

## **NOS/NGS ACTIVITIES TO SUPPORT DEVELOPMENT OF RADIO INTERFEROMETRIC SURVEYING TECHNIQUES**

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### **ABSTRACT**

An important part of the NOAA National Ocean Survey/National Geodetic Survey (NOS/NGS) mission is to develop improved geodetic surveying methods. Radio interferometry is producing some extraordinary experimental results, and NGS is working closely with researchers in other organizations to develop operational survey systems based on the technique. One aspect of this work involves the performance of special surveys using appropriately selected methods, which are already considered operational, to provide supplemental and comparative data for the analysis and evaluation of radio interferometric surveying (RIS) projects. In this paper, we review these NGS activities, including descriptive information about the field procedures, data reduction and analysis, and the results obtained to date.

## INTRODUCTION

The new vitality infused in geodynamics by the development and refinement of plate tectonics theories has created demands for geodetic data of unprecedented spatial and temporal resolutions. Since present methods of geodetic surveying cannot provide the required resolution, more accurate methods must be implemented.

Independent clock astronomical radio interferometry, commonly referred to as very long baseline interferometry (VLBI), has produced some extraordinary experimental results during the past few years (e.g., Robertson et al., 1978; Rogers et al., 1978; Niell et al., 1979). NOS/NGS is working with researchers at academic institutions and other government agencies, particularly the National Aeronautics and Space Administration (NASA), on the development of operational radio interferometric surveying (RIS) systems.

Before a new surveying method can be considered fully operational, studies must be conducted comparing the new method with current operational methods. Such tests serve a multiplicity of purposes: They broaden the interface between the developmental and operational communities, stimulate flow of information, and ensure a high confidence level in the new method. In addition they provide information about the compatibility of the new data with historical data and they often uncover operational limitations, deficiencies, or inconveniences in the new system that were previously overlooked or ignored.

NOS/NGS plans to use RIS methods to define and maintain a highly stable reference frame and to establish a national geodynamics control network. The former application involves the founding of a new generation polar motion and Earth rotation monitoring system, to be known as the POLARIS system. The status of the POLARIS project and some of the results of supporting studies are reported in other papers presented at this conference, i.e., "Project POLARIS: A Status Report" (W. E. Carter, 1979) and "Polar Motion and UT1 Comparisons of VLBI, Lunar Laser, Satellite Laser, Satellite Doppler, and Conventional Astrometric Determinations," (Robertson et al., 1979).

The establishment of a national geodynamics control network requires the measurement of a network of vector baselines designed to detect and separate local, regional, and continental scale motions of the Earth's crust. NASA and the Jet Propulsion Laboratory (JPL) have been developing a mobile RIS system for such applications. In support of this, NOS/NGS has performed special surveys of selected vector baselines in order to provide a basis for quantitative evaluation and comparisons of the experimental RIS systems. Some of the results of these special surveys are reviewed.

## Background

The surveying techniques that will provide the best determination of a vector baseline depend primarily on the length of the baseline and, to a lesser extent, on factors such as the height, latitude and longitude, terrain, climate, obstructions, and local clutter which are peculiar to each station and, in turn, to each vector baseline.

In table 1, the baselines are divided into three general categories, according to length, and the most appropriate survey methods, approximate accuracies which are presently attainable, and examples of NOS/NGS surveys in each category, are listed.

Table 1  
Summary of Methods and Accuracies of NGS Vector Baseline Surveys

Classifications	Baseline Length	Survey Method	Accuracy	Examples Actual Surveys
Short Baselines	Local to a few kilometers	3-dimensional geodesy	Few millimeters to about a centimeter	ARIES site surveys, Goldstone phase I Haystack-Westford
Intermediate Length Baselines	Few tens of kilometers	3-dimensional geodesy	Few centimeters to about a decimeter	Goldstone phase II, McDonald-Ft. Davis baseline Malibu-Palos Verdes baseline
	Few tens to few hundred kilometers	Doppler Relative Mode	About 25 centimeters	ARIES inter-comparison
Long Baselines	Several hundred to thousands of kilometers	Doppler point positioning mode	About 50 centimeters	Space systems International Inter-comparison

