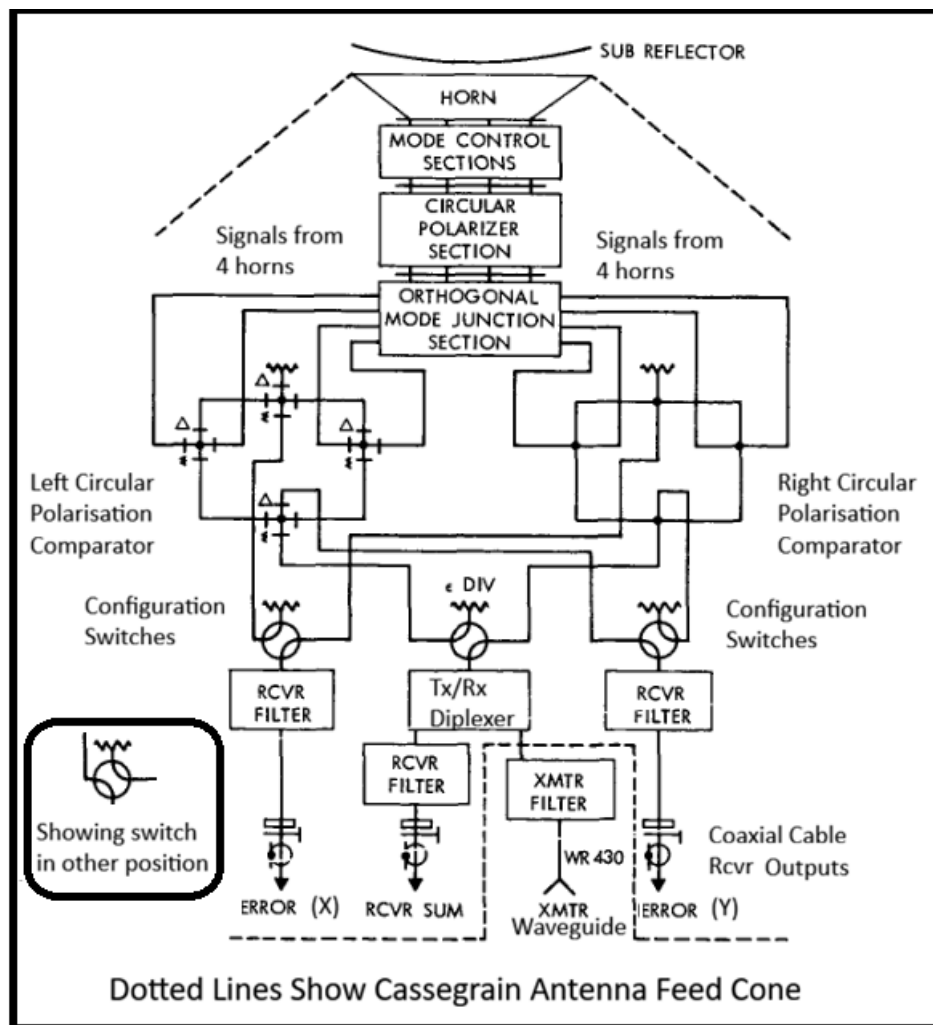


Figure 11: Antenna feed. [\[Attribution\]](#)

Referring to the diagram, this shows the main antenna and waveguide associated with the antenna feed. The captured signal is reflected from the main dish surface back to the sub reflector which focuses the received signal onto the feed horn. The horn is divided into 4 square horns. The mode and polariser sections are at the back of the horn. The orthogonal mode junctions provide the required modes. These are the source for the right and left circular comparators. They are operated

upon by the proper combination of magic-tee hybrids and transfer-switch positions to give the sum and two error channels. These are phase comparators, so the sum channel has a peak when aligned while the error channels (difference channels) have a null. The error channels drive the X and Y axes motors to align the antenna for minimal error automatically. The right or left circular polarization can be remotely selected by the switches.

The acquisition feed produced:

- A sum channel feeding the main receiver. This locks all the receivers to the carrier frequency. The other sum channel is not used.
- X and Y difference channels produced nulls when the spacecraft was centred in the beam. These are used when the antenna is in “auto-track” mode.
- Either the main antenna or the smaller acquisition antenna could be used in the Monopulse mode for auto-tracking.

This allowed the servo system to automatically steer the antenna toward the received beam from the spacecraft. The mono-pulse radar used continuous-wave (CW) signals rather than pulsed radar. The term refers to simultaneous comparison of receiver channels.

The isolation between transmit and receive is achieved by diplexer filters, waveguide, phase, and hybrids. The receive ports have >190dB isolation from the transmit frequency which is about 180 MHz lower in frequency. Transmitter spurious signals have >165dB isolation in the receiving band.

The Mono-pulse tracking could not be used with noisy signals, so it was limited to near-Earth operations. Deep-space tracking relied entirely on predictive pointing.

The low noise maser and additional switching for system temperature measurements on the sum channel were downstream of the antenna feed shown above. There was also switching for the acquisition antenna or the main antenna. The acquisition antenna had its own phase comparators.

Antenna and Pointing

A horizontally pointed antenna as in terrestrial point to point systems sees radio emissions coming from the ground which is normally in the field of view of antennas. The radiation is equivalent to an approximately 300 K (temperature) radio source. A deep-space antenna sees less than 3 K at S-band unless pointed at a star or the Sun.

The antenna position had soft limits using limit switches and the servo itself. It also had hard limits to minimise damage in a runaway situation. The operators continually monitored the antenna, but the alarm signal when the receivers dropped out as the antenna ran away helped operators to catch the antenna in time.

Pointing at the Sun must be avoided: the visible-light energy around 1000W/m^2 could damage the feed system. The power in the antenna aperture when pointed at the sun would be about 531 kW, from the 531 square meters antenna cross

The DSN Era at Honeysuckle Creek

section. Pointing the antenna near the ground could be hazardous to people, animals, and plants nearby due to the microwave radiation hazard from the transmitter. This was prevented by antenna limit switches.

The antenna pointing is controlled by an analogue servo system. This controlled the acceleration rate, speed and position of the antenna. The inputs for antenna tracking of a spacecraft were the auto track from the receivers and the pointing prediction from the computer punched tape. The operator could also select manual track ball positioning or insert computer offsets to the antenna position.



9) The USB System

The Unified S-Band (USB) system was developed for use in the manned space flight network (MSFN - Apollo) and the Deep Space Network. Development began in 1962, replacing the multiple radio systems used in Mercury and Gemini programs with a single unified microwave carrier system. The design reflects what was possible in the early 1960s. Integrated circuits hardly existed. Digital computers were rare, large, and expensive. Electronic designs were still transitioning from vacuum tubes to transistors, though transistors were certainly established where money was to be made. This was a time when transistors that operated around 2.3 GHz were not available. Around 1968 transistors capable of a few watts in this range became available.

The DSN used S-band frequencies from 2.2 to 2.3 GHz, with uplink and downlink channels separated by 180 MHz. The frequency plan allowed multiple carriers and accommodated Doppler shift. The modulation was phase-shift for ranging and used subcarriers with digital binary phase shift keying (BPSK) for telemetry and commands. While analogue FM was widely used in broadband microwave links, the USB system only used FM for slow scan analogue TV and voice during the manned missions. The DSN spacecraft had no FM.

Modulation and Spectrum

USB ranging used low modulation index phase modulation, ensuring the residual carrier remained strong enough for phase-locked loops (PLLs) to lock reliably.

“The modulation suppressed the carrier by 3 dB”.

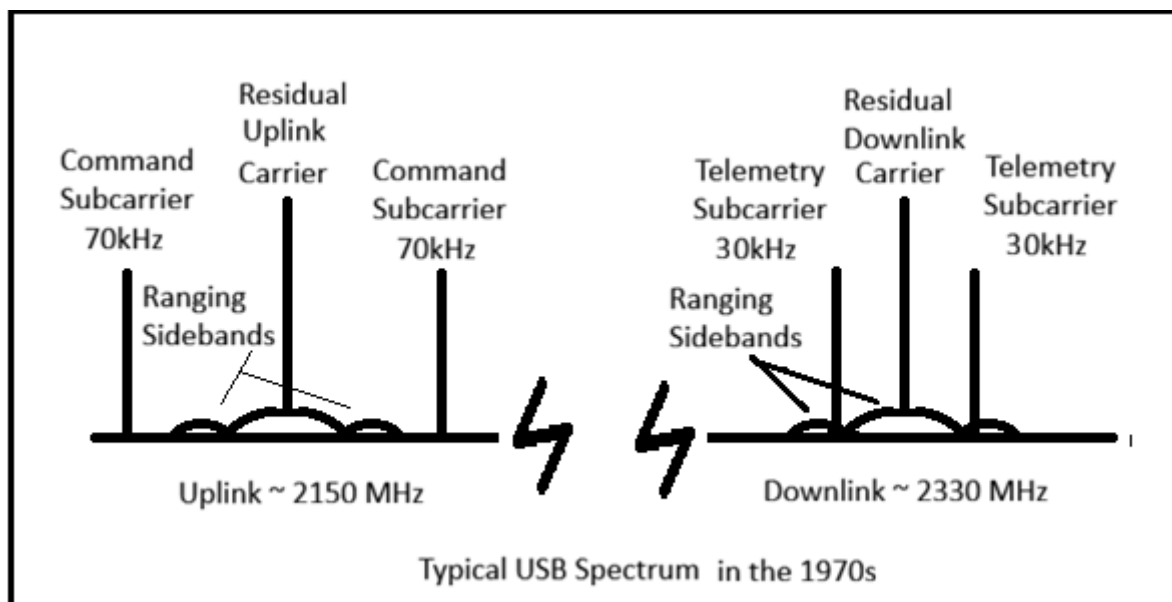


Figure 12: Possible Uplink and Downlink spectra during the 1970s. [\[Attribution\]](#)

The spectrum around the carrier can be undesirably suppressed by the modulation causing energy to disperse into sidebands. This is due to the amount of time the instantaneous frequency remains near the carrier frequency as it sweeps back and

forth. Digital commands and telemetry were placed on subcarriers, keeping their sidebands near the subcarriers and away from the carrier being tracked. This reduces the likelihood of the PLL locking to a sideband instead of the carrier or suffering excess noise leading to cycle slips.

This type of operation is called residual carrier tracking. A phase locked loop (PLL) works with this, as in the USB Block III receiver. This is the design used with weak (noisy) signals and slow data rates. The carrier part of the spectrum was deliberately avoided by using subcarriers, with only ranging being modulated directly on the carrier. The carrier residual represented about half the total received power.

During the early Voyager years, the received carrier level increased due to more transmitter power and increased antenna sizes on both the spacecraft transponder and the ground stations. A move to X band frequencies increased antenna gains due to the narrower beam. The signal to noise ratio increased, so the data rate could be increased. The sidebands of higher data rates spread right across the carrier frequency behaving like noise, but this was not a big issue. The design of Block IV receivers reflected this change in focus with stronger signals and a move towards high data rates. The residual carrier could be fully suppressed so that all the signal power was in the modulation. The Costas loop was introduced, as it can lock onto a signal without the need for a residual carrier.

Balanced Mixer

The diode mixer is a basic building block in microwave radio systems. It provides mixing at frequencies where active devices may not be suitable or available for down converting. Early Amplitude Modulation (AM) receivers used the nonlinear diode voltage-current transfer function with small signals. This was called a square law detector because the diode was biased into that region of its voltage - current transfer curve. It is an envelope detector so only works with AM. The carrier frequency must be present. With a larger signal the diode rectifies the signal so is still an envelope detector.

The diode used in early radio receivers (at the time of spark transmitters) was a primitive vacuum tube (thermionic valve) by Ambrose Fleming. It was primitive because it did not have a hard vacuum. Marconi used this in his radio system for ships (along with other detectors) as it was better than the earlier insensitive “coherer receivers”. A coherer using metal particles needed 10-20 volts of RF which caused it to switch to a low impedance state that then needed a physical tap to reset it. It could not detect modulation on signals. It detected that a radio signal was present or not.

Primitive point contact diodes were used in “crystal sets”, but the point of contact was found by the user probing the galena crystal with the wire “cat’s whisker” to find a suitable semiconducting region. It could not be considered “dependable”. These radios had no amplifiers so relied on high Q resonant circuits to increase the voltage of received signals. It also relied on large antennas and high transmitter power.

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Vacuum tubes and transistors were used as active mixer devices. Sometimes these were called product detectors because they used designs focussed on an analogue multiplier to produce “the product” of signal and local oscillator. A product detector was more likely to be made as a balanced mixer using active devices. The integrated circuit version is known as a Gilbert cell.

During WW2, a mixer diode was required for microwave radar receivers, as vacuum tube diodes could not operate at microwave frequencies.



Figure 13: Microwave point contact diode. [\[Attribution\]](#)

The example in the photo above looks just like the original 1N21 microwave mixer diode. It is a modern K band mixer diode. The metal point contact formed a kind of semiconductor junction that was like a Schottky diode and suitable for microwave frequencies. Mixers used a single diode mounted precisely in the waveguide.

This was a properly manufactured point contact diode where the point was “spot welded” onto the semiconductor material (highly purified and doped Germanium). These were the first commercial semiconductors. They led to transistor manufacturing in the 1950s. They are still used in microwave mixers where waveguide is in use.

The drawback of single diode mixers was the inability to suppress local oscillator or signal/modulation or harmonics in the output. More demanding filters were required. Single and double balanced diode mixers were developed in the 1920s using metal rectifier (copper oxide diodes) with telecommunications SSB carrier systems. With the advent of SSB systems in HF radio after WW2, balanced mixers using transformers and semiconductor diodes became popular. Microwave systems were developed using waveguide and strip line hybrid couplers to replace the transformers.

Balanced mixers/ring modulators/product detectors are useful for radio frequency analogue functions. They multiply by using diode transfer curves to approximate a logarithmic curve. Two logarithmically shaped signals are summed to multiply them. The result is $\log(x \text{ multiplied by } y)$. It is a non-linear multiply. Balanced mixers can create harmonics, mix frequencies (upper and lower sidebands), detect phase difference, and be used as an analogue inverter where the on/off modulation inverts the carrier.

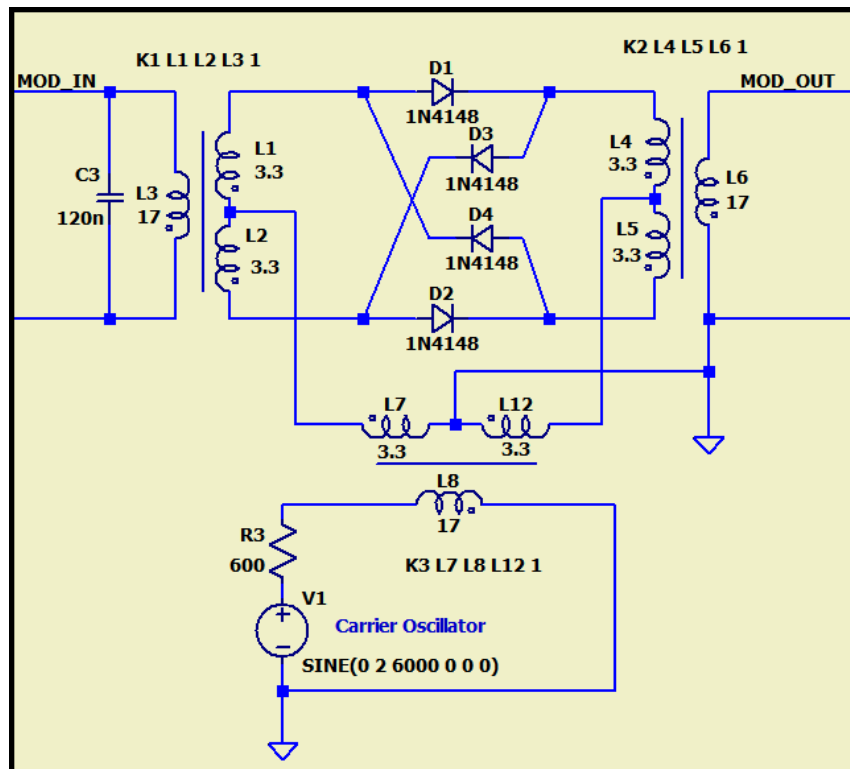


Figure 14: Double Balanced Modulator/Mixer. [\[Attribution\]](#)

The above diagram shows an LT Spice schematic of a double balanced modulator. It can suppress carrier and modulation from the output by balancing of the transformer windings. Other hybrid coupler devices based on coaxial lines, strip lines and waveguides can be used especially at microwave frequencies. Note that filters are required to select the sideband in the output and to limit the input modulation bandwidth.

