A PRECISION MICROWAVE FREQUENCY AND TIME DISTRIBUTION SYSTEM*

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ABSTRACT

This paper describes a precision microwave frequency and time distribution system capable of distributing frequencies with stabilities of several parts in 10^{-}[illegible], and time to the 10 ns level.

A method for distributing a hydrogen maser frequency standard between sites separated by 20 km is required by the Jet Propulsion Laboratory for the Deep Space Network. A distribution system offers several advantages over individual standards at each site. To verify the performance of a hydrogen maser, a minimum of two masers is required at each location, which becomes expensive when multiple sites are involved. A frequency distribution system allows several masers to be maintained at a central standards laboratory, where calibration, maintenance and data logging are more efficient. Since the frequency distribution system is substantially lower in cost than a hydrogen maser, significant cost savings can be realized if such a system is utilized. Using a frequency distribution system rather than individual standards also eliminates frequency offsets between sites, since one standard is effectively present at all the sites.

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INTRODUCTION

Distribution of stable frequencies over one-way radio links longer than a few hundred meters is not possible without degradation of the source stability: For example, a 50 km path has a stability of about 10^{-10} (reference = NRL RPT 7140). This limits the stability of the source after distribution to 10^{-10}, unless some type of compensation for the path can be provided. One method of compensation is to use a two-way link that allows measurement of and compensation for the path between the source (Master) station and the remote (Slave) station.

In order to distribute time, the path delay between stations must be estimated, and the time code advanced by that delay prior to transmission to the remote site. Such a process can be realized by techniques similar to those being employed in the frequency distribution system.

BASIC SYSTEM CONCEPT

The basic concept of the frequency distribution system is shown in Fig. 1. A frequency $\omega\underline{/\omega\tau}$ is transmitted from the maser site to the remote site. After encountering a delay of τ, the phase of the received signal is $\omega\underline{/0}$, the reference frequency to be distributed, at the reference phase angle. This signal is then returned to the master station, where the phase is $\omega\underline{/-\omega\tau}$. By forcing the transmitted signal to lead the reference phase by the same amount that the received signal lags the reference phase, correction for perturbations in the path can be effected. This whole system is predicated on reciprocity of the path. If τ is different for the two directions, it will be impossible to obtain proper correction. Any equipment that is common to both transmit and receive functions (coax, waveguide, antennas, etc) will be considered part of the path and will be corrected. Any phase shifts that are not reciprocal will appear directly at the output of the remote site.

PRACTICAL CIRCUIT CONSIDERATIONS

The circuit in Fig. 1 shows conceptually the operation of a self-correcting frequency distribution system. There are, however, a host of problems with the design as shown. Probably the most obvious difficulty is that both stations are simultaneously transmitting and receiving the same frequency. There are two simple solutions to this problem: have each station (Master and Slave) transmit at a different frequency, or alternately transmit and receive at each station. Unfortunately neither of these solutions is a perfect solution. If widely differing frequencies are employed the dispersive effects of the medium cause the path to become non-reciprocal, violating one of the basic premises of such a system. If the two transmitters operate at very nearly the same frequency (say .002% separation) broadband noise from the transmitter leaks into the receiver severely limiting the sensitivity. The second alternative is to transmit and receive at the same frequency but at different times. One major drawback with this system is keeping the transmitter leakage in the off state to an acceptable level. The required isolation is approximately 160 db for a 20 km path. (The isolation requirement increases as the path length increases). This amount of isolation is extremely difficult to obtain. A second difficulty is reflections off objects in the path. It is not unusual for the reflections to be 10 to 20 db stronger than the desired signal from the other station. This problem could be alleviated by employing a long pulse with a dead time to allow all reflections to die out. Such a system might be a viable solution (assuming the necessary isolation could be obtained), however it requires very narrow loop bandwidths. This requires a VCO at the slave station with medium-term stability not now available.

The solution settled upon is a combination of the two schemes mentioned above. The two transmitters are run at very nearly the same frequency (less than .002% separation) and the system is switched on and off. Any leakage or reflections of the transmitter, being at a different frequency than the received signal (100 KHz at 8 GHz) can be filtered out in the IF amplifiers. The problem of noise is eliminated since the transmitter and receiver are never operating at the same time.