The survey methods fall into two general categories: three-dimensional geodesy and Doppler satellite positioning. By three-dimensional geodesy, we refer to methods in which measurements of the astronomic positions, azimuths, zenith distances, and line lengths (and with certain assumptions, height differences determined by leveling) are combined in a three-dimensional least-squares adjustment to determine the components of the vector baseline (Vincenty, 1979; Heiskanen and Moritz, 1967; Rapp, 1975). Uncertainties in the angular and distance measurements caused by instrumental, observer, and atmospheric modeling deficiencies limit the useful range of these methods to a few tens of kilometers. As the distance grows beyond this limit, the uncertainties soon become excessive and the costs prohibitive.

Two modes of operation are used in Doppler satellite positioning: the relative mode and the point positioning mode. The relative mode is used to determine baselines a few hundred kilometers or less in length where it is possible to observe the satellite passes simultaneously from both endpoints. Certain errors, or portions thereof, become systematic biases that cause nearly equal shifts in the estimated positions of both stations. The difference in the positions is unaffected by the biases; there-

fore, the baseline components can be determined with improved accuracy. As it is impossible to collect a set of well-distributed simultaneous observations for longer baselines, the station biases become more disparate. The observing schedules are optimized for each station individually, and the reductions are performed in the point positioning mode. The baseline components are determined by simple differencing of the coordinates of the "independently" determined endpoint stations. For the highest degree of accuracy, the observations should be collected during the same date interval in order to minimize the disparateness of the biases.

### Short Baselines: The Haystack-Westford Survey

Rogers et al. (1978) reported the results of 11 RIS measurements of the Haystack-Westford baseline from October 1974 to January 1976. The scatter of the length, height, and two horizontal components was only 3, 7, 5 and 3 mm, respectively, in a Haystack altitude-azimuth frame of reference.

The vector baseline was defined to originate at the Haystack VLBI reference point and terminate at the Westford VLBI reference point. Figure 1 is a schematic sketch of the Haystack telescope. Figure 2 is a similar schematic sketch of the Westford telescope. Notice that the Westford telescope is an altitude-azimuth mounted instrument with offset (nonintersecting) axes.

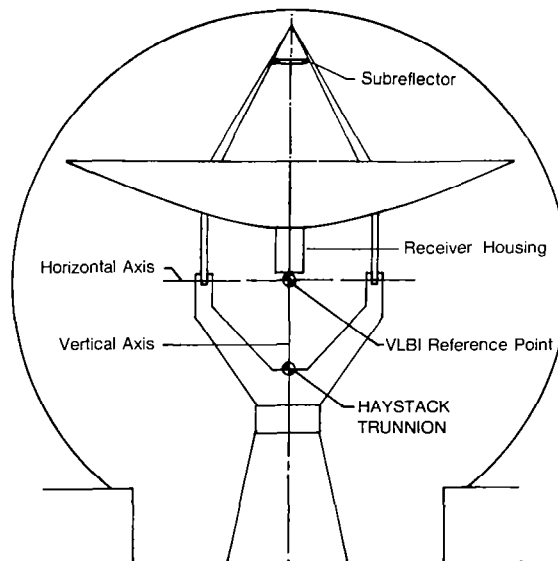


Figure 1. Haystack radio telescope.

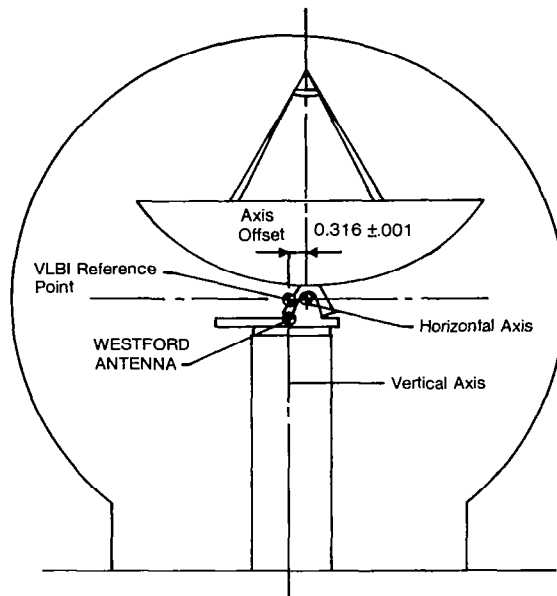


Figure 2. Westford radio telescope.

