ULTRA-LOW-NOISE MICROWAVE AMPLIFIERS*

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The Jet Propulsion Laboratory (JPL) has been active in the development and use of masers for more than 20 years (Reed et al., 1973). Cavity and traveling-wave masers in open- and closed-cycle helium refrigerators have been designed and built at frequencies between 900 MHz and 42 GHz. Noise temperatures of 2.1, 3.5, 8.5, and 13 Kelvins have been measured at 2.3, 8.4, 15, and 25 GHz respectively. More than 50 field-operational systems have been supplied to the NASA Deep Space Network (DSN); these systems have accumulated over 2 million hours run time. Current maser systems used in the DSN provide 40 MHz bandwidth. 150 MHz bandwidth has recently been demonstrated in the laboratory at 8.4 GHz. K-band masers (near 24 GHz) can provide 500 MHz bandwidth. The combination of a parametric upconverter with a K-band maser can provide a 500 MHz bandwidth at S-band or X-band frequencies with maser-like noise temperatures; a 3½ Kelvin noise temperature at 2300 MHz has been demonstrated.

The 64-meter antenna at Goldstone, California is shown in figure 1. Five ultra-low-noise traveling-wave maser (TWM) systems are in use; two at S-band (2300 MHz) and three at X-band (8400 MHz). Each maser operates in a closed-cycle helium refrigerator (CCR) at 4.5 Kelvin. Total system temperatures as low as 15 Kelvins have been achieved during spacecraft tracking operations at S-band. Typical X-band operating system temperatures are between 25 and 30 Kelvins.

A 960 MHz cavity maser cooled to 4.2 Kelvin in an open-cycle helium dewar was installed on a 26-meter antenna in September 1960. Figure 2 shows a liquid helium transfer at the prime focal point, 80 feet (27.84 m) above ground. The maser contains a 4-liter liquid helium tank and an 8-liter liquid nitrogen tank. The system will operate for 36 hours between refills on a moving antenna. Figure 3 shows 25-liter storage containers of liquid helium and liquid nitrogen.

A recently developed printed-circuit traveling-wave maser is shown in figure 4. This X-band TWM is particularly compact; several structures can be used in one super-conducting magnet. The ruby bar (shown just above the scale) has 44 one-half wavelength copper elements along a 8.5 cm length. A sapphire bar, shown just above the ruby bar, is placed against the copper elements; the ruby, copper, sapphire assembly is placed into the housing so that the sapphire bar contacts the resonant isolator assembly. The isolator assembly contains a continuous strip of polycrystalling yttrium-iron garnet between two alumina bars and is shown located in the housing. A beryllium-copper spring

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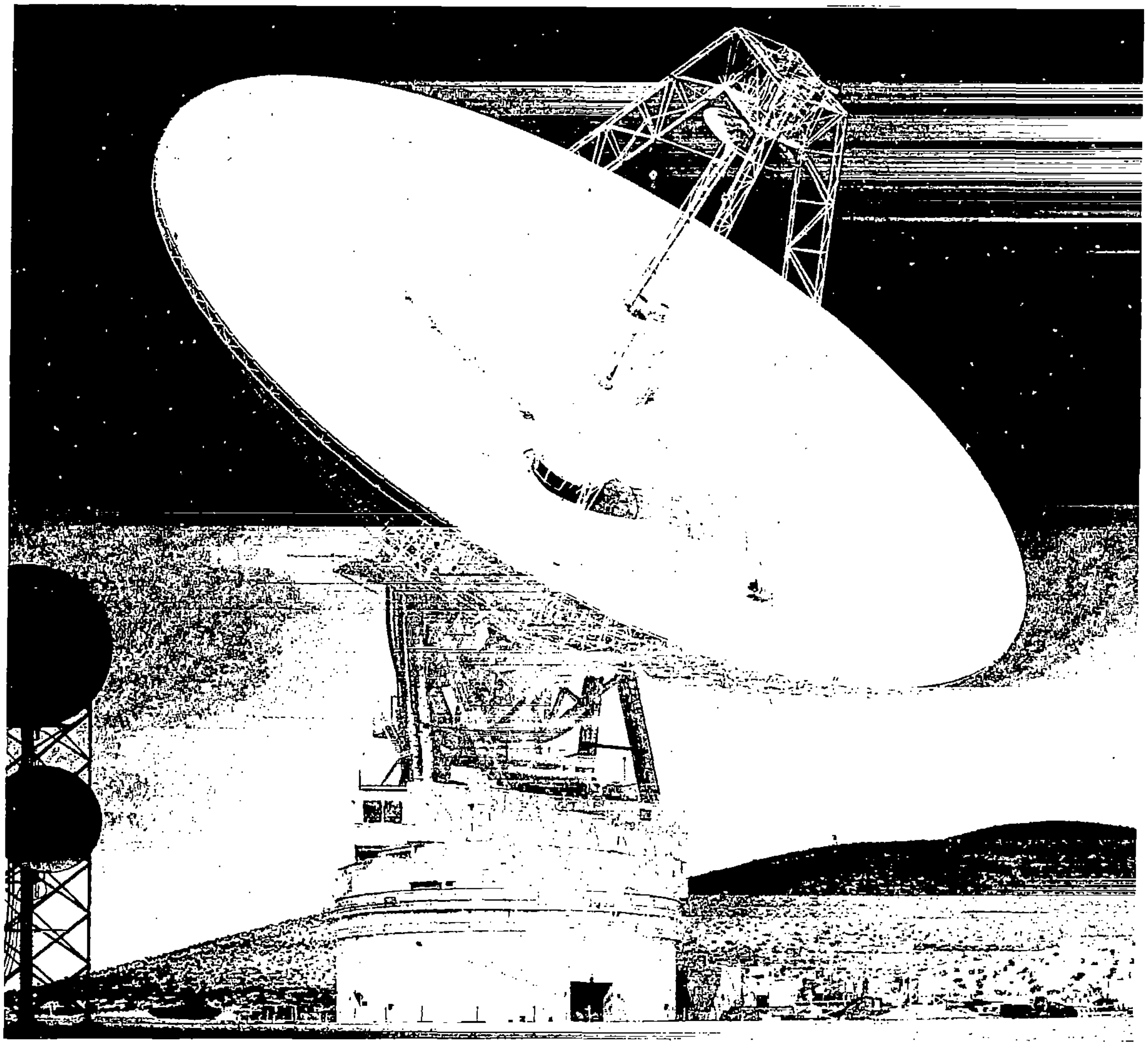

