(NASA-TM-85003) CRUSTAL DYNAMICS PROJECT SESSION 4 VALIDATION AND INTERCOMPARISON EXPERIMENTS 1979-1980 REPORT (NASA) 97 p HC A05/MF A01 CSCL 08E
N83-21486
Unclas
G3/43 09322

NASA

Technical Memorandum 85003

Crustal Dynamics Project (Session IV) Validation and Intercomparison Experiments 1979-80

P. Liebrecht, R. Kolenkiewicz, J. Ryan, and L. Hothem

MARCH 1983

National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

CRUSTAL DYNAMICS PROJECT

SESSION IV

VALIDATION AND INTERCOMPARISON EXPERIMENTS

1979-80

REPORT

Prepared By:

Phil Liebrecht
Session IV
Validation/Intercomparison
Experiment Manager
GSFC Code 850

Ron Kolenkiewicz
Satellite Laser Ranging
Data Analysis
GSFC Code 921

Jim Ryan
Mark III VLBI
Data Analysis
GSFC Code 974

Larry Hothem
Doppler and Survey Tie
Data Analysis
N.G.S. Rockville, MD

March 1983

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

ABSTRACT

As part of the Crustal Dynamics Project an experiment was performed to verify the ability of Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI) and Doppler Satellite Positioning System (Doppler) techniques to estimate the baseline distances between several locations in the United States. The locations chosen were Greenbelt, Maryland; Greenbank, West Virginia; Haystack, Massachusetts; Ft. Davis, Texas; Owens Valley, California; and Goldstone, California. Greenbelt, Maryland had no VLBI facility and Greenbank, West Virginia had no SLR site. Baseline distances determined were between 258 and 3930 km.

The Goddard Space Flight Center (GSFC) lasers were in operation at all five sites available to them beginning October 1979. The ten baselines involved were analyzed using monthly orbits and various methods of selecting data. The standard deviation of the monthly SLR baseline lengths was at the 7 cm level.

The GSFC VLBI (Mark III) data was obtained during three separate experiments. November 1979 at Haystack and Owens Valley, and April and July 1980 at Haystack, Owens Valley, and Ft. Davis. Repeatability of the VLBI in determining baseline lengths was calculated to be at the 2 cm level.

Jet Propulsion Laboratory (JPL) VLBI (Mark II) data was acquired on the Owens Valley to Goldstone baseline on ten occasions between August 1979 and November 1980. The repeatability of these baseline length determinations was calculated to be at the 5 cm level.

National Geodetic Survey (NGS) Doppler data was acquired at all five sites in January 1980. Repeatability of the Doppler determined baseline lengths results were calculated at approximately 30 cm.

An intercomparison between baseline distances and associated parameters was made utilizing SLR, VLBI, and Doppler results on all available baselines. The VLBI and SLR length determinations were compared on four baselines with a resultant mean difference of -1 cm. and a maximum difference of 12 cm. The SLR and Doppler length determinations were compared on ten baselines with a resultant mean difference of about 30 cm. and a maximum difference of about 60 cm. The VLBI and Doppler lengths from seven baselines showed a resultant mean difference of about 30 cm. and maximum difference of about 1 meter. The intercomparison of baseline orientation parameters were consistent with past analysis.

The authors wish to acknowledge the significant contributions of the following:

Mark H. Torrence
Satellite Laser Ranging Data Analysis
EG&G Washington Analytical Services Center, Inc.
Riverdale, Maryland

Mark III VLBI Development and Analysis Team

Goddard Space Flight Center
User Terminal and Location Systems Branch/Code 974

Massachusetts Institute of Technology
Cambridge, MA

Haystack Observatory, Northeast Radio
Observatory Corporation
Westford, MA

John Davidson, Karen Wallace
Jack Fanselow and Art Niell
Mark II VLBI Data Analysis
Jet Propulsion Laboratory
Pasadena, California

Jim Petty
Survey Tie Data Analysis
National Geodetic Survey
Rockville, Maryland

CONTENTS

ILLUSTRATIONS

TABLES

CRUSTAL DYNAMICS PROJECT

SESSION IV

VALIDATION AND INTERCOMPARISON EXPERIMENTS

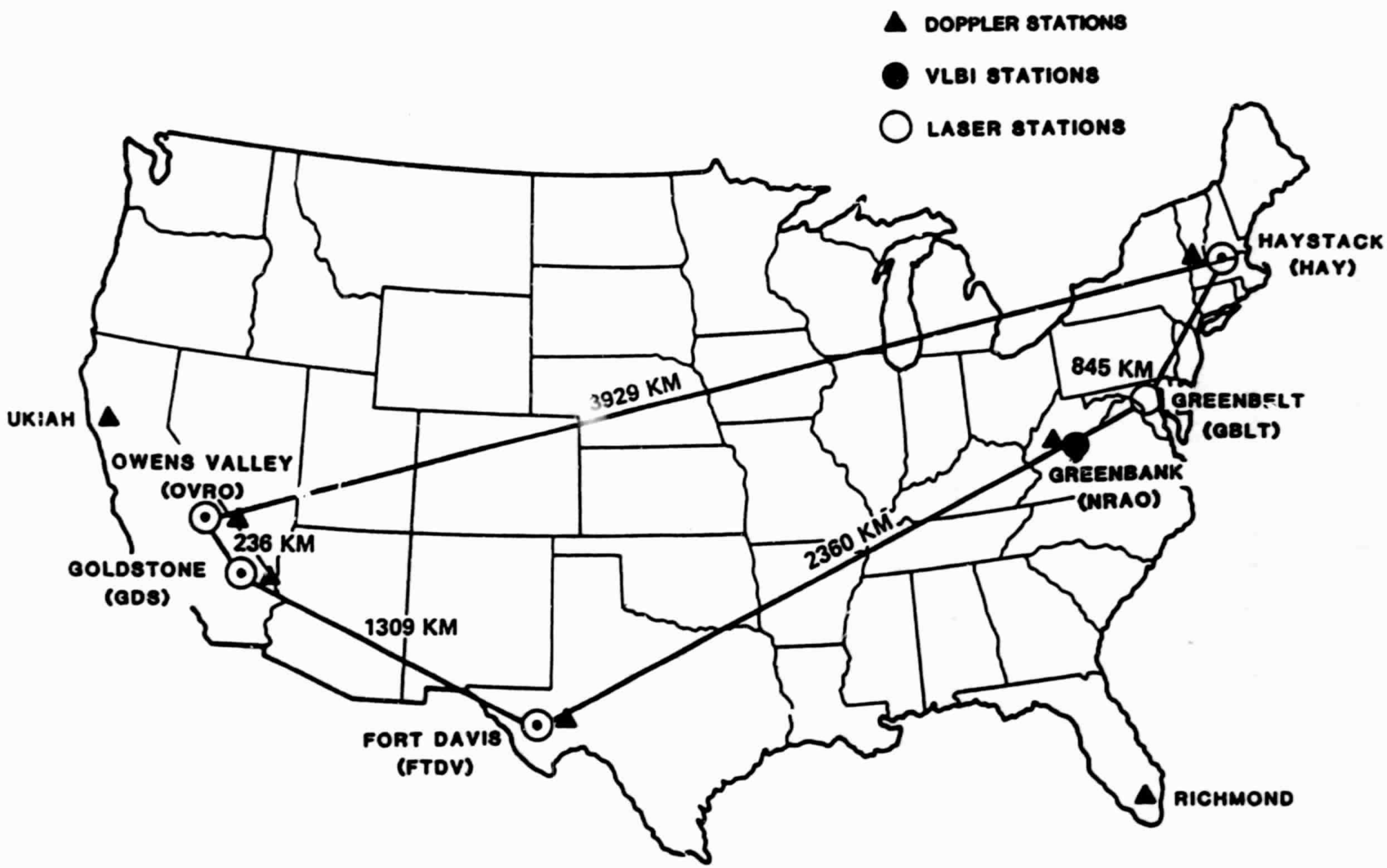
1979-80

INTRODUCTION

Starting in the fall 1979 and continuing well into 1980, a five-station Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Doppler Satellite Positioning System (Doppler) intercomparison test was conducted at the sites shown in Figure 1-1. All three of the above systems were collocated near Fort Davis, Texas; Barstow, California; Westford, Massachusetts; and Big Pine, California. Two of the above systems were collocated near Greenbank, West Virginia; and Greenbelt, Maryland. In addition, worldwide support stations were utilized for the SLR and Doppler satellite ephemeris determination. The priniciple stations are listed in Table 1-1 including the nearest geographical location, common name (and acronym) and individual system names and numbers. Throughout this report the common names and/or acronyms will be utilized to identify stations.

This experiment was the first time results of the new Mark III VLBI system were directly intercompared with those of the SLR systems.

ORIGINAL PAGE IS
OF POOR QUALITY



Doppler, VLBI, and Laser Stations for Intercomparison Test

Figure 1-1

PRINCIPLE STATIONS

NEAREST GEOGRAPHICAL LOCATION	COMMON NAME	SLR SYSTEMS		VLBI		DOPPLER	
		NAME	NUMBER	NAME	NUMBER	NAME	NUMBER
Ft. Davis, TX	Same (FTDV)	Ft. Davis	7086	Harvard Radio Astronomical Station (HRAS) Mark III	85	Ft. Davis	51219
Barstow, CA	Goldstone (GDS)	Goldstone	7115	Goldstone (Venus) Mark II	DSS-13	Goldstone	51266
Westford, MA	Haystack (HAY)	Westford	7091	Haystack Mark III		Haystack	54118
Big Pine, CA	Owens Valley (OVRO)	Owens Valley	7114	OVRO Mark III Mark II	130	Owens Valley	57105
Greenbank, WV	Greenbank (NRAO)	None	None	National Radio NRAO Mark III	140	Greenbank	54114
Greenblet, MD	Greenbelt (GBLT)	Greenbelt	7063	None	None	Greenbelt	52222

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 1-1

The Session IV experiments were a continuation of a very important phase in the development and implementation of high accuracy SLR and VLBI systems, as defined in the Crustal Dynamics Project Plan.

The objectives of the validation and intercomparison experiments are to assess current VLBI and Laser systems performance, to identify potential problems in the application of VLBI or Laser systems by NASA or other agencies, to assist system development to overcome systematic problems, and finally, to demonstrate readiness for geodetic applications.

The strategy to achieve these objectives is to intercompare SLR and VLBI results with survey and Doppler results, and to closely intercompare SLR and VLBI results.