A high-accuracy three-dimensional geodetic survey of the 1.24-km Haystack-Westford RIS vector baseline was conducted to determine the components with uncertainties of a few millimeters. Because local terrain, vegetation, and obstructions associated with the radio telescopes and the enclosing structures made direct measurement of the vector baseline impossible, it was necessary to use a network (figure 3). A detailed account of the survey, including complete listings of the input and output of the adjustment is contained in Carter et al. (1979). Table 2 has been extracted from that publication. Notice that the length and two horizontal components of the baseline, as determined by the three-dimensional survey, agree to within a few millimeters with the RIS values. Only the difference in the height component,  $\Delta Z$ , is significantly larger than might be expected from the quoted uncertainties. Subsequent studies have determined that gravitational flexure of the Haystack telescope is the major source of the discrepancy. A joint NOS/MIT/Haystack paper reporting these results is in preparation. Table 3, extracted from the draft of that paper, shows that the discrepancy is still largest in  $\Delta Z$  but is less than 1 cm.

Table 2  
Components of the Haystack-Westford Vector Baseline. All Units are Meters.

Component	3-Dimensional Survey	RIS	$\Delta$
B	1239.390 $\pm$ .001	1239.394 $\pm$ .003	-.004
$\Delta X$	-1149.592 $\pm$ .002	-1149.594 $\pm$ .003	+.002
$\Delta Y$	- 462.196 $\pm$ .003	- 462.200 $\pm$ .005	+.004
$\Delta Z$	- 30.024 $\pm$ .004	- 30.005 $\pm$ .007	-.019

## RADIO INTERFEROMETRY

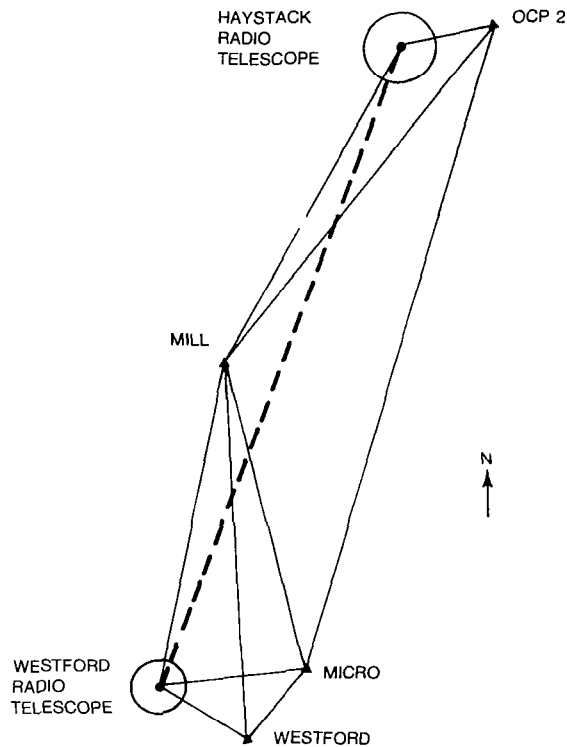


Figure 3. Haystack-Westford survey scheme.

Table 3  
Differences in Components of Haystack-Westford Baseline After Correcting  
RIS Values for Presently Known Flexures of the Telescopes and the Measured  
Offset of Westford Axes

	$\Delta X_H$	$\Delta Y_H$	$\Delta Z_H$	B
Survey - VLBI <sub>3</sub> (Units are Millimeters)	+2	+4	-6	-4

## Intermediate Length Baselines

For baselines a few tens of kilometers in length, three-dimensional geodetic surveys can achieve accuracies of a few centimeters and, at the present state-of-the-art of RIS, provide a useful standard for comparisons. The maximum useful range depends on the local terrain and the resulting complexity of the network required to span the baseline. The MALIBU-PALOS VERDE survey and the Goldstone Validation Survey – Phase II represent extremes in complexity.

