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13. ABSTRACT

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TIME AND FREQUENCY TRANSFER VIA MICROWAVE LINK

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Abstract

A two-way microwave link between the Naval Research Laboratory and the Naval Observatory has been established to transfer both time and frequency information with high accuracy. Time and frequency information is transmitted simultaneously by algebraically adding together a precision 1 MHz signal and 1 pps, thus providing continuous phase information for frequency comparison and epoch time by the pulse. Phase resolution is better than 10 nanoseconds and determination of epoch time better than 0.1 microseconds. Seven precision standards have been intercompared via the microwave link. Continuous phase recording since September 1969 has shown no diurnal dependence and very little effect due to seasonal and temperature changes.

A second microwave link has been established between The Naval Observatory and the Naval Research Laboratory's satellite research communications terminal in Waldorf, Maryland.

Introduction

This paper is concerned with the transmission of precise time and frequency information derived from the highest quality standards. The microwave link has proven to be a low noise, highly accurate method of time and frequency transfer which does not degrade the accuracy of the transmitted signals. This paper will describe techniques utilized in and results obtained from two existing microwave links with respect to establishing and/or maintaining epoch time at remote locations where precision frequency standards are maintained. The results also show great promise for application of microwave links to worldwide time transfer.

Microwave Link

Use of a microwave link for time transfer has yielded highly accurate results (better than 0.1 microseconds). Figure 1 shows a two-way microwave link which has been established between Naval Research Lab and the Naval Observatory and which transferred both time and frequency information. The path between the two locations was practically line of sight and its length was 11750 meters (7.3 miles). The transmitting frequency from the Naval Research Lab was 7137 MHz and the radiated power was 1 watt. The emission bandwidth was 20 MHz and the modulation frequency was 1 MHz which was derived from a hydrogen maser, the Laboratory's standard. At the Naval Observatory the transmitting frequency was 7415 MHz and the radiated power was 1 watt divided between a link to NRL and a second link to Waldorf, Maryland. The emission bandwidth was 20 MHz. The modulation was 1 MHz and 1 pps from the Observatory's Master Clock.

Figure 2 is a block diagram of typical instrumentation at a microwave terminal. At the Naval Observatory the 1 MHz and the 1 pps were combined and fed to the transmitter where a reflex klystron was repeller modulated. This produced a wideband frequency modulated (FM) signal which was fed by waveguide to a 4 foot paraboloid. The energy traveled through air with a delay of 39.3 microseconds to a receiving paraboloid at Naval Research Lab where the signal was fed through waveguide to the receiver for amplification and demodulation. The video output of the discriminator was very similar to the signal fed to the transmitter at the Naval Observatory. The unprocessed video signal was fed to the stop gate of a start stop counter. The counter was started by a pulse (tick) from the standard clock which was run by the phase shifted output of a cesium beam. The local tick starts the counter and the delayed tick stops the counter. The system was calibrated as having a delay of 40.6 microseconds, which included 0.5 microseconds delay at the Naval Observatory, 0.4 microseconds delay in the transmitter and receiver, 0.4 microseconds cable delay at the Naval Research Lab and 39.3 microseconds propagation time in air. The calibration was achieved with the use of a cesium beam traveling clock. The video signal was fed to a 1 MHz distribution amplifier with a 300 cycle bandpass which filtered out the tick information and delivered a pure sine wave for phase comparison to the hydrogen maser reference.

Perturbations to the Link

Figure 3 shows a section of a continuous phase recording. The green trace is the Naval Observatory's Master Clock via the microwave link compared against the NRL hydrogen maser. The blue trace and the purple trace are phase recordings of inhouse cesium beams against the

This is an interim report on a continuing problem. NRL Problem R08-12, Project XF 035 32010. Manuscript submitted June 17, 1970.

maser. The traces were so similar that it was as if the Observatory's master clock was in our own laboratory. Continuous phase recording, 24 hours a day, showed the technique to give results which were independent of diurnal shift. The link has been in operation since September 1969, and does not appear to be affected by seasonal and temperature changes. The only weather condition which seriously affected the link was one of heavy wet snow accumulating on the paraboloid which caused it to act as a microwave absorber. The transmission path was directly over National Airport which permitted evaluation of the effects of high density air traffic. The presence of individual airplanes was repeatedly observed by the amplitude of the signal on an oscilloscope but was not detectable on the phase recording.

