TRACKING THE LUNAR ROVER VEHICLE WITH VERY LONG BASELINE INTERFEROMETRY TECHNIQUES

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I. VERY LONG BASELINE INTERFEROMETRY (VLBI)

Very Long Baseline Interferometry is a highly accurate method for determining the angular positions of radio sources. This is done by recording the radio signal at two widely separated stations. The difference in arrival time of the signal at the two stations, τ, is used to determine the source angular position, θ, with the trigonometric relationship shown in Figure 1. A broad frequency signal is required to determine τ to a high resolution. A second method, not requiring a broad frequency signal, is to measure the frequency difference of the signal observed at the two stations. The frequency difference, which is proportional to the rate of change of τ, yields $\dot{\theta}$, the rate of change of the source angular position.

In early 1971, Mr. Irving Salzberg of the Metric Data Branch proposed using NASA's Unified S-band tracking network to interferometrically track the Lunar Rover as the astronauts drive across the surface of the moon.

II. THE UNIFIED S-BAND SYSTEM

Consider the capabilities of NASA's Unified S-band doppler tracking system for VLBI tracking. The system's ability to determine a change in θ, the source angular position, depends on its ability to determine a change in Δr, the range difference between the tracking stations and the signal source. That is,

$$B \cos \theta = \Delta r \tag{1}$$

Differentiating

$$d\theta = \frac{-d(\Delta r)}{B \sin \theta} \tag{2}$$

The USB doppler tracking system can observe range changes of less than 1 centimeter. The system is limited by the cesium frequency standard noise. Over a 10-second interval, the rubidium frequency standards show about half that noise. The H-master standards do not add appreciable noise to the 2 millimeter noise of the remainder of the system. Typical station separation is about 6000 kilometers.

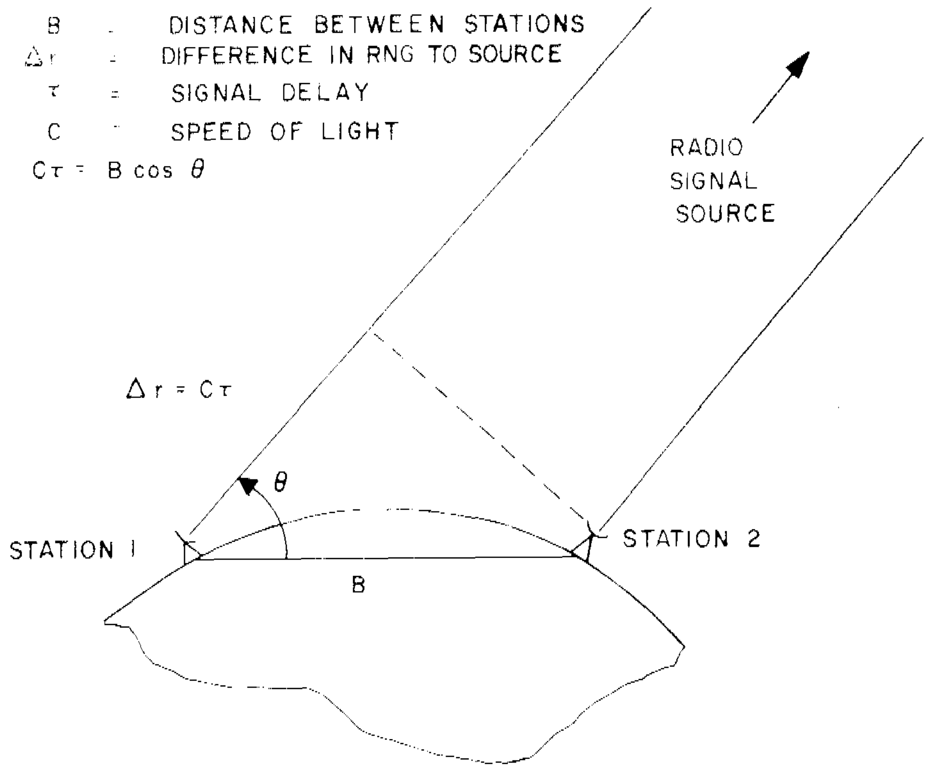

Figure 1. Very long baseline interferometry.