Figure 1. The 64-meter antenna at Goldstone, California.

behind the isolator assembly applies pressure to the assembly so the ruby bar will achieve intimate contact with a copper cover (not shown) to provide a good thermal path to the 4.5 Kelvin station of a closed-cycle refrigerator. Signal input and output connectors (with matching elements) are shown; the one at the left is disassembled to show details. Signals to be amplified travel through the assembly at 1/50 the speed of light. The "slowed-wave" interacts strongly with the ruby and is amplified as it travels through the structure. The ruby is biased with a 5000 gauss magnetic field along the direction of the fingers. A population inversion of the energy levels is achieved by saturating the ruby with pump energy (Siegman, 1964). Pump energy at 19 and 24 GHz enters at the left of the structure, through an alumina filled waveguide. The resonance isolator is properly shaped to operate in the 5000 gauss field required by the ruby for operation at 8400 MHz. The isolator highly

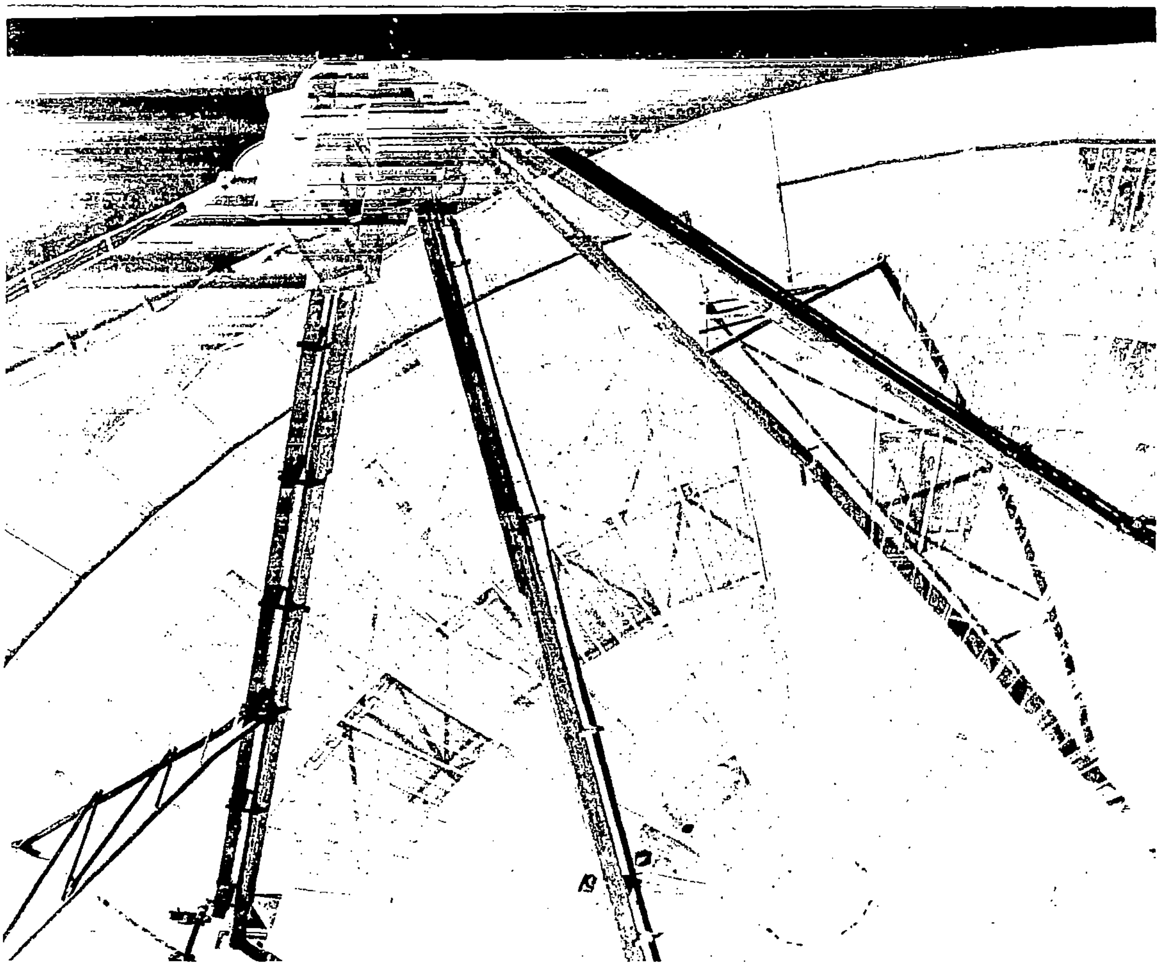

Figure 2. Liquid helium transfer at the apex of a 26-meter antenna.

attenuates signals traveling from output to input, thereby preventing regenerative amplification. The direction of amplification, with proper isolation, is determined by the polarity of the magnetic field and can be reversed by changing the direction of current flow through the 5000 gauss superconducting magnet. Amplifiers of this type can be used to achieve bandwidths of several hundred MHz with noise temperatures of less than 5 Kelvin.