The final difficulty with the configuration shown in Fig. 1 lies in the phase detectors. Such a circuit requires perfectly matched phase detectors. These detectors must remain matched over an entire cycle, since many cycles of phase go by in a typical system. The ideal solution here would be a system with a single phase detector that continuously operates at the zero point on the S-curve.

Fig. 2 shows a basic system that meets all of the criteria previously discussed. (It should be remembered that this is a basic circuit, and could not be implemented exactly as shown). Fig. 3 is the same diagram as Fig. 2 with all the phases and frequencies shown in general terms. Some mention should be made of the synthesizer marked "X M/N". This synthesizer multiplies the 5 MHz signal at its input by the ratio M/N (The ratio of slave to master station transmit frequencies) and shifts the frequency such that a 5 MHz input yields a 5 MHz output. This is a non-trivial synthesis. For example, in the first system constructed, the ratio M/N is 81001/81000. Since the input and output of the synthesizer are at the same frequency, and the multiplication is very nearly one (1.000012... in the system above) it might be interesting to consider the effects on performance if this synthesizer were to be deleted entirely. It is intuitively apparent that the correction in such a system will be in-exact, that is to say, there will be some artifacts of the path present in the output. These residual contributions of the path will be reduced over the uncompensated amount by some constant factor. If the amount of correction could be made sufficiently large, the contribution of the path would be sufficiently small as to be masked by the stability of the standard being distributed. The derivation of a correction factor for such an "approximate" system is presented in Fig. 3. If K can be made large, very large correction factors can be obtained. K is defined (Fig. 3) to be $F_{master}/(F_{slave}-F_{Master})$ or the frequency of the master station divided by the difference in frequency between the master and slave stations. In the first JPL system K=8100/.1=81000, yielding a correction factor of 1.6 X 10^5. It was mentioned earlier that the intrinsic path stability is approximately 10^{-10}. By employing such an "approximate system" the path stability is improved to approximately 6 X 10^{-16} : which is sufficient for frequency standards presently available. If, in the future, it becomes necessary to improve system performance the synthesizer could be added without disturbing the rest of the system.

JPL FREQUENCY DISTRIBUTION SYSTEM

The first distribution systems being constructed at JPL are approximate systems. There were two reasons for this decision. The first was mentioned above: sufficient performance could be obtained with the approximate system. The second reason is that it is questionable if the hardware in the link itself could be made sufficiently stable to observe the added performance that would be predicted by employing the synthesizer.

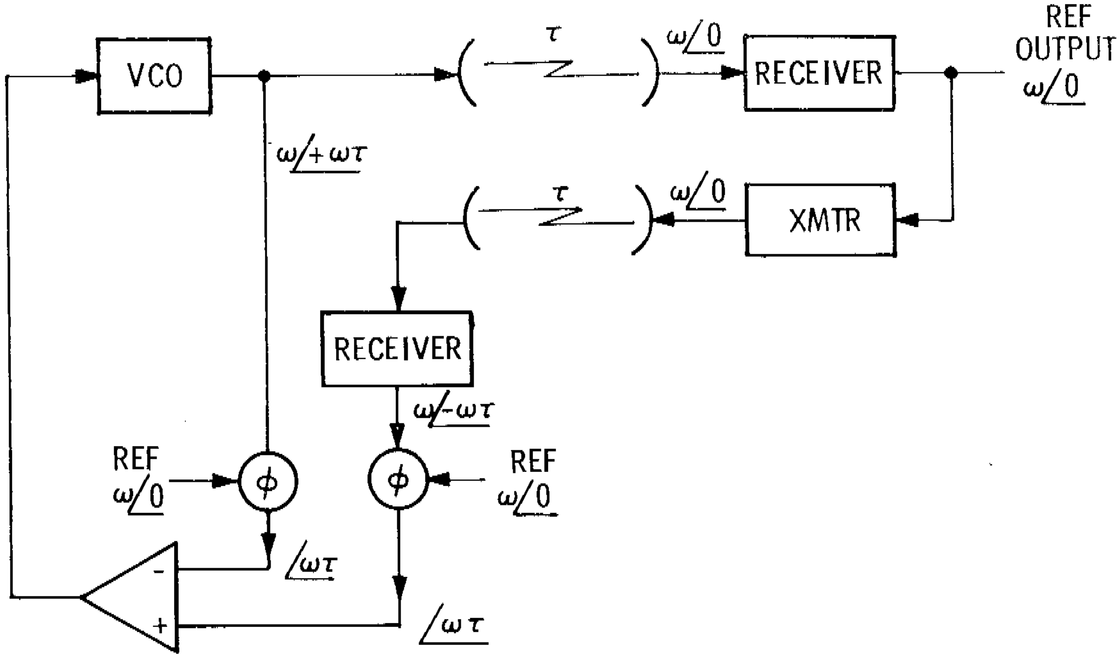
Upon completion of the first system, two sets of lab tests were run. The test configurations are shown in Figs. 4a and 4b. Fig. 4a shows the method used to measure the stability of the system with no path contributions. This stability was found to be about 2.3 X 10^{-15}. This is really a very good stability when one considers the large amount of hardware present in such a system. Fig. 4b shows the setup used to measure the correction factor. We were able to resolve correction factors of 10^5 with the setup shown in Fig. 4b. With this setup we were not able to measure the correction factor of the link, which implies it is probably near its theoretical value.