Simultaneous Time and Frequency Information

Simultaneous time and frequency information was transmitted by sending a precision 1 MHz signal and 1 pps, algebraically added together. Figure 4 shows the oscilloscope presentation of the composite signal. A storage oscilloscope triggered by an external precision tick was used. Thus, continuous phase information was available for frequency comparison and epoch time was provided by the tick. The correlation of the tick and the phase yielded a method of cross checking time which assured freedom from timing errors at the receiving end. In instances where the output of the 1 MHz was multiplied by 10 to 1000 times phase resolution was observed to be better than 10 nanoseconds. Figure 5 shows a phase recording of the signal multiplied by 100 times. Full scale is 10 nanoseconds. An alternate method of obtaining high resolution would be the transmission of a higher frequency (5 MHz or 10 MHz).

A crystal oscillator was phase locked to the 1 MHz output of the distribution amplifier which yielded an alternate method of preserving time and phase measurements through minor interruptions. The frequency of the oscillator was adjusted to that of the standards so if the link were interrupted the oscillator continued to provide continuity for determination of time.

Frequency Standards Compared

Frequency standards of the highest caliber were used at all terminals of the link. Figure 6 is a photo of the hydrogen masers at Naval Research Lab. Maser I on the right has operated for 6 years as the NRL standard. Figure 7 is a photo of a cesium beam primary frequency standard. A combination of these two types of standards permits implementation of an excellent method for the determination of precision time. Figure 8 shows data obtained at the Naval Observatory of a phase comparison of Naval Research Lab's hydrogen maser via the microwave link against the Naval Observatory's maser. The green trace showed a frequency adjustment of the Naval Observatory's maser. The smooth trace showed the excellent short term stability of the link as well as of both the standards. The Naval Observatory's data showed the USNO H10 #10 maser had a standard deviation of 5 nanoseconds for an averaging time of 5 days for readings taken every 3 hours. NRL H10 #1 maser via microwave link had a standard deviation of 8.2 nanoseconds for the same conditions. For 1.5 day averaging time USNO #10 maser had a standard deviation of 2.2 nanoseconds; NRL #1 maser + link had a standard deviation of 3.6 nanoseconds. Figure 9 shows data obtained and graphed at the Naval Observatory. These graphs show the performance of Naval Research Lab hydrogen maser via microwave link against the Naval Observatory's computed average. The top graph shows the frequency offset from 1 January 1970 to 2 March 1970 where full scale is 5 parts in 10^{12}. The lower graph shows the standard deviation in nanoseconds of a 1-day averaging time of readings taken every 3 hours from 1 January 1970 to 2 March 1970. It was noted that the sigma values fall below 8 nanoseconds.

Microwave Gear

Navy surplus microwave equipment was utilized for the link. Separate transmitter and receiver klystrons were used. Figure 10 shows a photo of the equipment at a microwave terminal - a transmitter and receiver connected by a diplexer. A diplexer was used to allow transmitting and receiving from the same 4 foot microwave paraboloid. The frequencies being used were in the 7 GHz range which allowed the use of highly directive parabolic antennas. Low transmitter power was utilized and interference was minimized by the narrow beams. Carrier frequency stability was not critical allowing the use of unsophisticated microwave terminals. The narrow beams reduced the multipath error to a minimum. The multipath which did occur came from sources close to the direct path and the timing error remained small. The first information arriving was the direct path so that in cases where multipath did occur the leading edge of a pulse was used to give time information. A start stop counter was used to minimize the effects of the multipath.

Waldorf Link

A second microwave link was recently established in conjunction with satellite timing experiments between the Naval Observatory and the satellite communications terminal at Waldorf, Maryland. Figure 11 shows a photo of the 6 foot microwave paraboloid on top of a 100 foot tower with the satellite communications antenna in the background. The 20 mile link was practically line of sight. Phase recordings have been made of the Naval Observatory master clock versus cesium clock #208 at Waldorf. The phase record of this link is shown in Figure 12. The chart has a full scale deflection of 1 microsecond and showed phase resolution to better than 10 nanoseconds.