Figure 5 shows a 2295 MHz maser developed in 1964. The TWM structure was purchased from Airborne Instruments Laboratories and the closed-cycle helium refrigerator was purchased from the Arthur D. Little Corporation. Fourteen systems of this type were installed in the DSN during the 1960's. The TWM is shown connected to a liquid-helium-cooled waveguide termination. The total system noise temperature in this configuration was measured at 15 Kelvins (Clauss et al., 1964). The equipment racks behind the maser contain: (1) temperature controllers for the permanent

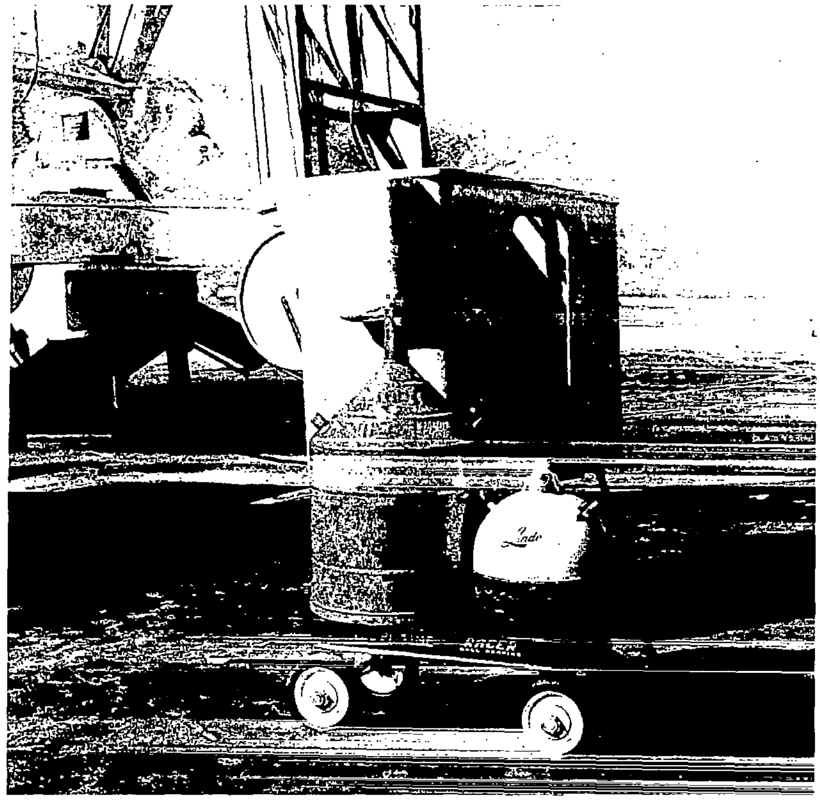

Figure 3. Containers of liquid helium and liquid nitrogen.

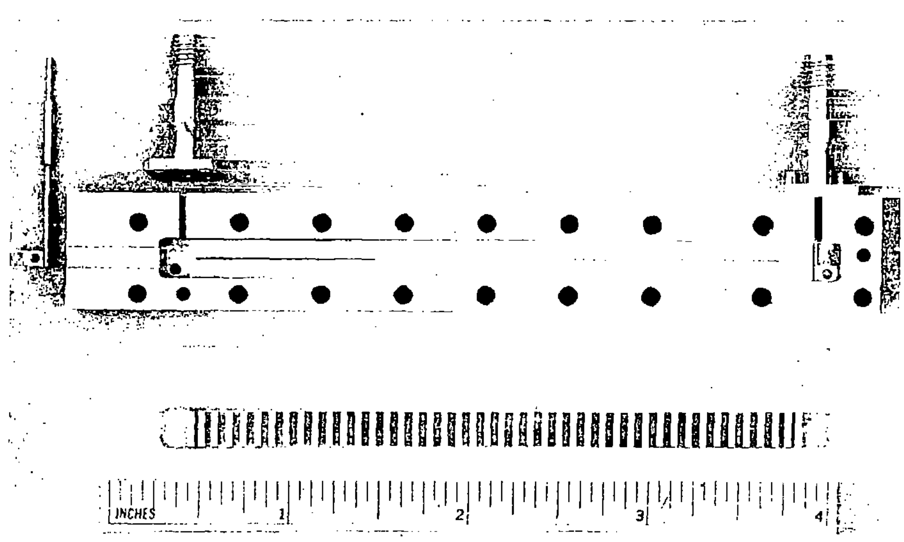

Figure 4. Printed circuit slow-wave comb structure for X-band maser.