The first link has been moved to Goldstone for preliminary testing with a real path. At this point, we have no actual performance data. The tests we have run seem to indicate the link is functioning: although its actual performance cannot be verified until the second link is installed. Fig. 4c shows the test that will be run once two distribution systems are available. With this setup a signal is distributed to the remote sight by the first link. A second link then distributes the output of the first link back to its origin. This allows direct comparison of the input signal to itself after passing through two sets of distribution systems. Testing in this manner removes uncertanties that are present if one link and two H-masers are employed for testing.

CONCLUSION

Self correcting microwave links appear to be a viable solution to the problem of providing multiple widely separated locations with stable frequencies. Besides being lower in cost than individual high performance frequency standards, they provide essentially the same frequency at each station, eliminating the frequency offsets that are inevitably present when separate frequency sources are employed. One requirement for the same reference frequency at multiple sites is when differential VLBI techniques are to be used for precision angle measurement of spacecraft, e.g., with respect to the fixed stars.

In the future it is planned to distribute time by suitably modulating the transmitters with a time code and using similar path compensation techniques to those employed in the frequency distribution system. Once the clocks are in synchronization they should remain so, since the same frequency is available at each site.


VCO
τ
ω/0
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τ
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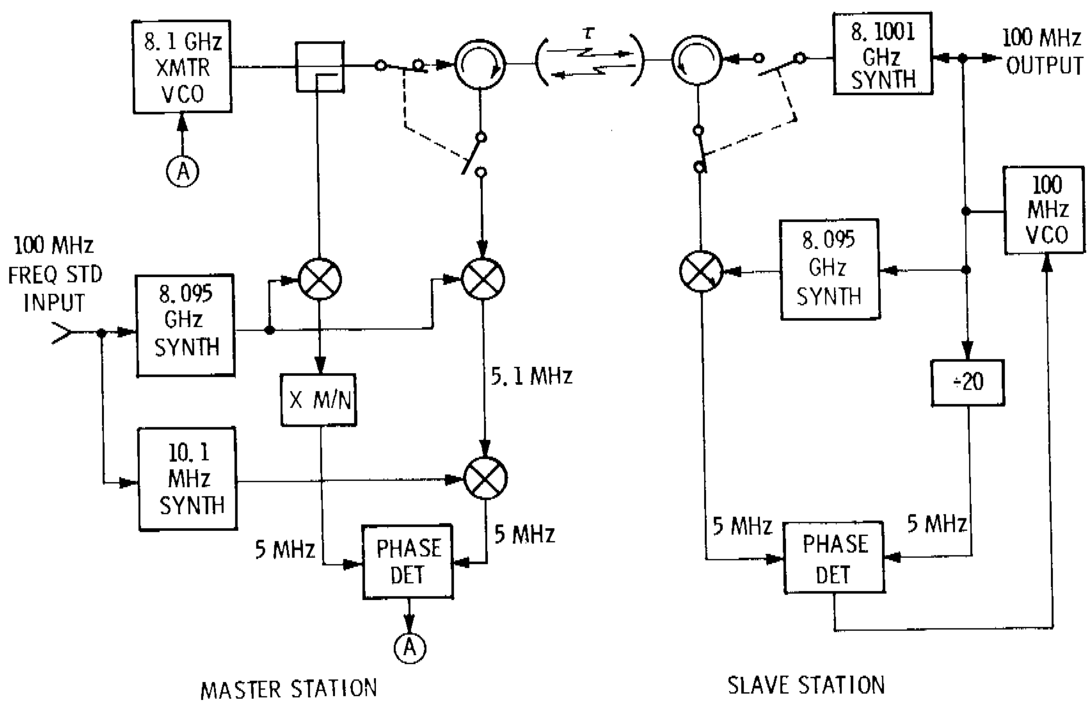
Fig. 1