### MALIBU-PALOS VERDE Survey

The JPL ARIES transportable RIS system was used to determine two vector baselines: OWENS VALLEY-PALOS VERDE and OWENS VALLEY-MALIBU. By differencing the two, the MALIBU-PALOS VERDE baseline was synthesized. This baseline is approximately 42 kilometers long and runs across the Santa Monica Bay in southern California. An unobstructed line of sight exists along the baseline allowing (except for the vertical offsets associated with the survey towers) the length and orientation to be measured directly. The only complications arise from the peculiar atmospheric conditions caused by the bay.

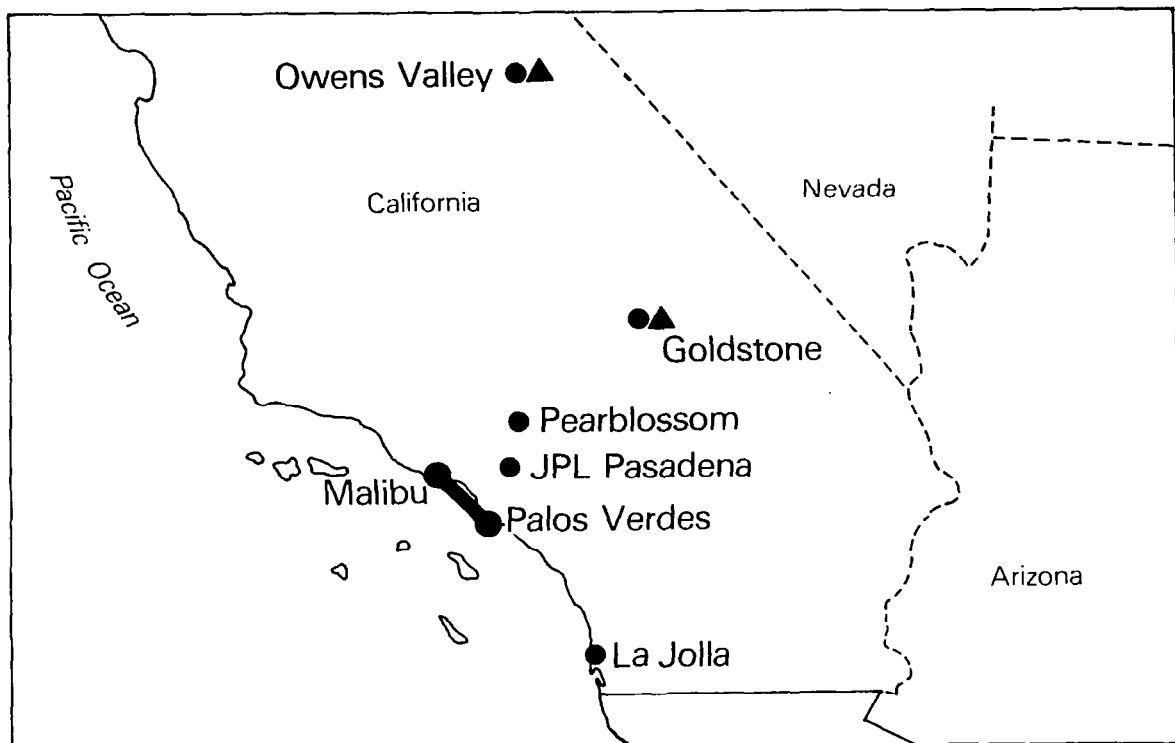


Figure 4. The MALIBU-PALOS VERDE baseline.

The NOS/NGS measured the length and azimuth of the baseline during July 1977. As the meteorological conditions were rather poor, the results must be considered less than optimal. Nevertheless, the RIS and three-dimensional survey results agree within 6 cm in length and 0.5 arc seconds in azimuth. The vertical component of the baseline was not determined with sufficient precision by the geodetic survey to provide a useful comparison. A more detailed account of this study can be found in Niell et al. (1979). NOS/NGS and JPL plan to perform additional measurements of the MALIBU-PALOS VERDE baseline using more accurate techniques to measure and remove the atmospheric effects.