Phase Locked Loop

A voltage-controlled oscillator (VCO) is locked to a reference frequency using a frequency/phase detector. The phase detector output is filtered using the loop filter and used as a feedback control signal to phase lock the VCO to the desired frequency.

The filtered control signal was like DC when the loop was in lock. When not in lock it is a beat frequency between the VCO and the reference. This sweeps the VCO and helps find the lock frequency. The phase detector was usually a product detector, which is an analogue multiplier. It could be a diode modulator as used for frequency mixing and amplitude modulation, or a Gilbert cell which is usually an integrated circuit with a balanced analogue multiplier intended as an AM modulator or a frequency mixer.

Functionally these analogue multipliers multiply one signal by another, which results in frequency mixing at the output ports, with harmonics, and amplitude modulation. Thus, reference frequency multiplied by the carrier at the same

frequency = VCO control signal (DC like). When the two signals are in phase (that is at the exact same frequency or a harmonic or subharmonic) the output is like a DC voltage representing the phase difference. The loop filter smooths the control signal by averaging the fluctuations. It can have a narrow bandwidth to reduce random noise. Sometimes the loop filter needs a second order (derivative or anticipating) term for better performance. FM or PM can be inserted at the VCO control input.

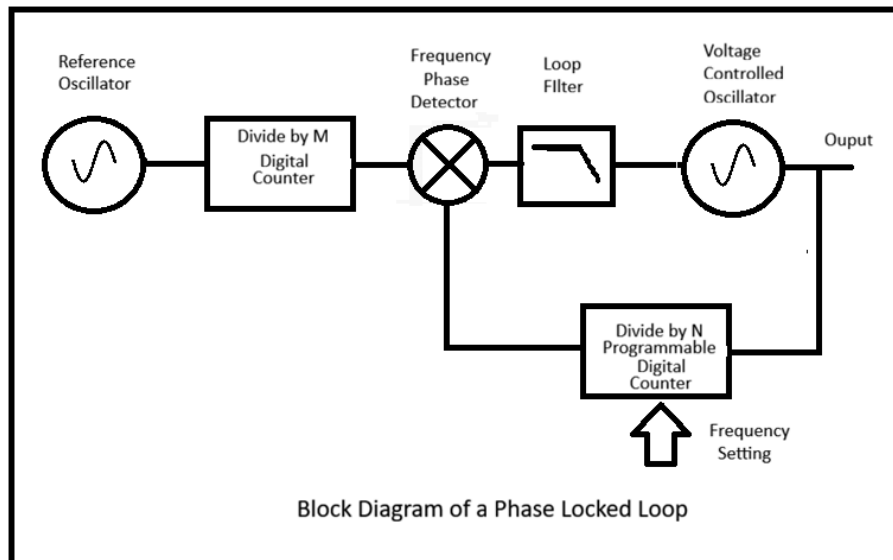


Figure 15: Block Diagram of a PLL [\[Attribution\]](#)

Programmable frequency dividers using digital counters can be inserted between the reference and the phase detector or the VCO and the phase detector. This means the VCO can operate at multiples, submultiples, or fractions of the reference frequency. The VCO output can also be multiplied or divided to get different frequencies. This is the method used for frequency synthesis using phase locked loops to lock the VCO to the reference.

The PLL above can lock to the carrier and provide the coherent local oscillator of a receiver. The IF output of the receiver is directly connected to the frequency/phase detector instead of the reference oscillator in the diagram. The dividers are not always required. However, operating the VCO at the receive local oscillator frequency was not feasible with transistors when the USB system was designed. Instead, the VCO operated at the IF frequency. It was adjusted by a push button synthesiser using the VCO as a reference, then multiplied to the required receiver local oscillator frequency using harmonic multipliers.

The phase locked loop needs a signal to noise ratio for the residual carrier of 10 dB or more to minimise cycle slips and the chance of losing lock. This is achieved by having a small loop bandwidth. A bandwidth much less than 1 Hz is possible, given the great stability of the DSN frequency references. This shows how the receiver can track the carrier at the low SNR that command and telemetry data can use.

The receiver noise level was around -173 dBm in a 1 Hz band, so the minimum tracking level was around -160dBm in this bandwidth, allowing for a 10 dB signal to

noise and the residual carrier of half the total power. It could be lower with a tighter PLL bandwidth (less than 1 Hz).

Costas Loop

A basic PLL cannot lock in the phase unless the carrier of a modulated signal is present in sufficient strength. The Costas loop can infer where the carrier of a modulated signal is despite the carrier itself being suppressed. Consider the modulation spectrum. The spectrum is the average signal amplitude at each point in frequency. The sidebands are frequency pairs equally spaced on either side of the carrier.

The Costas loop uses a VCO with two output phases. One is “In phase” and the other is in “Quadrature” (delayed by 90 degrees). Mathematically this is the sine and cosine of the VCO phase at discrete points of time. The VCO has I and Q phases. In this example the input signal is modulated as double sideband with suppressed carrier.

These VCO output phases drive two phase detectors which deliver two detected outputs that are used for VCO control signals. These represent the I and Q phases of the baseband. The phase detector I and Q outputs are multiplied and filtered to produce the VCO control signal. This multiplier outputs the non-linear product of the two baseband phases, which is the VCO control signal. It results in a +/- 0 to 1 signal pulling it towards lock in. This system can estimate the carrier frequency even when it is suppressed. There are variants, for example to provide AGC control output (amplitude of signal), or to decode distinct types of modulation, for example BPSK or QPSK. This type of loop detector was introduced with the USB Block IV receiver in the DSN.

In the diagram below the VCO is used to generate the receiver local oscillator. Demodulated output can be taken from the output of G though this depends on the requirements. In the DSS 44 era there was separate demodulators for components of the USB signal, while the Costas loop provided the carrier phase tracking for the receiver.

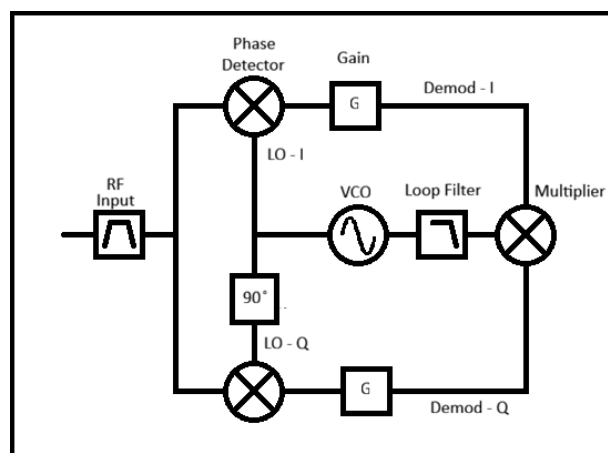


Figure 16: Costas Loop. [\[Attribution\]](#)

Modern radios use a small integrated circuit which is a radio transceiver with a lot of internal components including filters, analogue to digital converters, frequency synthesisers, a computer and multiple receivers and transmitters. The receiver is based on an I-Q mixer like the Costas loop diagram. This provides a Direct Conversion to baseband or an offset IF. Software does the filtering, the VCO and AGC control, and the demodulation. In this chip the VCO is a numerically controlled oscillator (NCO or synthesiser). This is usually a Direct Digital Synthesiser (DDS). This is the basis of mobile phone radios and could be the basis of an S-Band receiver as in the 1970s DSN. Look up the Analogue Devices ADRV9002 device. It is a 12 mm square package and costs 31.2 cents each in lots of 1000. It might cost less than a single bolt in an equipment cabinet of the 1970s.

Modulation using a phase locked loop (PLL)

Phase or frequency modulation can be introduced by injecting modulation into the control voltage of the VCO in a phase locked loop. The loop filter bandwidth must be sufficient for the modulating signal to be passed. Digital modulation typically used a subcarrier with binary phase-shift keying (BPSK). This was implemented with an analogue multiplier (product detector, e.g. a Gilbert cell) or an analogue inverting switch using transistors. The bit transitions were usually synchronised with zero crossings of the subcarrier which in turn was related to the radio carrier frequency.

Phase Modulation

With Phase Modulation (PM) the modulating signal varies the instantaneous phase of the carrier, such that the carrier maintains a constant amplitude and frequency. The modulation is represented by sidebands that are like FM sidebands. They are repeated at wider multiples in wider bandwidths. Phase modulation can be used for analogue or digital modulation. The modulation index is a dimensionless measure of how strongly a carrier is being modulated. For phase modulation it is the peak modulation in radians. A complete cycle of 360 degrees is 2 pi radians, so a radian is 57.2958 degrees.

Phase Modulator

The USB transmitter exciter used a balanced varactor diode method for quality phase modulation of the composite (baseband) phase modulation signal.

The image below shows a simplified Varactor diode phase modulator. It uses a single Varactor which is a specially designed PIN diode that is reverse biased, so it does not conduct with the modulating signal. As the bias is increased the capacitance decreases. The modulation signal and the bias voltage determine the instantaneous capacitance. The modulation is arranged so it varies the bias voltage. The capacitance in turn reacts with the impedance of the circuit that passes the carrier frequency through the modulator. This impedance can be provided by a transmission line, a resistor, or an inductor. The varying capacitance varies the phase of the carrier that is passing through the impedance. The method shown is far from ideal, because of non-linearity, and the modulating signal may

end up superimposed on the carrier too. A balanced arrangement with a pair of opposing diodes improves the performance. If a transformer or capacitor is used for coupling modulating signals the DC modulating component is lost.

A DC coupled version of a phase modulator is often called a phase shifter, because it can shift the phase and hold that state. Phase shifters are used in antenna phased arrays or interferometry. Phase shifting can also be achieved in a computer too.

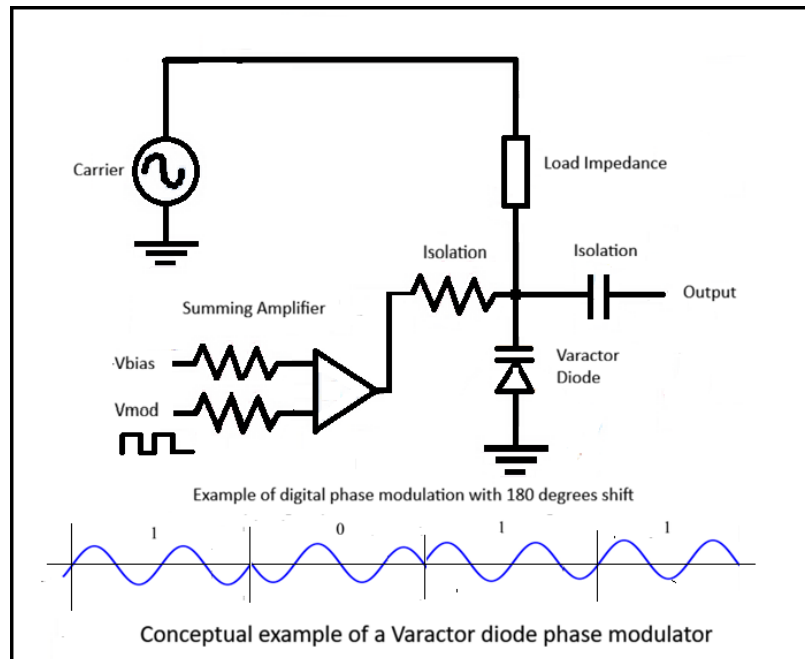


Figure 17: Varactor Diode Phase modulator. [\[Attribution\]](#)

A phase modulator or phase shifter varies the delay through the modulator circuit across the pass band of the carrier and sideband frequencies required. This varies the phase of the carrier. It is referred to a reference phase such as the carrier phase with zero modulation. The waveform of a digital signal is shown in the image. This is shifted 180 degrees as in a BPSK signal. The modulator for BPSK can be simpler as it can be a carrier polarity inverting switch driven by the binary data.

Phase Shift Demodulator

There needs to be a reference phase to demodulate phase shift modulation. This reference phase resolves the polarity of the demodulated signal, which implies the modulation is DC coupled. With analogue voice modulation the polarity hardly matters, but with digital modulation the polarity of the demodulated signal is important. In some cases, a local reference carrier phase can be used. The phase of the reference is important because it can invert the data if it does not match the demodulator needs. The length of cable might need adjustment, or the data might have a reversing switch for polarity of modulation. It is difficult to have a DC coupled phase modulation system so it is likely that the phase of the received signal can vary arbitrarily using a simple phase locked loop. It will tend to lock to the inverted or non-inverted form of the signal depending on the relative time

spent at the two phases. This means the demodulated polarity depends on the modulating data. That is why some encoding methods take the effort of adding extra bits to the data to balance the polarity. With radio the reference phase of the data or the carrier needs to be derived so that the polarity of the data is determined. One approach is to try to carry a reference with the modulated signal. The simplest method is to have the modulation “DC coupled”. Sometimes it can be “DC restored”.

“Having a proper reference carrier phase for the demodulator means the binary phases can be decoded with the correct polarity”.

There are encoding methods that allow the data to be self-clocking from which a reference polarity can be derived. Other methods can use reference levels such as start and stop bits in the data to determine the polarity. DC restoration can be used. With this, a reference point in the data is used to clamp that point in the signal to the appropriate voltage. The data stream is AC coupled, and the clamped coupling is held by the coupling capacitor until the next restoration point. Once digital techniques such as software modulators and demodulators became common the polarity was more likely DC coupled or could be determined by the software.

NRZ Line Code

Digital signals have a pre-modulation process called encoding and a post demodulation process called decoding. The line encoding is the form that the binary data takes when it is being transmitted “to the line” or modulator. It is commonly Non Return to Zero (NRZ) for BPSK. This encoding has desirable characteristics like more power per bit and half the bandwidth when compared with some other coding types. With NRZ there can still be periods around each character and/or packet where the signal returns to a known state like 0 or 1 for a periodical reference state. This means embedded start and stop periods that help the decoder to determine which polarity to use.

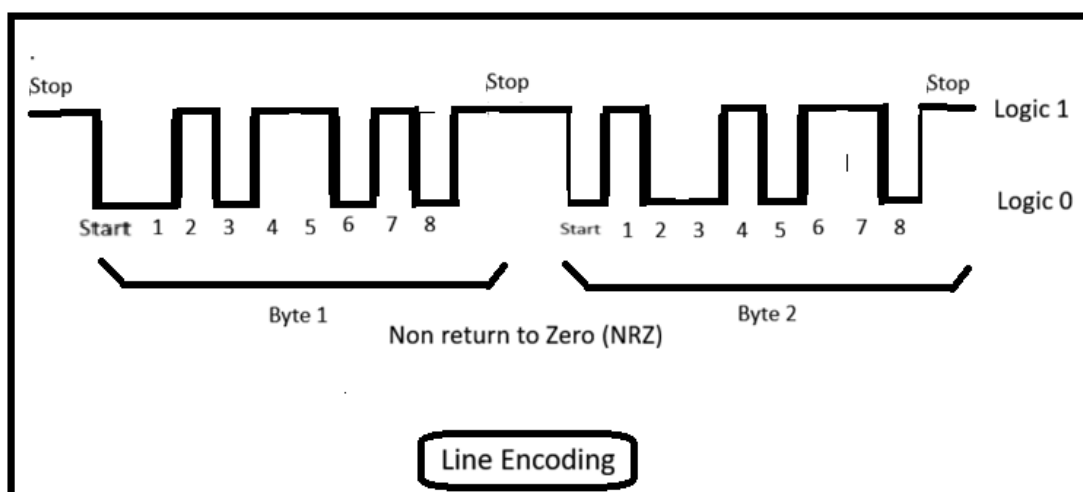


Figure 18: Line Encoding with NRZ. [\[Attribution\]](#)

Digital phase modulation was not popular before the advent of computers because of the extra complexity compared to FM.