Conclusions

The concept of using a microwave link to transfer precise time and frequency information with a high order of accuracy has been satisfactorily implemented. The capability to transfer data from remotely located standards is particularly important in eliminating systematic errors such as caused by temperature changes and power failures. At present, 7 precision standards are being intercompared via the microwave link.

The microwave link is in current use as part of an experimental program to disseminate time worldwide. At present, epoch time is being transferred to 2 satellite systems. Time has been transferred from the Naval Observatory to the Naval Research Laboratory's satellite research communications terminal at Waldorf. A description of one satellite time transfer experiment, between Brandywine and Hawaii, was recorded in Naval Research Laboratory's Memorandum Report 2110, "Time Transfer by Communication Satellite" of March 25, 1970, by R.R. Stone, J. Murray, D. Phillips, and D. Pritt.

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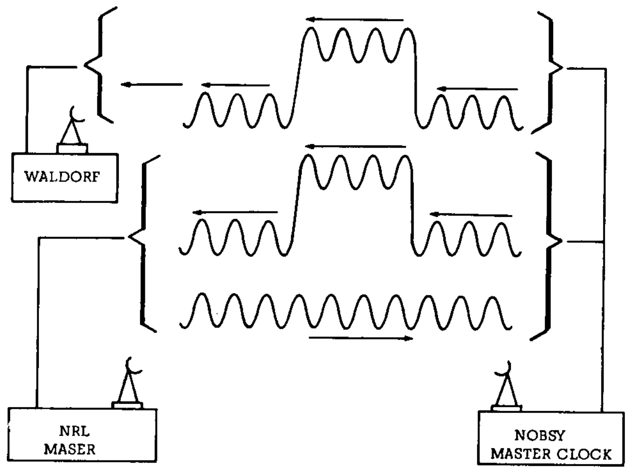


Equipment: Raytheon Television Microwave Relay Model KTR-1000G

<u>Naval Research Lab</u>

Trans. freq. - 7137 MHz
Power - 1 watt
Emission bandwidth - 20F9
Transmit hydrogen maser derived 1 MHz signal

<u>Naval Observatory</u>

Trans. freq. - 7415 MHz
Power - 1 watt
Emission bandwidth - 20F9
Transmit 1 MHz and 1 pps from Master Clock

<u>Results</u>

Total time delay - 40.6 microseconds. (0.5 microseconds cable delay at Naval Observatory, 0.4 microseconds delay in transmitter and receiver, 0.4 microseconds cable delay at NRL. 39.3 microseconds as time traveled in air. This is equivalent to 7.3 miles.)
Precision - 2.3 nanoseconds for one day average.
Phase accuracy - 10 nanoseconds.
Tick jitter - 22 nanoseconds tick to tick (average error over 1 minute was 5 nanoseconds).
Time transfer to better than 0.1 microseconds have been achieved.