8.1 GHz
XMTR
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SYNTH
100 MHz
OUTPUT
A
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SYNTH
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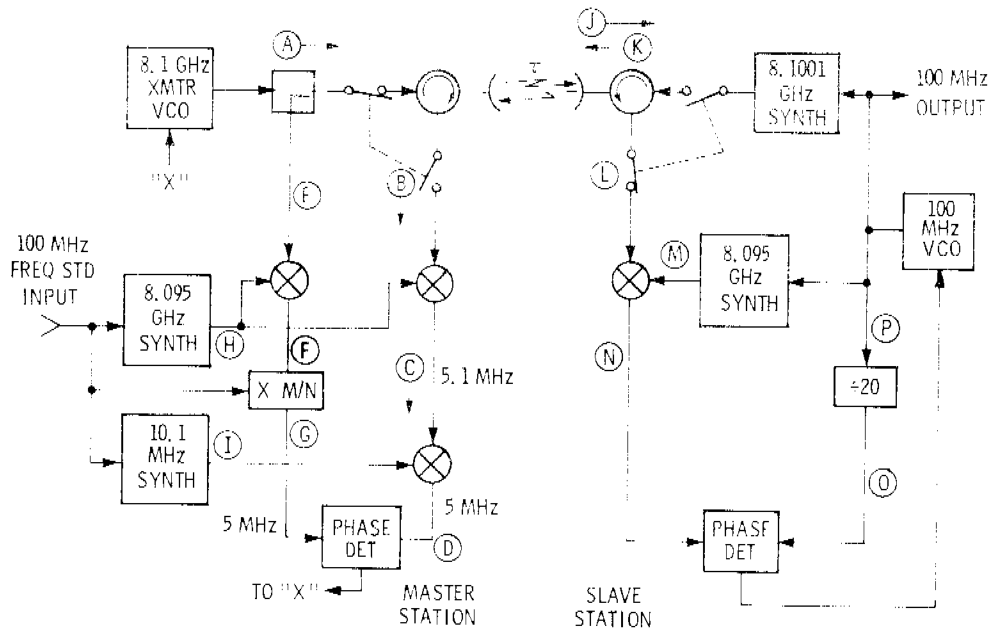
10.1
MHz
SYNTH
5 MHz
PHASE
DET
5 MHz
5 MHz
PHASE
DET
5 MHz
A
MASTER STATION
SLAVE STATION

Fig. 2



MASTER

(A) $K\omega_R \angle K\phi$

(B) $K - \angle (K+1)\,\omega_R\tau$

$= (K+1)\,\omega_R \angle (K+1)\phi - 2(K+1)\,\omega_R\tau$

(C) B - H

$= 51\omega_R \quad (K+1)\phi - 2(K+1)\,\omega_R\tau$

(D) = I - C

$= 50\omega_R \angle 2(K+1)\,\omega_R\tau - (K+1)\phi$

(E) = A

(F) = A - H

$= 50\omega_R \angle K\phi$

(G) $= \frac{(K+1)}{K}$ (F) (FOR PHASE ONLY)

$= 50\omega_R \angle (K+1)\phi$

G = D (WHEN SYSTEM IS LOCKED)

$\therefore \phi = \omega_R\tau$

SLAVE

(J) $= A - \angle K\omega_R\tau = K\omega_R \angle K\phi - K\omega_R\tau$

(L) = J, (K) = (K + 1) P

(M) $= (K-50)\,\omega_R \angle \theta$

(N) = L - M

$= 50\,\omega_R \angle K\phi - K\,\omega_R\tau - (K-50)\,\theta$

(O) $= 50\omega_R \angle 50\,\omega\theta$

(P) $= 1000\,\omega_R \angle 1000\,\theta$

N = 0 (WHEN SYSTEM IS IN LOCK)