Modern receiver systems use digitally sampled analogue receiver outputs with computer software for filtering, demodulating, decoding, processing, formatting, and forwarding data. The transmitter side uses software to create subcarriers and modulate them, with a digital to analogue converter where an analogue output is required. Direct digital synthesis (DDS) may be used inside a chip to produce I-Q phase coherent local oscillator signals. These methods can involve using I-Q modulator and demodulator hardware, but they are likely to be implemented in software.

During the 1970s, the DSN used phase modulation of the main carrier for ranging signals, and BPSK of subcarriers for telemetry and command data with NRZ line encoding. Additional encoding of the data signal allowed forward error correction. This was convolutional encoding. It involves adding extra bits according to a matrix (table), so that the bits in error can be detected and “repaired” after demodulation. The modulated subcarriers and ranging code were combined (summed) to provide the composite baseband signal passed to the phase modulator. The main loop demodulator used a PLL to track and demodulate using the residual carrier.

Forward Error Correction

The simplest idea for error correction is to determine when a character or packet is bad and request a resend. This assumes that both way communication is effective. As the DSN turnaround time is long, it could take hours for data to be recalled. It therefore needs significant storage of data sent, and a recall protocol, which was not practical with the earlier interplanetary spacecraft that had no computer. It is important to consider the type of interference or disruption to deal with. In the DSN the thermal noise from the receiver while receiving weak signals is the main cause of errors. Cross modulation and interference occurred between different components of the signal as their sidebands overlapped. With S band there is negligible fading or interference from other sources unless the beam is going past the sun. This causes multipath fading by wave interference between the direct and reflected paths. With terrestrial links multipath fading is normal but controlled by having a fade margin and planning the path clearances to minimise fading.

Viterbi decoding (of telemetry) was proposed in 1967 and used in decoding noisy convolutional coded data found in the DSN during the 1970s. Now there is a wide range of applications. These methods are used in digital networks and recording, mobile phones, modems, Wi-Fi, hard disk drives, memory devices, compact disks, satellite, digital radio and television broadcasting, and deep space data transfers. In non-AI speech recognition, the Viterbi algorithm matches the text to the sound phonemes. It is related to FEC, with both using a Hidden Markov Model (HMM).



10) Spacecraft Transponder

The spacecraft transponder received the modulated uplink carrier from the ground station and generated a clean, phase-coherent downlink. This was achieved using phase-locked loops (PLLs) in which a local voltage-controlled oscillator (VCO) was locked to the received uplink carrier.

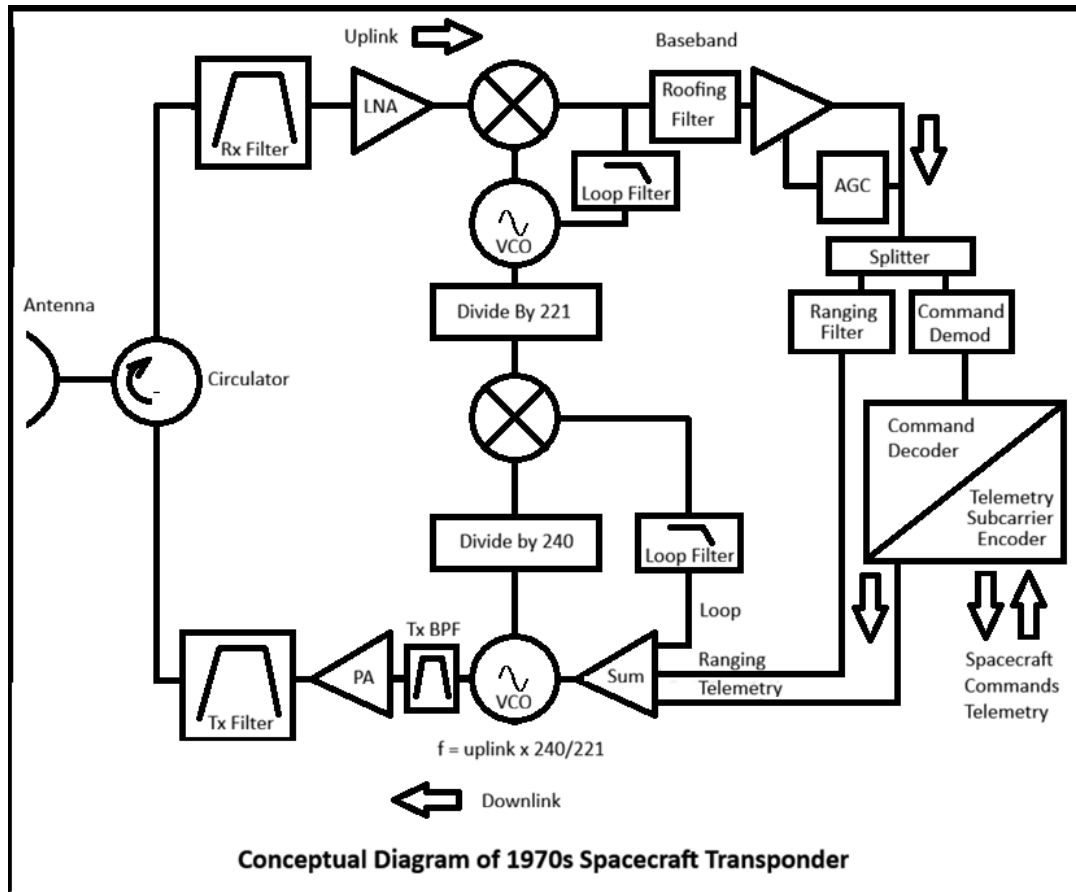


Figure 19: Conceptual Spacecraft Transponder. [\[Attribution\]](#)

The conceptual design in the diagram is simplified and does not coincide with any real transponder. The receiver VCO output was divided by 221, producing a precision reference frequency that preserved the uplink Doppler shift. This reference was then phase locked to a second VCO divided by 240, which was phase-locked to the received reference. The result was a downlink frequency that was:

- Phase coherent with the uplink.
- Shifted by the fixed ratio 240/221.
- Free of uplink noise and modulation due to the narrowband PLL. Anything more than a few Hz from the carrier is filtered out by the loop filter, so ignored.

This ratio shifted an uplink near 2.11 GHz to a downlink near 2.29 GHz, while preserving the uplink Doppler information needed for navigation.

Note that the conceptual diagram shows the Tx and Rx VCOs operating at the uplink and downlink carrier frequency. By the 1970s there were transistors such as gallium arsenide types that could do this. The receiver and transmitter are direct conversion to or from the baseband. In this diagram the ranging signal uses the “turn around” method which means the noise from the uplink receiver output is included in the demodulated ranging that modulates the downlink. The advent of pseudo noise (PN) ranging meant that the ranging signal could be “regenerated” at the spacecraft. This had some advantage because the regenerated ranging started with no noise modulating the downlink.

The signal to noise at the spacecraft receiver input was up to 30 dB better than at the ground station. This would make regeneration of the ranging and decoding of the commands much easier. Many details of the transponder such as group delay equalisers are not shown.

Signal Flow Through the Transponder

The spacecraft transponder needed to receive the uplink, then retransmit the frequency shifted version as the downlink. The downlink comes from the VCO which is modulated with the uplink ranging signal and any spacecraft telemetry data. The diagram shows a direct conversion receiver with the IF at baseband. In that era, the transponder usually had an IF with the VCO at the IF output. The VCO was multiplied to get to the local oscillator frequency rather than divided from the VCO as in this diagram.

Uplink Side

- The spacecraft received a signal typically 1000 times stronger (30 dB) than the Earth station’s received signal because of the different transmitter powers. This higher power at the spacecraft was also useful when the spacecraft was tumbling or its antenna off point or it was using its low gain antenna.
- The uplink VCO was phase locked to the carrier, which allowed the signal to be demodulated using the VCO as the “synchronous” or phase coherent local oscillator. This is called direct conversion as the local oscillator is the same frequency and coherent with the residual carrier and the signal is directly mixed to the composite baseband. The VCO provided a reference carrier frequency with no modulation, derived from the uplink.
- Uplink commands and ranging tones were extracted using filtering from the demodulated uplink baseband.

Downlink Side

- The downlink carrier was generated from the coherent VCO chain.
- The telemetry subcarrier and demodulated ranging tones were carefully phase-modulated onto the downlink carrier.

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- The ranging modulation index was kept constant by careful automatic gain control (AGC) action in the spacecraft receiver.
- Spacecraft transmitters were typically 10 W with antennas around 2 m in diameter. Voyager used 20 W and had X-band capability with a 4 m antenna. It was a large spacecraft that allowed greater data rate and range.

Coherence and Doppler Preservation

The coherent transponder architecture ensured that:

- The downlink frequency was a precise ratio of the uplink carrier.
- The uplink Doppler shift appeared on the downlink with the same fractional change as the uplink carrier.
- The downlink carrier was clean, with uplink modulation removed as it was derived from the VCO locked to the uplink residual carrier.
- Ranging tones and telemetry could be added to the downlink without disturbing the carrier used for Doppler tracking.
- This is why DSN ranging and Doppler measurements achieve precision like one meter range and one millimetre-per-second velocity.

The S-band ratio 240/221 was standard across DSN missions of the era. This shifts the uplink frequency upwards by about 180 MHz to form the downlink frequency.



11) Subsystems of the USB System

The Unified S Band (USB) system tied many subsystems together.

Uplink and Downlink

The USB system operated full duplex, which means transmitting and receiving simultaneously like a telephone call. The two directions used the same antenna. The transmit and receive signals required careful separation of the powerful uplink and the extremely weak downlink in the waveguide feed. Waveguide filters and frequency separation enabled this. In the DSN the returned signal could arrive hours after transmission.

Normally navigation uses triangulation based on any two of distance and angle of the triangle. With the DSN the angle is not as precise as needed. Instead, a combination of distance and velocity is used to first define a trajectory of the spacecraft, and secondly to determine a point on the trajectory between propulsive events that change the trajectory.

Navigation involves precision Ranging and Doppler shift to get the range rate. Range and/or range rate can also find the other parameter as they are related. The range and range rate allow the trajectory of the spacecraft to be found by plotting the position over time. The position is updated by finding the point on the trajectory that has the range and the range rate at a point in time. During the time for a range measurement the position has changed, which makes the position determination easier when using both parameters. The results in the 1970s were about 1 m ranging error and 2 mm/s velocity error at interplanetary range. It is much the same now. This accuracy is necessary to be able to conduct landings from orbit. It is also important nowadays when interferometry is used. That is the synchronisation of antennas to synthesise a much bigger antenna than can be built. On earth a practical limit is a 100 meter dish. This is due to distortions of the shape with attitude becoming excessive, especially impacting higher frequencies.

Navigation

The navigation of spacecraft uses measurements based on the range and relative velocity from earth. During these measurements, the spacecraft has moved with a rate like 50,000 km/h or more at times. That is about 14 km/s. Between propulsive events the spacecraft is on a ballistic trajectory. Software can be used to determine the state vector of the spacecraft which defines the orbit and so predicts its position on the trajectory into the future. As range and range rate can be interchanged mathematically using time, either one can be used alone, but both is more robust, along with the antenna pointing angles. Note that precision time and frequency are also needed.

The author has not been able to determine what ranging system was used by DSS 44 in the 1970s. Instead, the more likely system has been described. Modern ranging consists of both ranging systems, known as Pseudo Noise (PN) and Tone Sequential. The implementation has changed back and forth over time, but the

interested reader is referred to the modern systems in the references of this article. The modern system of choice is the tone sequential system for historical reasons.

Navigation: Ranging

DSS 44 used Tone Sequential Ranging, suitable for both near-Earth and planetary distances. Ranging measured the round-trip light time (RTLT) by carefully comparing the phase of transmitted and received tones. The tones were phase modulated on the carrier with about 1 radian of deviation to ensure the system retained a residual carrier.

A sequence of tones from 1 to 10 kHz was transmitted, one at a time. A single 1 kHz tone gives an unambiguous range of 300 km two way that is 150 km one way; combining various tones sequentially using Chinese Remainder Logic extended the unambiguous range to interplanetary distances. Significant processing gain was achieved by integration. This means narrow band filtering.

Downlink and uplink phase measurements were time-tagged using the station clock. The time of the transition at the beginning of a 1 second pulse is known as an epoch and is the time in UTC coded down to nanoseconds. It is used for the sample time of received range, transmitted range and doppler at the receiving station. The actual determination of range was done at JPL because it involved coordinating values from different stations, calibrations, and the need for a bigger mainframe computer with closer supervision.

Ranging Errors were dominated by turnaround delay calibration and group-delay ripple ($\approx 6 \text{ ns} \approx 1 \text{ m}$). Turnaround delay is the delay through the equipment, defining the point behind the antenna that represents the terminal point of the distance measured. The delay of the signal path varies with frequency. Group delay is the variation of signal delay versus frequency. It is caused by components like filters, whether in the waveguide, the antennas, the transmitter and receiver filters and the modulator demodulator. These delays are passed through delay equalisers, and the main variations are cancelled, leaving a much smaller ripple of the delay across the frequency pass band of transmitter and receiver with spacecraft transponder in the middle. Individual sections are equalised separately because measurements may be done using different combinations of ground stations.

The time tagged transmitter and receiver phase measurements were sent to JPL where the range was determined by software. As the phase measurements are comparing the phase, the transmit and receive carrier frequencies need to be the same. This is achieved by adding the doppler offset frequency (including the turnaround frequency ratio) to the transmit signal reference. There are corrections for the time through the station equipment and spacecraft. The ranging accuracy has been verified using a laser reflected from a spacecraft body (which involves earth orbiting satellites at closer range). The laser reflection method eliminates many errors at the shorter ranges where it can be used.

Other Ranging Systems

A pseudo noise (pseudo random) code is a digital code that looks like random noise yet can be regenerated at will. It can be generated using a shift register with appropriate feedback or a similar process in software. The pseudo noise (PN) code is phase modulated to the carrier in a comparable way to sequential ranging tones. The received code can then be compared with the transmitted code to find the precise delay that matches the transmitted sequence to the received sequence. Conceptually the two signals (one is delayed) could be recorded on separate strips of paper. Next slide one back and forth to find the delay required to match. This is what cross correlation does. The peak of correlation indicates the value of time at the matching point. Processing gain comes from the integration of the noisy PN that is received. A single long PN code is impractical. Several shorter PN codes are needed to remove ambiguity. These were unravelled by Chinese Remainder Logic as with the sequential tone method.

Note: there is conflicting information about use of PN ranging in the 1970s. This is because of different terms and changes to methods during different eras. Descriptions have ended up as a mixture of what was used at various times. There is no supporting documentation of what ranging was used at DSS 44 during the 1970s. Overall, there is the two systems, tone sequence (also called sidetone), and PN. The concepts were developed during the 1960s and first used with other systems than the USB system. They have been used with various approaches during different eras ever since. The earlier years were confined to analogue techniques and noisy narrowband signals. When digital methods became more available digital cross correlation was used for both systems. The tone sequence and PN methods converged, and both are available.

The Apollo missions used a hybrid PN ranging system with a period of sidetone added (2 bits) to increase the resolution using phase. This system is the one usually mentioned online. It was a bit of both systems. It did not use a digital computer. It had a state machine along with shift registers and a magnetic delay line. This PN method could not be extended to suit interplanetary distances though the principles are similar.

The PN technique for the DSN had to wait for development of a suitable digital computer method to determine range at planetary distances. Before DSS 44 the DSN used sequential tones with a sinewave format. This is assumed to have continued during the 1970s DSN operations. The sequential tones were a low frequency sinewave (1 kHz to 10 kHz) to suit the operation of the narrowband system during that era. Later, the tones changed from sine to square waves, for compatibility with the PN system involving digital computer operation. In the late 1970s and early 1980s, digital pseudo-noise (PN) ranging was introduced, including in-flight upgrades for Voyager.