Fig. 1 - Microwave link

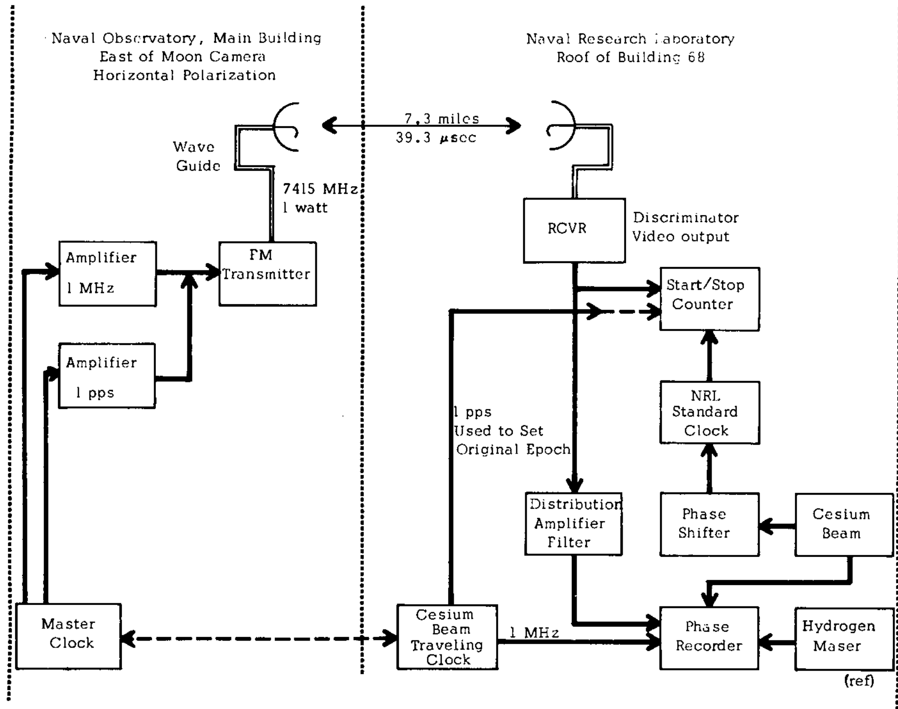


Fig. 2 - Microwave time transfer block diagram

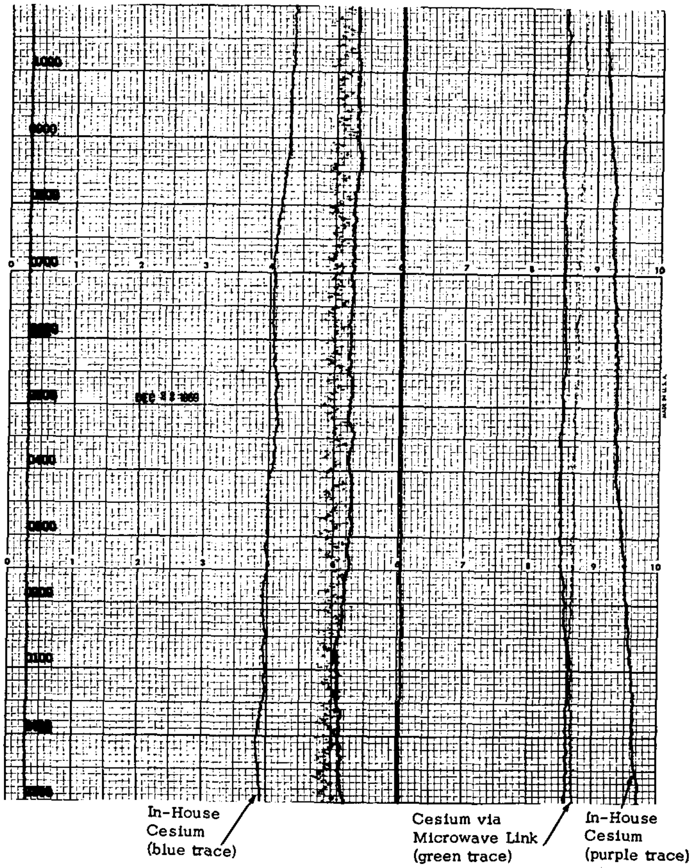
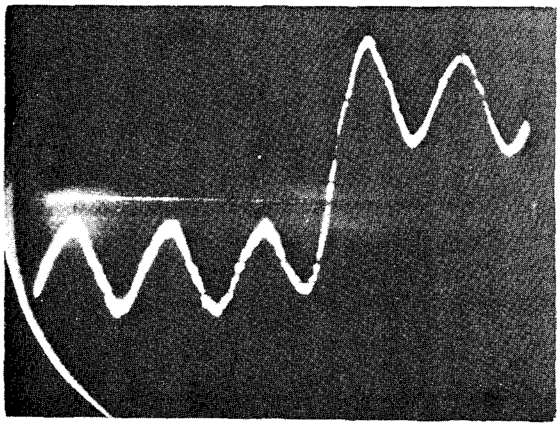


Fig. 3 - Twelve-hour multiple phase recording at Naval Research Laboratory

Vertical = 0.2 V/cm

Horizontal = 0.5 μsec/cm



Attenuation:

Pulse - 2 db

1 MHz - 4 db

Vertical = 0.2 V/cm

Horizontal = 2.0 μsec/cm

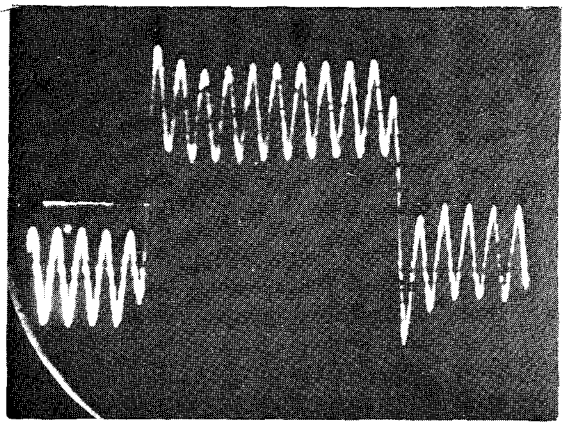


Fig. 4 - Storage oscilloscope presentation of received pulse (Microwave link pulse and 1 MHz transmitted)

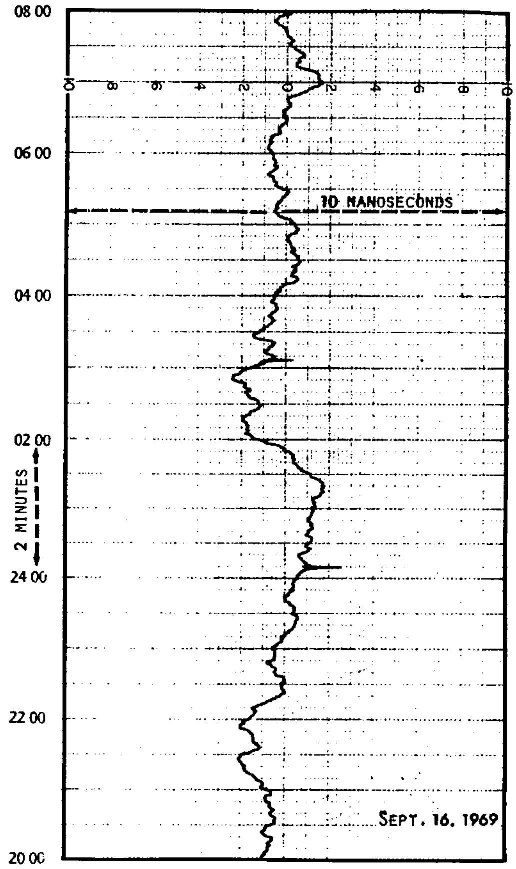


Fig. 5 - Short-term phase comparison of 1 MHz signal with maser (Difference between master clock at Naval Observatory and standard at Naval Research Laboratory)