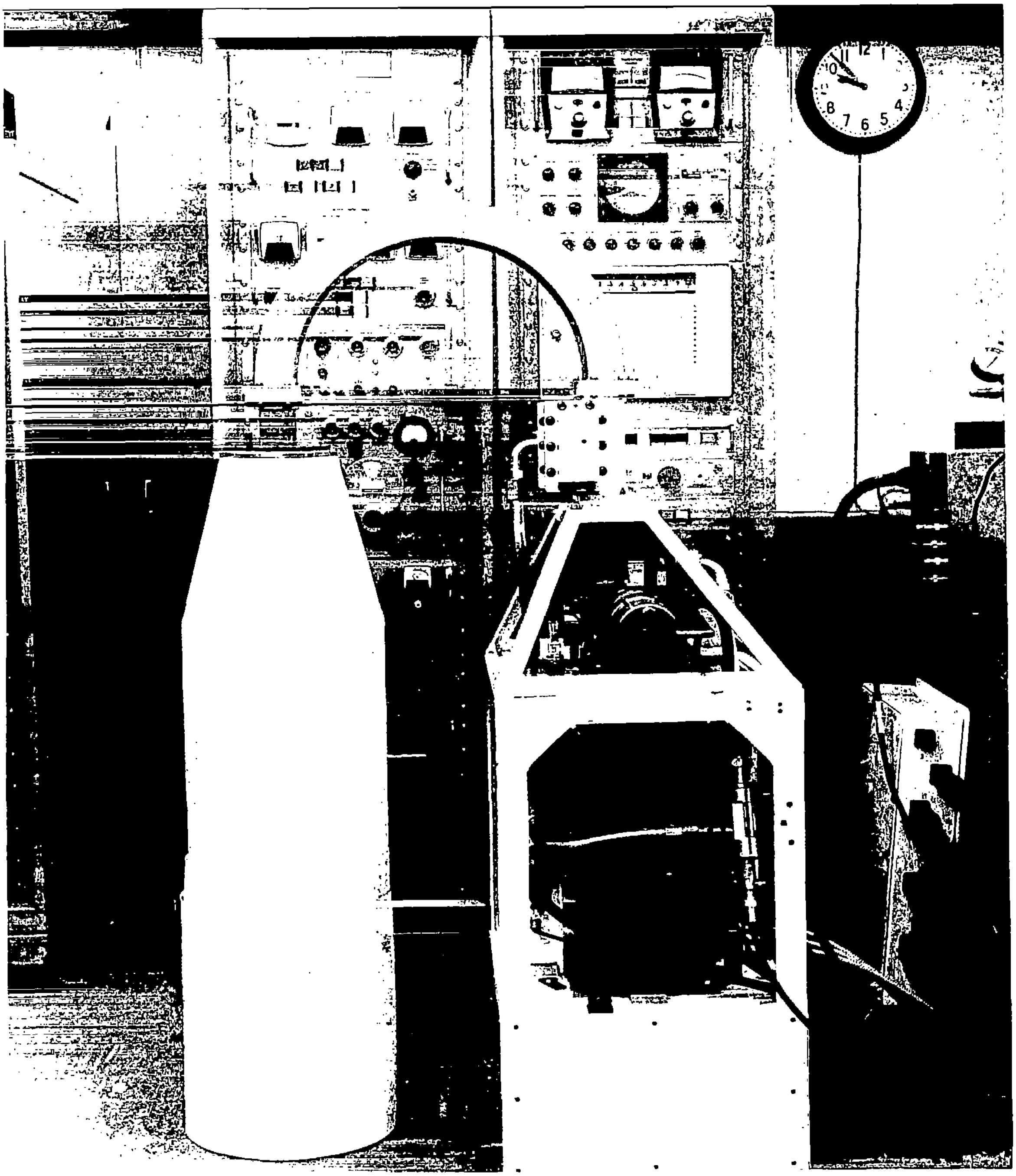

Figure 5. S-band maser and liquid helium-cooled waveguide termination.

maser magnet, (2) a spectrum analyzer, (3) a strip chart recorder to record stability performance, (4) calibration switch controls, (5) noise source power supplies, (6) detectors with adjustable bandwidth and integration times, (7) refrigeration controls and monitors, (8) a klystron (pump) power supply, (9) the maser magnet trim power supply, and (10) a signal generator used for measuring maser gain. A super-hetrodyne receiver is used to monitor maser performance. A helium compressor used with the cryogenic refrigerator is now shown. Helium gas lines, cables, and junction boxes are also needed. This complete system is typical of a maser installation in the DSN; it is easy to see why each system costs several hundred thousand dollars.

Figure 6 shows an X-band TWM structure typical of those used in the DSN today. A net gain of 45 dB is achieved, flat within 1 dB, from 8400-8440 MHz. The effective input noise temperature is 8 ± 2 Kelvins. A TWM like this one is being assembled for the portable 4-meter antenna station for radio interferometry. It will be modified for performance in an open-cycle helium dewar with reduced gain ($\simeq$25 dB) and increased bandwidth ($\simeq$140 MHz).

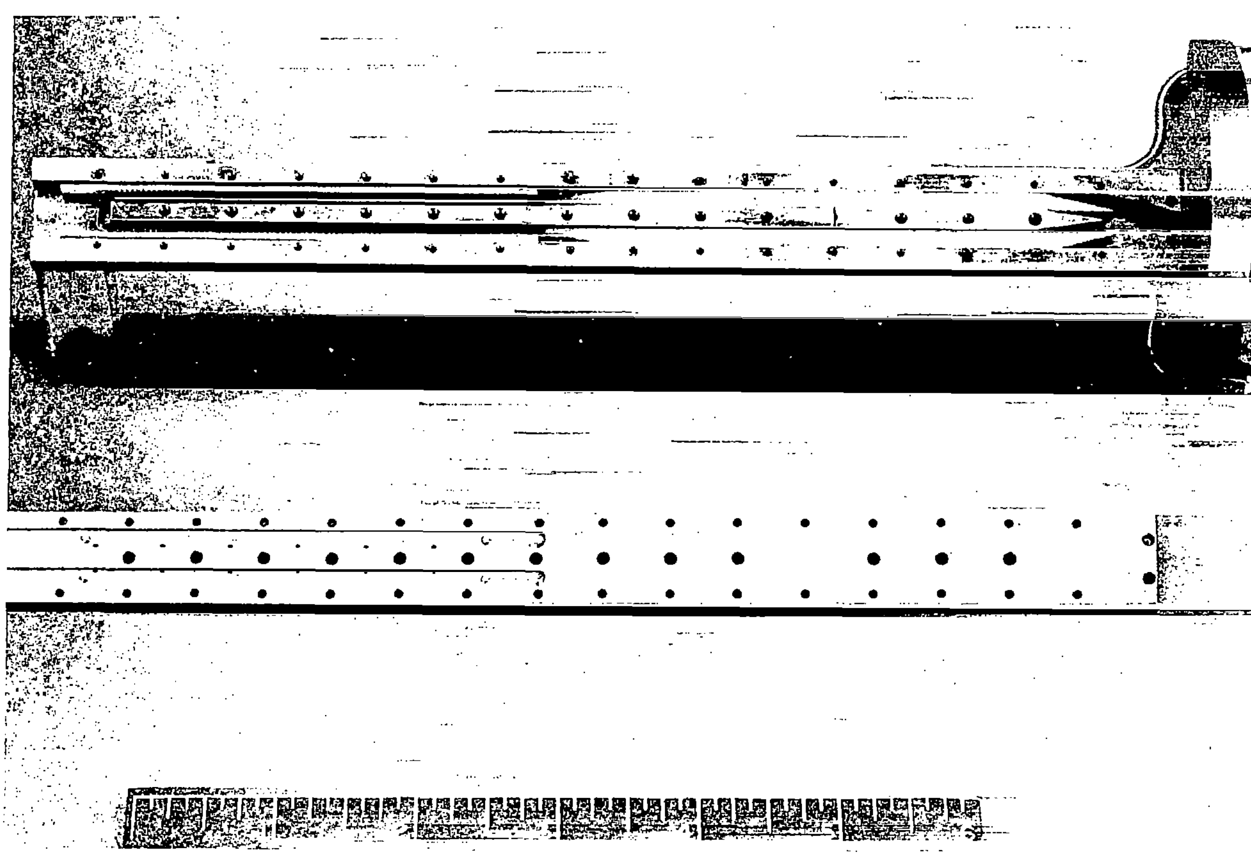

Figure 6. Typical X-band comb-type traveling-wave maser.