Nowadays the preferred DSN ranging is tone sequential. This is stated to be for “historical reasons”. The square wave is being changed to sinewave again, used for lower interference with telemetry and commands. The tones start at around 1MHz

and are divided by two all the way to a few Hz. The PN system can be equivalent to the tone sequence method when using a turnaround method at the spacecraft. That is where the received codes are demodulated then remodulated to the downlink carrier of the spacecraft. The uplink noise is passed to the downlink in a turnaround system. The PN performance can be much better when using regeneration at the spacecraft. Here the PN ranging code is regenerated (without the uplink noise) before being modulated on the downlink.

The origins of tone ranging was likely a device called a tellurometer once used by surveyors, invented in South Africa, and using a sine wave frequency modulation of a microwave carrier with a transponder at the remote end. The phase of the sinewave modulation was compared with the source.

Navigation: Range Rate (Doppler)

Range-rate was measured using the Doppler shift of the received carrier. The DSN achieved precision at the level of millimetres per second. Earth rotation and astronomical motions were accounted for in processing.

A general formula for the Doppler effect in free space is:

$$f = f_0 \times \frac{c \pm v_r}{c \mp v_s}$$

where:

- f = Observed frequency
- f_0 = Emitted frequency
- c = Speed of light
- V_r = Speed of the receiver (observer)
- V_s = Speed of the transmitter (source)

Free space implies there are no effects like reflection or refraction or changes of velocity of the radio wave. This Doppler example is for a stationary transmitter with a spacecraft moving at a speed of 50,000 km/h and for simplicity using $c = 300$ million m/s or 300,000 km/s. The fastest spacecraft speed so far is 692,000 km/h which is 192km/s. This result is smaller than typical Doppler offsets because the transmitter is stationary. The rotation of the earth causes the doppler to cycle as a sine wave. Using the characteristics of this sine wave cycle various parameters can be determined.

$$f = 2300\text{MHz} \times (300 \text{ million m/s} - 1400\text{m/s}) / (300 \text{ million m/s} + 0)$$

$$f = 2300\text{MHz} \times (0.9999...)$$

$$f = 2299.289\text{MHz. or about } -10.73\text{kHz offset.}$$

If the spacecraft is moving away from the earth, the Doppler shift is positive with a one way link, or with the two way link as used by the DSN. The frequency received is lower. That is “red shift” according to the astronomical terminology.

The station receiver tracked the downlink carrier frequency using PLL techniques. This allowed the doppler to be extracted by comparison with the uplink frequency. The doppler result included uplink and downlink doppler. The doppler offset was added to a frequency of 1 MHz so that there is no zero to pass through.

Helios spacecraft occasionally relied on Doppler-only navigation when solar noise made ranging less accurate as the signal passed near the Sun. Note that range rate relates to range so range can be calculated between points in time on the known trajectory of the spacecraft.

Navigation: Antenna Pointing

Antenna pointing was continuously available and essential for reacquiring the spacecraft each day. The 26-metre antenna had a beamwidth of about 0.5° so pointing accuracy needed to be high.

A collimation tower near the station provided calibration for pointing and included a test transponder. The 24 bit shaft encoder was such a high resolution that the strain on the large steel shafts became evident. This calibration was not precise, but predictions took account of previous pointing readings.

During launches, a smaller acquisition antenna with a broader beam width was used before handing over to the main dish which could operate once predictions were established.

Digital Commands

Commands allowed uploading of schedules, parameters, and even full reprogramming of some spacecraft. They were transmitted using Binary Phase Shift Keying (BPSK) modulation of a 70 kHz subcarrier. This BPSK is a form of digital modulation where the carrier or subcarrier phase is switched between two values that represent binary data (zeroes and ones). The phase states were 0 and 180 degrees. This represents an inversion of the carrier at each digital transition.

Digital Telemetry

Telemetry was received as BPSK modulation of a telemetry subcarrier, keeping sidebands away from the residual carrier used for Doppler and ranging. The data rates would be chosen according to the link budget and the spacecraft capabilities. The data rate was quite slow at DSS 44 during Pioneer 10 and 11 missions. Typical bitrates the author remembers are 8.33 bits/s to 33 bits/s. While it seems slow today, it is still faster than the transatlantic telegraph cables were.

Spacecraft transmitted housekeeping data such as power usage and status, science instrument readings, and stored data including images. Note that Pioneer 10 and 11 spacecraft had some core memory but no proper computer or mass storage tape recorder). This information was formatted into a “telemetry signal”.

Station Clock

The USB system required a phase-coherent system with extremely stable timing. Honeysuckle Creek used a rubidium frequency standard with stability around 10^{-13} , corresponding to a drift of one second in 300 000 years. This clock produced various references like 10 MHz, the one Pulse Per Second epoch marker and a UTC time clock.

The clock was regularly checked against more absolute caesium beam or hydrogen maser standards at Tidbinbilla. This was monitored using the analogue TV broadcast signal. The time stamp of the first synch pulse received after midday was recorded at the two separate locations. Any drift would be shown as a change in the difference.

The DSN network used UTC time synchronized to within 20 microseconds using an X-band Moon-bounce link between Canberra or Madrid and the DSN master clock at Goldstone – an impressive achievement rarely needed due to the stability of the clocks. There were also physical comparisons made by transporting a portable standard clock around the world.



12) Transmitter and Exciter

The S-band uplink transmitter at Honeysuckle Creek used a high-power klystron amplifier made by Varian Associates. It could deliver up to 20 kW of RF power. Its output fed the S-band waveguide system, which included transmit/receive diplexer filters before reaching the antenna feed-horn. Combined with over 50 dB of antenna gain, this produced an extremely high power density in the uplink beam. The transmitter was normally used with 10 kW output. The klystron specifications were:

- Drive level: +25 to +30 dBm (0.3 W to 1 W)
- Saturation output: 18-20 kW
- Gain: 43-45 dB

The klystron was mounted in the equipment cabin at the rear of the antenna and cooled with distilled water produced on site to ensure low conductivity. This conductivity was tested regularly. Note that pure water does not last for long as carbon dioxide in the air dissolves in the water so that it becomes slightly acidic.

DC power for the klystron came from a Ward-Leonard Drive, a motor-generator system supplying 10-20 kV at about 3 A. The power input of the motor was considered as 66 KVA.

The klystron was driven by a precision RF exciter located in the main building with a typical output power of 0.5 watt. This power level could be achieved using a lower frequency power amplifier and varactor diode frequency multiplier chain.

Exciter

The exciter used the high-precision station clock as its reference. The uplink carrier was generated by a VCO/multiplier chain locked by a phase-locked loop (PLL). A push-button synthesizer provided the required frequency offset so that the transmitted frequency would arrive at the spacecraft at the correct value near the centre of the tuning range after accounting for Doppler shift.

Manual Sweep (“Tuning Knob”)

Operators could manually sweep the uplink frequency by ± 1 kHz using a “tuning knob”. This injected a small DC offset into the VCO control voltage, allowing the uplink to be smoothly aligned with the spacecraft’s expected receive frequency during handovers. At this stage, the carrier was a pure sinewave, with no modulation applied.

Transmitter Modulation

The ranging tones and the 70 kHz command subcarrier were summed to form the composite baseband modulation signal. This signal drove a balanced varactor phase shifter, which acted as the phase modulator.

A varactor phase modulator works by varying the capacitance of a reverse-biased varactor diode. The diode reacts with an impedance like an inductor or resistance,

altering the phase of the carrier passing through this network. The modulation index was small, ensuring the residual carrier remained strong for coherent tracking.

The modulated carrier was then multiplied to the final S-band uplink frequency before driving the klystron.

Varactor Diode Technology

Varactors act as voltage controlled capacitors. They were used in many roles:

- VCO tuning elements.
- Variable reactance in a phase modulator.
- Frequency multiplier (varactor multipliers) using nonlinear capacitance.
- Parametric amplifiers as used for the low noise amplifier (LNA) before Apollo missions. This was a “cooled” LNA in the sum receiver channel.

Varactor diodes were used in microwave systems of this era because microwave transistors were not available when the USB system was designed. Typically, a VCO or local oscillator would start as a lower frequency that was multiplied by stages to get the desired microwave frequency. A typical frequency multiplier had a nonlinear device to create harmonics. These were mostly from the second to the 7th harmonic. The desired harmonic was selected using resonant circuits with an idler circuit for improved efficiency.

Here is an example from another system of that era, not the DSN. A varactor multiplier could start with 50 W at 50 MHz and, through multiple stages and using non-linear capacitance changes, produce 0.5 W at 4 GHz. This diagram shows a Tripler with its idler resonator and bias resistor. The diode conducted briefly to charge the bias resistor.

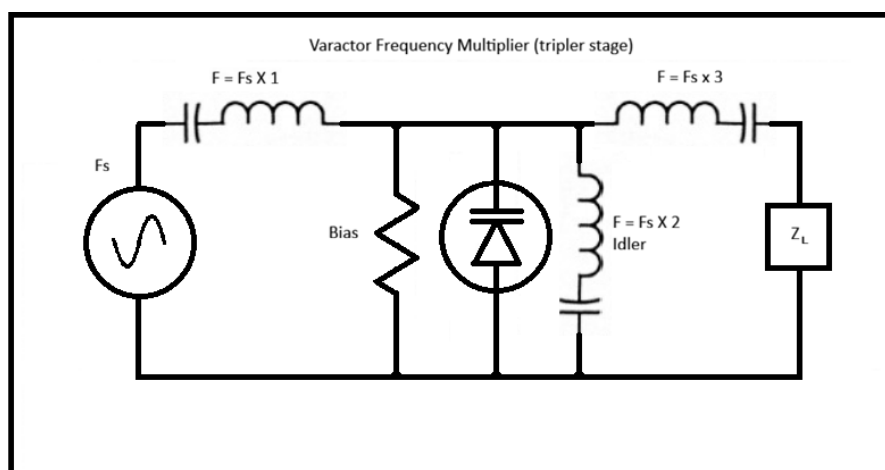


Figure 20: Varactor Multiplier Stage [\[Attribution\]](#)

These multipliers could deliver enough power at S-band to drive the transmitter Klystron with one watt to provide up to 20 kW output. Others could deliver 10 mW,

enough power for a local oscillator mixer. The design used multiple stages, each with idler circuit and matching and tuning to the desired harmonic.

The diagram above shows a typical Varactor multiplier stage. Other kinds of diodes can be used with this circuit.

Step-recovery diodes (SRD) are also used for frequency multiplication stages, exploiting their extremely fast switching transitions to generate rich harmonic content that could be filtered. Nowadays they are equivalent to varactor multipliers in efficiency and power levels. Multipliers were necessary to reach microwave frequencies with high phase purity. Both varactor diodes and SRDs are limited to smaller devices nowadays. In those earlier multiplier chains, they could have stud mounted packages for higher power levels.

The earliest S-band transistors were available in about 1968, too late for the Apollo era. The SRD was not used much at that time, though it was used in a Hewlett Packard synthesiser to generate a decade of frequencies at around 30 MHz as part of the synthesis process. The range of specialised diodes available at the time was limited but did cover the needs of that era.

Klystron Technology

Klystrons, along with cavity magnetrons and travelling wave tubes, are among the few vacuum tubes still used. They outperform semiconductors in terms of High power at microwave frequencies. The 70 m DSN dishes have a Klystron capable of more than 400kW output power at 8.4 GHz. This high power X band Klystron cannot be operated above 90 kW without special permission from civil aviation. The DSN also has Klystrons for the 32 GHz K-bands. The S band transmitters are now 80kW.

A vacuum tube transfers electrical charge as a stream of electrons in a hard vacuum. The electrons are emitted from the red hot thermionic cathode and accelerated towards the anode. A control grid between these two elements uses the input voltage to modulate the amplitude (current) of the electron stream. In this case the electrical current is carried by physical electron flow. The energy in the electron stream can be transferred to external circuits and represents a gain in the power output compared to the input. The charge does not travel at the speed of light, but at the speed of the electrons in transit. That is related to the voltage on the anode. Vacuum tubes become less useful in the VHF region above 100 MHz This is because the transit time of the electron stream becomes significant in terms of the wavelength of the signal. Phase shift occurs that leads to loss of gain or instability (parasitic oscillation). World War II was a catalyser for the development of microwave amplifiers and other components. There was a need for ever higher radio frequencies, especially for radar and navigation systems.

The Klystron is attributed to the Varian Brothers who developed it in 1937. It makes use of transit time to allow operation of vacuum tube amplifiers with high gain and high power at microwave and even beyond to Terahertz frequencies. The approach is to modulate the velocity of an electron beam instead of the amplitude

(current). This causes bunching along the electron beam which is equivalent to current variations along the beam.

The Klystron uses a thermionic cathode and a focussed electron beam, with focussing magnets to keep the beam parallel along its length which may be a meter or more in large amplifiers. This is like the electron beam in a cathode ray tube, but involves a lot more power. There are input cavity resonators (bunchers) near the cathode end, and the output cavity resonator (catcher) at the collector end. The beam passes through a grid in the cavities. The input power is coupled into the input cavity at a frequency near the resonant frequency of the cavity. Standing waves in the cavity cause voltage to appear across the grid. The resulting electric field modulates the velocity of the beam by varying the attraction of electrons in the beam. There are usually intermediate buncher resonators to increase the effect. The beam passes through a drift space where the bunching forms up. The kinetic energy in the beam is transferred to the output resonator and coupled out, usually as electromagnetic waves in a waveguide.

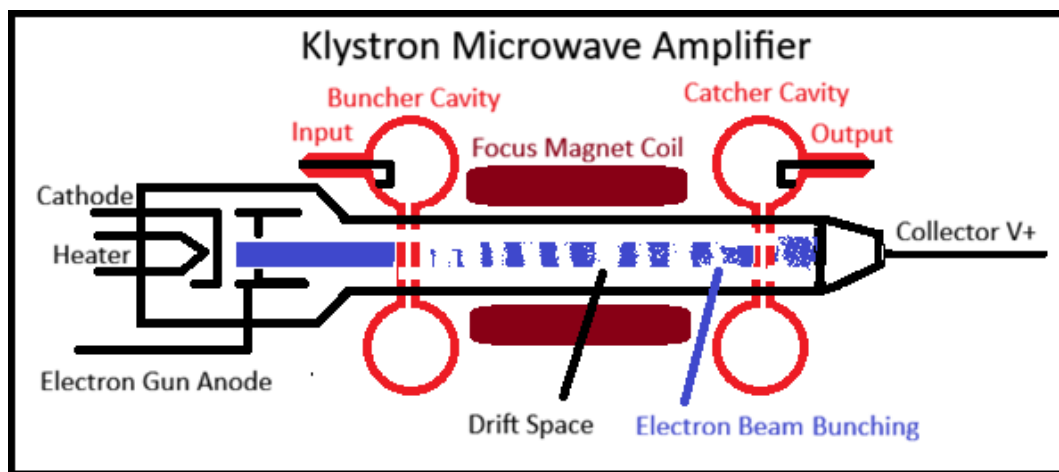


Figure 21: Klystron Power Amplifier. [\[Attribution\]](#)

The efficiency is the ratio of output radio energy to the DC energy used. It is around 30%. The collector is usually water cooled. The author remembers that staff that worked near the Klystron wore radiation badges because of the incidental X-ray radiation due to the high voltage electron beam striking the collector during the transmitter operation.

Earlier FM microwave communication systems of the 1950s used a self-oscillating reflex klystron for the receiver local oscillator, and the transmitter could be a 5 W reflex klystron using frequency modulation.



13) Receiver and Demodulators

By the mid-1970s, electronics and communications were transitioning from analogue processing to digital processing. At first there were specific digital devices built for a task, but later this processing was done with digital computers. The sophistication of digital processing increased as suitable computers became available. Software became far more useful compared to using digital hardware. Just think of following a “list of steps” or “if... then...” conditional statements. In radio engineering, this shift enabled digital modulation techniques - particularly more specialised modulation and error correction - the DSN was an early adopter.

