Pioneer Venus 1978 Mission Support

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The differential long baseline interferometry experiment for the purpose of measuring the wind velocities in the atmosphere of Venus as a part of the Pioneer Venus 1978 multiprobe mission is described.

I. Introduction

The Pioneer Venus multiprobe mission includes a differential long baseline interferometry experiment, which will attempt to measure the wind velocity in the atmosphere of Venus as four probes descend through the atmosphere. Basically, the experiment will be using interferometry techniques to measure the components of the wind velocity perpendicular to the line of sight (Earth–spacecraft direction) and established doppler techniques to measure the velocity components along the line of sight. As described in previous articles, the bus spacecraft is retarded by a trajectory correction after it releases the four probes, so that it will enter the Venusian atmosphere after all four probes have reached the surface of the planet. In this way, the bus serves as a reference signal, undisturbed by the Venusian atmosphere. A corrected difference is taken between the bus signal and each of the probe signals at a particular tracking station to eliminate ionospheric and interplanetary effects, and a second difference is taken between pairs of tracking stations which produces a measure of the rate of change of the angle subtended by the two stations and a probe.

Each pair of stations resolves only one component of the velocity. In order to resolve both components of the wind velocity perpendicular to the line of sight and to provide some measure of redundancy, four stations will be equipped to support this experiment. The two 64-meter DSN stations located at Goldstone, California, and Canberra, Australia, will be utilized, along with 12-meter Spaceflight Tracking and Data Network (STDN) stations located at Santiago, Chile, and Guam. The Principal Investigator for this experiment is Dr. Counselman and the Co-Investigator is Dr. Pettengill, both of the Massachusetts Institute of Technology. The Tracking and Data Acquisition Office of the Jet Propulsion Laboratory is responsible for seeing that all four ground stations are equipped for this experiment. The experimenters will be responsible for all nonreal-time processing of the data.

II. Basis of Differential Long Baseline Interferometry

The fundamental concept of interferometry and its application in the Pioneer Venus case are illustrated in Fig. 1. Pictured are two tracking stations located on the surface of Earth and two signal sources located near the planet Venus. For simplicity, consider that the two spacecraft and the two tracking stations are located on lines which are perpendicular to the Earth–Venus line of sight. Looking first at a single spacecraft, since the distance from Earth to Venus, r, is very much greater than the displacement of the spacecraft from the line-of-sight, y, then using similar triangles, the angles ϕ and θ are approximately equal. The difference in path length from the spacecraft to the two stations is shown as the distance δ; δ equals ϕd, where d is the distance separating the two stations. Similarly, y is equal to $r\theta$. Since ϕ is approximately equal to θ, then y is approximately equal to $(r/d)\delta$. δ represents the phase difference between the single spacecraft signal received simultaneously at the two tracking stations. As an indication of the potential power of the interferometry technique, if it were possible to measure δ to within 1 degree of phase at S-band, using the fact that 1 Hz at S-band is approximately 13 cm, an Earth–Venus distance of 50,000,000 km and a station separation of 8,000 km in the expression derived above, the displacement of the spacecraft could be resolved to within 3 meters at Venus. Unfortunately, there are several sources of error which would prevent making such a direct measurement. The two most significant effects are that the signal will have traveled through two completely different locations in Earth's ionosphere and, second, that in order to process the received signal, it is necessary to beat the signal against a local oscillator at each of the two stations. Differences in the local oscillators at the two stations would map directly into an error in the determination of δ. The differential technique is utilized to virtually eliminate both of these error sources.

Returning to Fig. 1, if a second spacecraft located in the vicinity of the spacecraft of interest is tracked simultaneously, then the same expression as derived above could be used to derive a differential expression:

$$y_1 - y_2 \cong \frac{r}{d}(\delta_1 - \delta_2)$$

Now, with a differential measurement, two important things happen. First, because the two spacecraft are located close to each other compared to the Venus–Earth distance, their signals will follow essentially the same ray path through Earth's ionosphere; therefore, differencing the signals will cancel out the ionospheric and atmospheric effects of Earth. Second, if the two signals are received through a single receiver at each of the stations, then at a particular station, both signals will have been beat against the same oscillator, and therefore, when they are differenced, the variations in the local oscillator will cancel out. This latter point is very important when considering the requirements on the ground equipment. In looking at the error sources of the experiment due to contributions from station equipment, because of this differential effect, only error sources which introduce a differential phase error between the two received signals have a significant effect on the experiment. Error sources which cause equal changes in the two received signals (such as local oscillator drift) have no first-order effect on the experiment.