A reflected-wave K-band maser is shown in figure 7. Only one-half of the amplifier is shown so the circulators, matching sections, and ruby-filled waveguides are visible. The unit was developed at JPL under a contract from the National Radio Astronomy Observatory (NRAO). The cooperative effort between JPL and NRAO has produced a wide-band maser design that will find application for both radio astronomy and planetary spacecraft communication (Moore and Clauss, 1979). Signals are directed to and from ruby-filled waveguides by circulators built in reduced height WR-42 waveguide. The round circulator ferrite elements are surrounded by white alumina matching elements. Three circulators are terminated with poly-iron loads; these circulators act as interstage isolators. Each ruby-filled waveguide is connected to a circulator through a multistep matching transformer. The opposite end of the ruby-filled waveguide (not shown) contains a waveguide-beyond-cutoff filter used to introduce pump energy. The signal is amplified as it travels from the circulator to the pump filter. At the filter, it is reflected and travels back towards the circulator, being amplified a second time. The circulator directs the signal to the next stage of amplification. Four stages are used to achieve 30 dB net gain with 240 MHz bandwidth at the center of the maser tuning range. The tuning range is limited by the circulator bandwidth, in this case, from 18.3 to 26.5 GHz. A 10 kilogauss superconducting magnet is used (Cioffi, 1962); improvements in the magnet design at NRAO resulted with 550 MHz maser bandwidth at 30 dB net gain.

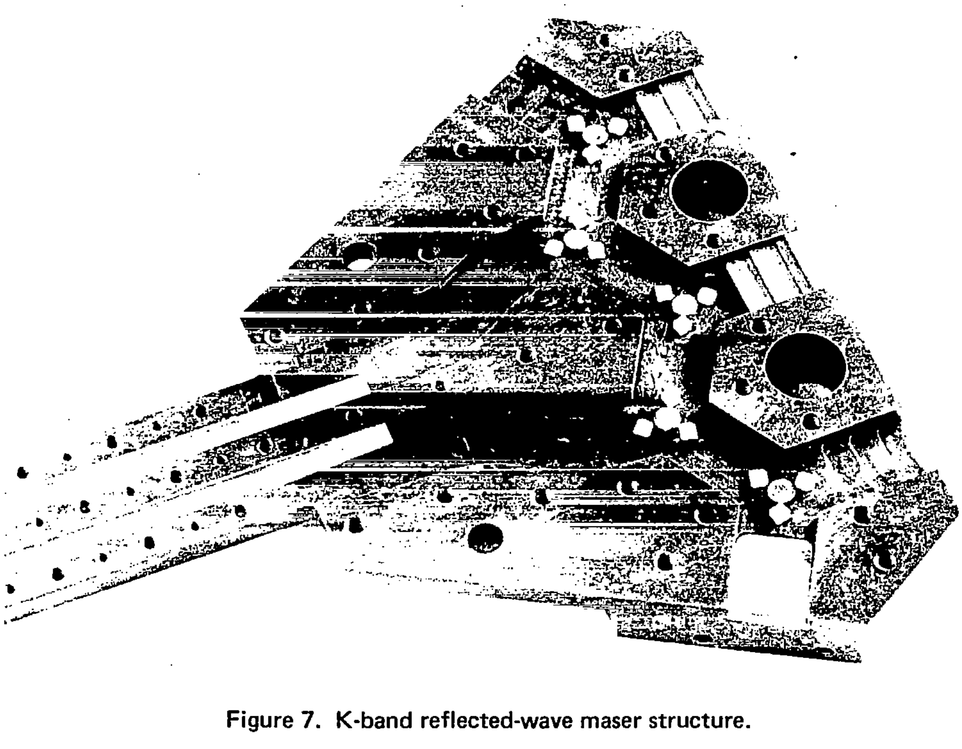

Figure 7. K-band reflected-wave maser structure.

The maser and magnet operate in a closed-cycle refrigerator at 4.5 Kelvin (Higa and Wiebe, 1967). The package is shown in figure 8. The input waveguide connection is shown at the top. Units of this type have achieved an effective input noise temperature of 10 Kelvins.