The following were the specific objectives of Session IV of the Intercomparison Experiment listed in the order of priority:

a. To intercompare the parameters of baseline length and orientation between VLBI, SLR, and Doppler solutions.

b. To employ a number of sites which will provide sufficient geometrical redundancy, so that the combination of length only solutions will yield some information concerning orientation as well.

c. To intercompare the Mark II VLBI system with the Mark III system.

ORIGINAL PAGE IS
OF POOR QUALITY

To achieve these objectives, appropriate experiments were planned and documented in the "Session IV Validation and Intercomparison Experiments, 1979 - 1980" dated March 1980. The experiments were conducted as defined in this plan with the exceptions of the addition of Mark III observations in July 1980 and the Deletion of Mark II observations in April 1980 (See Figure 1-2, "as conducted" experiment schedule).

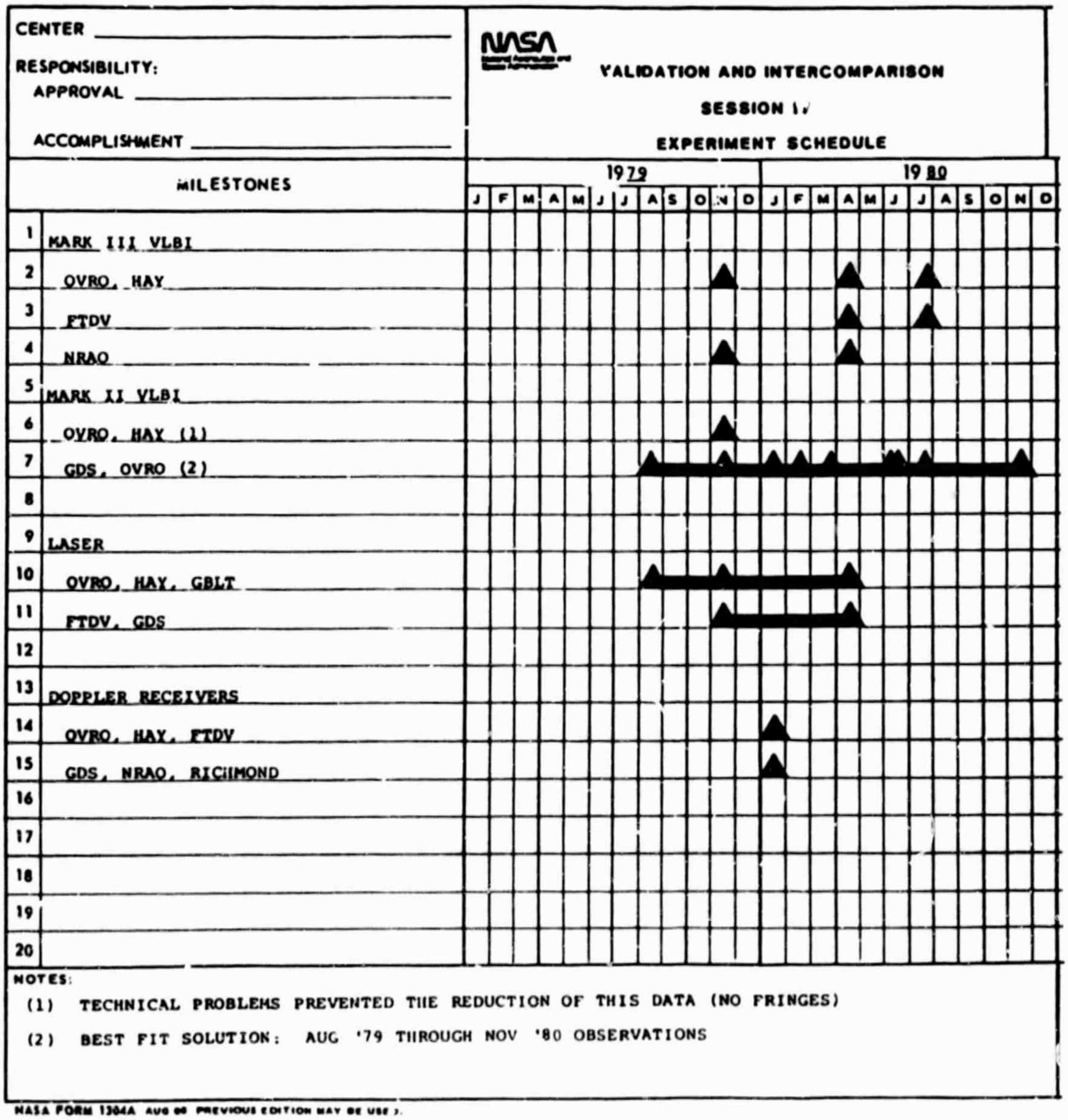


Figure 1-2

The implementation of the plan proceeded along the following four basic steps:

a. Conducted VLBI experiments conciding with SLR and Doppler receiver collocation/occupation near the VLBI antennas.

b. Employed five Laser stations and four VLBI stations during the experiments.

c. Data was forwarded to the respective central data centers for processing and correction of individual vector solutions for each station/ collocated system to a common site reference. (See Sections 4, 5, 6, and 7)

d. Intercompared point and baseline parameters of three techniques. (See Section 2)

Sections 4, 5, 6, and 7 of this report contain information on the first three steps (one section for each system) including: Data Collection, Analysis of Data Reduction, Self Consistency (within system) and Vector Results. Section Two contains the Intercomparison of the Baseline and Position Vector Results and Section Three, the Conclusions of this Intercomparison Experiment.

VALIDATION AND INTERCOMPARISON EXPERIMENTS

SESSION IV

SECTION 2

SESSION IV INTERCOMPARISON RESULTS

The single most important intercomparison parameter from a Geodynamics consideration is that of baseline length. It is the precision of this parameter that ultimately determines how accurately motion across plate boundries can be established. Accordingly, it is the parameter which is treated with the greatest emphasis in the Session IV Test Planning, Implementation, and Analysis.

Some other parameters which are intercompared are those of baseline orientations. These differences normally do not significantly effect baseline lengths, however, they help us to understand differences in system origins and coordinate systems. They also can be useful in weeding out systematic errors within systems.

The last intercomparison parameter of this report is position vectors between the SLR and Doppler solutions. As with the baseline orientations differences in these vectors do not usually effect baseline vector determinations. They are however, useful for systematic error detection and understanding origin differences between the SLR and Doppler solutions.

VLBI SLR Intercomparison

Summary of Differences: MK III-SLR

Baseline Differences	Length (M)	Longitude (Sec)	Declination (Sec)
HAY OVRO	-0.12 ± 0.06	0.158 ± 0.016	-0.019 ± 0.010
HAY FTDV	0.07 ± 0.08	0.158 ± 0.017	-0.005 ± 0.009
FTDV OVRO	-0.08 ± 0.11	0.108 ± 0.021	-0.027 ± 0.017
OVRO GDS (1)	0.09 ± 0.09	(0.017 ± 0.085)	(0.078 ± 0.071)
STATISTICS			
Mean Diff	-0.01 ± 0.06	0.141 ± 0.016	-0.017 ± 0.006
Std Deviation	±0.11	± 0.029	± 0.011
LMV Estimate (2)	-0.01 ± 0.04	0.147 ± 0.010	-0.014 ± 0.006
Range Estimate (3)	± 0.09		

(1) MKII VLBI - Not included in Mean and LMV estimates of orientation parameters.

(2) Linear minimum variance estimate (See Appendix B).

(3) Range estimate for sigma (See Appendix B)

TABLE 2-1

Signifance Testing:

Utilizing a Chi Square Test with three degrees of freedom. A 50% confidence level one sigma is 12 cm.

<u>Orientation Differences:</u>

There is a significant difference in longitude between two systems of 0.15±.02 Asec. Determinations of the longitude difference between the systems by the NGS (Ref. 2) were .19 ± .01 Asec.

The origin of this difference is the references utilized to establish the zero meridian (i.e., Stalas longitude for SLR, etc.), and thus it is arbitrary in origin.

There was a slight difference in declination between the systems of -0.014 ± .006 Asec. NGS determinations ranged between .01 and .04 Asec. This difference is expected to be primarily from noise in the polar motion.

<u>MK III - Doppler Intercomparison</u>

Doppler baselines scaled by -.5 PPM before comparison was made with VLBI (See Reference 2).

Summary of Differences: MK III-Doppler

Baseline Diff	Length (M)	Longitude (Asec)	Declination (Asec)
NRAO OVRO	0.19 ± 0.60	0.904 ± 0.041	0.006 ± 0.038
HAY OVRO	-0.38 ± 0.50	0.821 ± 0.034	0.006 ± 0.032
HAY NRAO	-1.03 ± 0.60	0.732 ± 0.163	-0.137 ± 0.147
NRAO FTDV	0.39 ± 0.60	0.763 ± 0.062	-0.058 ± 0.055
HAY FTDV	-0.56 ± 0.50	0.705 ± 0.044	-0.059 ± 0.040
FTDV OVRO	-0.60 ± 0.50	1.001 ± 0.091	0.164 ± 0.083
OVRO GDS (1)	0.02 ± 0.60	(+1.368 ± 0.667)	(-0.766 ± 0.484)
Statistics			
Mean Diff	-0.29 ± 0.19	0.821 ± 0.046	-0.013 ± 0.041
Std. Deviation	± 0.50	± 0.113	± 0.101
LMV Estimate(2)	-0.32 ± 0.23	0.818 ± 0.020	-0.010 ± 0.019
Range Est. (3)	± 0.50		

(1) Mark II VLBI - Orientation parameters not included in mean and LMV estimates.

(2) Linear minimum variance estimate (See Appendix B).

(3) Range Estimate of Std. Deviation (See Appendix B).

Table 2-2

Significance Testing:

Using a Chi Square Test (with 6 degrees of freedom), a one sigma error on length differences between VLBI and Doppler with 50% confidence level is .6m.

Orientation Differences:

There is a significant difference in longitude between the two systems of .81 Asec ± .05. A similar difference has been reported before by L. Hothem (NGS) (.80 ± .01, Reference 2) and is attributed to arbitrary differences in the reference of coordinate systems. There is no significant difference in declination between the two systems.

SLR - DOPPLER INTERCOMPARISON

Doppler baselines scaled by -.5 PPM (Reference 2).