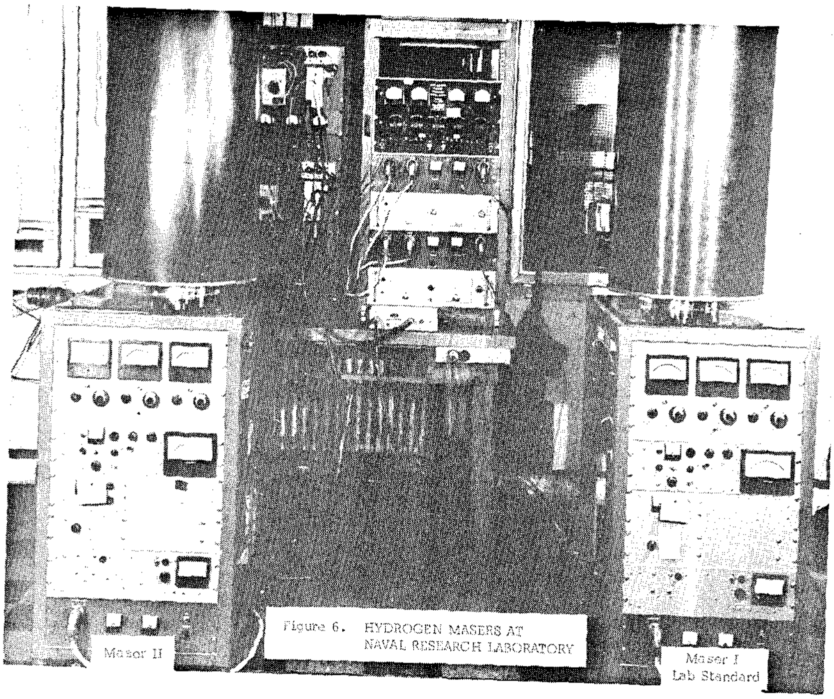


Figure 6. HYDROGEN MASERS AT NAVAL RESEARCH LABORATORY

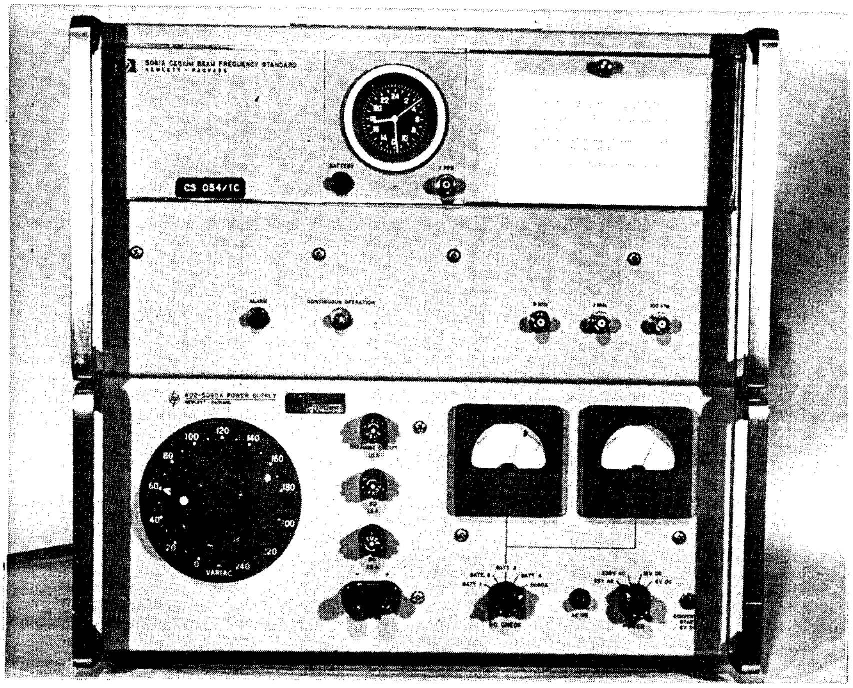


Fig. 7 - Traveling clock — time and frequency standard