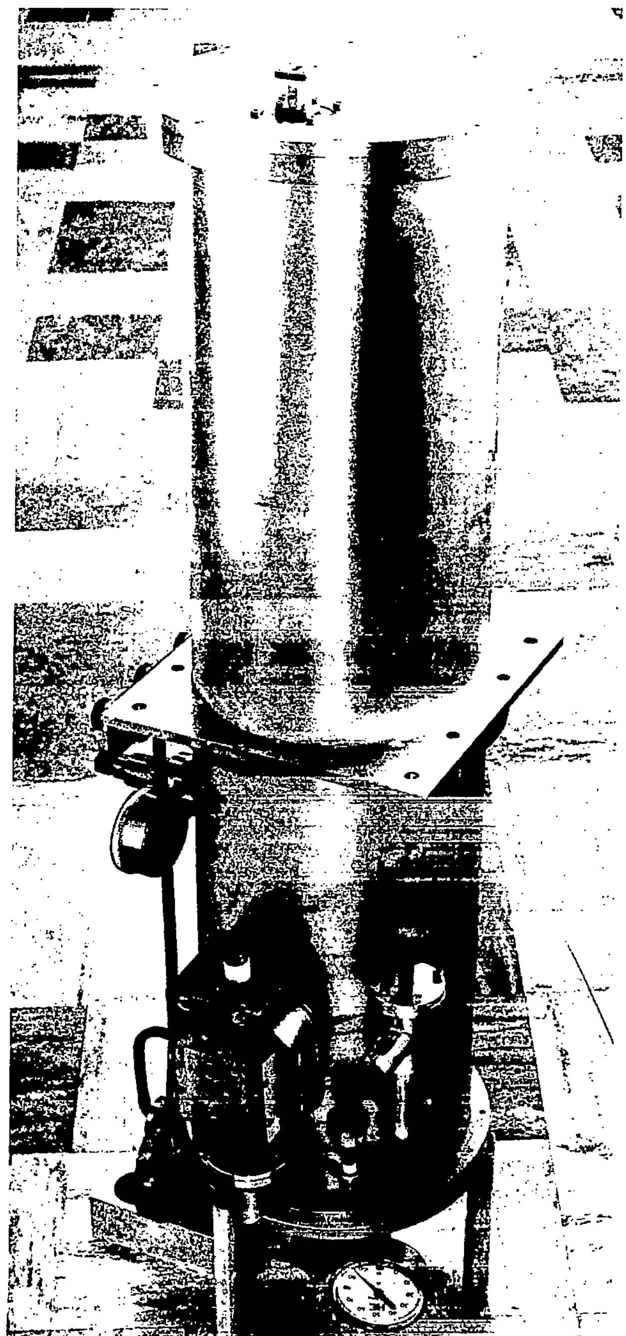

Figure 8. K-band maser package.

Figure 9 shows the combination of an S-band to K-band up-converter and a K-band maser in a 4.5 Kelvin CCR. The input transmission line center conductor is cooled to 4.5 Kelvin along its entire length. A fused quartz dome provides a vacuum seal in the ambient S-band waveguide. This combination provides maser like noise temperatures with bandwidths up to 500 MHz (Petty et al., 1978).

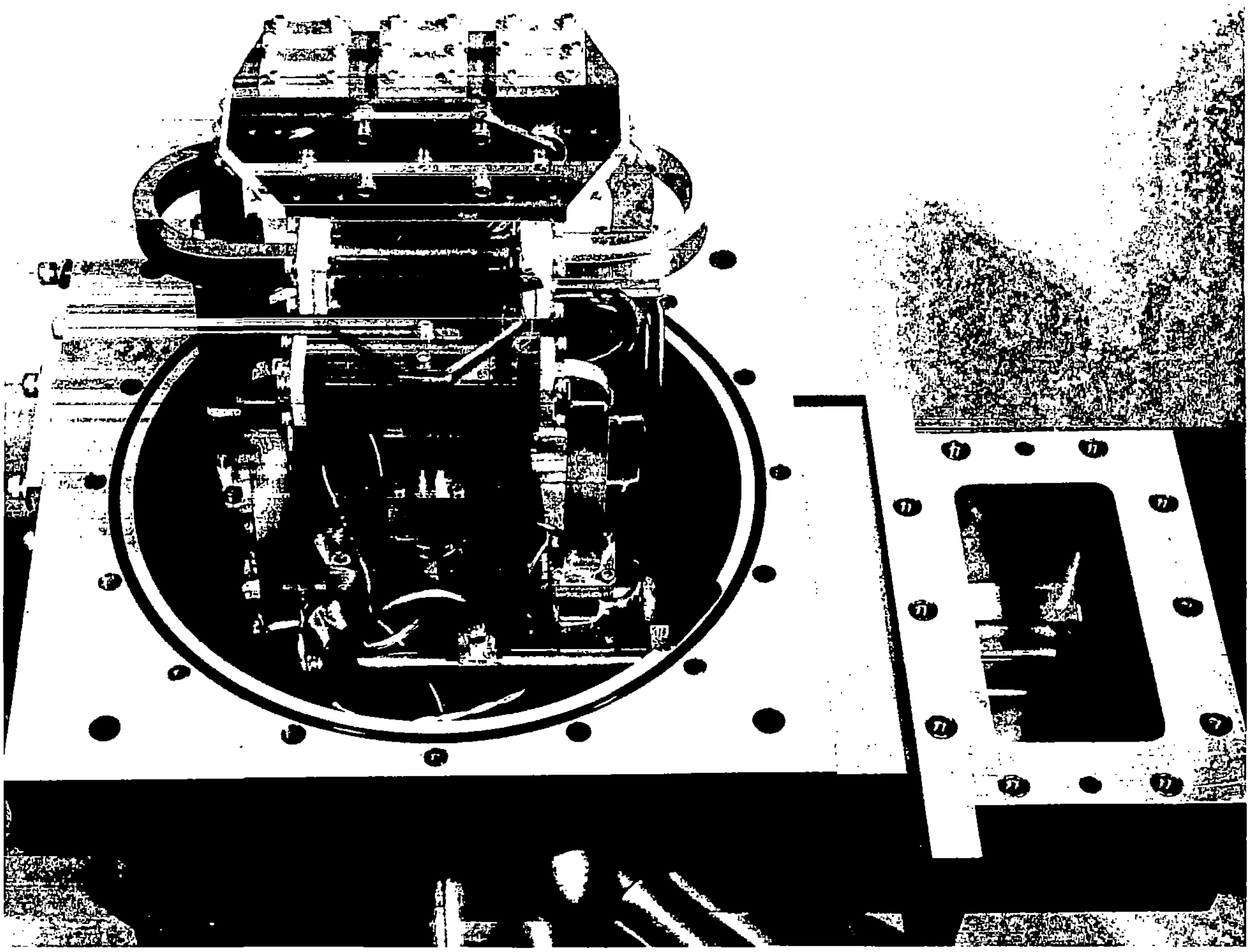

Figure 9. S-band to K-band up-converter with maser and low-loss input line.