Digital methods using computers eventually allowed:

- Improved forward error correction with the modern capability to get error rates like 1 per million bits with signal to noise around -10dB. This is reliable extraction of data from signals below the noise level. The reduction of SNR required for a given error rate like one in a million has been almost 20 dB compared to BPSK without error correction.
- Higher data throughput per unit bandwidth because of better modulation schemes with multiple bits per symbol. Multiple subcarriers can be generated using digital signal processing. Error correction also improves the data rate.
- Precision frequency setting using digital frequency synthesiser with ten digits. There has been a move towards numerically controlled oscillators as VCOs.

After the 1970s, signal processing gradually moved from analogue filters and demodulators and slicers with analogue integrators to digital algorithms running on computers. Modern systems may implement much of an exciter or receiver in a computer using mathematical expressions for modulation, demodulation, filtering, and algorithms for data decoding and formatting.

While digital computers were improving the signal processing, it was still important to extract every fraction of a dB improvement in signal to noise possible as this translates to greater range and data rate. This was achieved on earth stations and spacecraft by:

- Higher transmitter powers.
- Larger antennas for more antenna gain.
- Using higher frequencies to increase antenna gain, although there are greater atmospheric losses to consider.
- Improved waveguide layout for lower losses.
- Ultra-low noise amplifier for the receiver (Cryogenic Ruby Maser).

This pattern has repeated, though the first leap forward was due to the USB system. The single largest gains came from better and bigger spacecraft like Voyager.

The Ruby Maser

A dramatic improvement in the receiver performance came from low noise ruby masers introduced to the DSN in 1960 (1961 for S-band masers). These were cooled to liquid helium temperature which allowed the maser input noise to be referred to around 4 kelvins. The word maser comes from Microwave Amplification by Stimulation Emission of Radiation.

The reader might notice this is like a Laser which was once known as an optical maser. Masers were first discovered, then lasers (the same thing with light) were developed. At first the laser was seen as an interesting gadget, but no-one knew what to do with it. Nowadays lasers are ubiquitous while masers are exotic. Lasers are more often used as a coherent light source than an amplifier. However, lasers are used in fibre optic cables to implement communications in a comparable way to a microwave radio system with coherence, modulation, mixing and filtering.

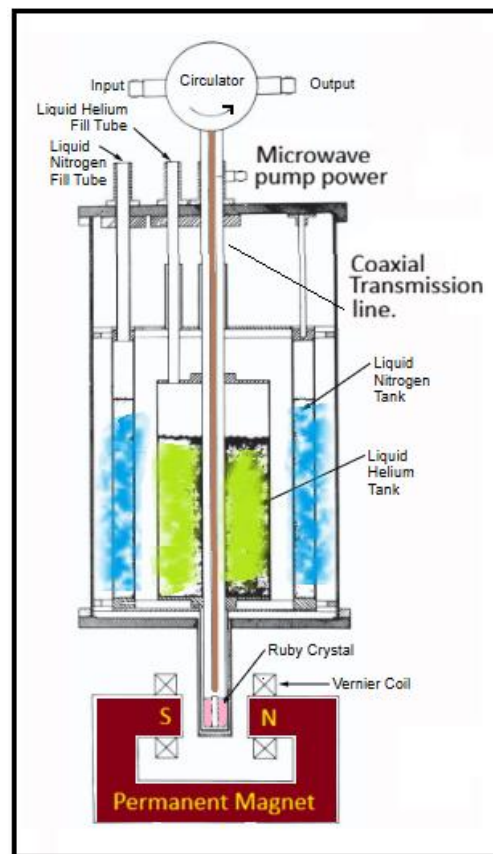


Figure 22: Diagram of Cavity Maser and Cryogenics. [\[Attribution\]](#)

In the diagram above, the input from the antenna enters the circulator and passes down the coaxial line to the ruby crystal which is a paramagnetic material and held in a magnetic field of around 0.25 Tesla. The microwave excitation also passes down the coaxial line. The output of the maser passes back up the coaxial line and through the circulator to the output.

When atoms in a material have been stimulated into an excited energy state (using a microwave source as the excitation pump), they can amplify radiation at a frequency particular to the element or molecule used as the masing medium.

Masers rely on a population inversion of the photons. The artificial ruby was selected for its suitability, compared to gaseous masers. It is a particularly low loss material. Also, it has emissions around the chosen S-band downlink frequency which may be why that frequency band (2300MHz) was chosen for the downlink.

In operation the DSN masers were not fussy devices. They did not need fiddly or regular adjustments. The cryogenics with liquid helium was more troublesome. At the chilled liquid helium temperatures there are no gases. Most materials are solid. Any contaminants block the tiny refrigeration orifice. There was a procedure to pump the system down to a high vacuum initially and purge any material inside the refrigeration pipes. Of course, leaks had to be absolutely eliminated.

The maser finds its main use as an extremely low noise amplifier, or in high precision hydrogen maser (atomic) clocks. It has characteristics not expected for electronic devices. That is because it is a photonic device. Even so it can operate with several watts of “interference” such as leakage from the transmit/receive diplexer. It is a linear device. There is no intermodulation. It is one of the magic devices of radio. It explains how the transmitter and receiver can work with a diplexer that allows interference at the transmitter frequency into the receiving port that is much stronger than the received signal. The Block III receivers used an S-band Maser known as a travelling wave maser (TWM). There are also cavity masers and reflective masers.

A typical maser has a gain like 45 dB. The carrier/noise density threshold is around -173 dBm. It starts to reach saturation with around -80 dBm input. As the input signal level increases further, the gain gradually reduces until it becomes an attenuator. It is powered by a small Klystron in the X band range. There is also a permanent magnet with coils to adjust the magnetic field slightly.

Modern DSN receivers now use the High Electron Mobility Transistor (HEMT) for low noise front ends, replacing the ruby masers of the 1970s. HEMTs use wave heterostructure semiconductor layers with different band gaps, achieving lower noise figures with less cost and space than a Maser. The HEMT also allows greater frequency flexibility.

Tuning and Intermediate Frequencies

During the 1970s HSK used a Block III receiver/exciter design. The receiver was a coherent PLL design based on superheterodyne principles. It had a first and second IF. This allowed the output to be at frequencies where better phase detectors and analogue filters could operate. The receiver's first local oscillator was generated by a synthesizer in the 24 MHz range, referenced to the PLL VCO at 10 MHz when in lock. This synthesizer output was multiplied by 3, then by 32, producing a first LO at the 2.304 GHz range.

This yielded:

- First Intermediate Frequency (IF): 50 MHz.
- Second IF: 10 MHz.

- Frequency references locked to the station clock.

The 10 MHz IF output was split to feed the filters and demodulators for telemetry, ranging, Doppler and AGC.

Receiver tuning used a predicted synthesiser frequency to offset the local oscillator (LO), placing the downlink carrier, including Doppler shift, within the PLL capture range. As Doppler changed during a pass, the PLL tracked the carrier by using the tracking VCO as the synthesiser reference. The synthesiser output was then multiplied up to the first LO frequency to maintain phase lock.

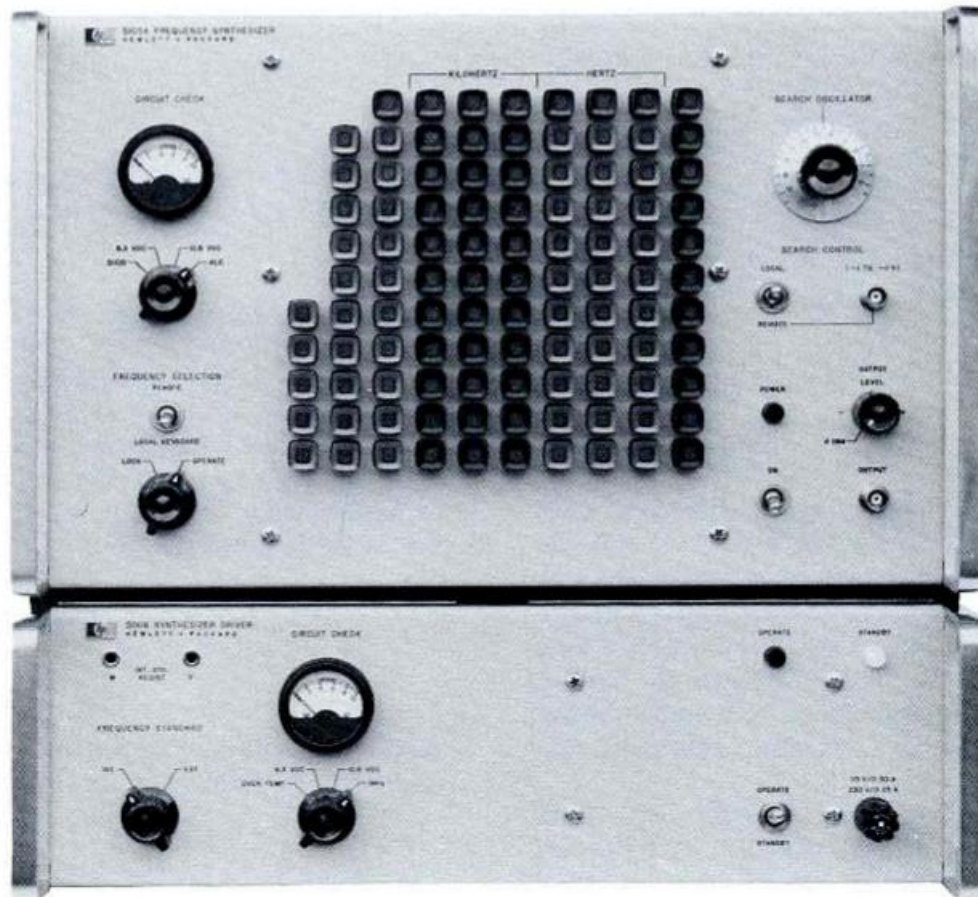


Figure 23: HP 5105B-5110B Frequency Synthesiser and driver. [\[Attribution\]](#)

The photo of a synthesiser above which is almost identical in appearance to the Hewlett Packard 5100A - 5110A frequency synthesiser that was used. This frequency synthesiser family did not use a phase locked loop (PLL) method. It is a direct synthesis type of synthesiser (not to be confused with a Direct Digital Synthesiser) using step recovery diodes to generate a signal with many harmonics. The different frequencies to form a decade of reference frequencies are picked out with synchronous filters. The synthesiser uses multiply, mix, filter, divide and sum to provide a decade of frequencies ranged around 30 MHz from the reference. The pushbuttons select a frequency from this reference decade for each decade using a diode switching matrix. The selected frequencies from the reference decade are scaled in frequency to suit the 10 decades. The selected frequencies in each

decade are then combined to a single frequency around 300 MHz. This is then converted to the required range of zero to 49 999 999.99 Hz (50 MHz) as in the HP 5100A model that was used. The lower enclosure in the photo is the 5110 A or B synthesiser driver. It starts with an external reference frequency to produce several common frequencies used by the synthesiser. It can drive several synthesisers at once.

Automatic Gain Control (AGC)

The AGC system maintained a constant IF output level despite variations in received signal power. This was essential because DSN ranging and Doppler measurements required extraordinary precision.

A small amplitude change could produce a significant phase error:

- A change in amplitude of 1 % $\approx$ 0.01 radians (0.57°).
- For a 1 kHz ranging tone, 0.01 radians $\approx$ 1.6 μ s.
- The time difference of 1.6 μ s corresponds to 480 m of range error.

To keep range error below 1 m, amplitude stability would need to be about 0.00017 dB – far beyond what AGC alone can provide.

Thus, DSN receivers relied on:

- Extremely stable IF amplifiers.
- Temperature-controlled IF stages.
- Highly linear AGC detectors.
- Narrowband tone-extraction filters.

The AGC system served several functions:

- Hold the IF output constant.
- Prevent slow amplitude modulation from contaminating ranging tones.
- Keep PLL detectors in their linear region.
- Keep telemetry demodulators within input range.
- Provide accurate RF input level readings.

The IF output level was very stable. The AGC system used the tracking VCO shifted by 90 degrees to demodulate the signal level accurately using a phase detector. The AGC provided an output representing the received signal level in dBm. This was used for monitoring the station operation.

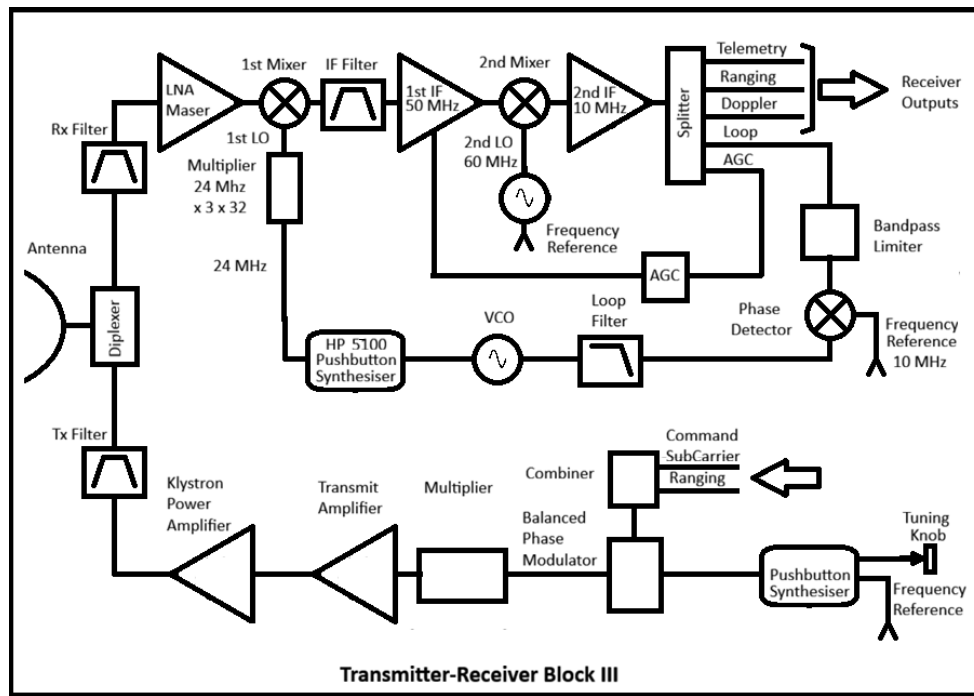


Figure 24: Block III transmitter/Receiver. [\[Attribution\]](#)

Receiver Front End and Maser Performance

A system temperature of 32 K corresponds to ~0.5 dB of effective loss at room temperature. This loss came from:

- Waveguide components.
- The waveguide changeover switches.
- Diplexer filters.
- Magic-T hybrid couplers.

The low-noise amplifier was a **ruby maser**, pumped by a small X-band klystron:

- Gain: ~45 dB.
- Noise temperature: ~4 K.
- Cryogenic cooling:
 - First stage: 3.5 kW compressor
 - Final stage: 75 mW of heat flow (cooling) to keep the ruby at 4 K.

This Maser gain ensured that mixer noise was negligible compared to the amplified Low Noise Amplifier and sky noise.

Modern DSN systems use cryogenic HEMTs, slightly outperforming masers, and supporting today's multiband and cross-band systems. A HEMT is a more ideal type of transistor (MOSFET) with two different bandgap materials, e.g. germanium and silicon. This allows switching speed in the picosecond range and operation at millimetre wavelengths. Modern DSN system design targets improvements of signal

to noise ratio in the realm of 0.1dB, which would be irrelevant to most terrestrial radio systems.

Demodulators

A single carrier to or from the spacecraft contained several types of modulation simultaneously:

- Residual carrier used for locking to and tracking the frequency and Doppler shift. The small amount of modulation around the carrier is ignored by the narrow band phased lock loop. The spectrum around the carrier is diminished when modulation causes energy near the carrier frequency to be dispersed at other frequencies called side bands, which carry the information.
- Telemetry subcarrier. From the spacecraft. Typically, a subcarrier above 10kHz and around 30kHz to avoid ranging tones. It had BPSK modulation depending on the rate.
- Command subcarrier. Typically sent as BPSK of a 70 kHz subcarrier, used by the spacecraft.
- Ranging tones. Between 1kHz and 10 kHz, phase modulated on the baseband.