### Goldstone Validation Survey – Phase II

The Goldstone Deep Space Communications Complex includes several antennas that are scattered throughout an area several kilometers wide and about 25 kilometers long. The MARS site is located at one extreme of the complex; the VENUS site at the other. The MARS site has been used extensively for RIS developmental work. NOS/NGS performed a three-dimensional geodetic survey to support the intercomparison studies discussed later in this paper. The results are contained in Carter and Pettey (1978). NASA plans to make extensive use of the VENUS site for RIS activities, particularly as a base station for use with the transportable ARIES system. Also, the MARS-VENUS baseline will be used to study RIS capabilities over distances of a few tens of kilometers. NOS/NGS, with JPL funding, is performing a high-accuracy three-dimensional survey between the MARS and VENUS sites. The objective of the survey is to determine the components of the baseline with uncertainties of less than 5 cm.

Unfortunately, the terrain within the Goldstone complex is rugged and the antennas are located in low “pockets” where they are sheltered by surrounding hills. As a result, the survey scheme is relatively complex (figure 5), and achieving the desired accuracies will be challenging. The field portion of this survey is now in progress; it will be several months (early 1980) before the results are available. This survey approaches the limits, in terms of complexity and cost, over which it is reasonable to use the three-dimensional geodetic survey methods – relative mode Doppler satellite methods rapidly become more attractive for more complex surveys.

NOS/NGS has only recently begun to explore the potentials of the relative mode of Doppler satellite surveying. The accuracy figure quoted in table 1 (25 cm) is only a rough estimate based on the experiences of those who have used the relative mode and an extrapolation of our results with the point positioning mode.

NOS/NGS and Defense Mapping Agency (DMA) teams recently completed the field portion of a multi-phased relative mode Doppler satellite survey of “space systems” sites in California. There were a total of four phases of data collection. Figure 6 shows the network occupied during Phase 4. The vector baselines included in this study range in length from the 42-kilometer MALIBU-PALOS VERDE baseline to the 780-kilometer UKIAH-LA JOLLA baseline. Table 4 summarizes the observational data collected during each of the four phases.

We had hoped to present the initial results of our reductions and analysis of these data today, but equipment failure has caused unavoidable delays in processing the data.

### Long Baselines

During 1978, NASA and NOS/NGS, with the cooperation of several other government agencies and academic institutions, sponsored and executed an intercomparison study of satellite laser ranging, RIS, and Doppler satellite methods over the three-station network formed by the Haystack, Owens