SOLVING FOR θ

$\theta = \phi - \omega_R\tau$

IN APPROXIMATE SYSTEM (X M/N IS DELETED)

F = D

SOLVING FOR ϕ

$$\phi = \frac{2(K+1)}{(2K+1)}\,\omega_R\tau$$

$$\text{ERROR} = \left|\, 1 - \frac{2(K+1)}{(2K+1)} \,\right| = \frac{1}{2K+1}$$

$$\text{CORRECTION FACTOR} = \frac{1}{\text{ERROR}}$$

$$\text{DEFINITION:}\quad K = \frac{F_{MASTER}}{F_{SLAVE} - F_{MASTER}}$$

Fig. 3

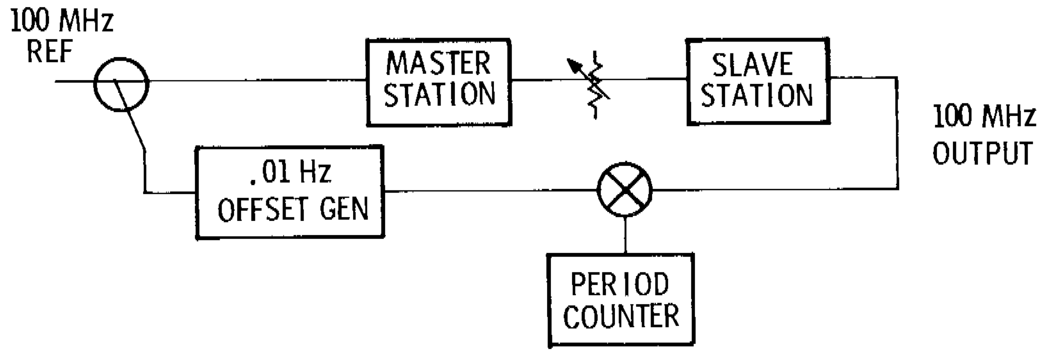


Fig. 4a

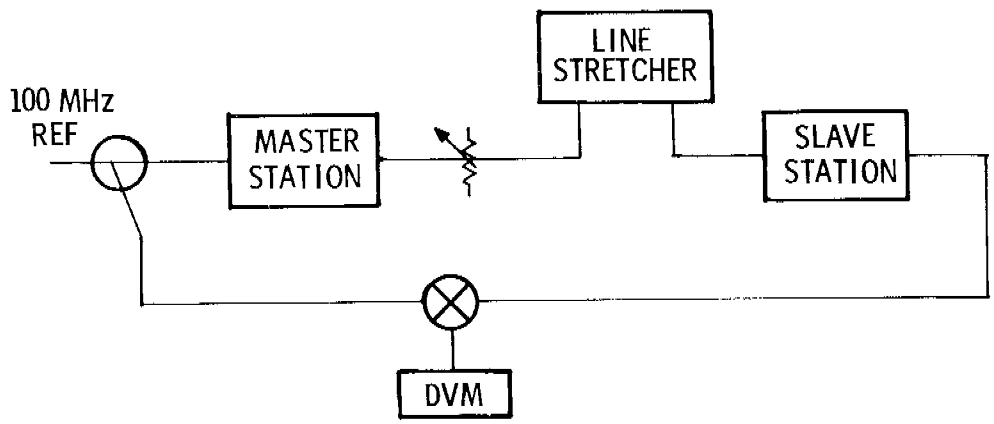


Fig. 4b

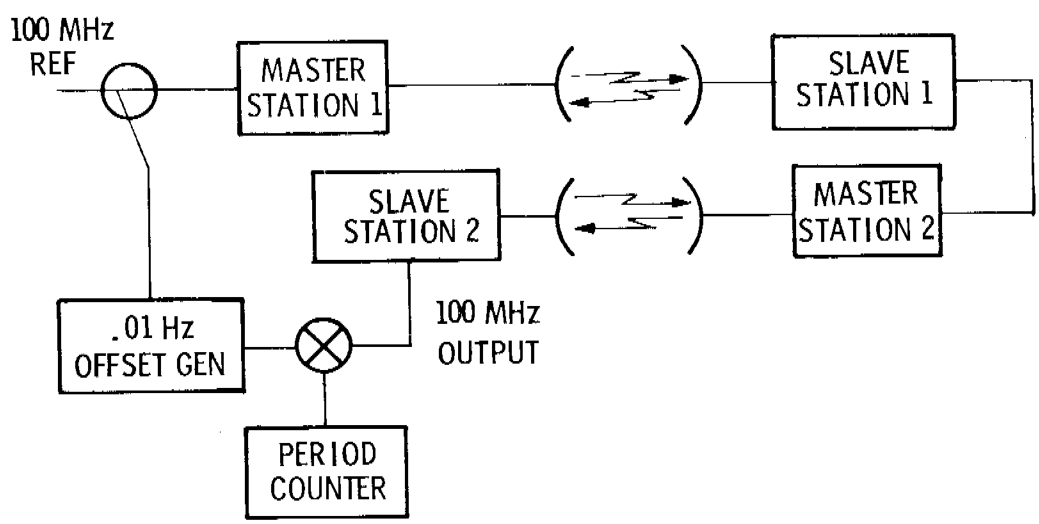


Fig. 4c

QUESTIONS AND ANSWERS

MR. DANE CURKENDALL, Jet Propulsion Laboratory:

How is it working?

MR. MACCONNELL:

Like I said, we haven't been able to measure it against the maser. We measured it looking at the return signal from the other station, and we could see the path on it and see it correcting. It looks like it is working okay. But until we actually do a round trip with a pair of stations or get a pair of masers, we can't be positive it works, although I really don't see any reason it shouldn't.

DR. VICTOR REINHARDT, NASA Goddard Space Flight Center:

You mentioned you got about 2.5 parts in 10^{15}. Over what averaging time was that?

MR. MACCONNELL:

One hundred seconds. I think we'll find it's going to be fairly white noise. I think that we will be able to improve upon that after we get a chance to work with it. This is really the first prototype system, and we have some ideas about what's causing that and may be able to improve it three or four times.

DR. REINHARDT:

Did you look at the phase stability at longer intervals for diurnal shifts?

MR. MACCONNELL:

We ran some phase measurements on the thing sitting in the lab with the air conditioning going up and down, and we could see maybe two or three degrees peak-to-peak phase drift at X-band. For a clock, I think this would be really a nice system because you could take two clocks and sync them up -- two or three degrees at X-band doesn't correspond with very many nanoseconds offset between clocks.