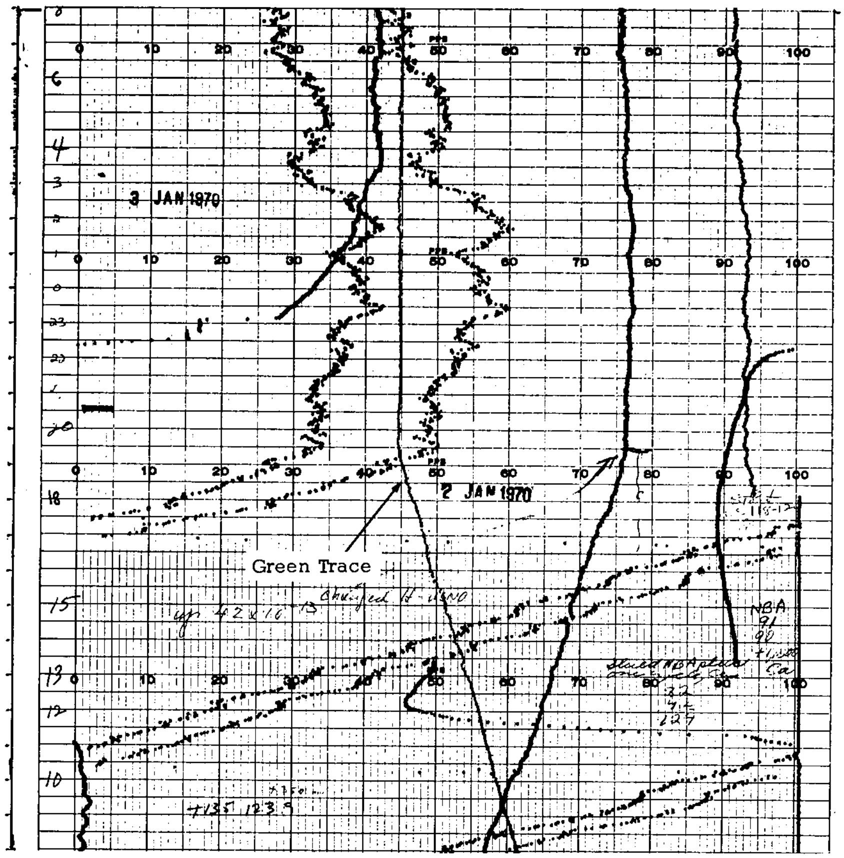


Fig. 8 - Tuning of USNO H10 #10 maser with NRL H10 #1 maser via microwave link

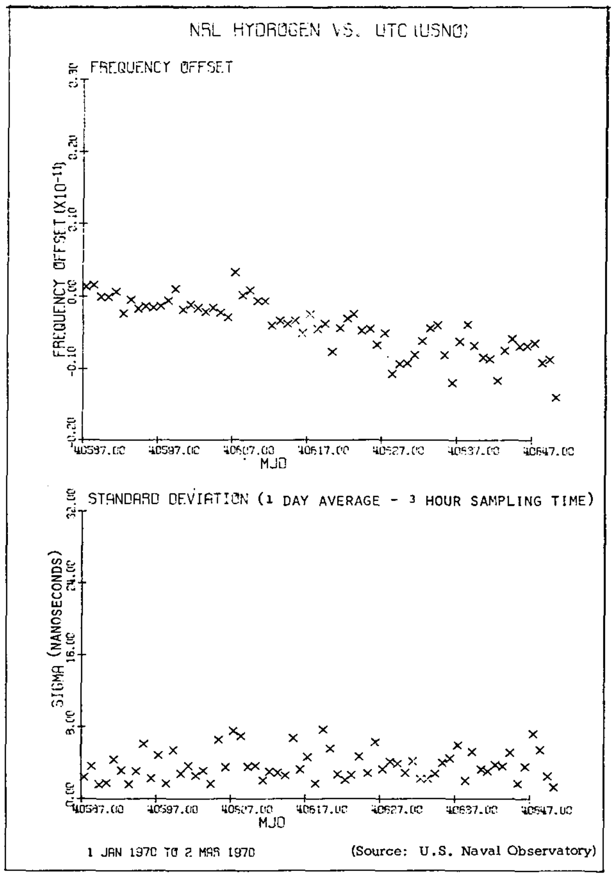


Fig. 9 - NRL hydrogen vs UTC (USNO)