Solving for $d\theta$,

$$d\theta \approx \frac{10^{-2}}{5 \times 10^{6}} = 2 \times 10^{-9} \text{ radian} = 0.005 \text{ sec}$$

That is about the height of an ant at 100 miles! At lunar distances that amounts to 0.8 meters.

The present doppler tracking system can be used for Lunar Rover VLBI tracking without additional equipment. The data is recorded in a highly compact form; the hundreds or thousands of recording tapes normally needed for VLBI are not required. Weeks are not needed to reduce the data: real-time data processing is possible.

III. THE ANALYSIS METHOD

Figure 2 shows how doppler tracking is utilized for Lunar Rover tracking. The doppler frequency shift is a measure of the range-rate, the radial component of the source velocity.

$$\dot{r} = \hat{r} \cdot \vec{V} \tag{3}$$

The difference in radial velocity from the two stations is equal to the component of the velocity in the direction $(\hat{r}_1 - \hat{r}_2)$.

$$(\dot{r}_1 - \dot{r}_2) = (\hat{r}_1 - \hat{r}_2) \cdot \vec{V} \tag{4}$$

With a third station, one can measure the velocity component out of the plane of the page. The third velocity component is determined by constraining the Lunar Rover to the surface of the moon. The lunar surface features are modeled by adjusting the local lunar radius, R_L. The range-rate itself cannot be used to determine this third velocity component, since the Rover transmitter frequency, being only quartz crystal controlled, may be biased by one part in 10^5. In fact, the range-rate is used with the lunar ephemeris to solve for the transmitter frequency in the differential doppler reduction.

There are several problems associated with this method. During the course of a track the ionospheric phase path length may change several meters. A one meter change in the phase path length results in approximately a 100-meter error in the Lunar Rover position. A frequency standard bias of one part in 10^{12} produces a 100 meter per hour bias in the Lunar Rover tracking. Station location uncertainties produce similar errors.

These error sources are eliminated by doppler tracking both the Rover and the Lunar Module transmitters at each station. The Lunar Module is used as a reference benchmark and all Lunar Rover measurements are made with respect to the Lunar Module (Figure 3). By subtracting the Lunar Module doppler range-rate from that of the Rover, all systematic biases common to both signals, such as those due to the phase path medium, the frequency standard, station location and the lunar ephemeris cancel to the first order. If there are no

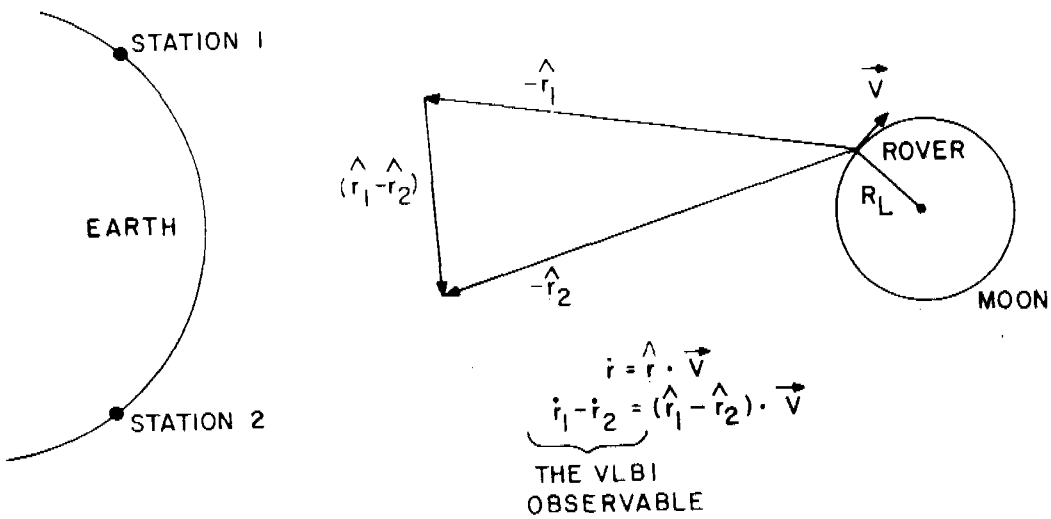

Figure 2. The VLBI observable.