Summary of Differences: SLR-Doppler

Baseline Diff	Length (M)	Longitude (Sec)	Declination (Sec)
HAY OVRO	-0.26 ± 0.50	0.663 ± 0.033	0.025 ± 0.033
GBLT OVRO	0.03 ± 0.51	0.700 ± 0.036	0.076 ± 0.035
HAY GBLT	-0.20 ± 0.41	0.593 ± 0.238	-0.357 ± 0.208
GBLT FTDV	-0.28 ± 0.40	0.565 ± 0.050	0.013 ± 0.047
HAY FTDV	-0.62 ± 0.51	0.548 ± 0.043	-0.054 ± 0.040
FTDV OVRO	-0.52 ± 0.51	0.893 ± 0.091	0.190 ± 0.083
OVRO GDS	-0.10 ± 0.60	1.394 ± 0.664	-0.963 ± 0.483
HAY GDS	-0.54 ± 0.60	0.608 ± 0.033	-0.021 ± 0.033
GBLT GDS	-0.21 ± 0.61	0.637 ± 0.036	0.028 ± 0.036
FTDV GDS	-0.48 ± 0.61	0.753 ± 0.102	0.070 ± 0.096
Statistics			
Mean Diff	-0.32 ± 0.07	0.735 ± 0.080	-0.099 ± 0.106
Std. Deviation	± 0.21	± 0.253	± 0.335
LMV Estimate (1)	-0.32 ± 0.16	0.640 ± 0.015	0.017 ± 0.014
Range Estimate (2)	± 0.21		

(1) Linear minimum variance estimate (See Appendix B)

(2) Range Estimate of Std. Deviation (See Appendix B)

Table 2-3

Significance Testing:

Utilizing a Chi Square Test with nine degrees of freedom, a one sigma error tolerance on length differences with a 50% confidence level is 25 cm.

Orientation Differnces:

There is a significant difference in longitude of 0.64 ± 0.05 Asec. Previous NGS determinations are 0.61 ± 0.01 Asec (Ref. 2). This difference is attributed to arbitrary coordinate system references in the data reduction.

There is no significant difference in declination between the systems.

SLR - Doppler Position Vector Intercomparison

The position vector intercomparison analyses between two systems was conducted utilizing the NGS Program "ClassI" (See Reference 2). This program allows for the simultaneous least squares adjustment of translation (X, Y, Z), rotation (about Z) and scale differences between the systems. For this analysis, the rotation about the X and Y axis were fixed at 0. The Laser position vectors uncertainties were fixed 10 cm in X, Y, and Z and the Doppler vector uncertainties were fixed at the station a priori estimates (as defined in Section 6 of this report). Table 2-4 summarizes the best fit differences between the systems. All of the differences agree (within one and one-half sigma) with the system differences given in Reference 2. The analysis in Reference 2 included many more stations (over 100 Doppler and about 40 SLR versus 6 each for Session IV) and also had global coverage versus the Continental U.S. only coverage of Session IV data.

SLR - Doppler Differences

	X	Y	Z
Translation (Meters)	-0.3 ± 0.6	1.3 ± 0.6	4.3 ± 0.5
Rotation (Asec)	-	-	0.64 ± 0.02
Scale .6 ± .1 PPM			

Table 2-4

VALIDATION AND INTERCOMPARISON EXPERIMENTS

SESSION IV

SECTION 3

SUMMARY AND CONCLUSIONS

Table 3-1 lists the summaries for baseline length repeatability. A comparison with the Crustal Dynamics Project baseline standard deviation needs in Table 3-3 shows that the Session IV STD deviation results for baseline precision are very close to the required level and the one sigma errors are better than the useful level with 99% confidence (Chi Square Test). It is also clear that the Mark III System results come very close to the project identified goal. The Mark II VLBI results appear quite good considering the fact that several experiments were S-band only and the bandwidth was limited compared to the Mark III experiments. The Laser baseline precision results were roughly proportional to the one sigma uncertainty in the raw ranging observable of the Laser Network at the time. As the newer narrow pulse lasers become operational, the prospects for improving range uncertainties and also baseline lengths is very promising. Some of the new lasers exhibited a 2 cm precision in range during field tests. Theoretically, this should affect the approach to the project goal of a 2 cm baseline standard error. The Doppler baseline precisions were consistent with past determinations with comparable amounts of data acquisition time.

Repeatibility of Baseline length	Average (one sigma) Uncertainty	
	STD Deviation	.99 Confidence (1)
MK III VLBI	2 cm	3 cm
SLR	7 cm	10 cm
MK II VLBI	5 cm	10 cm
Doppler	33 cm	60 cm

Table 3-1

(1) Chi Square Test

The intercomparison (listed in Table 3-2) uncertainties between the Mark III and Laser baselines were approximately 60% larger than would be expected by the root sum square combination of the individual system uncertainties. This discrepancy is believed to be due to unmodeled or unknown systematic errors between systems. The Baseline intercomparisons between Doppler and the other systems were all within the uncertainties of the Doppler.

Intercomparison of Baseline Length

System Differences	Number of Baselines Compared	Mean ± STD Deviation
VLBI - SLR	4	- 1 ± 11 cm
SLR - Doppler	10	-32 ± 21 cm
VLBI - Doppler	7	-29 ± 50 cm

Table 3-2

Factors Needed to Supply Velocity Results

CRUSTAL DYNAMICS PROJECT NEEDS	VELOCITY STANDARD DEVIATION* (CM/YR)	MEASUREMENT SPAN (YEAR)	BASELINE DETERMINATION STANDARD DEVIATION (CM)	LASER RANGING MEASUREMENT STANDARD DEVIATION (CM)	VLBI DELAY MEASUREMENT STANDARD DEVIATION (CM)
Useful	2	5	11	8	8
Required	1	5	6	4	4
Goal	.4, .7	5, 3	2	1	1

*Assumes a series of measurements with 0.5 years between individual measurements.

Note. This table lists the baseline determination precisions, one-minute normal point laser ranging standard deviations, and VLBI delay standard deviations, which are needed to obtain the needed velocity results.

Table 3-3

ORIGINAL PAGE IS OF POOR QUALITY

The intercomparison of baseline orientation parameters (see Table 3-4) was consistent with past analyis (see reference 2). The orientation parameters for Session IV data are of limited use for science as the uncertainties in polar motion and universal time are believed quite large compared to noise and other systematic error sources. The fixed differences in longitude are due to arbitrary references of coordinate systems, and are not of concern. Some of these problems will be overcome by future processing of the SLR and VLBI data together in the same software system.

Intercomparison of Baseline Orientation

System Differences	Longitude (Asec)	Declination (Asec)
VLBI - SLR	0.15 ± .03	-0.01 ± .01
SLR - Doppler	0.64 ± .25	0.02 ± .35
VLBI - Doppler	0.81 ± .11	0.01 ± .10

Table 3-4

As with the baseline orientation parameters, the position vector intercomparison (see Table 2-4) was consistent with past analyses (reference 2) within uncertainties. The limited data which went into Session IV analysis conmbined with the fact that the Continental U.S. data was exclusively utilized, makes the estimation of translationn parameters weak. Global data coverage as provided in reference 2 is desirable for these determinations.

VALIDATION AND INTERCOMPARISON EXPERIMENTS

SESSION IV

SECTION 4

SATELLITE LASER RANGING RESULTS

Ronald Kolenkiewicz

DATA COLLECTION

During the 6-month period between October 1979 and March 1980, the NASA Goddard Space Flight Center Satellite Laser Ranging (SLR) Systems participated in a Validation and Intercomparison experiment conducted by the Crustal Dynamics project. The purpose of this experiment was to determine the inter-site distances, or baselines between satellite laser tracking systems located in the continental United States and tracking an artifical earth satellite. The satellite tracked for this experiment was the Lageos spacecraft, launched in May 1976. This passive satellite, designed exclusively as a laser ranging target, consists of a heavy sphere covered with cube corner retroreflectors. The physical characteristics of the spacecraft and its orbit are given in Table 4-1.

TABLE 4-1

CHARACTERISTICS OF LAGEOS

Mass = 406.9 kg

Diameter = 60.0 cm

Semi-major axis = 12265.82 km

Eccentricity = 0.00428

Inclination = 109.835 deg

The five prime geographical locations of the lasers sites were the stationary laser (Stalas) at Greenbelt, MD; and four mobile lasers at Haystack, MA; Fort Davis, TX; Owens Valley, CA; and Goldstone, CA. Other SLR systems, located worldwide, also participated in this experiment. Figure 4-1 shows the geographical positions for the locations of the 16 U.S. and foreign lasers participating in collecting data for this experiment. The daily number of Lageos passes tracked by each of these locations is graphically illustrated in Figure 4-2. Note that there are two listings for Greenbelt, MD. The first is for the primary laser, Stalas; and the second is for a Mobile laser (MOBLAS IV) which was supporting the experiment. The actual number of range data points taken by each of the laser tracking stations, during monthly intervals while the experiment was being conducted, are shown in Table 4-2. It should be noted that the number of points shown in Table 4-2 are not proportional to the number of passes tracked since the laser range pulse rate (one per second for NASA lasers) differ for some of the other systems.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 4-2

''SER TRACKING SITES SHOWING LAGEOS DATA COLLECTED

STATION LOCATION	NUMBER OF RANGE DATA POINTS COLLECTED					
	Oct	Nov	Dec	Jan	Feb	Mar
Greenbelt, MD	16636	5377	8178	2668	188	11656
Fort Davis, TX	7843	6656	5760	7459	12939	15749
Haystack, MA	23841	22673	17599	17766	23429	6244
Owens Valley, CA	23495	13181	14436	5680	20041	10424
Goldstone, CA	13155	27532	18422	15156	14811	14737
Arequipa, Peru	148	778	844	903	154	216
Natal, Brazil	20	51	37	14	26	76
Orroral, Australia	164	233	963	610	1098	3588
Patrick, AFB, FL	40	0	0	147	159	219
Greenbelt, MD	1084	6241	15852	128	1266	20813
Yaragadee, Austra.	2425	0	4567	17022	47746	42890
Kwajalein	0	0	0	1745	0	0
American Samoa	4439	1181	5401	0	1505	11542
Kootwijk	0	143	771	0	165	103
Wetzell, GDR	0	0	0	160	4820	1720
Grasse, France	0	228	180	0	0	0
Totals	93290	48274	93010	69458	128347	139977

ANALYSIS OF DATA REDUCTION

The raw Lageos data collected during the experiment was preprocessed and put into a format compatible to the analysis programs to be used. This essentially consists of range measurements, time at which the measurement was made, and tracking station identifiers arranged in chronological order. These data were analyzed to obtain the baseline distances.