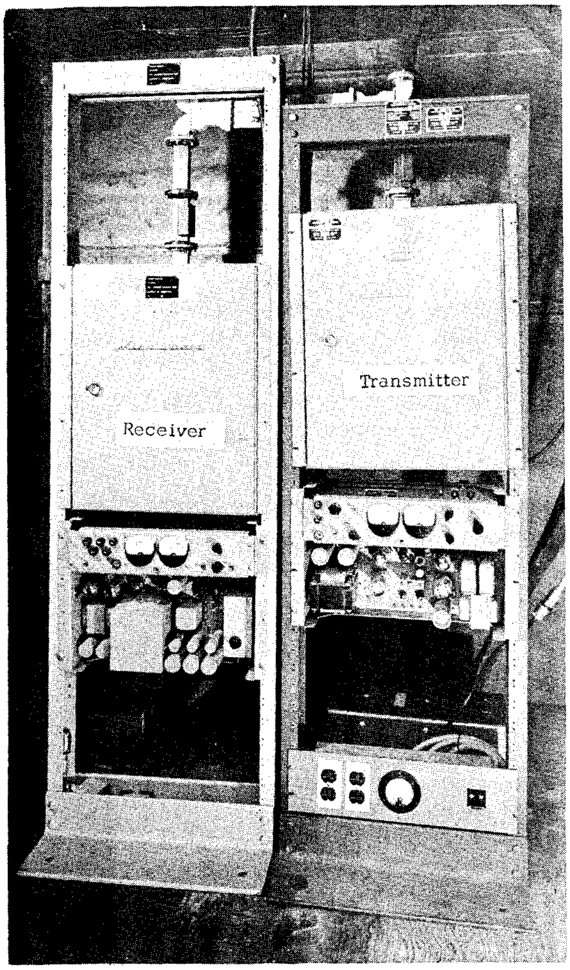


Fig. 10 - Microwave gear

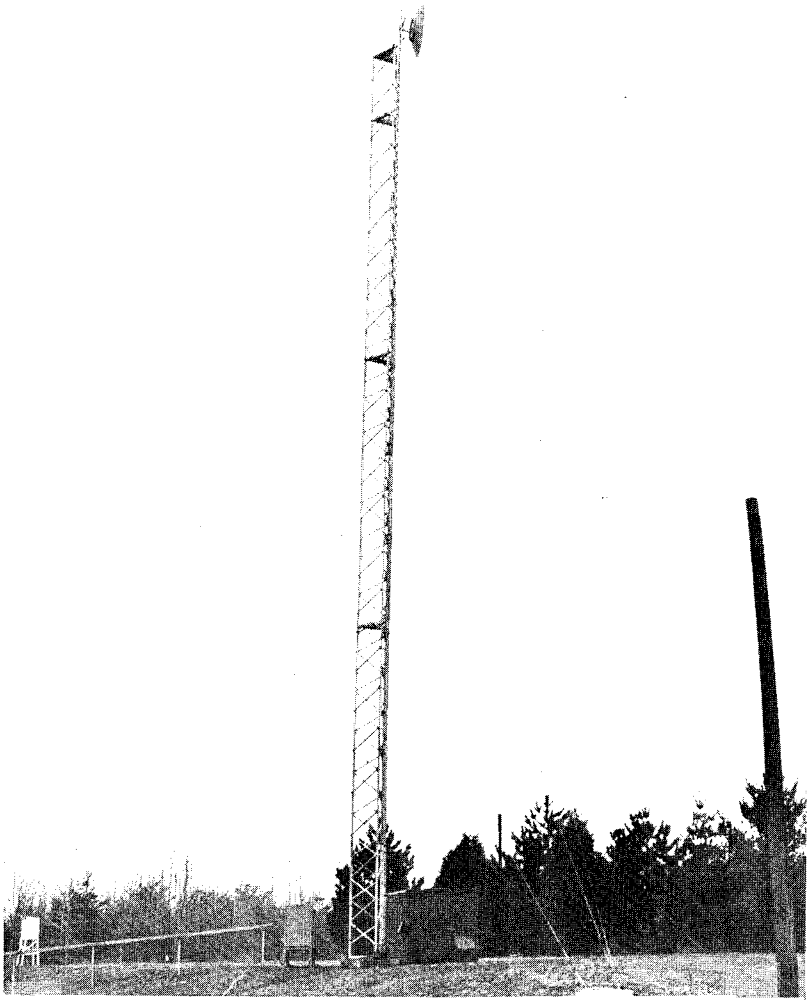


Fig. 11 - Microwave tower and antenna at Waldorf, Maryland

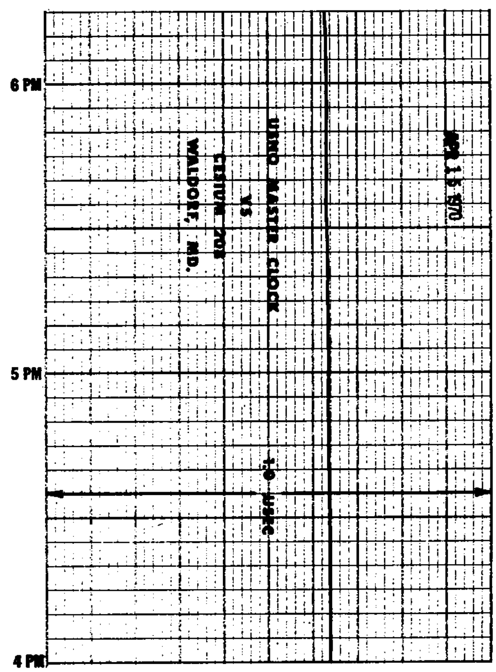


Fig. 12 - Phase recording at
Waldorf, Maryland