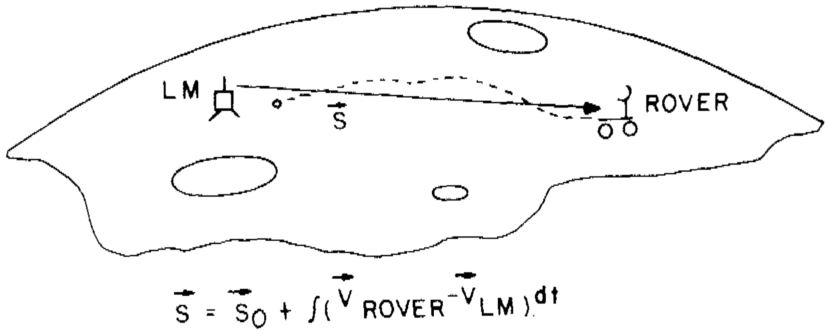

Figure 3. Lunar Rover tracking by differential VLBI.

inter-receiver phase drifts, only the differential VLBI observable remains as a first order quantity. The position of the Rover with respect to the Lunar Module, $\vec{S}$, is determined by integrating the differential velocity from the known initial position.

$$\vec{S} = \vec{S}_o + \int (\vec{V}_{Rover} - \vec{V}_{LM})\, dt$$

In summary, Lunar Rover VLBI tracking requires three widely separated stations, doppler tracking both the Lunar Rover and the Lunar Module.[1]

IV. APOLLO-16 LUNAR ROVER TRACKING

During the first Rover traverse of Apollo 16, four stations participated in Lunar Rover tracking. The four stations Madrid, Ascension Island, Merritt Island, and Goldstone are shown in Figure 4. MIL–ACN–MAD and GDS–ACN–MAD form the large triangles needed for sensitive Lunar Rover tracking. The triangle formed by GDS–MIL–MAD is only fair; that formed by GDS–MIL–ACN, very poor.

Figure 5 is a time line of the events during the traverse. There were three portions to the traverse. The first, from the Lunar Module area to Plum Crater, where the astronauts stopped for scientific activities. The second, from Plum Crater to Spook Crater for more rock collecting, then back to the Lunar Module. When the astronauts dismount from the Rover, they switch the Rover transmitter from PM to FM for TV transmission. The USB system is unable to doppler track an FM transmitter.

MAD, ACN, and MIL participated during the entire traverse, a total of 63 minutes of tracking. GDS participated only during the last two portions, for 34 minutes. The entire traverse totalled more than 4 km.

[1]See *STDN Metric Tracking Performance Apollo-16 Final Report*, NASA/Goddard X-832-72-203 for a discussion of the algorithm. The report is available at the Goddard Space Flight Center Library.