Analysis consisted of using all of the data collected world wide and fitting orbital arcs approximately thirty days in length while solving for a number of geophysical parameters. The computer program used, GEODYN (Ref. 4-1), is a least squares orbital analysis program. A description of the force model parameters used is given in Table 4-3.

TABLE 4-3

FORCE MODEL PARAMETERS

Gravity Field: Goddard Earth Model, modified GEM 10.

GM = $398600.44 \times 10^9\ m^3/sec^2$

Earth's equitorial radius = 6378144.11 m

Loves' number (solid earth tide) = 0.2850

Phase lag (solid earth tide) = 1.935 deg

Solar radiation pressure coefficient = 1.1729

Velocity of light = 299,792,458 m/sec

Average along track acceleration = $-2.86 \times 10^{-12}\ m/sec^2$

The geopotential model, GEM 10 (Ref. 4-2). was modified by solving for even and odd degree pairs of coefficients through order nine using the Lageos data from May 1976 through July 1981 (Ref. 4-3). This solution was also used to derive the values of GM, Loves' number, and Phase lag. A discussion of the along track acceleration used in this solution can be found in reference 4-4. In this analysis of the validation data all ten baselines from the five primary laser tracking sites were obtained simultaneously. Details of the analysis follows:

1. break the data up into six one-month arcs.

2. use GEODYN, to fit an orbit to each one-month arc by solving for:
   a. the state vector (the six orbital elements).
   b. polar motion.
   c. length of the day.
   d. along track acceleration.
   e. station coordinates (three for each station). While keeping the latitude and longitude of Goldstone, CA and the longitude of Arequipa, Peru fixed.

The six monthly orbital arcs were then dynamically combined by using the GEODYN and SOLVE programs to yield the best estimate for the location of the laser stations, and thus the baseline distances between them. The final solution for the five intercomparison station locations is given in vector component form in Table 4-4.

TABLE 4-4

SATELLITE LASER RANGING: RAW VECTORS

(Relative to Laser Reference Markers)

SITE	X(cm.)	Y(cm.)	Z(cm.)
Greenbelt*	113071172.5	-483137092.5	399408915.9
Fort Davis	-133012932.3	-532852556.0	323625020.2
Haystack	149245041.5	-445727987.1	429681572.4
Owens Valley	-241042574.3	-447780084.3	383868666.0
Goldstone	-235086510.3	-465554449.5	366099788.1
Arequipa*	194278758.4	-580407923.0	-179691943.8
Natal*	518646551.5	-365385982.6	-65432209.8
Orroral*	-444754629.3	267713751.0	-369499730.7
Patrick*	91795560.9	-554837403.4	299878805.7
Greenbelt	113068365.1	-483135637.5	399411264.3
Yarragadee	-238900211.3	504333095.1	-307852608.7
Kwajalein*	-614344962.7	136470471.4	103416328.1
American Samoa	-610004655.2	-99619884.9	-156897684.0
Kootwijk*	389922397.9	39673960.2	501507399.9
Wetzel*	407553066.7	93177833.4	480161818.6
Grasse*	458169241.5	55615560.5	438935888.0

* coordinates for these stations are measured to the laser optical axis.

The vectors are measured in a right handed rectangular coordinate system whose origin is the center of the earth (Ref. 4-1). The terminal point of the vectors, except for stations marked with an asterisk (*) is to a survey mark located on the concrete slab which the laser is occupying. For the remainder of the stations the vector is from the center of the earth to the laser optical axis.

In order to compare the laser derived results with that of other systems (VLBI and DOPPLER) with which they are collocated, a common validation point was defined (see Table 7-1). The transfer vector components from the laser reference mark to the validation mark for each prime site are given in Table 4-5 (Ref. 4-5).

TABLE 4-5

SATELLITE LASER RANGING: TRANSFER VECTORS

(Laser Reference to Validation Survey)

SITE	DX(cm.)	DY(cm.)	DZ(cm.)
Greenbelt	1611.0	4743.0	4716.0
Fort Davis	-75530.9	-22029.6	-50762.5
Haystack	0.0	0.0	0.0
Owens Valley	77825.2	-56637.2	-16243.1
Goldstone	0.0	0.0	0.0

Results for the experiment based on the six months of data are given in Table 4-6. These consist of the baseline distance between validation markers of the intercomparison sites and were obtained from the expression:

$$\text{Baseline} = [(Xv_1-Xv_2)^2 + (Yv_1-Yv_2)^2 + (Zv_1-Zv_2)^2]^{1/2}$$

where Xv = DX+X and the subscripts indicate the two sites whose baseline is being determined.

TABLE 4-6

SATELLITE LASER RANGING: BASELINE DISTANCES

(Between Validation Markers)

STATIONS		DISTANCE (cm)
OWENS VALLEY TO	GOLDSTONE	25760971±6
	HAYSTACK	392897491±6
	GREENBELT	356132710±8
	FORT DAVIS	150011314±11
GOLDSTONE TO	HAYSTACK	390059577±6
	GREENBELT	350190932±8
	FORT DAVIS	129401985±9
HAYSTACK TO	GREENBELT	60196900±7
	FORT DAVIS	313954809±8
GREENBELT TO	FORT DAVIS	262340955±6

DISCUSSION OF THE SATELLITE LASER RANGING RESULTS

Discussion of the Satellite Laser Ranging portion of this experiment, in this section, will be confined to the precision (or repeatability) of baseline vectors between the five continental U.S. tracking sites that are implied by these analyses. Comparisons with results obtained by other technologies, which infer accuracies, will be discussed in a subsequent section.

The SLR baselines and a measure of their precision for the ten baselines between the five primary laser tracking sites is given in Table 4-6. They range in value from a low of 5.9 cm. for the Owens Valley to Haystack baseline to a high of 11.0 cm. for the Owens Valley to Fort Davis baseline. These one sigma values are the standard deviation about the mean calculated by the formula

$$SIGMA = (\Sigma(B-Bm)^2/(n-1))^{1/2}$$

In which n is the number of monthly baselines, B is the length of the individual monthly baselines, and Bm is the mean of the monthly baselines.

$$Bm = \Sigma(B)/n$$

The values of B were obtained by using baseline distance results, considered to be equally weighted, from analysis of six independent one month orbital arcs. In the case of the Greenbelt, only five months of data were used due to insufficiient tracking during the month of February (see Table 4-2 and Figure 4-2). The mean of all of the one sigma standard deviations given in Table 4-6 is 7.4 cm.

Using the data in Table 4-4 and 4-5 the values for the azimuth and elevation (see Appendix C) can be calculated from the following equations.

$$\text{Azimuth} = \arctan\left((Yv_1-Yv_2)/(Xv_1-Xv_2)\right)$$

$$\text{Elevation} = \arctan\left(Zv_1-Zv_2/((Xv_1-Xv_2)^2+(Yv_1-Yv_2)^2)^{1/2}\right)$$

The subecripts have the same meaning as those in the Baseline equation. Table 4-7 lists the angular components of the baseline vectors and their one sigma precisions.

TABLE 4-7

BASELINE VECTOR AZIMUTH AND ELEVATION ANGLES

(Between Validation Markers)

STATIONS		AZIMUTH		ELEVATION	
		Deg	Degx10^{-6}	Deg	Degx10^{-6}
OWENS VALLEY TO	GOLDSTONE	288.3453771	±10	-43.5612095	±12
	HAYSTACK	0.3096294	±3	6.6984597	±2
	GREENBELT	354.3067326	±3	2.5043349	±1
	FORT DAVIS	321.7516189	±4	-23.6964342	±4
GOLDSTONE TO	HAYSTACK	2.9530923	±2	9.3813787	±2
	GREENBELT	357.1096993	±2	5.4588319	±1
	FORT DAVIS	326.5746313	±4	-19.1904046	±4
HAYSTACK TO	GREENBELT	225.9593779	±4	-30.1864536	±8
	FORT DAVIS	197.1536498	±3	-19.7551843	±2
GREENBELT TO	FORT DAVIS	191.4240244	±2	-16.8055887	±1

These one sigma values are the standard deviation about the mean calculated by the same formula used to calculate the baseline sigma.

They were obtained by using vector orientation results, considered to be equally weighted, from analysis of six one month independent orbital arcs. Again, in the case of the Greenbelt dependent baselines only five months were used due to insufficient tracking during the month of February (see Table 4-2).

In summary, SLR thirty day orbital arc analysis techniques employed in this paper is capable of obtaining baseline distances between laser sites to a one sigma precision on the order 7 cm. Other methods of analysis using shorter orbital arc lenghts and different solved for parameters are being investigated.

The results listed in Table 4-6 can be used to directly compare results obtained by other baseline measuring system collocated at the SLR sites. These were the VLBI sites at Haystack, MA; Fort Davis, TX; and at Owens Valley and Goldstone, CA., and the Doppler stations at each of the five SLR prime sites.

COMMENTS ON INTERCOMPARISONS

In previous papers discussing data from SLR and other systms (Ref. 4-6) there have been comparisons of the angular components of the baseline vectors. This seems to be a reasonable approach when the determination of angular components are obtained by the same analysis techniques. However, comparing angles between SLR, VLBI and Doppler may cause confusion since each of these technologies will be corrupted by method of analysis and coordinate system orientation differences. The interpretation of angular differences between different measuring systems is a complex problem that is difficult if not impossible to resolve. This objection may be overcome in the future when SLR and VLBI data are to be analyzed together.

REFERENCES

4-1 Putney, B.H., "General Theory for Dynamic Satellite Geodesy", NASA SP-365, Part I, pp. 319-334, Washington, DC, 1977.

4-2 Lerch, F.J., Klosko, S.M., Laubscher, R.E., and Wagner, C.A., "Gravity Model Improvement Using Geos3 (GEM 9 and 10)", Journal of Geophysical Research, Vol. 84, No. B8. July 30, 1979.

4-3 Torrence, M.H., Christodulidis, D., Dunn, P.J., Knode, S., Anders, S., Kolenkiewicz, R., Wyatt, G., and Smith, D.E., "Geodetic Parameters from Laser Tracking of the Lageos Spacecraft", Abstract, EOS, Vol. 63, No. 18, May 4, 1982.

4-4 Rubincam, D.P., "On the Secular Decrease in the Semimajor Axis of Lageos's Orbit", Celestial Mechanics 26 (1982) 361-382.

4-5 Hothem, L.D., Private Communication.

4-6 Hothem, L.D., "Determination of Accuracy, Orientation, and Scale of Satellite Doppler Point-Positioning Coordinates", Proceedings of the 2nd International Symposium on Doppler Positioning, Austin, Texas, January 22-26, 1979.