The receiver's intermediate frequency (IF) output was split into multiple paths, each feeding a dedicated demodulator designed for the specific function. The demodulation process first requires that the VCO be locked to the residual carrier at the IF output. This provides the frequency reference for the synthesiser which is set to the predicted Doppler offset. The synthesiser output frequency is multiplied up to the First LO frequency. The residual carrier will end up at 10MHz. The demodulated analogue outputs were digitised and transferred to the digital processes of station computers. The basic processing only involved time tags and formatting of the data for recording and sending to JPL in the USA, where data could be decoded.



14) Station Computers

The station computers were minicomputers, the first class of computers to become widely used in industrial, academic, and medium-scale business environments. When HSK was reconfigured for DSN operations in late 1974, these systems replaced the earlier MSFN-era Univac computers used during Apollo.

“The HSK station computers were known as minicomputers... HSK was re-configured for the DSN role around late 1974”.

About Modcomp Computers

Most of the station computers were Modcomp II minicomputers with 16 bit data bus and 64 kilobytes of ferrite core memory (RAM) which was expandable to about 128 kilobytes. They had a CPU clock around 20 MHz, faster than the later desk top PCs. The CPU had some pipelining and a proper interrupt architecture with priorities for low latency. It was intended for real time operations. The fast response time was important for time stamping the telemetry and navigation data.



Figure 25: Modcomp II minicomputer. The keys allow a short bootstrap or test program to be entered into memory manually. [\[Attribution\]](#)

Minicomputers were physically large by modern standards, typically rack-mounted in cabinets with substantial 5-volt power supplies and ferrite-core memories of around 100 kilobytes (kB). CPUs were built on large circuit boards populated with TTL medium-scale integration (MSI) chips; each chip contained a few logic gates or

a counter or latch typically. The other side of the Modcomp circuit board was a maze of wires using wire wrap techniques instead of printed circuit boards.

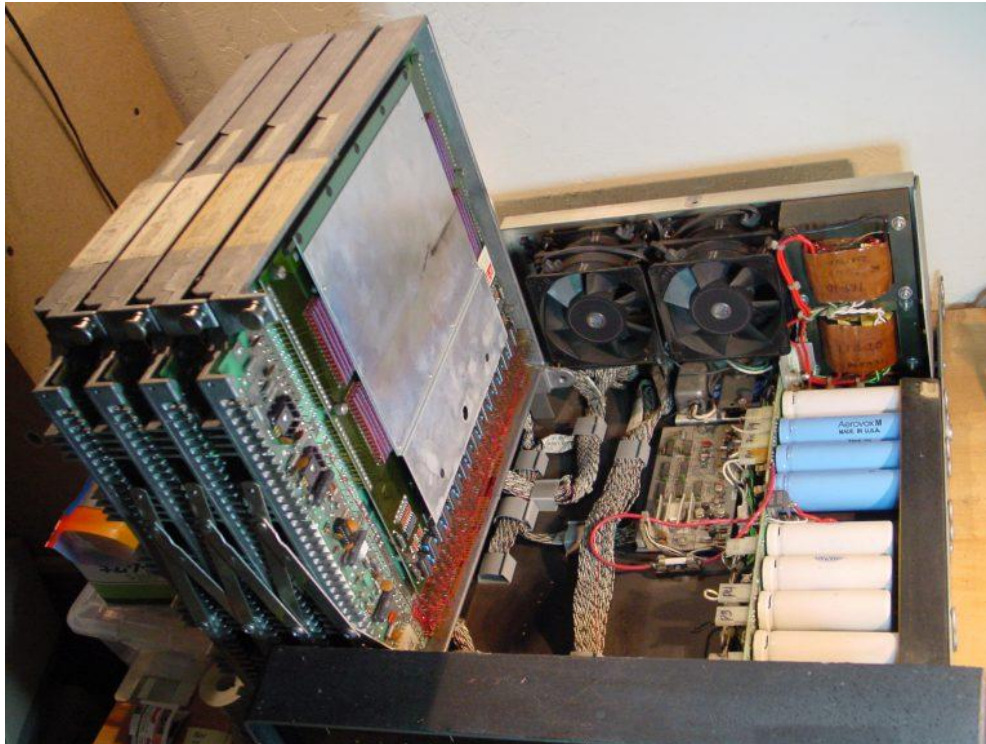


Figure 26: Inside a Modcomp II minicomputer.

[\[Attribution\]](#)

Later minicomputers used very-large-scale integration (VLSI), reducing the CPU to a few chips, and eventually to a single chip (system on a chip). Programs were written in assembly language for efficiency and loaded into the memory from punched tape using high-speed optical readers or teleprinter tape readers. The Mylar tape used was more rugged than a paper tape.

Minicomputers had no firmware, but a bootstrap loader was keyed in by the operator after switch-on. Operators and techs had collections of short programs around 20 bytes written on scraps of paper for basic things like load from paper tape or memory test or printer test.

“Programs were written in assembly language and loaded from punched tape... The user interface... was mostly a teleprinter at 110 baud”.

Operations consoles displayed key station parameters such as received signal level on early RGB colour monitors using Sony Trinitron CRTs, with ~900 characters per screen.

A more modern PIC32 embedded computer on a chip has a clock rate of 80MHz, cache, a range of onboard peripheral drivers, with similar memory size as ram and flash memory, so is equivalent to or better than the Modcomp. It costs \$10 and uses a few hundred milliwatts at maximum power. The physical size is around one cm square.

About Core Memory

Magnetic core memory was made using fine wires threaded through small toroidal ferrite cores, one core for each bit. There was a version that behaved like a ROM using the wire threading to store ones and zeros permanently. These ROMs were used in the Apollo spacecraft to store software, considering a paper tape reader was not suitable. Core memory was read and write non-volatile static RAM. They had a data wire, a sense wire and X and Y wires that accessed the address. The core itself became tiny at 0.33 mm diameter.

Current through the X or Y wires alone was not enough to change the core magnetisation. With both wires energised the magnetisation of the core at the intersection of X and Y wires was flipped. The diagonal wire at this intersection detected the state of the bit as it flipped.

If the power failed the machine state could be saved to a memory stack as the power dropped away, and the memory retained its current values. Thus, the computer could be restarted at the same point the power failed and continue. The memory access time was around 1 microsecond. This kind of memory was sensitive to temperature and voltage. However, it can be dependable, and in space applications core memory is considered resistant to ionising radiation. In space applications extra memory bits are added for parity error checking.

Spacecraft Computers

The Pioneer 10 and 11 spacecraft did not have a complete computer on board. They had a more dedicated machine that could receive and execute commands. They had some core memory, but no onboard tape recorder. Later spacecraft tracked by DSS-44 carried small computers using ferrite-core memory. These designs of the early 1970s relied on TTL logic chips for custom CPU boards.

The RCA 1802 CMOS processor is often mentioned in connection with Viking and Voyager, but this is historically unlikely. Early samples appeared in 1974, and production devices in 1976 – after the designs of Viking and Voyager were frozen.

[“While it was said that the Viking and Voyager spacecraft used the RCA 1802... the designs... were frozen before the 1802 chip was available”.](#)

The 1802 was notable for its radiation resistance, static CMOS design, low power consumption (10-15 mA at 5 V for a small system), and 8-bit data / 16-bit address architecture. It was an early example of a simple, RISC-like instruction set. The Galileo spacecraft later used several 1802 chips. The author developed a small computer and programmed and operated these in a telemetry system using HF radio.

As small computers became practical for spacecraft, missions could better store and interpret commands, format and encode digital telemetry, operate instruments, and record data on magnetic tape.

Spacecraft with computers could be reprogrammed in flight. Due to limited onboard computing capability, command sequences were generated on Earth. A lot

of Commands were sent during active parts of missions. Pioneer 10 received about 14,000 commands in 60 days during its Jupiter encounter. Other spacecraft received even more commands.

Antenna Computer

The HSK antenna used a specialised 24-bit Xerox computer, intended to match the resolution of the shaft encoders that measured antenna pointing angles.

“The antenna had a specialized 24-bit computer made by Xerox... used to measure and control the pointing angles of the antenna”.

The predictions for each pass were received via NASCOM landlines before each pass. They had antenna pointing data for five minute intervals. This computer performed continuous interpolation between “predicts”. It was essential for accurate tracking of distant spacecraft.

Telemetry and Navigation Computers

Earlier rocket telemetry used FM subcarriers demodulated and recorded on analogue magnetic tape or chart recorders. The Apollo missions used a variation of this to record analogue telemetry. As computers became available, DSN ground stations adopted minicomputers for real-time processing and storage.

HSK had up to eight x 16-bit Modcomp minicomputers with associated I/O hardware. These were housed in sixteen computer cabinets. There were two computers for each function, using hot-standby configurations for improved reliability.

“There were around sixteen Modcomp cabinets containing up to 8 x Modcomp 16-bit minicomputers...”

These machines performed several key functions:

- Real-time station control, including monitoring and display of subsystem status.
- Telemetry digitization, converting receiver analogue outputs into digital streams for recording and transmission to JPL.
- Tracking data packaging, including Doppler, range, AGC, and antenna angles.
- Command link verification, ensuring commands from JPL or local origin were valid and correctly formatted.
- NASCOM interface, handling global data exchange with JPL and the DSN Data Centre.

Two 12-bit analogue-to-digital converters digitized the demodulated analogue receiver output at sufficient sampling rate for digital processing.

The DSN Era at Honeysuckle Creek

“A pair of 12-bit Analogue to Digital Converters digitized the demodulated analogue signal...”

The digitized data preserved timing, Telemetry, Doppler and ranging in real-time. Analogue and digital magnetic tape archives and transmission to the US via NASCOM ensured that JPL could later extract telemetry using forward-error-correction techniques. Navigation was also a JPL role.



15) Receiver Sensitivity and Noise

A radio receiver cannot detect arbitrarily weak signals simply by using more gain. Thermal noise from the antenna, ground, sky, and receiver is a fundamental limit.

Information theory defines the bit-error rate achievable for a given carrier-to-noise ratio (C/N), bitrate, and energy-per-bit to noise-density ratio (E_b/N_0) or normalized SNR.

These parameters can be traded: reducing receiver bandwidth improves signal to noise ratio (SNR) by filtering out some of the noise but limits data rate because the bandwidth cannot pass enough information.

A key figure of merit in deep-space receivers is system temperature. That is, receiver noise is according to a theoretical resistor at an equivalent temperature connected to the input of an ideal amplifier. The noise parameters can be used with received power determinations to predict overall performance such as bit error rate.

At DSS-44, the typical system temperature was about 32 K, measured before each pass using a temperature calibrated waveguide resistor. This was a form pf overall verification of the receiver sensitivity.

Thermal Noise Calculations

This KTB formula is the basis of thermal noise power calculations for a resistor:

$$P_n = k_B T_n B$$

Noise power per hertz:

$$P_n/B = k_B T_n$$

Where:

- $k_B = 1.381 \times 10^{-23}$ J/K [Boltzmann Constant]
- T_n = noise temperature (K)
- B = bandwidth (Hz)

The power generated in the resistor depends on the temperature. It does not depend on the resistance. However, the voltage across the resistor does depend on the resistance and the temperature.

System Temperature Measurement (Y-Factor Method)

System temperature was measured using hot and cold loads:

- Cold load: antenna pointed at quiet sky (≈ 4 K at S-band)
- Hot load: precision resistor at ≈ 298 K, typically room temperature.

Measured receiver outputs. The measurement is a noisy signal from the receiver. A chart recorder was the display so it can match a noisy plotted line with the

average power by eye. An attenuator using switched dB ratios can be used to avoid linearity issues in the receiver and chart recorder. These are arbitrary units to obtain a ratio:

- $P_{\text{cold}} = 1$
- $P_{\text{hot}} = 9.1667$

Y-factor:

$$Y = \frac{P_{\text{hot}}}{P_{\text{cold}}} = 9.1667$$

Receiver system temperature:

$$T_{\text{rx}} = \frac{T_{\text{hot}} - YT_{\text{cold}}}{Y - 1} = 32 \text{ K}$$

“System temperature was around 32 kelvins”.

This system temperature matched the expected performance of the maser-based front end.

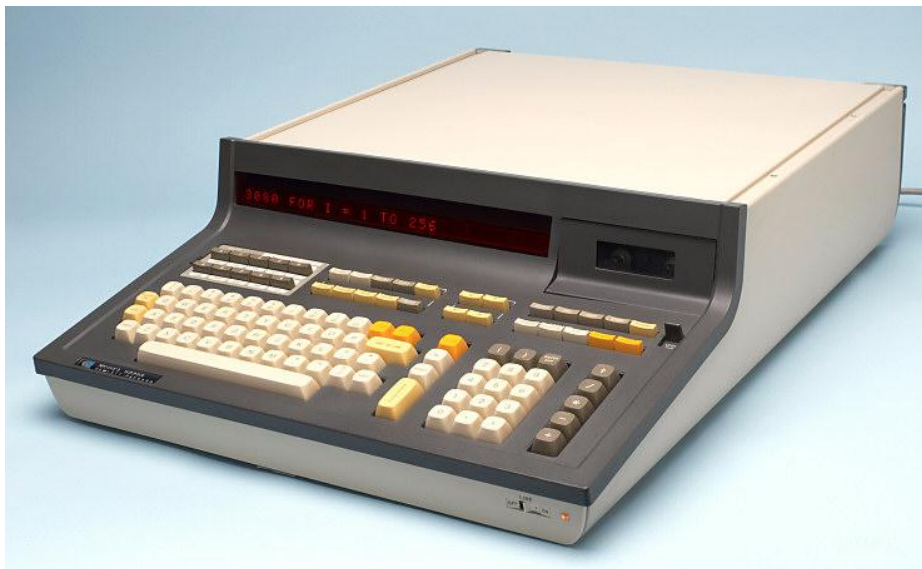


Figure 27: A HP 9830 Calculator/Computer. [\[Attribution\]](#)

The calculator shown above allowed operators to enter data to calculate system temperature using a user program stored on a magnetic card. The results were printed on a thermal printer. It had a maximum of almost 32K of ram, and was an early (expensive) desktop computer, though originally marketed as a calculator because it was felt that people would think it did not look like a computer. Technicians had their own methods like slide rules, personal nomograms and handheld HP-41C calculators before this.



16) Preparing for a Pass

During the cruise phase of a mission, a typical tracking pass began as the spacecraft rose above the eastern horizon. The station would track it for about eight hours as it moved through overhead and toward the western horizon.

Station control from the United States was directed to each DSN site individually. Operators at HSK knew little about activity at other stations unless it directly affected handovers or mission operations. There was negligible chit chat on the order wire. All was at a highly professional level.

Before tracking began, operators performed a series of checks to ensure the station was fully prepared.

Predicts and Pre-Pass Data

Before each pass, JPL sent predicted values for 5 minute intervals:

- Receiver frequency.
- Transmitter frequency.
- Expected Doppler.
- Expected AGC.
- Transmitter power.
- Expected antenna pointing angles.

These predicts were printed on a line printer for quick reference by operators.

The DSN evolved toward standardised capabilities and procedures so that client missions could rely on consistent station behaviour. Parameters such as bit rate, tracking bandwidth, transmitter power and frequencies were set according to mission requirements.

Pre-Pass Preparation

Operators loaded the required software into the station computers and selected the appropriate options. NASCOM circuits were tested to ensure reliable communication with the USA.

Facilities staff were notified that tracking was about to begin so they could ensure adequate power generation capacity.

The antenna structure was inspected for loose objects or safety issues.

Starting the Antenna and RF Systems

An operator brought the antenna system online by enabling the hydraulic power. Receiver and transmitter parameters were entered. The system temperature was measured to confirm receiver performance.

The DSN Era at Honeysuckle Creek

The motor-generator supplying power to the high-power transmitter was started. Meanwhile, the DSN controller in the USA contacted the local Operations Supervisor via the order wire to exchange readiness reports.