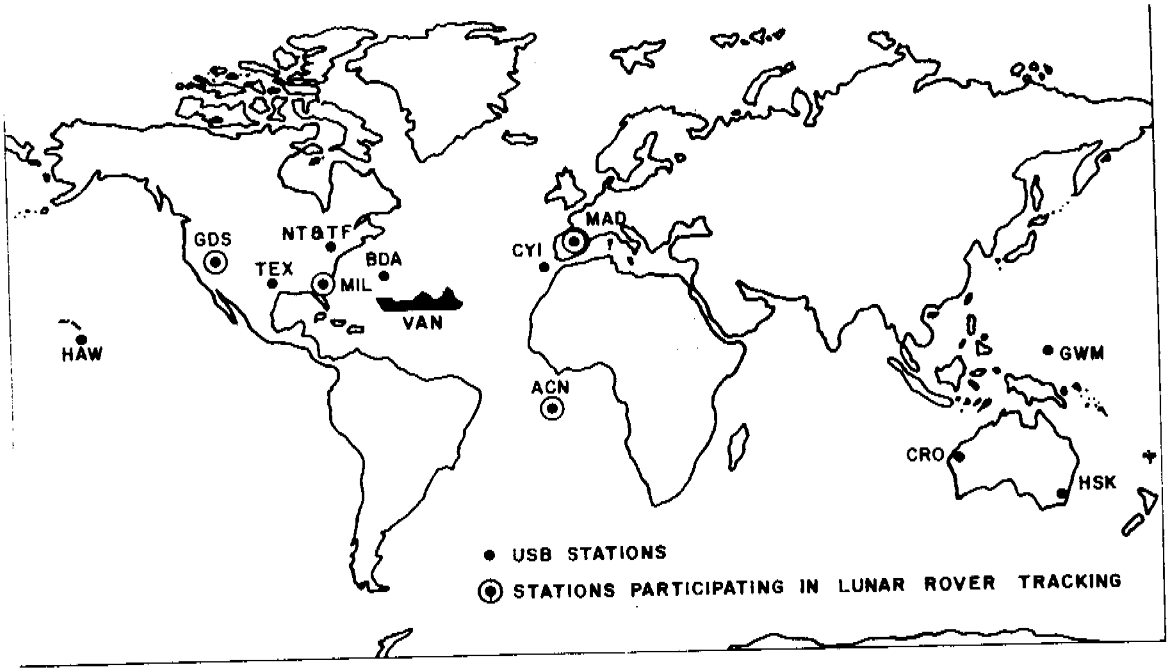

Figure 4. The USB Manned Space Flight Network.

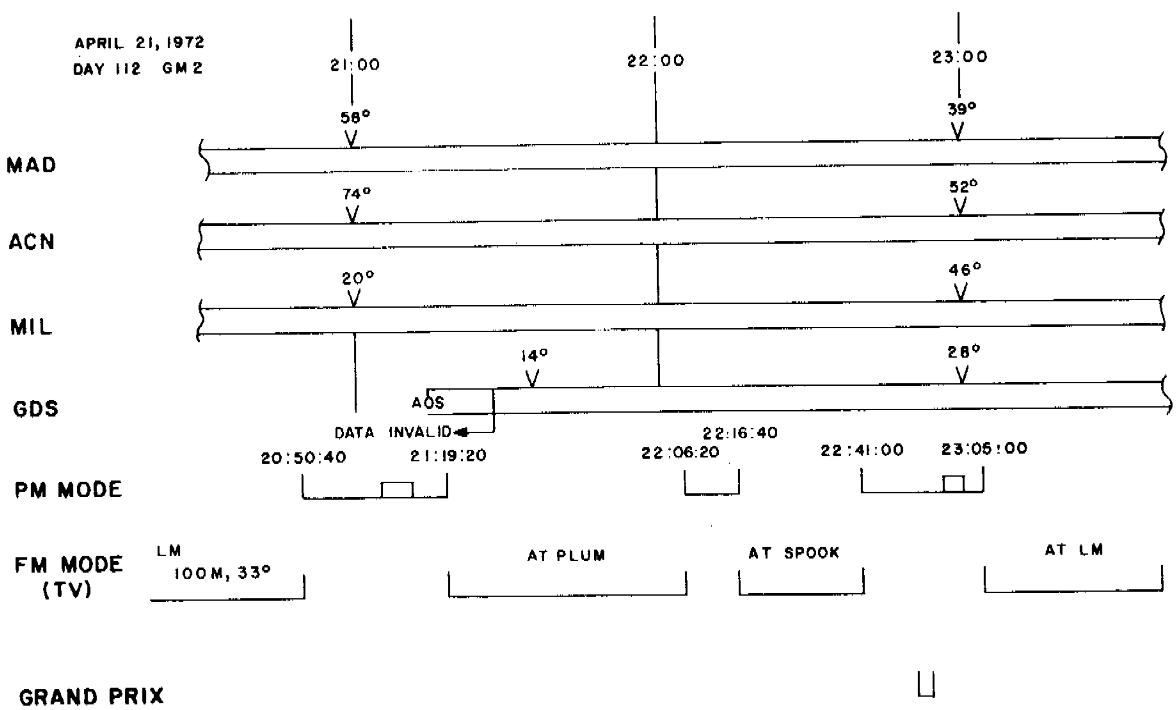

Figure 5. Events and time-line for traverse of EVA-1, Apollo-16.

V. APOLLO-16 TRACKING RESULTS

Figure 6 is a map of the Rover traverse determined by Lunar Rover tracking.[2] These results were compared to the astronauts readings of the Rover on-board navigation system. The Rover on-board navigation system has a granularity of 100 meters in range and one degree in bearing to the Lunar Module. Although the on-board navigation system is also susceptible to error from wheel slippage and alignment error, nevertheless, the on-board navigation results agreed with the Lunar Rover tracking results to well within 50 meters.