In the above simplified discussion, one point which was ignored is the fact that δ in practice contains an unresolvable ambiguity. In practice, δ is many wavelengths long (one S-band wavelength is approximately 13 cm, where δ can be on the order of hundreds of kilometers) and should be better represented by the expression

$$\delta = n\lambda + \frac{p\lambda}{2\pi}$$

where λ is the signal wavelength, n is an unknown integer, and p is the fractional phase difference expressed in radians. p is defined as the fringe phase. Since it is not possible to determine n to sufficient accuracy, only the time variation of p is meaningful, and it is the time variation of p which is termed the fringe frequency in radio interferometry. However, in the Pioneer Venus case, that is exactly what is desired. Determining the time rate of change of p, we have the time rate of change of δ and therefore the derivative of y, which represents the velocity of the spacecraft perpendicular to the line-of-sight:

$$\frac{d(y_1 - y_2)}{dt} \cong \frac{r}{d}\frac{d(\delta_1 - \delta_2)}{dt} = \frac{r}{d}\frac{\lambda}{2\pi}\frac{dp}{dt}$$

where dp/dt, the fringe frequency, is the observable.

III. Differential Long Baseline Interferometry Requirements

The key requirements for the Pioneer Venus 1978 differential long baseline interferometry wind measurement experiment will be briefly described.

The objective of the experiment is to be able to measure the wind velocities as the probes fall through the atmosphere of Venus to about a 10-cm-per-second accuracy using a 100-second integration time for the signal-to-noise ratios expected at the DSN 64-meter antennas. It is fairly easy to show that this requirement translates into the need to be able to determine the phase difference between pairs of signals when averaged over 100 seconds to within 1 degree of phase at S-band. For the 9-meter STDN stations, which will have a significantly less favorable signal-to-noise ratio, it will clearly be necessary for the experimenters to integrate over much longer times in order to achieve the same accuracy, therefore sacrificing time resolution in the rate of change of the velocity. It is this 1 degree of relative phase error versus time over the bandwidth of interest requirement that will be the most difficult to meet, and the DSN and the STDN have not yet determined what can actually be achieved. Pre- and post-experiment calibration of the station equipment involved in the experiment will be necessary, as well as some form of calibration signals recorded along with the actual data. The experimenters are confident that a number of that order can be achieved based on similar experiments that were performed at lunar distances using ALSEP signals.

As was described in previous Progress Report articles, the total bandwidth which the five signals from the multiprobe mission might occupy (four probes plus the bus) is 1.7 MHz. It is therefore necessary to have receivers which can pass a 2-MHz bandwidth, and open-loop receivers will be modified for this purpose. Analog recording is felt to be incapable of meeting the differential phase requirement of this experiment, and therefore digital recordings will be made in real-time. Three-bit quantization is required, and this, together with the 2-MHz bandwidth, means that the recorders will have to be able to operate at at least 12 megabits per second. These recorders represent the most significant implementation for the Pioneer Venus mission.

The experiment also requires that the mean rate fractional accuracy of the sampling be three parts in 10^{12} and that the jitter on the samples be held to 10 nanoseconds root-mean-square. Additionally, the calibration tones which will be inserted in real-time should have an absolute accuracy of three parts in 10^{12}. This requirement will be met by hydrogen masers set with cesium standards at the DSN stations and cesium standards at the STDN stations.

IV. Ground Station Configuration

Four stations will be equipped for the Pioneer Venus 1978 differential long baseline interferometry wind measurement experiment. Figure 2 is a block diagram of the configuration which will be implemented at the DSN 64-meter Goldstone and Canberra stations and the STDN 9-meter Santiago and Guam stations. The five spacecraft signals will be detected by low-noise amplifiers, which at the STDN stations will be parametric amplifiers with a total system temperature of 100°, and at the DSN stations ruby masers with a total system temperature of less than 24°. Some form of yet-to-be-determined calibration reference frequencies will be inserted at this point in order to calibrate out drifts in the system. The five signals plus calibration tones will then pass through the open-loop receivers, which will pass a 2-MHz bandwidth. Signals will then go through an analog-to-digital converter and sampler and onto the 12-megabit-per-second digital recorders. The recorders will be redundant at each of the stations. The recorders will be able to record the 12-megabit-per-second rate at 76 cm (30 inches) per second, and therefore 80 minutes of recording will be possible between tape changes.

There are two principal remaining open areas in the differential long baseline interferometry wind measurement experiment. First is the determination by the DSN and the STDN of what is the actual differential phase error achievable by the ground equipment at a given signal-to-noise ratio. The second area concerns the details of both the pre- and post-experiment and real-time calibration. The complexity and sophistication of the required calibration will be dictated by the DSN and the STDN determined error contributions introduced by each of the elements in the ground station configuration.