There was no formal checklist for routine passes that the author remembers, but daily procedures and extensive training ensured that each operator knew their responsibilities. No doubt these existed because they were brought out during critical phases like launches.

Approaching Handover

As the Earth rotated, the spacecraft gradually moved out of view of the previous station. When Goldstone (in California) approached its western horizon, HSK prepared to take over. At the end of HSK's pass, the spacecraft would be handed over to Madrid.

These handovers required precise timing, stable frequency control, and close coordination between stations.



17) Handovers

As the Earth rotates, each DSN station can view a deep-space spacecraft for around eight hours. To maintain continuous communication, the uplink and downlink must be handed over smoothly from one station to the next.

The goal was to ensure:

- No sudden phase jumps.
- No abrupt frequency changes or brief loss of signal.

These could cause the spacecraft's PLLs to lose lock. Note that the spacecraft received signal was about 30 dB (1000 times) stronger than the ground station signal.

Why Smooth Phase Matters

The spacecraft and ground-station receivers used phase-locked loops (PLLs) to track the residual carrier. A sudden phase discontinuity could cause the loop to drop lock.

If the uplink frequency arrived too far from the nominal "at rest" VCO frequency, the spacecraft's VCO control loop would be stretched, increasing the risk of losing lock or cycle slips.

The Handover Technique

The DSN developed a method to avoid phase or frequency discontinuities during station handovers. Incoming stations had to point the antenna at the spacecraft using predicts.

1. Outgoing station sweeps slowly toward the incoming station.

The outgoing station slowly tuned its uplink frequency toward the frequency that would match the incoming station transmitter as it arrived at the spacecraft. The tuning rate was extremely gentle - fractions of a hertz per second - to avoid disturbing the spacecraft's PLL unduly.

2. Frequencies chosen so both signals arrive at the spacecraft at the same frequency.

Because each station experiences a different Doppler shift, the two stations transmitted at different frequencies so that, after Doppler, the spacecraft received identical frequencies.

This required accurate predicts from JPL for Doppler offset frequency for transmitter and receiver.

3. One-second overlap

At the designated moment:

- The incoming station turned its transmitter on.

- The outgoing station turned its transmitter off.

A one-second overlap ensured continuity.

4. Incoming station recentres the uplink

Once the transfer was complete, the new station slowly tuned the uplink back toward the centre of the Doppler range to minimise tracking loop stress.

Handover Mistakes

As the handover required manual skills, there were risks associated with the procedure.

Dropping lock

If the spacecraft PLL lost lock, operators might not know for hours – the round-trip light time.

“A jump in transmitter tuning could cause the spacecraft or earth station receiver to drop lock”.

Locking onto a sideband

This was tuning to a sideband instead of the true carrier.

“One mistake was to tune to a sideband... instead of the actual centre frequency”.

To avoid this Doppler offset was checked against predicts after the acquisition.

The Antenna pointing was verified using predicts which showed expected angles and received signal level in dBm. Small pointing offsets were inserted in the antenna computer to find the true peak of the antenna beam.

Eventually these procedures were automated. The tuning was adapted to use a small motor that gave a smooth drive during upgrades around 1977. Later upgrades included computer control.



18) Facilities Building

The facilities building was separate from the main building. The main purpose was the station power generation. It was powered by several Caterpillar diesel generators, producing 3 phases at 440V. The phase to neutral would be 254V with half that (127 V at 60 Hz) provided by transformers. The station did not use Australian mains power; all power was generated onsite because the equipment was all according to USA standards. In those days, an iron cored transformer was used for internal equipment power supplies. When motors and transformers designed for 60 Hz supply are operated at 50 Hz, the additional current can be excessive, and the transformer can burn out. A 127V transformer would also burn out quickly if subjected to 230V.



Figure 28: The Powerhouse [\[Attribution\]](#)

The facilities staff maintained other facilities like building, electrical, water, sewerage, fuel, transport, antenna mechanical systems, and antenna hydraulics. The hydraulic oil and cooling water for the transmitter klystron were regularly checked for contamination.



19) Ancillary Communication System

Honeysuckle Creek relied on extensive external communications to exchange data with NASA facilities around the world, particularly JPL in the United States. NASA operated a global network of leased private lines for data and voice circuits. This was known as NASCOM, which provided the backbone for telemetry, tracking, and command traffic.

NASCOM

NASCOM was NASA's worldwide communications system, carrying DSN and other telemetry, tracking, and command data to and from JPL in the USA. It also provided a voice order wire between the US operations centre (callsign **TRACK**) and HSK operations (callsign **44**). A backup telegraph connection was via the international TWX (Telex) network. This was an automated network using teleprinters.

Tracking predictions ("predicts") for antenna pointing and other tracking parameters were sent from JPL via NASCOM before each pass.

Early "high-speed data" used 2400-baud modems over leased telephone links. International submarine cables used 3 kHz-spaced channels, unlike the 4 kHz spacing of domestic carrier systems. Over time, data rates increased to 28 kb/s and later 56 kb/s, though these improvements occurred after the DSS-44 operational period.

These data circuits were operated with high reliability during missions; maintenance work on PMG microwave links (including Seacom Brisbane - Cairns) was prohibited during Gemini and Apollo operations.

"The author remembers directives to PMG staff... that no maintenance work was to be performed on microwave links during the Gemini and Apollo missions. This was jokingly called 'Nicht der fingerspoken'".

NASCOM leased services from Australian providers as required. As time went on satellite channels with better performance became available. Eventually fibre optic cables replaced satellites, terrestrial microwave, and undersea coaxial cables. NASCOM was the first global digital network.

Australian Providers

In Australia, the Overseas Telecommunications Commission (OTC) operated international links, while domestic circuits were leased from the Postmaster General's Department (PMG). During the Apollo era, the PMG installed dedicated microwave relay links specifically for NASA missions. There was a TV link from Parkes to HSK. Another PMG microwave link carried TV from HSK creek to a PMG centre in Canberra then to Sydney for international distribution.

"Data and the voice order-wire ran between HSK and the PMG Deakin Telephone Exchange via Tharwa bridge. From there, leased channels connected to the COMPAC (Sydney) and SEACOM (Cairns) submarine cables..."

The DSN Era at Honeysuckle Creek

The COMPAC cable, with 80 telephone channels, operated from 1963 until the mid-1980s, when satellite links and later fibre-optic systems superseded it.

Microwave Link with Tidbinbilla

During the Manned Space Flight Network (MSFN) era, missions such as Apollo sometimes required the Tidbinbilla DSN station. Tidbinbilla did not process Apollo data onsite; instead, signals were relayed via a microwave link to Honeysuckle Creek, which served as the primary MSFN station for the Canberra Australian region.

This link saw little use once HSK transitioned to deep-space operations.



20) Launches

Launch operations began months before liftoff with training countdowns at each DSN station. These rehearsals formally qualified both equipment and personnel.

Launches were unpredictable - delays and last-minute changes meant that tracking predictions could be inaccurate, especially in the first minutes after liftoff.

During launch, the spacecraft transmitted telemetry at higher data rates, unlike the slow 8.33 or 16 b/s cruise mode of spacecraft. The signals were strong, allowing operators to tune manually using the receiver's spectrum analyser.

Tracking was often performed with a smaller acquisition antenna mounted on the main 26-metre dish. Both the acquisition antenna and the main antenna could use auto track. The broader beam of the acquisition antenna helped locate the signal. There was a trackball for manual positioning and antenna sweep methods to search methodically.

Tracking Geometry During Launch

Launch tracking differed dramatically from deep-space operations. Instead of rising in the east like a planetary spacecraft, a newly launched vehicle appeared on the western **horizon** of HSK.

Its apparent motion:

1. Rising rapidly from the west.
2. Moving eastward across the sky.
3. Slowing near the HSK station's longitude.
4. Reversing direction and drifting westward as it reached orbital velocity.

This reflected:

- Launch from Florida.
- Ascent vertically while moving eastwards with apparent motion as the spacecraft rises.
- Transition from vertical ascent to horizontal acceleration westwards at an altitude where high speed can be used (no atmosphere).
- HSK's position relative to the launch site.

Operators had to be prepared for an unexpected position in the sky and faster changes in position and Doppler.

Mono-pulse Tracking During Launch

Because predictions were less accurate after a launch, HSK used mono-pulse auto-tracking during ascent. The acquisition or main antenna produced sum and difference channels that allowed the servo system to automatically steer toward the spacecraft beam once it was within the antenna beam. When necessary the

operator could manually steer the antenna into the beam using a trackball, one of the servo input modes.

This method worked only because the launch signal was strong with low noise as a result. It could not be used for noisy deep-space signals.

Time to Orbit

The author recalls several launch operations, including Viking and Voyager, launched on the Titan IIIE:

- Time to Earth parking orbit: 11 to 12 minutes.
- Voyager's trajectory: direct to interplanetary injection, leaving the gravity well of the Earth within about one hour.

These numbers are Titan IIIE ascent profiles and the unique “fast escape” design of the Voyager missions.



21) Engineering Practices

The equipment at Honeysuckle Creek was built to high reliability standards, reflecting both NASA practice and the military/aerospace heritage of much of the hardware.

Most equipment was mounted in 19-inch racks inside cabinets on a raised floor with a chilled-air plenum beneath. Air at approximately 5 °C cooled the equipment inside cabinets uniformly. The author remembers the spurts of chilly air on his legs that came from leaks between the floor panels.

Equipment and Cabinet Wiring

Several construction techniques were chosen specifically for long-term reliability:

- Wire-wrap connections on computer backplanes for gas-tight joints. These are considered as high reliability connections. Ribbon cable with press on connectors has now taken over for interconnections between circuit boards and are also high reliability.
- Conformal coating on circuit boards. This prevents contaminants including water/humidity from damaging circuit board tracks, components, and modifying performance.
- Gold-plated PCB tracks. This helps avoid corrosion as gold is so inert.
- Teflon-insulated, silver-plated wires in cables. Teflon is a highly stable insulator. Silver plating protected copper wires with a surface less likely to corrode and of high conductivity (considering skin effect).
- Made-to-measure cables with Mil-Spec connectors. These cables were made under contract in the US. The author remembers that these cables always fitted during upgrades.

These practices were more rigorous than other high reliability telecommunication installations of the era.

Active Circuits

The active components included:

- Discrete transistors and other components mounted on printed circuit boards.
- Monolithic integrated circuits. The resistor-transistor-logic (RTL) was already obsolete. Faster bipolar transistor designs such as TTL for logic and analogue designs like early op-amps were the norm, but PMOS, NMOS and CMOS was introduced during the 1970s too.
- Hybrid modules. These hybrid circuits were in metal transistor TO-5 style packages (~8 mm diameter) containing miniature circuit assemblies on ceramic substrates. They used small transistor and integrated circuit dies about a millimetre square, with miniature capacitors, inductors, and

resistors. The internal connections were made of silver metalized ink and thin gold wire, depending on the manufacturer.



Figure 29: Inside a vintage hybrid module. [\[Attribution\]](#)

Hybrid circuits combined discrete and monolithic components in one package. They were hermetically sealed and had mechanical ruggedness, stable electrical characteristics, and small size, so offered high reliability. The device above is not from the DSN. It has been repurposed as an earring. The DSN versions had brightly coloured objects inside that made them look like jewels.

Passive Devices

The analogue systems of the time used specialised filters to achieve performance. Radio frequency filters were used in the IF sections of the receiver and demodulator assemblies. They were often quartz crystal filters for very narrow bandwidth. Surface Acoustic Wave (SAW) filters were used too. The larger capacitors often used Teflon for the dielectric. This offered long term stability. Electrolytic capacitors were avoided as they were in other higher reliability systems. There were all kinds of switches and relays. Many of these had solid silver or gold plated contacts for better reliability. The most reliable relays were those from the telegraph world called mercury wetted (contact) relays.

Analogue systems are often temperature sensitive. Devices such as oscillators, tuned circuits, filters and even amplifiers can be stabilised by small temperature controlled ovens.

RF Modules (“Gold Bricks”)

RF modules were housed in metal enclosures, gold-plated to minimise corrosion. These “gold bricks” were mounted on panels in drawers in cabinets and interconnected with “mil spec” connectors. The photo below shows a gold brick module from the Australian Telescope at Narrabri in NSW. It is a cryogenic low noise amplifier using a HEMT transistor.

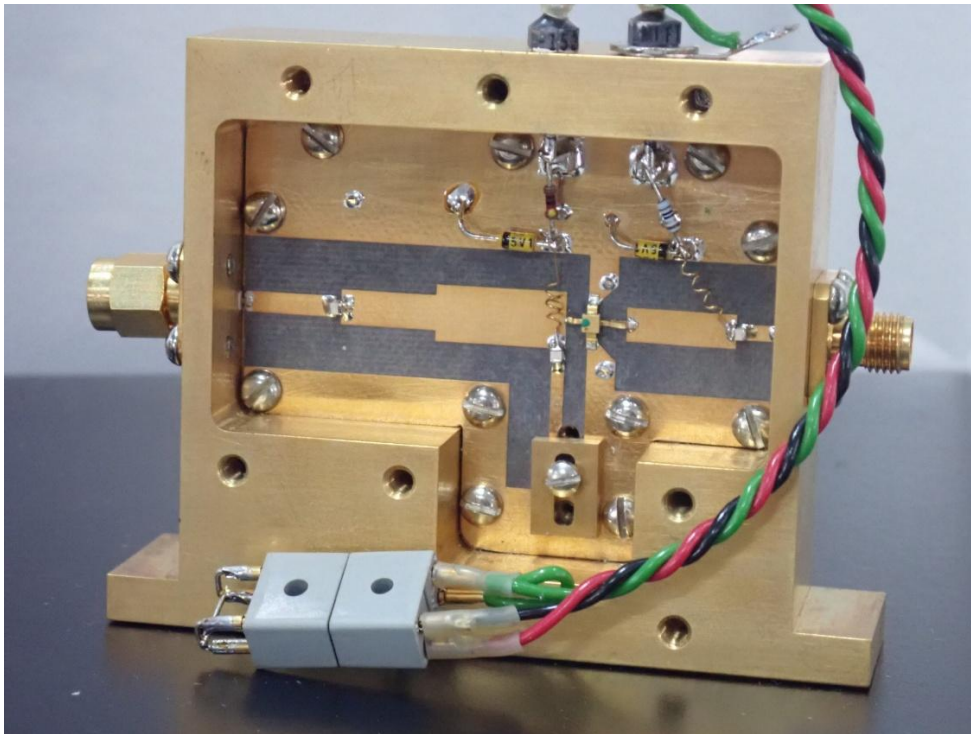


Figure 30: Modern day Gold Brick Module. [[Attribution](#)]

Layout and Serviceability

Many subsystems were built as pull-out drawers in the cabinets, allowing technicians to service modules without disturbing adjacent hardware.

The Transmitter power amplifier and the receiver maser and associated waveguide components were all mounted in the feed cone in the main dish and equipment cabin behind the main dish.



22) Operational Incidents

Although DSN equipment was exceptionally dependable, a few incidents occurred during the DSS 44 era. These were rare - sometimes years apart - but they illustrate the engineering discipline required to maintain continuous service for NASA's mission clients.

Snow Accumulation on the Antenna

Heavy snowfall occasionally accumulated on the 26-metre dish, distorting the reflector surface and degrading the beam shape. The first symptom was a weakening signal, followed by loss of lock as the distorted beam moved off-axis.

The only remedy was to break track, tilt the antenna, and shed the snow load. Operations resumed once the reflector surface was clear and the spacecraft was reacquired.

Waveguide "Aging" and Arcing

This phenomenon occurs in high-power radar systems too. Over time, microscopic contaminants can accumulate inside high-power waveguide runs. When transmitting at multi kilowatt levels, these particles can arc, producing bursts of interference that appear in the receiver.

At DSS 44, the entire S-band waveguide run had to be replaced after a spare was flown in from the United States.

Runaway Antenna (Servo Failure)

One of the more dramatic incidents involved a failure in the antenna servo system. The culprit was an early Philbrick chopper-stabilised op-amp used in the servo feedback loop. These amplifiers used discrete components, before monolithic integrated circuits. It relied on a mercury-wetted relay to act as the chopper and so achieve a DC amplifier with low offset and drift.