ORIGINAL PAGE IS
OF POOR QUALITY

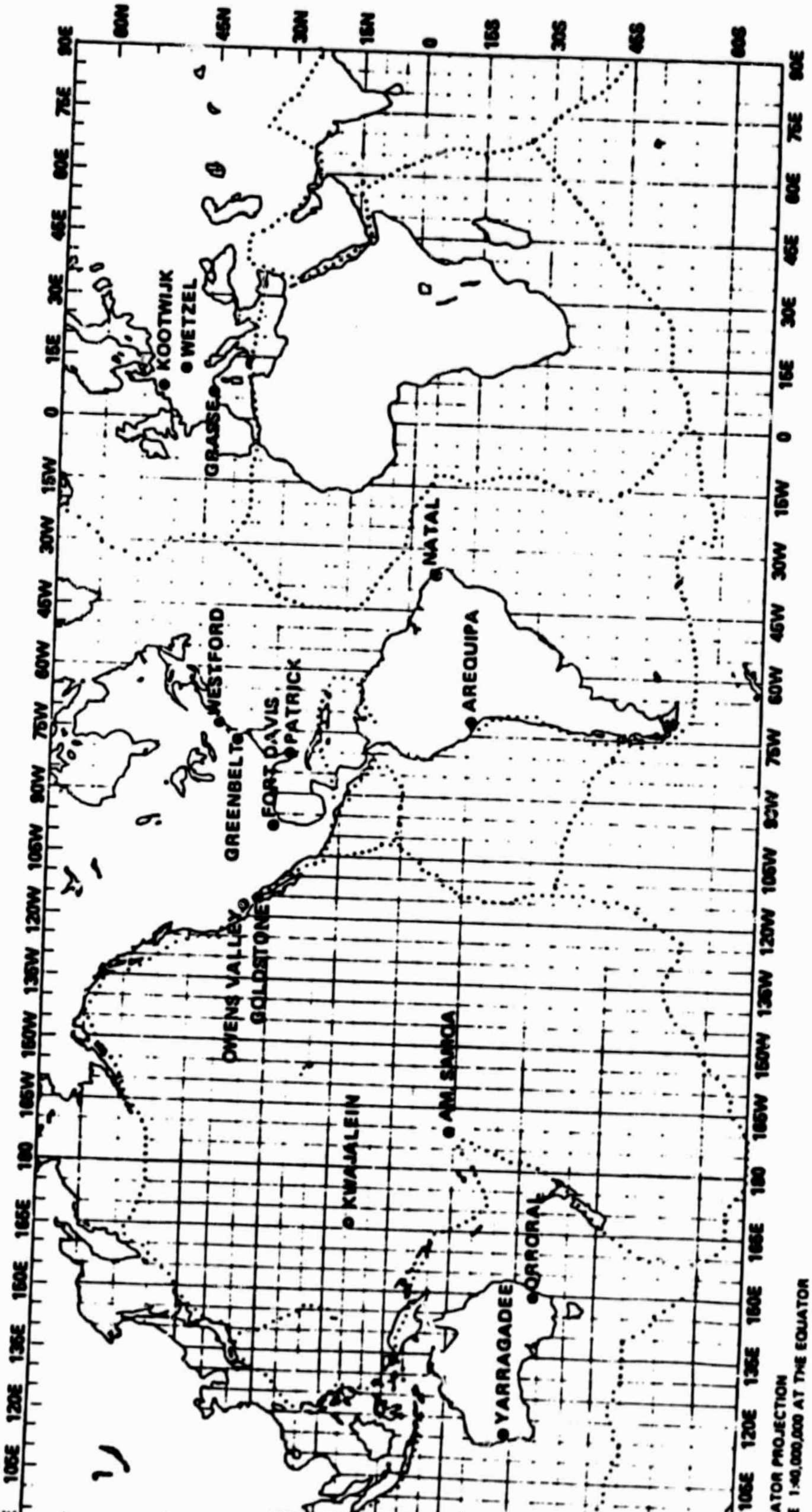


FIGURE 4-1

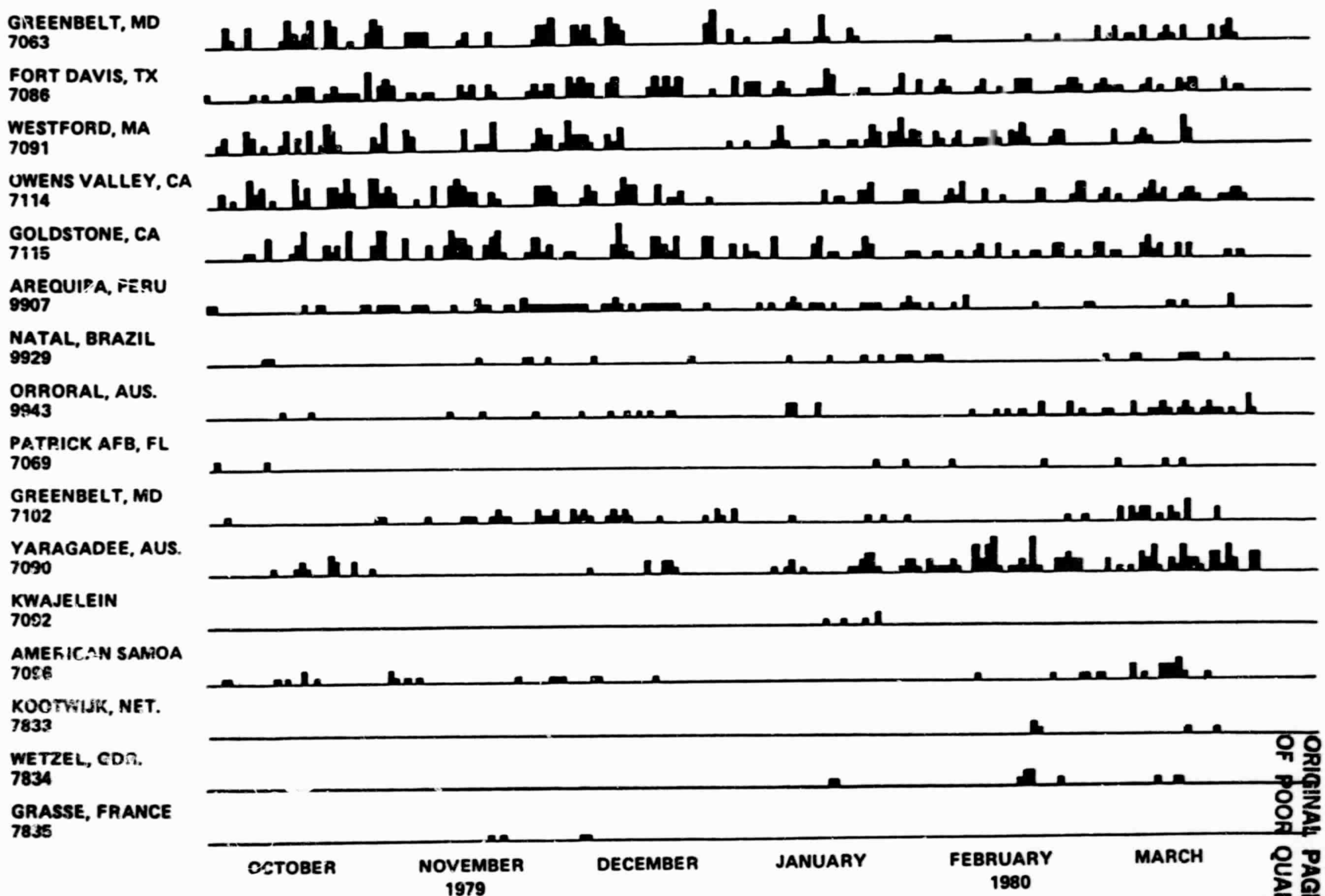

GREENBELT, MD
7063
FORT DAVIS, TX
7086
WESTFORD, MA
7091
OWENS VALLEY, CA
7114
GOLDSTONE, CA
7115
AREQUIPA, PERU
9907
NATAL, BRAZIL
9929
ORRORAL, AUS.
9943
PATRICK AFB, FL
7069
GREENBELT, MD
7102
YARAGADEE, AUS.
7090
KWAJELEIN
7092
AMERICAN SAMOA
7096
KOOTWIJK, NET.
7833
WETZEL, GDR.
7834
GRASSE, FRANCE
7835
OCTOBER
NOVEMBER
1979
DECEMBER
JANUARY
FEBRUARY
1980
MARCH

FIGURE 4-2

VALIDATION AND INTERCOMPARISON EXPERIMENTS

SESSION IV

SECTION 5

MARK-III VLBI RESULTS

James W. Ryan

and

Phil Liebrecht

The Mark-III VLBI contribution to the Session Four Intercompar'son Experiments consisted of four observing sessions of approximately 1 day in duration each. These occurred on November 25, 2979, April 11, 1980, July 26, 1980, and July 27, 1980. The attached table tabulates the baseline results from these sessions. The following is a description of the sessions and of significant problems which were encountered.

1. November 25, 1979

The November 25 observing session consisted of a portion of one day of a 5 day experiment involving Haystack, NRAO, OVRO, Onsala, and Effelsberg. This session was carried out with a U.S. geodesy schedule; the other days of the November 1979 experiment were carried out with radio astronomy or European geodesy schedules. The data base $79NOV25X contains 518 observations on the ten baselines between the five telescopes. Seventy-eight observations were deleted during the post-processing leaving 440 observations in SOLVE least-squares adjustment. These spanned the period 79NOV25 at 2101 to 79NOV26 at 1258 - a total of 15 hours. The SOLVE solution which generated the infor-

...ution presented in Table 5-1 had 40 recovered parameters. These consisted of: the positions of all sites except Haystack, one tropospheric zenith delay parameter for each station, clock parameters at all stations except Onsala, and the coordinates of 1749+701, 3C390.3, and 0552 + 398. The coordinates of 3C454.3, VR422201, 2134 + 00, 3C345, OJ287, 3C120, NRAO150, 4C39.25, and 3C273B were held fixed at canonical values from the 76-78 grand solution. The tropospheric refraction was calibrated using the Chao model, not surface weather data, and no cable calibration was applied. The weighted-rms-of-fit observation scatter from the solution was .10 nanoseconds and .15 pico-seconds per second for delay and rate respectively.

The following is a list of problems encountered in processing this data:

A. Two clock breaks occured at Haystack - one on November 25 at 2350 and the second on November 26 at 1059. One clock break occurred at OVRO on November 26 at 0329.