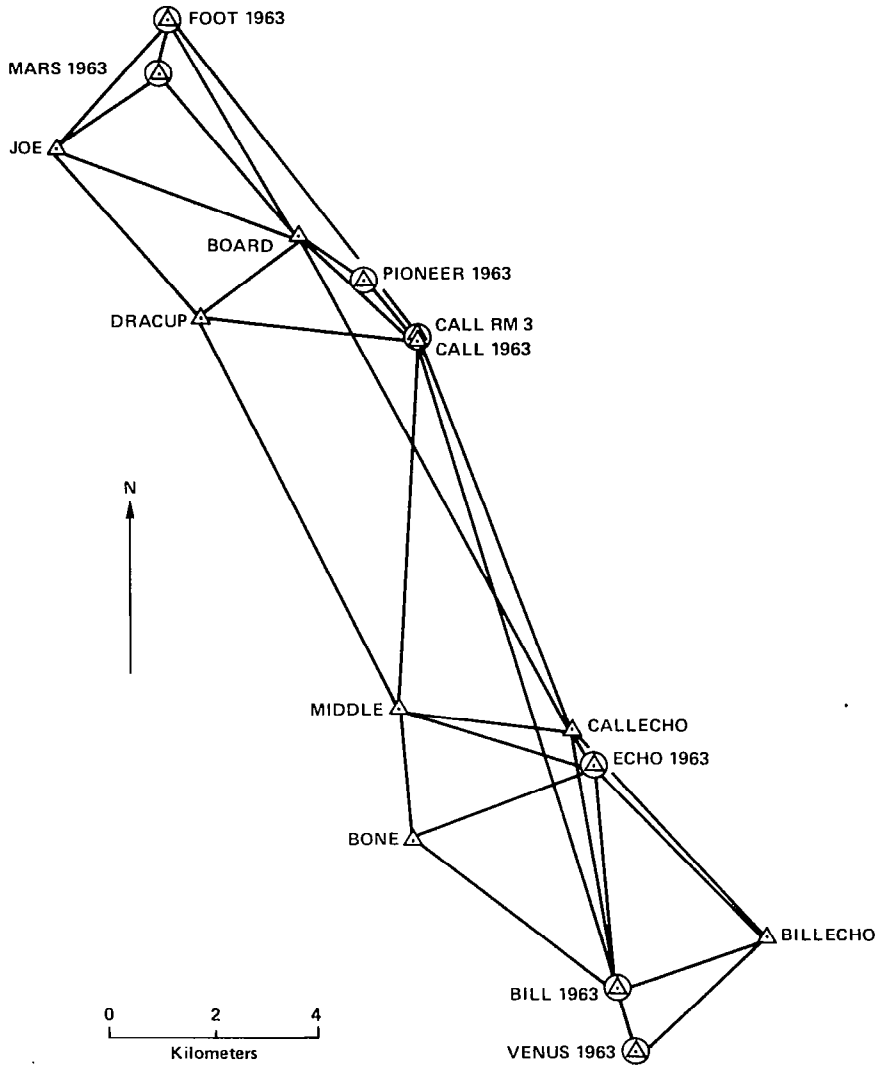


Figure 5. Goldstone validation survey - Phase II.