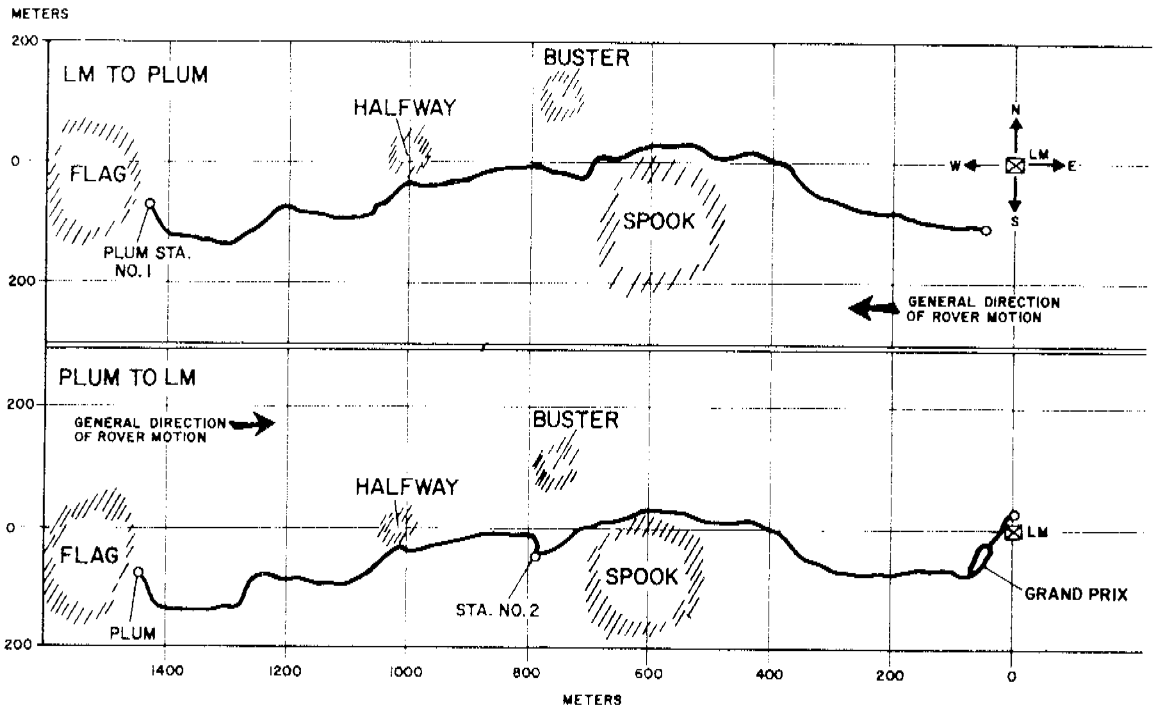

Figure 6. Map of the Lunar Rover track.

[2]A complete Lunar Rover Track ephemeris is contained in Bendix technical memorandum MDO-72-297 *Apollo-16 Lunar Rover Tracking – Final Results*. The memorandum is available from the Metric Data Evaluation Office; Bendix Field Engineering Corp.; 6811 Kenilworth Ave.; Riverdale, Md.

The 20-second incremental motion of the Lunar Rover during portion 1 is plotted in Figure 7. Note that a stationary period is clearly visible. This six-minute stationary period occurred just south of Halfway Crater (see Figure 6) while the astronauts debated with the Mission Control Center whether the crater they had just passed was Flag Crater or Halfway Crater. This vividly demonstrates the astronauts need for a reliable navigation system. A second stationary period occurred after the Gran Prix maneuvers while one of the astronauts was setting up mortar charges for a seismographic experiment. These two known stationary periods were used to evaluate the Lunar Rover tracking noise and drift. The drift and 1 σ noise of the MIL–ACN–MAD configuration is presented in Table 1.

The Mission Control Center reported that at the end of the first traverse the Lunar Rover parked a few meters north of the Lunar Module. This agrees very well with the Lunar Rover tracking results listed in Table 2.