B. The ionosphere correction could not be derived from the S/X dual band data due to difficulty in resolving the ambiguities in the S-band data. This difficulty was caused by the combination of the small S-band ambiguity (12.5ns) and the clock breaks at Haystack and OVRO.

C. The short duration of this session - only 15 hours - significantly limits the potential of this data set. As a general rule, 24 hours is considered as minimum duration for a well planned geodetic experiment.

2. April 11, 1980

The April 11, 1980 geodetic observing session consists of the first 1-1/2 days of a 3 day experiment involving Haystack, Fort Davis, OVRO, and NRAO. The last day of the experiment marked the first participation of the refurbished Fort Davis station (HRAS 085) in a Mark-III VLBI experiment. Among the modifications and equipment installed at Fort Davis were a Mark-III terminal, a NR-type hydrogen maser frequency standard, and new shaft encoders on the telescope mount. This experiment also marked tha last time that NRAO was a participant in a Mark-III geodetic experiment through the present date (July 1981). The session spanned April 11 at 2042 to April 13 at 1159, a period of 38 hours. 1297 observations were produced of which 1196 passed editing in SOLVE. The solution used to produce the results (in Table 5-1) had 65 recovered parameters. These consisted of: the coordinates of all stations except Haystack, one tropospheric refraction zenith path delay parameter every 12 hours at each station, clock parameters for all stations except NRAO, and the coordinates of 0552 + 398, OQ208, and 1642 + 69. The coordinates of 4C67.05, NRAO150, 3C120, OJ287, 4C39.25, 3C273B, 3C345, 2134 + 00, VR422201, and 3C454.3 were held fixed at the canonical values. The weighted rms residuals scatter of this solution was .17 nanoseconds and .14 picoseconds per second for the delay and rate respectively. Tropospheric refraction corrections from surface weather data and cable calibration were applied. The following are a list of problems encountered in this data set:

A. The hydrogen maser at Fort Davis had a faulty attenuator which caused the level of the 5-MHz output signal to jump between two levels. This caused the phase of the Mark-III phase calibrator to jump erratically. Also, a diode clipper in the phase calibrator was not operating properly and this caused the phase calibrator to vary throughout the session. Both of these problems combined to cause the Fort Davis data to be initially quite poor. In order to circumvent these problems, the Fort Davis delay data was post-processed to remove the phase calibration entirely. This produced data which appeared to be much improved, but which still contained a number of clock breaks. Both equipment problems were repaired before the July 80 experiment.

B. Three clock breaks were detected at Haystack. This is an unusually large number of breaks for a fully operational station and seems to be symptomatic of a continuing problem with the maser at Haystack.

C. Two clock breaks occured at OVRO.

D. Because of the many clock breaks and because of the small S-band group delay ambiguity it was not possible to resolve the ambiguities in the S-band data. As a result of the data could not be calibrated for the effects of ionospheric refraction. (Based on experience gained in this experiment the S- and X-band frequency sequences for the July 1980 and MERIT experiments were modified to increase the size of the S-band group delay ambiguity.)

In spite of the problems cited above, the long duration of the session and the number of data points produced allowed a solution to be produced with formal errors in all lengths which were less than or equal to 2 cm.

3. July 26, 1980

The July 26 observing session was first day of a 3-day experiment involving Haystack, Fort Davis, OVRO, Onsala, and Effelsberg. The second day was also a geodetic experiment and the last day consisted of a series of engineering tests. The session spanned the period July 26 at 0056 to July 26 at 2359, a period of 23 hours. With five stations making up ten baselines, a total of 1327 observations were produced. Of these a total of 1028 observations were used in the SOLVE solution which produced the results cited in the attached table. Most of the edited points were deleted on the basis of fringe quality code, not SOLVE editing. In the solution, 66 parameters were recovered. These consisted of: the positions of all stations except Haystack, one atmosphere parameter per 12 hours at OVRO, Onsala, and Effelsberg, clock parameters at all stations except Haystack, and the coordinates of 1633 +38, 1749 + 096, 1642 + 690, 0234 + 285, 0106 + 013, 0235 + 164, 0552 + 398, OK290, 1219 + 285, 1354 + 195, 1502 + 106. The coordinates of 3C345, 2134 + 00, VR422201, 3C454.3, 4C67.05, NRAO150, and 4C39.25 were held fixed at their canonical values. The weighted rms of fit was .13 nanoseconds for delays and .17 picoseconds per second for the rates. Cable calibration, tropospheric refraction corrections from surface weather data, and dual frequency ionosphere corrections were applied. This was the first successful dual frequency experiment since August 1979.

The following are a list of problems encountered in this data:

A. The schedule was constructed such that for every observation, the source being observed was visible at all stations. As a result, there were no low elevation observations at the stations in the middle of the array, namely Haystack and Fort Davis. This caused the data to have very little sensitivity to the tropospheric refraction parameters for these stations, and it was not possible to solve for refraction parameters for Haystack and Fort Davis. On the other hand, it was found that the data was sensitive to the a prior model of the troposphere used to calibrate the data from these stations. This is an undesirable situation since the data are sensitive to model parameters which cannot be successfully adjusted. (In geodetic schedules generated since the July 80 experiment care has been taken to see to it that low elevation data are acquirred at all staions.)

B. There were three clock breaks at OVRO and one at Fort Davis. Some of the difficulty at OVRO may have been caused by turning the Mark III off to remove some video converters needed by ARIES. A Canadian group was operating in a piggy-back mode, and some of the video converters were reset for them.

C. Haystack lost some data because an unidentified signal which interfered with the phase calibration in one video converter. The problem has not occurred again.

D. One upper sideband track was faulty in the correlator. The loss of the phase calibration signal caused the frequency to be rejected in fringing. All effected data were reprocessed.

4. July 27, 1980

The July 27 observing session was the second day of the three-day experiment as discussed above. It spanned the period July 27 at 0009 to July 27 at 2124 and was 21.5 hours in duration. Out of 1111 observations which were produced, 859 were used in the solution cited in Table 5-1. Most of the edited observations were deleted on the basis of poor fringe quality. The solution contained 61 recovered paramaters and was comparable to that for the previous day except for the number of clock parameters. The weighted rms of fit was .12 nanoseconds for the delay data and .14 picoseconds per second for the rate data. Cable calibration, tropospheric refraction from surface weather data, and ionospheric refraction from dual frequency observations were applied to the data. This observing session was heir to the same set of problems as the previous day. Even the clock breaks occurred at the same stations. (It is worth noting here that the poor clock performance at OVRO during this experiment did not repeat during the 14-day MERIT experiment which occurred during September and October 1980.)

ORIGINAL PAGE IS
OF POOR QUALITY

SESSION FOUR - INTERCOMPARISON RESULTS
VECTOR BASELINE PARAMETERS

EXPERIMENT	LENGTH CM	DECLINATION DEGREES	LONGITUDE DEGREES
		HAYSTACK-OVRO 130	
79NOV25	392888165.4±6.3	-6.6984296±3.3E-6	-179.6904112±6.7E-6
80APR11	67.2±4.5	325±3.2E-6	231±6.5E-6
80JUL26	65.3±3.9	262±3.2E-6	255±6.5E-6
80JUL27	64.6±4.2	280±3.2E-6	278±6.5E-6
LMV EST*	65.6±2.3	291±1.6E-6	221±3.3E-6
		HAYSTACK-FORT DAVIS	
80APR11	313564105.5±6.6	-19.8505596±3.7E-6	-162.7467654±7.1E-6
80JUL26	04.3±2.7	521±3.1E-6	674±6.3E-6
80JUL27	07.9±3.9	547±3.1E-6	701±6.5E-6
LMV EST*	05.5±2.1	550±1.9E-6	678±3.8E-6
		HAYSTACK-NRAO 140	
79NOV25	84512983.0±2.7	-24.6700846±6.4E-6	-142.5289251±8.5E-6
80APR11	82.1±6.0	971±6.4E-6	501±7.9E-6
LMV EST*	87.0±2.5	909±4.5E-6	385±5.8E-6
		NRAO 140-OVRO 130	
79NOV25	332424424.4±6.9	-1.8191501±3.7E-6	172.2834047±7.1E-6
80APR11	21.6±3.9	512±3.3E-6	3966±6.6E-6
LMV EST*	22.0±3.4	507±2.5E-6	4006±4.8E-6
		FORT DAVIS-NRAO 140	
80APR11	235463405.2±5.4	17.6010702±4.3E-6	10.4618700±7.9E-6
		FORT DAVIS-OVRO 130	
80APR11	150819537.6±6.0	23.7111597±5.8E-6	141.8144802±8.7E-6
80JUL26	36.6±3.6	621±5.8E-6	736±7.6E-6
80JUL27	34.7±2.7	631±4.3E-6	717±7.1E-6
LMV EST*	36.3±2.0	620±3.0E-6	746±4.5E-6

*LMV EST - Linear Minimum Variance Estimate (See Appendix B)

TABLE 5-1

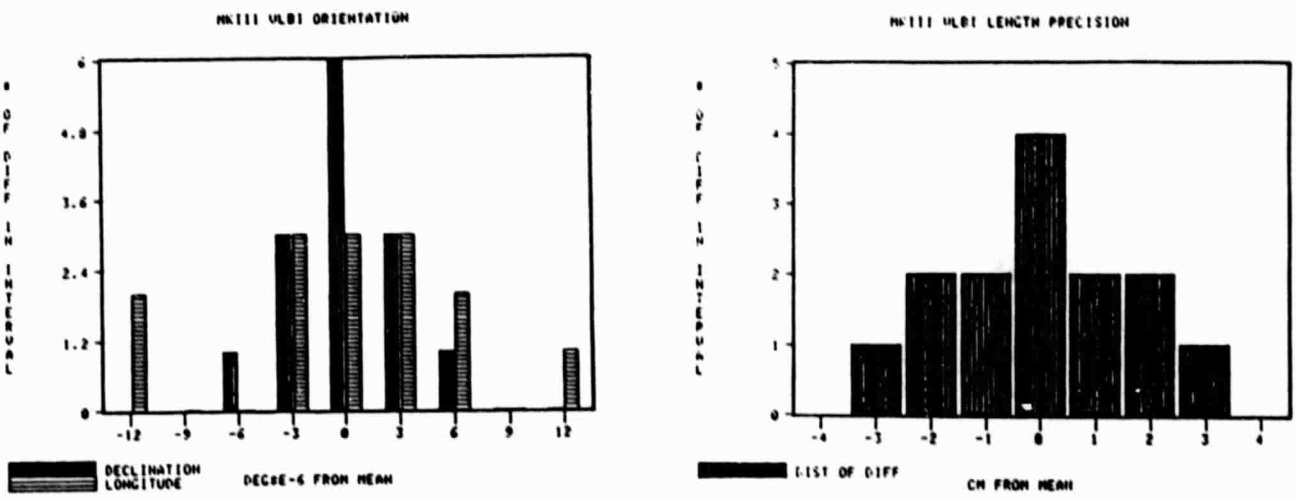
ORIGINAL PAGE IS OF POOR QUALITY

To investigate the repeatability of the VLBI length results, the mean and standard deviation of the differences between the individual baseline vectors and the unweighted mean baseline vectors were computed and listed in Table 5-2. A Histogram of these differences are plotted in Figure 5-1. The differences appear to be approximately distributed normally even though the sample size is small.