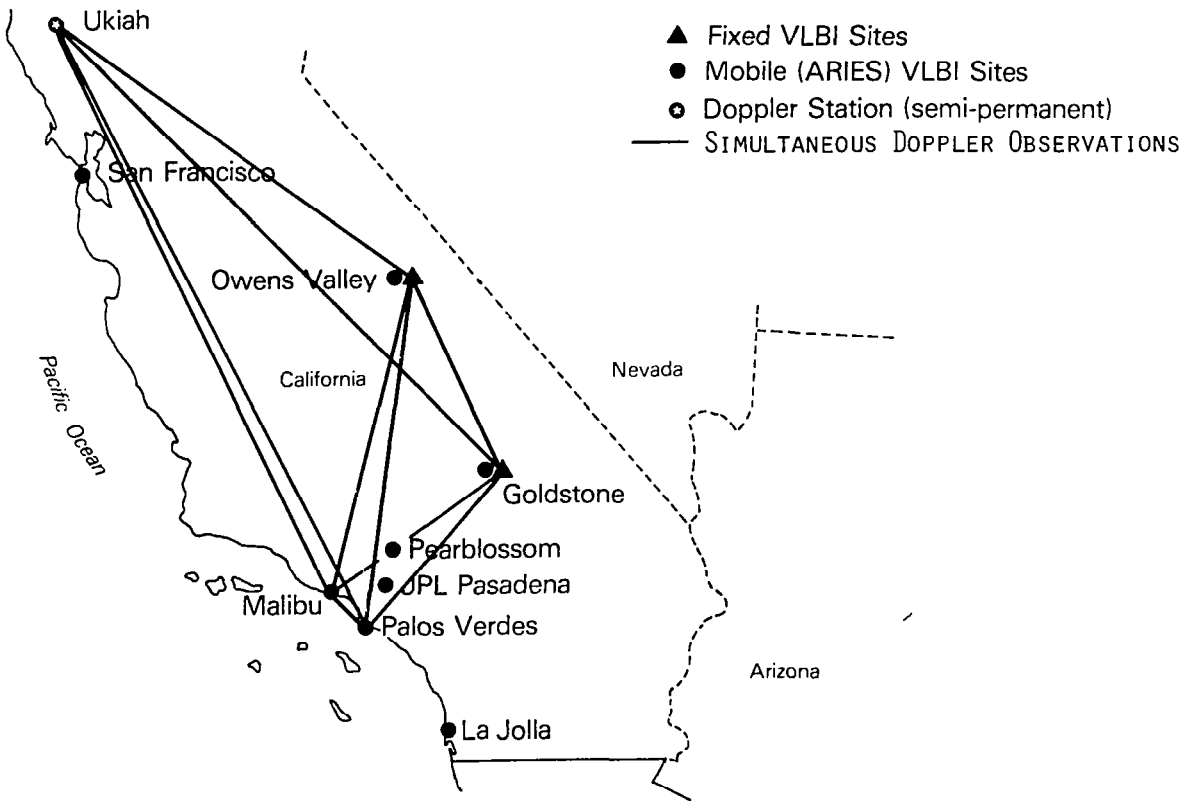


Figure 6. Doppler observation campaign – Phase IV  
(November 1978 – February 1979).

Table 4  
Doppler Observation Campaign ARIES VLBI Network  
(November 1978 - February 1979)

Station Site	Passes Observed			
	Phase I (11/6-11/22/78)	Phase II (11/28-12/12/78)	Phase III (1/5-1/26/79)	Phase IV (1/30-2/19/79)
Ukiah	192	168	164	166
Owens Valley	157	150	162	161
Goldstone	-	174	191	166
San Francisco	202	-	-	-
La Jolla	159	-	-	-
Pasadena	-	158	190	-
Pearblossom	-	-	174	-
Malibu	-	-	-	231
Palos Verdes	-	-	-	209

Valley, and Goldstone radio observatories. Various combinations of the systems were also operated at other sites.

Preliminary results of this intercomparison were reported by Hothem (1979); the figures and tables cited have been excerpted (with slight modifications) from that paper.

Figure 7 shows the deployment of the various systems. Table 5 contains a summary of comparisons between the Doppler and Mark I (VLBI) RIS determinations. Table 6 compares the Doppler and Mark II (VLBI) RIS results. The "raw" Doppler values had been corrected  $-0.4$  ppm in scale for known deficiencies in the computations of the precise ephemerides of the TRANSIT satellites.

Differences in the orientations of the baselines, expressed in terms of their equatorial altitude (declination) and equatorial azimuth (Greenwich hour angle) indicate no significant bias in the former, but a bias of about 0.8 arc second in the latter. These numbers agree with previous studies which suggested that the Doppler coordinate system is aligned to the CIO, but has a significant offset in its origin of longitude.

NOS/NGS is also cooperating with researchers of other nations to study very long baselines that are several thousands of kilometers in length.