Figure 10 shows an S-band maser and feed-horn on the roof of our building at JPL. A well-matched microwave absorber is shown above the horn; it introduces ambient noise into the system. Removal of the absorber allows the 5 Kelvin sky noise to enter the system. Precise measurements of the power change are used to determine the total system operating temperature; 8 Kelvins were measured. The maser contributes 2 Kelvin, 1 Kelvin is contributed by the waveguide transducer and feed-horn; the remaining 5 Kelvins are contributed by the atmosphere and cosmic background at 2.3 GHz.

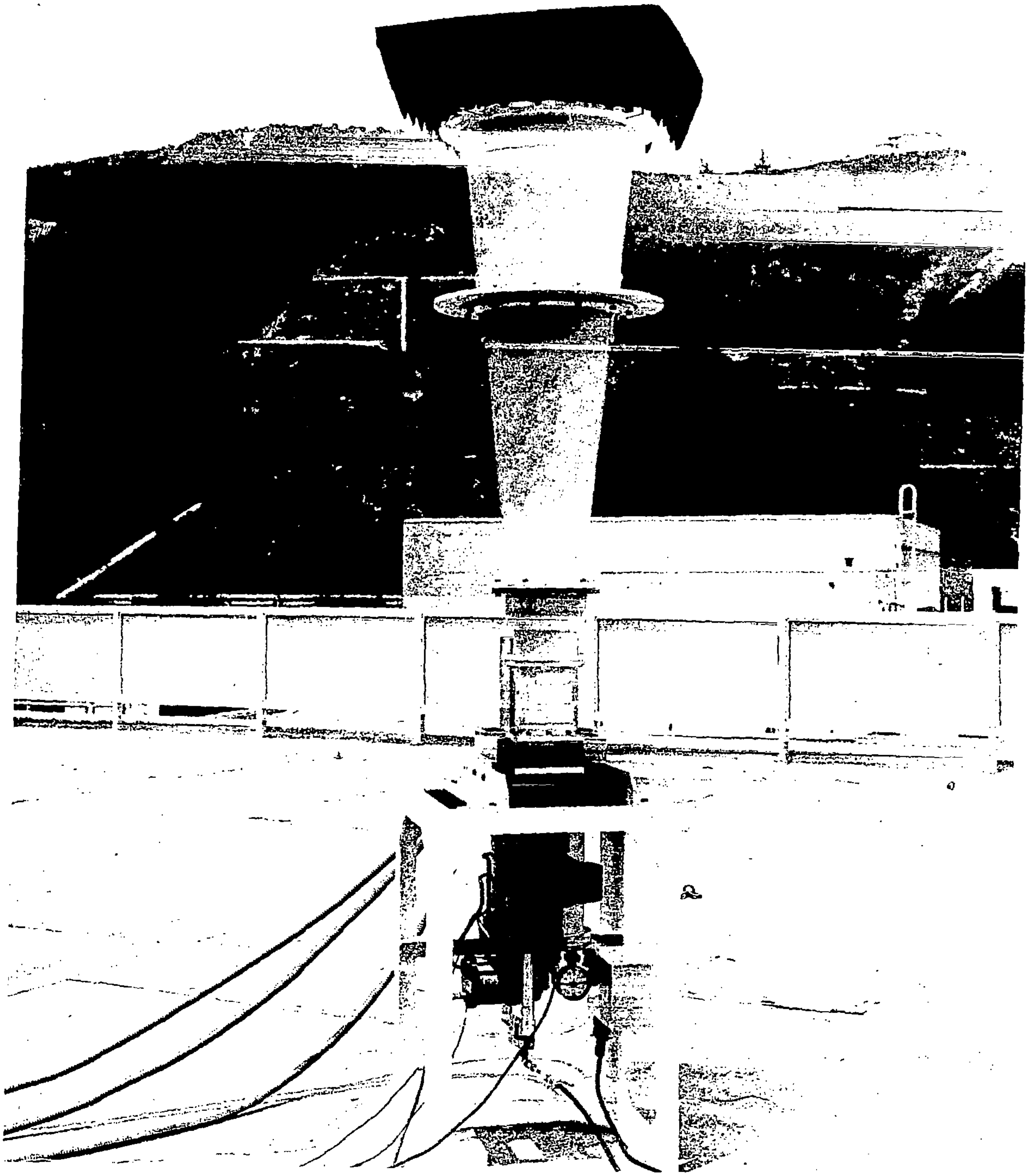

Figure 10. Low-noise S-band maser during noise temperature evaluation.

A summary of noise temperatures measured since 1960 is shown in figure 11.

Figure 12 shows maser bandwidths achieved since 1960. Our first cavity maser (at JPL) achieved a bandwidth of 0.7 MHz with 20 dB net gain. Many other organizations were involved in the development of masers during the late 1950s and the 1960s. Much of their technology was used in JPL maser designs. By the late 1960s most workers discontinued the development of masers; bandwidth limitations together with the high cost and complexity of 4 Kelvin cryogenic systems seemed to indicate a limited future for the ultra-low-noise amplifiers. Satellite communications systems required much greater bandwidth than had been achieved with masers. Increased transmitter power in satellites was used to assure the needed signal to noise ratio at the earth stations without the use of ultra-low-noise amplifiers. In contrast, deep space communications did not require extremely wide bandwidth and spacecraft transmitter power was limited. The use of ultra-low-noise receiving systems for deep space communications was a cost effective way to assure the reception of signals, including high quality television pictures, from distant planets. A significant omission from figure 12 and from the presentation of this paper in June was the achievement of a 130 MHz bandwidth with a C-Band maser using rutile. The rutile-meander-line maser was developed by the NASA-Goddard Space Flight Center (Johnson, 1967). Recent cooperative work between JPL and NRAO show that it will be possible to build a ruby maser at 40 GHz with a bandwidth of 1 GHz (Neff et al., to be published).

Figure 13 shows the stability characteristics of a maser using a super-conducting magnet on a moving antenna. Measurements of maser performance on antennas and in the laboratory (Trowbridge, 1975) were used to compute the typical values shown.

Figure 14 shows a wide range of costs associated with the construction of masers systems. Development costs are not included; the dollar amounts indicated are for existing designs. Commercially available components are used where possible. Procurement, fabrication, manpower, and overhead costs are included using current (1978-1979) experience at JPL as a guide.