Differences From Mean Determinations

	Length (CM)	Declination (10^{-6} Deg)	Longitude (10^{-6} Deg)
Mean Diff ± S.D.	.029 ± 1.7	-0.021 ± 3.2	0.014 ± 6.6

TABLE 5-2



Histograms of Differences From Mean Baselines

Figure 5-1

The errors listed in Table 5-1 are from a combination of Formal (Noise) and systematic error sources. To begin with all formal errors were multiplied by three to account for systematics in clock and atmosphere parameters and source coordinaates. Additional errors were also included in the orientation parameters due to the BIH polar motion and UT-I uncertainties. A discussion of the systematic errors used for intercomparison follows:

ORIGINAL PAGE IS OF POOR QUALITY

A. Length: The length uncertainties listed in Table 5-1 are the formal errors multiplied by three. The smallest uncertainty is approximately 3 cm. Utilizing a Chi-square test with 13 degrees of freedom, on the residuals from the mean determinations, the $P[\sigma^2 \geq 3\ cm] \leq .01$. This combined with the fact that most standard length errors are greater than 3 cm makes our three times formal errors a conservative estimate for the Session IV data. With respect to length uncertainties, one note of caution is in order: The Linear Minimum Variance Estimates were computed assuming the errors in each determination were independent of each other. This is not completely correct, as some errors are believed correlated, however, the LMV estimate error tolerances are most likely still quite reasonable due to the conservative approach taken above.

B. Orientation Errors: The largest known systematic errors in orientation parameters for the Session IV VLBI Data are the errors in the BIH UT-1 and Polar Motion (P.M.). The UT-1 errors map directly into longitude uncertainty and the P.M. errors into declination uncertainty. Published BIH errors (one sigma) for the Session IV experiments and RMS differences between BIH and MARK III determinations of UT-1 and P.M., provided by the NGS are as follows:

BIH ERRORS

Source	Polar Motion X(mAsec)	Polar Motion Y(mAsec)	UT-1 (mS)
BIH November 25, 1979	10	9	.8
April 11, 1980	7	7	.8
July 26 & 27, 1980	6	6	.8
RMS Difference Between VLBI and BIH (NGS)	10	-	1-1.5

TABLE 5-3

To be conservative, the largest values were chosen and rss'ed with three times the formal (noise) errors and are listed in Table 5-1.

10 mAsec P.M.	2.8×10^{-6} Deg. Declination
1.5 mSec UT-1	6.3×10^{-6} Deg. Longitude

There may be other systematic error sources in the orientation parameters (source positions, etc.), however, it is expected they are small compared to the BIH errors and are conservatively treated by using three times formal error rss'ed with the BIH error. These error levels of Table 5-1 agree approximately with the standard deviations of Table 5-2.

ORIGINAL PAGE IS
OF POOR QUALITY

The vectors chosen for intercomparison purposes are the LMV values in Table 5-1. Once again, a word of caution is in order. As with the length LMV estimates, the covariances between most samples are assumed equal to zero, however, the errors for orientation are correlated for vectors measured on July 26 and 27 due to the common BIH data used. The effect of this correlation is expected to be small.

NOTES.

1. The baseline declinations and longitudes are referenced to the current conventional MARK-III VLBI coordinate system. This system is defined by the adopted cartesian coordinates of Haystack, the adopted coordinates of the source 3C27B, the Circular D. values of the pole position and UT1 for May 17, 1978, and the theoretical models used to reduce the VLBI data. Of particular importance among these models are the models of precession and nutation. The precession model was based on the new IAU recommended value of precession constant. The longitude tabulated above are consistent with the new precession constant and the value of the earth's diurnal spin rate appropriate to the new precession constant.

2. SOLVE run number for the above solutions:

79NOV25	10281-1658
80APR11	11166-1201
80JUL25	11163-1712
80JUL26	11163-1816

MARK III GEOCENTRIC BASELINE VECTORS (METERS)

FROM TO	X	Y	Z
NRAO OVRO	-3292480.757	446132.315	-105527.591
HAY OVRO	-3902005.555	-21083.223	-458278.530
HAY NRAO	-609524.815	-467215.865	-352751.092
NRAO FTDV	-2207090.893	-407541.046	-712012.366
HAY FTDV	-2816615.844	-874756.686	-1064763.238
HRAS OVRO	-1085389.707	853673.595	606484.798

TABLE 5-4

ORIGINAL PAGE IS
OF POOR QUALITY

MKII VLBI Results

(Provided by K. S. Wallace, J. L. Fanselow, J. M. Davidson, and A. E. Neill, all of JPL)

The Mark II VLBI Results are the best fit OVRO to GDS (DSS-13) baseline from the combination of aries solutions of experiments 79N thru 80A.

Table 5-5 lists the individual experiments, the dates conducted, which transportable system was used at JPL and the water vapor calibration used. It should be noted that seven experiments were strictly S-band and three were X-band.

MARK II EXPERIMENTS

Exp't(a)	Date	Stations	Transp'le Telescope	Water Vapor Calibration(b)
79NS	08/29	JPL/OVRO/DSS-13	9 Meter	N/N/D
79QS	11/21	JPL/OVRO/DSS-13	9 Meter	N/S/D
80AS	01/04	JPL/OVRO/DSS-13	9 Meter	N/S/D
80BX	01/06	JPL/OVRO/DSS-13	3.7 Meter	N/S/D
80CS	02/05	JPL/OVRO/DSS-13	9 Meter	N/S/D
80DS	03/25	JPL/OVRO/DSS-13	9 Meter	N/S/D
80FS	06/03	JPL/OVRO/DSS-13	9 Meter	D/H/S
80GS	06/11	JPL/OVRO/DSS-13	9 Meter	D/H/S
80IX	07/28	JPL/OVRO/DSS-13	3.7 Meter	N/H/H
80LX	11/	JPL/OVRO/DSS-13	3.7 Meter	S/H/N

(a) X = X-Band experiment, S = S-band experiment.

(b) S = surface meteorology model used, N = NEMS WVR used, D = Div 33 WVR used, H = solar hygrometer used.

TABLE 5-5

The analysis of this data is documented in the following excerpts from the "1980 Aries MK II data package for geodynamics archive. Description of data reduction" excerpts of which are included here.

Analysis

(a) General

The Mark II video tapes from the stations were processed on the CIT/JPL Block 0 correlator. Post-correlation processing was done using the DSN/GD codes: PHASOR, PCAL, MERGE, CALIBRATE, OMC, and SOLVE. This version of MERGE used two tones for phase calibration. These two tones were separated by 1.0 MHz and were approximately centered in the 2 MHz width channel. All of the post-processing from MERGE onward was done using the CIT/JPL VAX computer, located in the Robinson Building on the Caltech campus. Much of the PHASOR and PCAL running was done on the CIT IBM/370 located in the Jorgenson building on the Caltech campus. The last two modules in this software chain comprise the code popularly known as MASTERFIT.

(b) The Earth Model

i.) General. Extensive documentation is in preparation by J.L. Fanselow to describe the earth model contained in the OMC part of MASTERFIT. It will not be reproduced here. Rather, we present enough information to make our processing traceable and, hopefully, reproducible by an other user of MASTERFIT or, indeed, of any sufficiently sophisticated VLBI fitting code.

ii.) UT1-UTC, Polar Motion. The BIH/Circular-D values corrected with ocean tide terms were used. The uncertainty in these values was taken to be 2.1 msec in UT1-UTC and 10.3 marcsec in polar motion. These were estimated parameters with the above given a priori uncertainties.

iii). Precession/Nutation. The 1980 IAU theory of nutation (Wahr model) was used. Precession quantities are 1976 IAU values.

iv.) Source Positions. The right assention of 3C 273 was fixed at 12:29:6.6997. All other source coordinates were solve-for parameters and were given a priori values, and a priori accuracy estimates (1.0D-02 radians) for both right assention and declination: that is, all other source coordinates were a priori unconstrained.

v.) Station Locations. The coordinates of OVRO were fixed for all experiments. All other station coordinates were estimated parameters and were a priori unconstrained. Separate station location estimated coordinates were determined for each experiment.

vi.) Clocks. Linear clock drift and offset and frequncy offset were separate estimated parameters for all station clocks. The OVRO clocks were constrained to have values of zero for these parameters for the first "clock section" of each experiment, thus establishing a reference clock.

vii.) General Relativistic Gamma Factor. The general relativistic gamma factor was set equal to one. This was not an estimated parameter.

viii.) Solid Earth Tide Parameters. The vertical and horizontal love numbers were set equal to 0.609 and 0.0852, respectively. The tidal phase was set equal to 0.0. These were not estimated parameters.

ix.) Axis Offset. The axis offsets were put in explicitly for all telescopes. This was not a solve-for parameter.

x.) Speed of Light. The speed of light used in MASTERFIT was 2.99792458D+05 km/sec.

(c) Ionosphere Calibration

No attempt has been made to correct for the effect of the ionosphere, except that in the case of the S-band experiments, only data recorded during the ionospheric night (approximately local 8 P.M. to 4 A.M.) were used. For the X-band experiments, all data were used.

We warn the recipient of this data package that there may be a residual systematic extension in the baseline lengths because of this approach. The size of this extension for the S-band experiments will be about 7 cm per 1.0D=17 eletrons/m**2 of zenith columnar ion content for a baseline of 250 km length. The effect for X-band experiments will be smaller by a factor of about 13. The size of this effect, for the relatively short ARIES baselines, scales approximately with total baseline length and is also fairly insensitive to baseline orientation, expecially at night.