## RADIO INTERFEROMETRY

January-March 1978

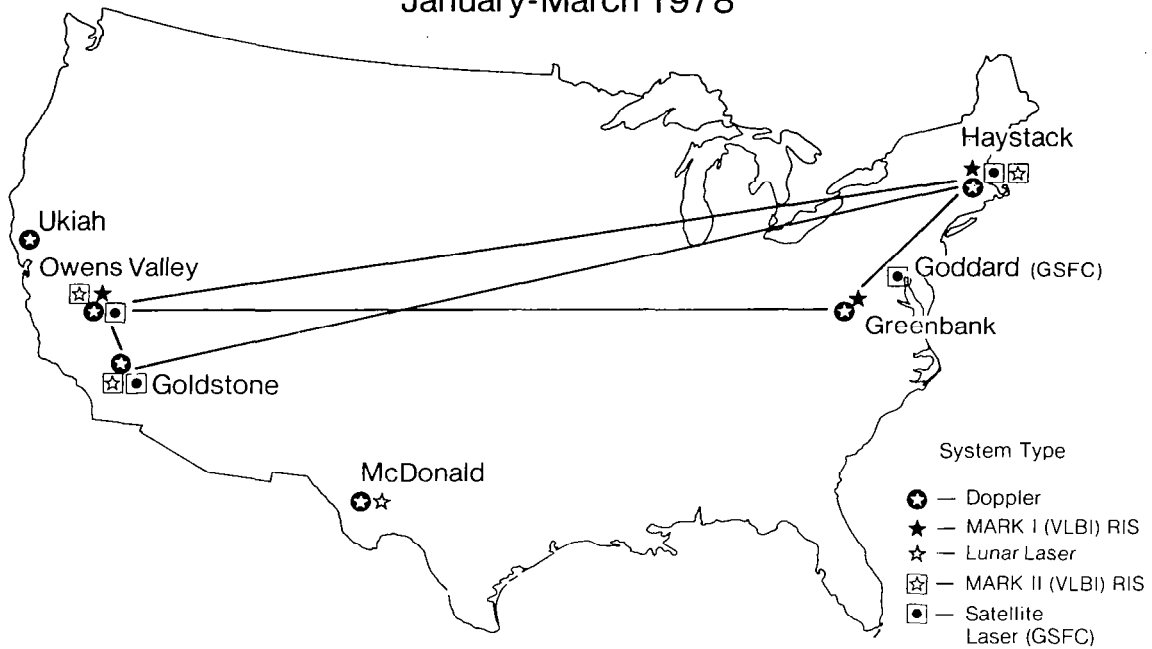


Figure 7. Deployment of systems within the United States for the 1978 long baseline intercomparison studies.

Table 5  
Comparison of Doppler Satellite and Mark I (VLBI) RIS Results

STATIONS FROM TO	BASELINE			EQUATORIAL ALTITUDE DIFFERENCE (SEC)	EQUATORIAL AZIMUTH DIFFERENCE (SEC)
	DOPPLER* (M)	VLBI (M)	DIFFERENCE (CM) (PPM)		
<b>PRE-1978 DOPPLER WITH PRE-1978 VLBI DATA</b>					
HAYSTACK-GOLDSTONE	3899844.74	3899844.87	- 13 -0.03	+0.024	-0.801
HAYSTACK-OWENS VALLEY	3929896.88	3929896.72	+ 16 +0.04	+0.044	-0.728
GREENBANK-OWENS VALLEY	3325637.47	3325637.10	+ 37 +0.11	+0.018	-0.828
<b>1978 DOPPLER AND PRE-1978 VLBI DATA</b>					
HAYSTACK-GOLDSTONE	3899844.68	3899844.87	- 19 -0.05	+0.049	-0.824
HAYSTACK-OWENS VALLEY	3929896.69	3929896.72	- 3 -0.01	+0.080	-0.738
GREENBANK-OWENS VALLEY	3325637.09	3325637.10	- 1 -0.00	+0.066	-0.849
<b>1978 DOPPLER AND 1978 VLBI DATA**</b>					
HAYSTACK-OWENS VALLEY	3929896.69	3929896.78	- 9 -0.02	-0.022	-0.784

\* DOPPLER DISTANCES CORRECTED FOR SCALE OF -0.4 PPM.

\*\* VLBI DATA OBSERVED FEBRUARY 24, 1978, SOLUTIONS PRELIMINARY.

Table 6  
Comparison of Doppler Satellite and Mark II (VLBI) RIS Results

STATIONS FROM TO	BASELINE			EQUATORIAL ALTITUDE DIFFERENCE (SEC)	EQUATORIAL AZIMUTH DIFFERENCE (SEC)
	DOPPLER* (M)	VLBI** (M)	DIFFERENCE (CM) (PPM)		
HAYSTACK-GOLDSTONE	3899844.68	3899845.17	- 49 -0.13	+0.033	-0.795
HAYSTACK-OWENS VALLEY	3929896.69	3929896.82	- 13 -0.03	+0.034	-0.804
OWENS VALLEY-GOLDSTONE	237191.43	237191.21	+ 22	-0.055	-0.487

\* FROM 1978 DATA, SOLUTIONS PRELIMINARY, DISTANCES CORRECTED FOR SCALE OF -0.4 PPM.  
\*\* DATA OBSERVED FEBRUARY 24, 1978, SOLUTIONS PRELIMINARY.

### Concluding Remarks

The intercomparison studies, past, present, and planned, include vector baselines ranging in length from a few hundred meters to several thousand kilometers. When all these baseline studies have been completed, there should be no doubt about the validity and power of the geodetic applications of radio interferometric surveying methods.

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