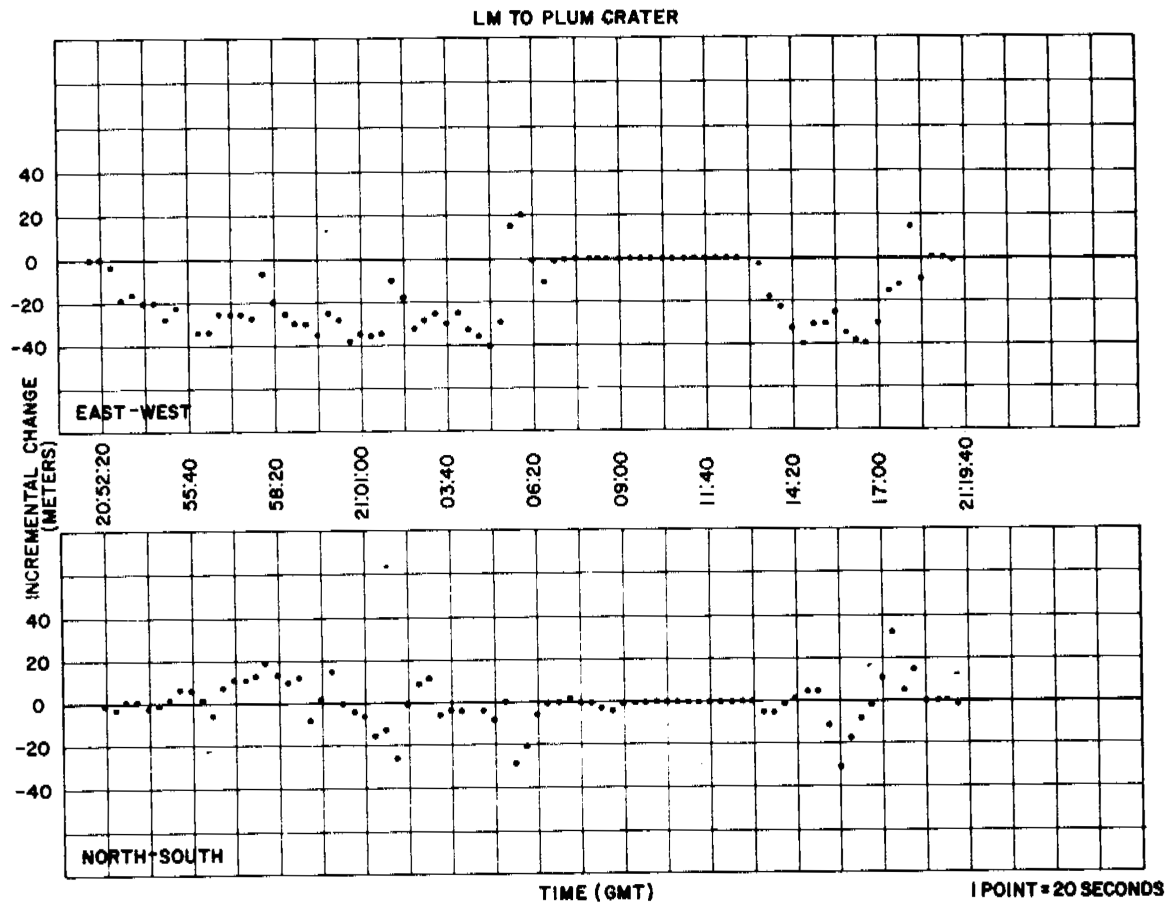

Figure 7. Incremental motion of the Lunar Rover.

Table 1
Lunar Rover Tracking—Noise and Drift.

Stationary Period (GMT)	Noise (Meters)	Drift (mm/sec)
21:06:04-21:12:40		
N-S	0.97	-8
E-W	0.40	-7
22:55:00-23:01:40		
N-S	0.69	-7
E-W	0.54	-4

Table 2
Lunar Rover Tracking Closure Results.

Station Configuration	N-S (Meters)	E-W (Meters)
MIL - ACN - MAD	6.0	9.0
GDS - ACN - MAD	7.4	5.6
GDS - MIL - MAD	-8.8	0.3

VI. APOLLO-17

For the coming Apollo-17 mission, Lunar Rover tracking has been scheduled to support all three Rover traverses. This amounts to about seven hours of tracking covering 34 kilometers. The tracking information is needed to aid the astronauts' navigation and to provide an accurate traverse map for the Traverse Gravimeter and the Surface Electrical Properties experiments. The data will be processed in semireal-time. That is, the data will be received at Goddard Space Flight Center in real-time and will be batch processed within ten minutes of each Lunar Rover stop.

[3] Personal communication.