Acknowledgment

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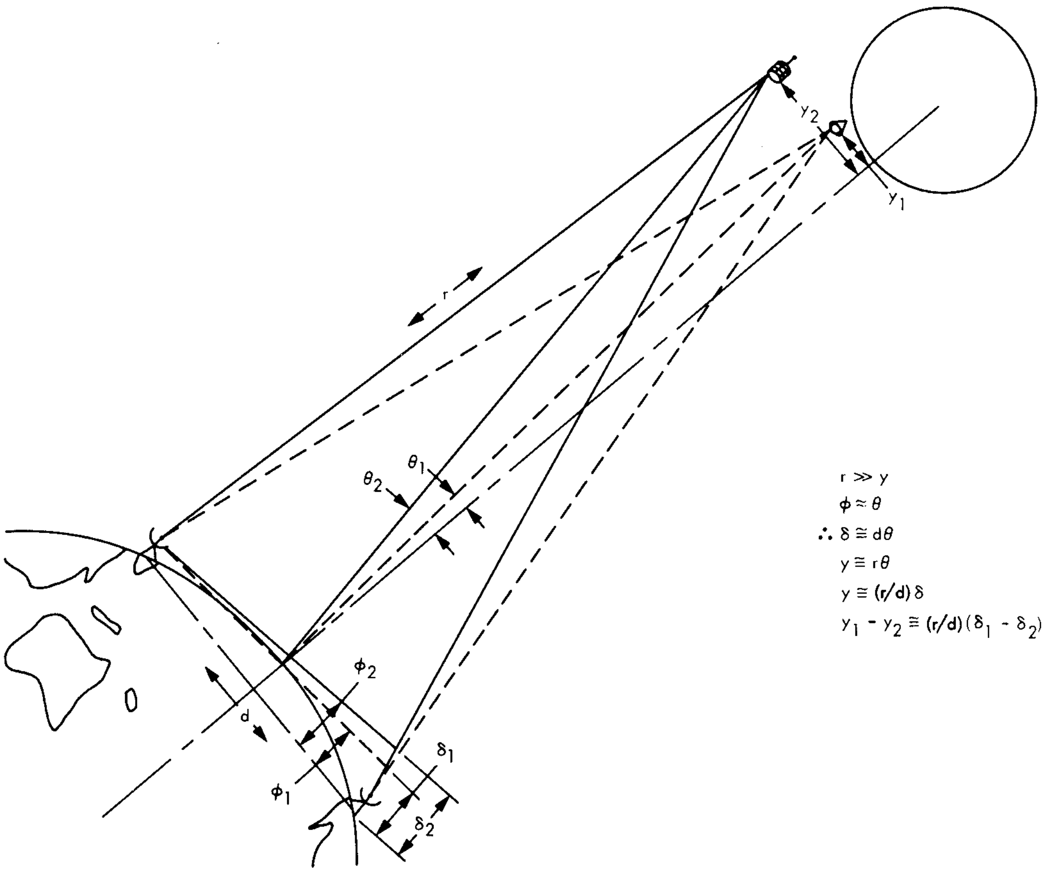
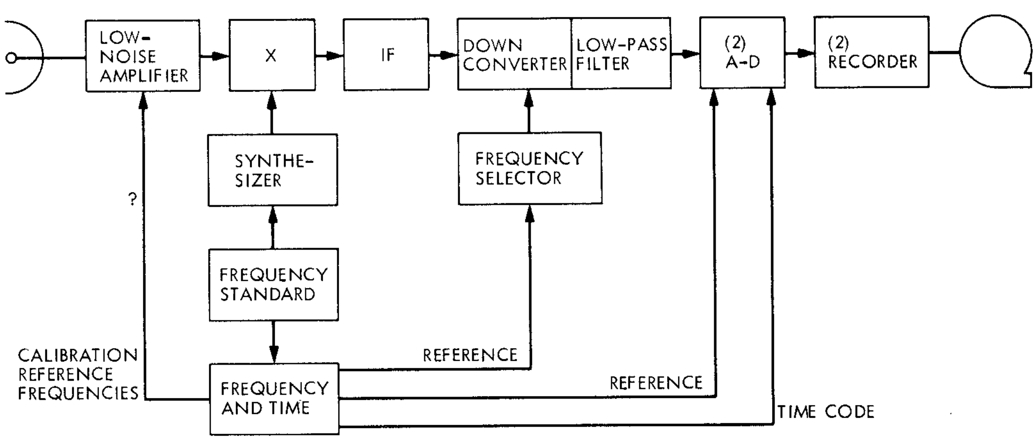


Fig. 1. Differential long baseline interferometry



	LOW-NOISE AMPLIFIER	FREQUENCY STANDARD	ANTENNA
DSN STATIONS	24°	H-MASER	64-meter
STDN STATIONS	100°	CESIUM	9-meter

Fig. 2. Differential long baseline interferometry configuration for Pioneer Venus 1978 multiprobe wind measurement