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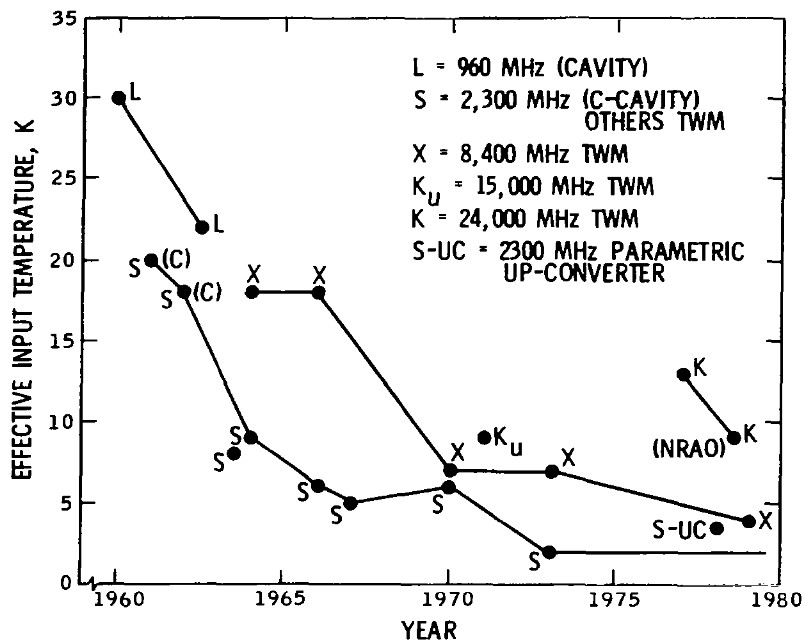

Figure 11. Maser noise temperatures.

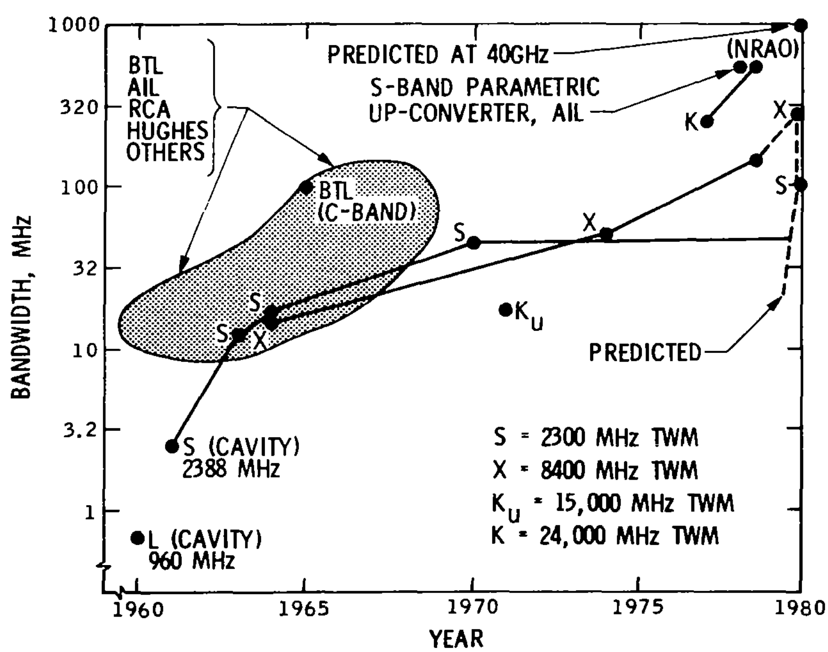

Figure 12. Maser bandwidth.

- CHANGES IN PUMP FREQUENCY, PUMP AMPLITUDE, AND REFRIGERATION TEMPERATURE ARE THE MAIN CONTRIBUTORS TO INSTABILITY FOR MASERS USING SUPERCONDUCTING MAGNETS.
- USE OF PERMANENT MAGNETS TYPICALLY DEGRADES MASER STABILITY BY A FACTOR OF FIVE.
- RAPID ANTENNA MOTION THAT CHANGES REFRIGERATOR POSITION BETWEEN VERTICAL AND HORIZONTAL CAUSES TEMPORARY GAIN CHANGES ($\approx$1 MINUTE) OF UP TO 1/2 DB.

MASER STABILITY VS. TIME

TIME INTERVAL	GAIN (DB)	PHASE (DEG.)	DELAY (NANOSECONDS)
1 SEC	± .01	± .1	± .01
10 SEC	± .02	± .2	± .02
100SEC	± .05	± 1	± .1
8 HOURS	± .2	± 3	± .3

Figure 13. Maser stability characteristics on a moving antenna.

. PARAMETRIC UP-CONVERTER --------- \$10,000 TO \$20,000 EA.
. UP-CONVERTER PUMP --------------- \$10,000 TO \$40,000 EA.
. MASER AND S.C. MAGNET ----------- \$40,000 TO \$60,000 EA.

. PUMP PACKAGE -------------------- \$15,000 TO \$30,000 EA.
. WAVEGUIDES, WINDOWS, HARDWARE --- \$10,000 TO \$40,000
. POWER SUPPLIES, CONTROLS -------- \$15,000 TO \$50,000

. CABLES, GAS LINES, SUPPORT EQUIP. \$15,000 TO \$50,000
. MONITOR AND CAL. EQUIP. -------- 0 TO \$50,000
. CRYOGENICS, DEWAR --------------- \$ 5,000 TO \$10,000
CLOSED CYCLE (4K) REFRIG. ----- \$35,000 TO \$70,000

. DOCUMENTATION AND MANUALS ------- \$ 2,000 TO \$50,000
. TOTAL COST FOR MINIMUM SYSTEM ----------\$102,000
. TOTAL COST FOR DUAL MASER,
MULTIPLE-UP-CONVERTER SYSTEM -------- \$800,000

Figure 14. Ultra-low-noise microwave amplifiers cost ranges.

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