VII. FUTURE APPLICATIONS

Recently a modification to the tracking station receiver has been designed and tested by Dr. Hinteregger of MIT. This modification, shown schematically in Figure 8, will permit the direct recording of the differential doppler phase of two signals with only one receiver. The IF signal is wide enough to carry both transmitter signal frequencies. The receiver is locked onto one signal frequency while the other signal frequency, which contains the differential doppler phase, is tapped of the IF signal and converted to a frequency acceptable to the doppler recorder. The resulting differential doppler phase shows a stability improvement in noise and drift of more than two orders of magnitude.[3] This stability improvement is gained with a 33 percent reduction in the tracking network resource requirement.

The differential VLBI tracking technique makes a large set of tracking methods and scientific experiments now possible. For example, lunar librations are presently being measured by differential tracking of the ALSEP scientific transmitters on the moon. Results to within one second of selenographis arc, a factor of ten improvement in our present knowledge, are expected. Other applications include the measurement of wind velocity on

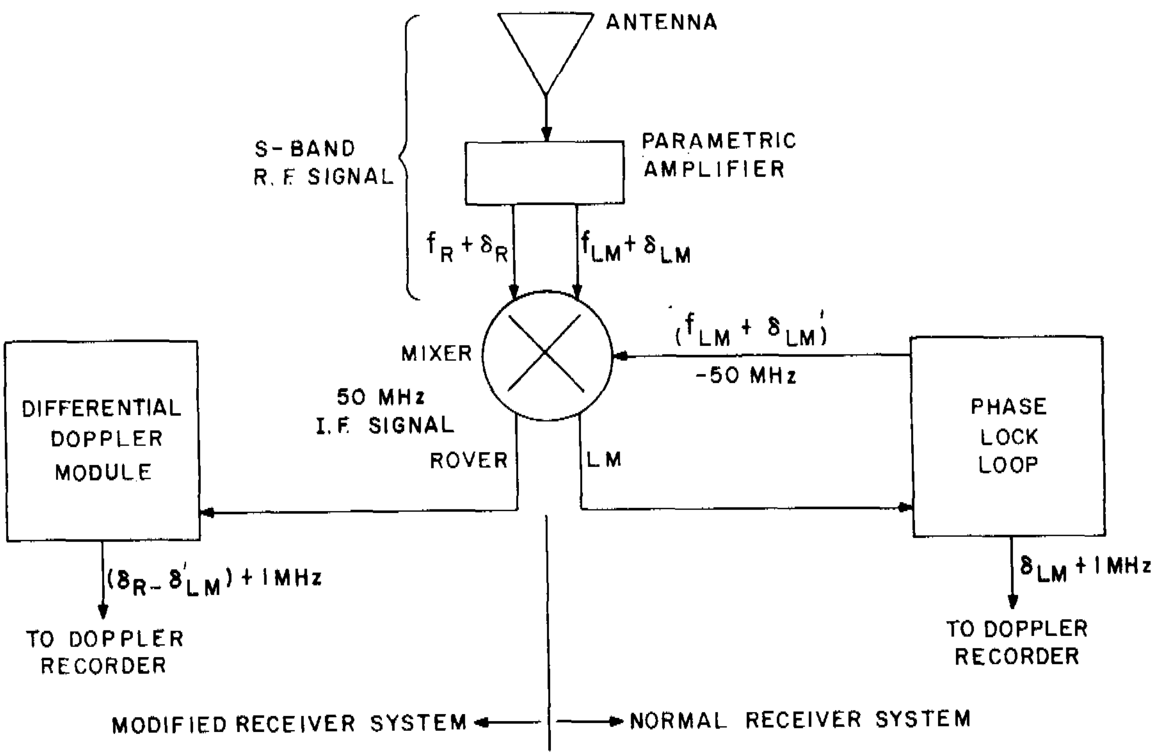

Figure 8. Receiver modification for recording differential doppler frequency.

Venus, mother-daughter satellite tracking, the measurement of the lunar mascons, and the measurement of planetary gravitational fields.[4,5]

In conclusion, differential VLBI has been used to track the Apollo-16 Lunar Rover with better than 25-meter accuracy and noise of less than one meter. This technique, which will support Apollo-17 Lunar Rover experiments and navigation, has application to a wide range of future space navigation and astrophysical experiments.

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[4]Councilman, C. C., H. F. Hinteregger, and I. I. Shapiro, *Science*, vol. 178, pp. 607-608.

[5]Invaluable support in the theory and the reduction techniques of differential VLBI was provided by Drs. Hinteregger, Councilman, and Shapiro, of MIT.