When the relay eventually failed, the servo amplifier saturated, causing the antenna to drive at full speed toward its mechanical hard stops.

Boresight TV Camera Issues

The antenna's boresight camera used a Vidicon tube and discrete transistor circuitry. As in much of 1970s television equipment, electrolytic capacitors were a common point of failure. Loss of capacitance caused:

- Excessive mains ripple.
- Poor video synchronisation as the system tended to synchronise with the mains frequency.
- Degraded low-frequency response.

Telecommunications systems had long avoided electrolytic capacitors for reliability reasons, but video equipment of the era still depended on them. This was

exacerbated by the camera being mounted in a sealed metal housing in the full sun on the antenna.

Telemetry “Event Showers”

Occasionally, the telemetry processing computers experienced bursts of spurious events - “event showers”. These were triggered by interactions between:

- The shared 1 Hz precision clock interrupt.
- Certain signal conditions in the receiver chain.

In hindsight, these episodes may have been caused by cycle slips in the receiver’s PLL, though not explained at the time.

Viking 1 Lander

On November 13, 1982 - 6 years, 3 months, 22 days after it launched, the Viking 1 Lander failed due to human error. The Landers communication ended after a software update caused the antenna to fail. The Viking 2 lander ceased operation earlier due to a battery failure. Spacecraft were often able to escape total failure due to hardware redundancy or clever work arounds or reprogramming. Eventually they ran out of a resource like propellant or power. The Voyager spacecraft have been operating for 50 years but are near the end of the Radioisotope Thermoelectric Generator (RTG) life now.

Reliability

Despite these incidents, downtime was extremely low. The clients were involved in expensive operations so did not want any failures. There were many events involving spacecraft hardware. In most cases a procedure was developed that overcame or worked around the failure using commands or even reprogramming the spacecraft computer. This was partly because of redundancy and foresight in the designs.



23) Radio Science Use

The DSN was an instrumentation network serving scientific clients, including NASA missions and radio-science experiments.

One radio science experiment the Author remembers was an attempt to measure the gravitational bending (lensing) of radio waves from the Helios spacecraft as the waves passed near the Sun. Unusually, a science program leader in the U.S. came on the order wire to explain that this was about to occur. However, S-band signals suffered excessive noise from the solar corona, limiting the experiment's precision. Scintillation of the radio wave was an issue.

Amplitude scintillation was variations in the signal level caused by multipath fading as the radio beam passed the sun's corona. Part of the beam reflects off the solar corona and recombines with the main beam further on causing wave interference that can partially cancel the signal. This flutters due to the spacecraft motion. This is a similar process to multipath fading on earth where radio beams reflect off the ground. Scintillation of phase occurred when the radio beam passed through "dispersive media". This is due to patches of charged particles that interact with the radio wave and cause slight changes in velocity, hence phase noise. These patches must be accounted for in ranging. Scintillation can cause cycle slips too.

There have been many DSN Radio Science experiments using occultation. Modern equivalents use:

- Distant radio sources.
- Higher frequencies.
- Very Long Baseline Array (VLBA) interferometry to achieve far greater angular resolution and sensitivity.

The scientific lineage stretches back to the 18th century: Cook's expedition used the newly invented marine chronometer to measure longitude during astronomical transits. The DSN, with its precision clocks and global baselines, continued that tradition of exploration and measurement.

Another radio science measurement made by the DSN was accurate measurement of the Astronomical Unit (AU, which is the average distance from earth to the sun).



24) References and Source Materials

The following references were used in preparing this document. They include primary DSN engineering manuals, historical accounts, technical papers, and contemporary resources on deep-space communication systems with hints from the author's memory.

Primary NASA Resources

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https://descanso.jpl.nasa.gov/monograph/series10/03_Reid_chapt%2B3.pdf
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Apollo Era Unified S-Band System (USB)

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https://en.wikipedia.org/wiki/Unified_S-band
- AB9IL Technical Article - Apollo S-Band System
<https://www.ab9il.net/aviation/apollo-s-band.html#sigchars>
- Apollo Communication Modules (YouTube Series)
<https://www.youtube.com/watch?v=v49ucdZcx9s&t=119s>
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- Article about the pseudo noise ranging during Apollo missions.
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- Wikipedia: A shorter version of the history of the DSN using the Uplink Downlink book (Mudgway) as the source.
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<https://descanso.jpl.nasa.gov/>
- NASA papers (technical references index) for the DSN
<https://descanso.jpl.nasa.gov/history/DSNTechRefs.html>
- CSIRO — DSN 70 m and 34 m Antenna User Guide. Includes a drawing of the beam waveguide system now used.
<https://www.atnf.csiro.au/observers/DSN-RA-UserGuide-v1a.pdf>



25) Appendix A - Link Budget Example: Pioneer 11

This appendix provides a worked example of a deep-space link budget using Pioneer 11 at the orbit of Saturn (≈ 9 AU). The receiving station is as for DSS 44 during the DSN era, using its 26-metre antenna. The calculation is basic rather than rigorous, but it illustrates the essential principles of path loss, received power, noise density from measured system temperature, carrier to noise ratio and bit-rate performance. There is also a calculation for the minimum received level represented by the spacecraft at 50 AU. For a deeper understanding with many more parameters and considering residual carrier subcarrier and various digital phase modulation see: <https://descanso.jpl.nasa.gov/dstse/DSTSE.pdf>



Figure 31: Artist's Illustration of Pioneer 11 at Saturn in 1979. [Attribution]

The photo above shows an Artist's drawing with Pioneer 11's antenna facing back towards earth. You can also see the Radioisotope Thermoelectric Generator (RTG) and a sensor on booms. That is Saturn in the background, first visited by Pioneer 11.

This example represents the approximate maximum range at which a 26-metre station could support a telemetry rate of 16 bits per second from Pioneer 11. Information like the FSPL for 1 AU, EIRP of the spacecraft and DSS 44 antenna gain can be found online or using online calculators.

What is an AU? It is an astronomical unit of distance, being the average distance from the Earth to the Sun. The distance is about 8.35 light minutes.

Noise Spectral Density from System Temperature

Thermal noise power in a 1 Hz bandwidth:

$$N_0 = k_B T_n$$

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In decibels:

$$N_0 = -228.6 + 10\log_{10}(T_n) \text{ dBW/Hz}$$

For a system temperature of 32 K:

- $N_0 = -213.54 \text{ dBW/Hz}$
- or -183.54 dBm/Hz

Path Loss and Received Power (Pioneer 11 at 9 AU)

Distance scaling from 1 to 9 AU:

$$20\log_{10}(9) = 19 \text{ dB}$$

Free-space path loss at S-band (2.3 GHz):

- FSPL at 1 AU $\approx 272 \text{ dB}$
- FSPL at 9 AU $= 272 + 19 = 291 \text{ dB}$
- FSPL at 50 AU $= 272 + 34 = 306 \text{ dB}$

Spacecraft parameters:

- Transmitter power: 8 W
- Spacecraft effective isotropic radiated power (EIRP): $\approx 52 \text{ dBW}$

Ground station:

- Receive antenna gain (26 m at 2.3 GHz): $\approx 54 \text{ dBi}$.

Received downlink power at 9 AU:

$$P_{rx} = 52 + 54 - 291 = -185 \text{ dBW} = -155 \text{ dBm}$$

Received power at 50 AU:

$$P_{rx} = 52 + 54 - 306 = -200 \text{ dBW} = -170 \text{ dBm}$$

Allowing for waveguide and feed losses (arbitrary loss of 1dB overall):

$$P_{rx} \approx -156 \text{ dBm at 9 AU}$$

This is total received power, not the carrier alone.

Ratio of Carrier to Noise Density (C/N_0)

$$C/N_0 = -156 - (-183.54) = 27.54 \text{ dB-Hz}$$

Energy per Bit to Noise Density Ratio (E_b/N_0)

For a telemetry rate of 16 bps:

$$10\log_{10}(16) = 12 \text{ dB}$$

$$E_b/N_0 = 27.54 - 12 = 15.54 \text{ dB [Normalised SNR]}$$

An $\frac{E_b}{N_0}$ of 15 dB (Normalised SNR) is adequate for BPSK especially with forward error correction (FEC). Note that this calculation does not take account of the residual carrier and ranging which is around half of the total power. It would depend on the tracking loop bandwidth. The telemetry signal could operate faster than shown, as only 11 dB SNR per bit is needed for one bit in a million error rate without FEC. In that era about 6 dB SNR per bit was required for one bit in a million error using convolutional encoding with Viterbi decoding.

“Normally an E_b/N_0 of at least 7 to 8 dB would be required for BPSK. This would give a modest error rate of 1 error in a few thousand bits, according to curves for BPSK bit error rate versus E_b/N_0 ” without FEC.

Thus, the DSN achieved a viable link at 2.5 hours round-trip light time – an illuminating demonstration of deep-space communication capability using a 26-metre antenna. Note that about 10 dB above the noise in the loop bandwidth is needed for dependable PLL tracking of the residual carrier. The noise is about minus 183.5 dBm with 1 Hz tracking bandwidth. It shows that the DSS 44 system could stay in lock with -173 dBm signal as with Pioneer 11 at 50 AU range. This was in fact a signal level the Author remembers.

The author was told that the maximum range was 50 AU, which gives a received signal of about -170 dBm using the calculations above. The residual carrier at that time would be 3 dB lower so close to -173 dBm. The telemetry signal was therefore also -173 dBm. The residual carrier to noise ratio would be about 10 dB-Hz. This would depend on the PLL bandwidth to get that 10 dB SNR of the residual carrier to maintain lock. Of course, telemetry also depends on the bitrate, but modern Forward Error Correction can operate with -8 dB (normalised SNR = E_b/N_0) to deliver 1 error per million bits. The 8.33 b/s rate becomes +1.2 dB normalised SNR, so the 50 AU range is possible with a margin of about 9 dB using modern FEC. This link has a RTLT of about 14 hours.

“The Author remembers that the tracked signal was sometimes -173dBm with a bit rate of 8.333 b/s and a RTLT of about 16 hours. This is more than 50 AU range”.



26) Acknowledgements

The images in this document have links to show attributions. If you have an online image that you want attributed to you instead of a link to a website, please contact the Author at the email address under the topic "[About the Author](#)".

Definitions of terms and units has been copied from the Author's memory but may coincide with online sources that can be seen as reliable sources.

Here are the image attributions:

- [1] PLL conceptual diagram by the Author.
- [2] Phase Modulator conceptual diagram by the Author.
- [3] Line encoding - NRZ diagram by the Author.
- [4] Modcomp computer front view from <https://wsjsociety.com/news/out-about-with-members/>
- [5] Modcomp computer inside view from <https://wsjsociety.com/news/out-about-with-members/>
- [6] HP desktop calculator from <https://www.hpmuseum.org/hp9830.htm>
- [7] Example X-Y antenna from NASA Green Book SP-87.PDF
- [8] Signal and noise diagram by the Author.
- [9] Steradian and a sphere diagram by the Author.
- [10] Antenna feed from NASA Green Book SP-87.PDF.
- [11] The powerhouse photo by Ian Hahn, from [Honeysuckle Creek](#).
Vale - Kaz Kijak, Ted Burt.
- [12] HP 5105B-5110B Frequency Synthesiser and synthesiser driver from https://www.hpmemoryproject.org/an/pdf/an_96.pdf
- [13] Antenna with Cassegrain feed system by Hamish Lindsay from <https://www.honeysucklecreek.net/station/index.html>
Vale - Hamish Lindsay.
- [14] Conceptual spacecraft transponder diagram by the Author.
- [15] Block III Transmitter Receiver diagram by the Author.

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- [16] Varactor multiplier stage diagram by the Author.
- [17] Klystron power amplifier diagram by the Author.
- [18] Costas Loop diagram by the Author.
- [19] Integration used to decode noisy data. Diagram by the Author.
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- [21] Typical USB spectrum. Diagram by the Author.
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- [24] Example of a TTL chip. (Plastic Package)
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- [25] Apollo is gone, DSS 44 begins. Hamish Lindsay
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- [26] Sketch of Pioneer Spacecraft.
<https://science.nasa.gov/resource/pioneer-spacecraft-diagram/>
- [27] USS Vanguard tracking Ship. Scanned by Colin Mackellar
https://honeysucklecreek.net/other_stations/ships/index.html
Public Domain,
<https://commons.wikimedia.org/w/index.php?curid=1844442>
- [28] Diagram of cavity maser, modified by the author, from
https://descanso.jpl.nasa.gov/monograph/series10/03_Reid_chapt%2B3.pdf
- [29] U.S. Air Force Douglas C-124C Globemaster II Landing, from
<https://aerocorner.com/aircraft/douglas-c-124-globemaster-ii/>
- [30] Double balanced mixer using transformers. Diagram from an LT Spice simulation by the Author.

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- [31] Microwave diode as used in waveguide mixers. Photo from https://www.semigen.net/updates/reliable_ka-band_point_contact_mixer_diodes_with_low_noise_figure_and_vswr_ideal_f_or_doublers_modulators_and_double_balanced_mixers/
- [32] Gold brick modules. Modern version from the Australian Telescope. Photo from Clifford Heath.
- [33] Inside a vintage hybrid device. This device is converted to jewellery. <https://www.chipsetc.com/signetics.html>
- The section separator was drawn by the Author.

I would like to thank these people who helped me with this article:

- Colin Mackellar for his encouragement and assistance with website and attributions and corrections.
- Clifford Heath for his encouragement and assistance with the DSS 44 ranging system and many corrections and improvements to the document.



27) About the Author

The author's name is Eric Gill. I worked at Honeysuckle Creek Tracking Station from early 1975 to early 1978 during its Deep Space Network (DSN) era. As one of the youngest members of the technical staff at that time, I gained hands-on experience with the Unified S-Band (USB) system, deep-space telemetry, and antenna operations.

The organisations I worked for are:

- Postmaster General's department (PMG). (Commonwealth of Australia).
- Department of Posts and Telegraphs, Trunk Projects (PNG administration).
- Private company partnership (Electrical Contracting) in Indonesia.
- Honeysuckle Creek Tracking Station, Fairey Aviation (Contractor to the Department of Supply, Commonwealth of Australia).
- The Australian Institute of Marine Science (Commonwealth of Australia)

During my working life I had experience in Telecommunications and Radio systems including FDM carrier systems, broadband microwave links, HF radio, ISB radio, Broadcast Radio (HF), VHF mobile radio, VHF links, and Analogue TV. I worked in electrical contracting particularly with diesel generator installations.

I later worked at a Science Research Institute where I designed remote and underwater and laboratory instruments for scientists. I was involved in radio telemetry and field and laboratory science instrumentation. I designed small low powered computers and wrote software, particularly for telemetry and monitoring systems. My whole work experience involved telecommunications, communications, power systems, telemetry, radio, and monitoring systems.

I had many other experiences not related to the telecommunications and radio and marine science fields, including 2 years in the Militia as an infantry signaller.



Figure 32: Douglas C124-Globemaster II. [\[Attribution\]](#)

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During the 1960s, a Globemaster II (C-124, a large piston engined aircraft of that era) brought NASA caravans to Townsville (Australia) during the leadup to Gemini missions. I connected the telephone to these caravans on a few occasions. Little did I know that one day I would work in this field.

During this era some of the tracking ships also came into the Townsville port. Presumably they operated in the ocean to the north east.



Figure 33: USS Vanguard Tracking Ship. [\[Attribution\]](#)

This document is a reconstruction of Honeysuckle Creek (DSS 44) as I experienced it, supported by memory, documentation, and engineering reasoning. Some of it is from other documents I wrote.

Use of AI in Verification

Reconstructing a complex technical system after fifty years requires more than memory alone. The author used a modern AI tool to examine remembered details, test them against physics, and compare them with surviving DSN documentation such as NASA SP-87, a document on an Apollo era conference (see the references). AI helped reveal which of my memories were dependable. It also helped locate obscure references.

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