DR. REINHARDT:

That one or two degrees at X-band is less than a picosecond, which is considerably less than a nanosecond.

MR. RONALD WEIMER, National Radio Astronomy Observatory:

You've mentioned transferring time, and I was just wondering if you have done anything like that?

MR. MACCONNELL:

At this point, we haven't built a system for controlling the time. However, we have some ideas about how we are going to do it. I think we can do it by controlling the on and off pulsing of the transmitters and receivers. The system will have a loop around it similar to the frequency control loop to take out the path delay. Also, because we have such good resolution of the X-band phase, we'll be using that somewhat too.

MR. WEIMER:

How do you currently control the turning on and turning off of these things?

MR. MACCONNELL:

We have a small frequency synthesizer that is just controlling the gates on the transmitter and receiver. We run at about 150 kHz for the on-off ratio. We have another synthesizer at the slave station. We have a system that has ten phase-lock loops, which are all auto acquire. Before it turns on the last transmitter, it lines up the phase of the synthesizer with the phase of the incoming burst of rf. When it gets lined up, it switches over and turns on its transmitter. Then it is running purely open loop at that point. Both synthesizers are locked to the same reference, so there is no problem there.

On the burst of rf: Actually, both transmitters transmit at the same time, but there is a delay before the burst of rf that it transmits gets to the second station. So we set it up so we have an integer number of half cycles of the switching array in the path. The frequency that we chose to switch the transmitter and receivers on and off is a function of the path length. We decided to choose 150 kHz because we wanted a frequency higher than 100 kHz so sidebands due to the switching wouldn't lay on top of the other station.