For baseline components perpendicular to length, covarience analyses and physical intitution both predict no systematic shift. However, a comparison of S-band with S-X solutions given some empirical indication of a systematic effect on the transverse component (perpendicular to both the length and the local vertical), perhaps half as large in size as the length extension.

The above described effects are as much qualitative in nature as quantitative, because we know of no ionsphere mapping model adequate for the accuracy requirements of VLBI geodesy. Moreover, the existance of such a model would be of questionable value, because we know of no ionsphere total electron content (TEC) data which is of adequate reliability for the requirements of VLBI geodesy.

However, for the benefit of the VLBI community in general, and for the possible repudiation of the preceeding paragraph, we include REPORTED values of zeneth TEC for the dates of these experiments. These were measure using a Faraday rotation monitor, lovated on the Goldstone complex, and were provided to us by Dr. Herbert Royden, JPL. We warn the receipient of this data package that the overall normalization of these TC values is uncertain and they may be biased by any number of incremental steps of 0.42D+17 electrons/m**2.

(d) Troposphere Calibration

i.) The Dry Tropsphere. The dry troposphere calibration was determined from a simple measurement of the barometric pressure. An a priori error of 3 mbars is assumed for this. This was an estimated parameter within the above a priori uncertainty.

ii.) The Wet Troposphere. Three different techniques were used to calibrate the wet troposphere. Where they were available, water vapor radiometer (WVR) data were used. The second choice was solar hygrometer data. When both of these were unavailable, the Berman day/night model was used.

No attempt was made to include the uncertainties in these techniques in calculation of the baseline solution errors. For the benefit of the recipient of this data package, who may want to attempt this himself, we include a very rough estimate (provided to us by Geoerge Resch) of the uncertainties D as follows: for the surface meteorology model, D = 50% of the total; for the water vapor radiometers,

D = A0*SQRT(A1 + A2/N + (A3*L)**2),

where L is the line-of-sight total wet delay in cm and the other quantities are constants:

A0 = 1.0 (Approximately. It could be 0.5 to 2.0)
A1 = .36 CM**2
A2 = .56 CM**2
A3 = 1/15 CM
N = Number of samples, typically 8.

These errors are non-random in the sense that they represent a systematic bias in the calibrtion at any given station on any given day. They are random in the sense that they will be uncorrelated for the same station on different days or for different stations separated by hundreds of km.

(e) Parameterization, Data Included and Site Vectors

The solve-for parameters include source coordinates, station locations, dry zeneth troposphere, UT1-UTC, polar motion, and clocks for all stations, with a priori uncertainties as given in the preceeding subsections.

Results

The Vector Baseline results of the analysis are presented in Tables 5-6 and 5-7 as follows. Plots of the baseline solutions for the OVRO/Goldstone are shown in Figure 5-2.

ORIGINAL PAGE IS
OF POOR QUALITY

1979-1980 Goldstone/OVRO Length Determinations
(meters)

August 31	1979	79Ns	257,587.456	+/-	.040
November 21	1979	79Qs	257,587.588	+/-	.046
January 4	1980	80As	257,587.502	+/-	.042
January 6	1980	80Bs	257,587.440	+/-	.033
February 5	1980	80Cs	257,587.434	+/-	.032
March 26	1980	80Ds	257,587.480	+/-	.037
June 3	1980	80Fs	257,587.425	+/-	.046
June 10	1980	80Gs	257,587.432	+/-	.042
July 28	1980	80Ix	257,587.425	+/-	.036
November 2	1980	80Lx	257,587.449	+/-	.033
		Average =	257,587.458	RMS =	.051m

TABLE 5-6

Using a Chi square test with 9 degrees of freedom, a one sigma length uncertainty with 50% confidence level is .053m.

Scatter of Length Determinations About the Mean

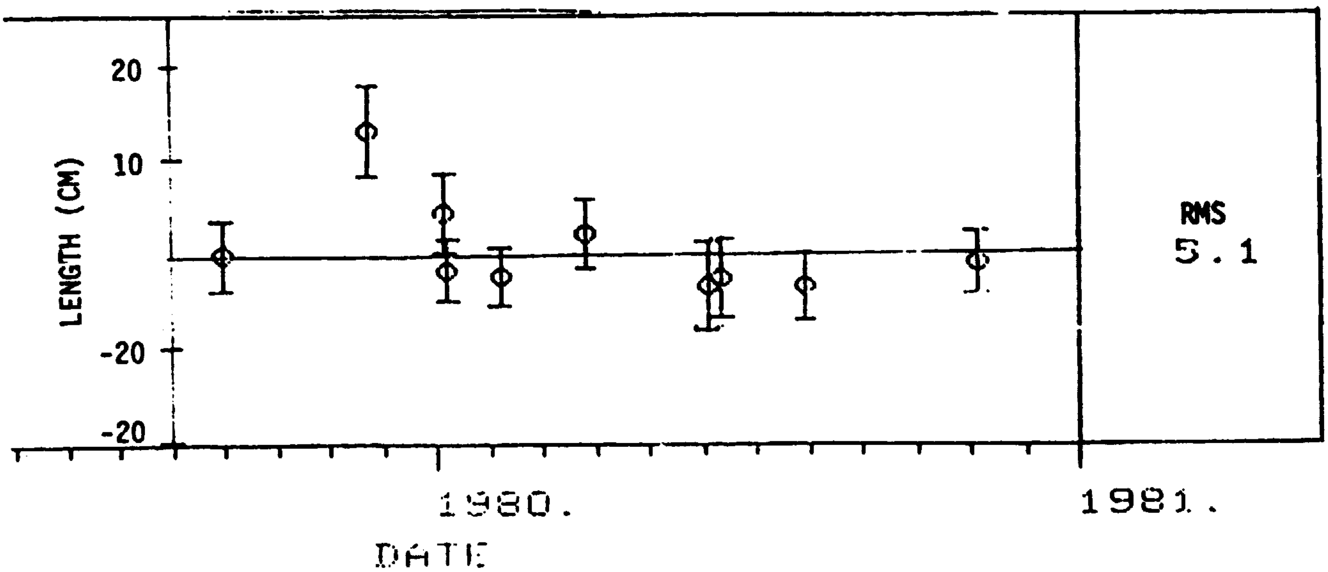


Figure 5-2

Mark II Geocentric Baseline Vectors for Intercomparison

From	To	X(M)	Y(M)	Z(M)
OVRO	GDS	58471.635	-177127.470	-177646.400

Length (M)	Longitude (Deg ± 10^{-6})	Declination (Deg ± 10^{-6})
257587.49 ± 0.05	-71.731402 ± 21	-43.602774 ± 16

Table 5-7

VALIDATION AND INTERCOMPARISON EXPERIMENTS

SESSION IV

SECTION 6

DOPPLER POSITIONING SYSTEM RESULTS

Larry Hothem

The National Geodetic Survey in cooperation with the Defense Mapping Agency performed Doppler observations at the six stations of the Seesion IV Intercomparison sites. Stations were occupied with Magnavox Geoceivers as shown in Figure 1.

The data sets used for the point position determinations were not based on simultaneous observations. Data observed at Greenbelt were observed during an independent Doppler survey project. Although portions of the data sets for the other five stations were observed simultaneously all data were used in the solutions.

All data were reduced with the National Geodetic Survey's version of the point positioning program DOPPLR, dated February 1976. This version does not include a parameter for tropospheric scale bias or a correction to the ranges for the effect of the Earth rotation due to r/c where r is range and c is speed of light.

A summary of the point position results are given in Table 1. Comparison of Doppler station occupation information and DOPPLR solution statistics between Sessions II and IV are given in Tables 2 and 3, respectively. Except for the Greenbelt station, the Doppler sets for Session IV had less than one-half of the passes available for corresponding stations during Session II, also the overall quality of the data was better during Session II. A probable reason the data quality was worsee for Session IV was because the observations were made during maximum solar flare activity. Recent studies have shown a strong correlation between poorer precision for the Transit satellite orbit determinations and the intensity of solar flare activity.

In addition, three data sets are questionable in quality due to equipment problems or site environment conditions. These data sets are for the station at Haystack, Greenbank, and Greenbelt (Goddard). Observations at Greenbelt may be poorer due to use of a crystal standard for the receiver's reference frequency rather than an atomic standard. Also, there was evidence that the satellite signals were affected by local RFI. The point position coordinates derived at Haystack may have been biased by reflection problems. Shortly after the observations began at Haystack, there were heavy snows. The antenna was located in among deep snow drifts. Also, at this site, the Haystack dome is an obstruction.

Another factor that may have affected the data quality at Haystack was the reference frequency standard. Haystack's hydrogen maser was used as the external source, but because the signal had to travel over a long cable that had been left in place since the Session II campaign, the quality of the signal may have been affected. Something was causing an intermittent problem with the stability of the reference frequency; the cable may have been one of the causes.

Comparison of the point position coordinates between Session II and IV are summarized in Tables 4 and 5. Table 4 compares the geocentric coordinates and Table 5 summarizes the baseline differences.

A revised version of program DOPPLR has been implemented for routine data reduction. However, reductions with the improved version for the Session II and IV data sets were not completed in time for this report.

The estimated a priori signma for Doppler coordinates expressed in the geodetic horizon system are:

Lat.	=	60 cm
Long.	=	80 cm
Height	=	100 cm

These signmas are for 30-pass solutions; therefore, the a priori sigmas for other data sets are weighted according to the number of passes where,

$$\sigma_N = \frac{\sigma_{30}}{\sqrt{\frac{N}{30}}}$$

and N = number of passes in a data set.

For example, the values for σ_ϕ, σ_λ, and σ_h for a 100-pass solution would be

33, 44, and 55 centimeters, respectively.

The reason the geodetic horizon system is a better choice for expressing the sigmas is because investigations have shown the covariance matrices of Doppler point position coordinates in the XYZ system usually exhibit a high degree of correlation. However, the correlations become much smaller and often insignificant if the covaraiance matrices are transferred to the horizon system at the point in question. Correlations among stations are not considered in point position solutions.

Recent studies of long term repeatability for Doppler coordinates have yielded indications of significant coordinate variations, primarily and annual period and a long term drift that may be associated with the 11-year solar cycle. Tests have shown that the improved version of DOPPLR yields reduced coordinate variations from 18-day solutions for data observed at Ukiah and Owens Valley, California, since January 1977. These plots are also representative of coordinate variation studies performed on data sets observed in Arizona, Virginia, Belgium, and Federal Republic of Germany.

Doppler Station Occupation - Session IV

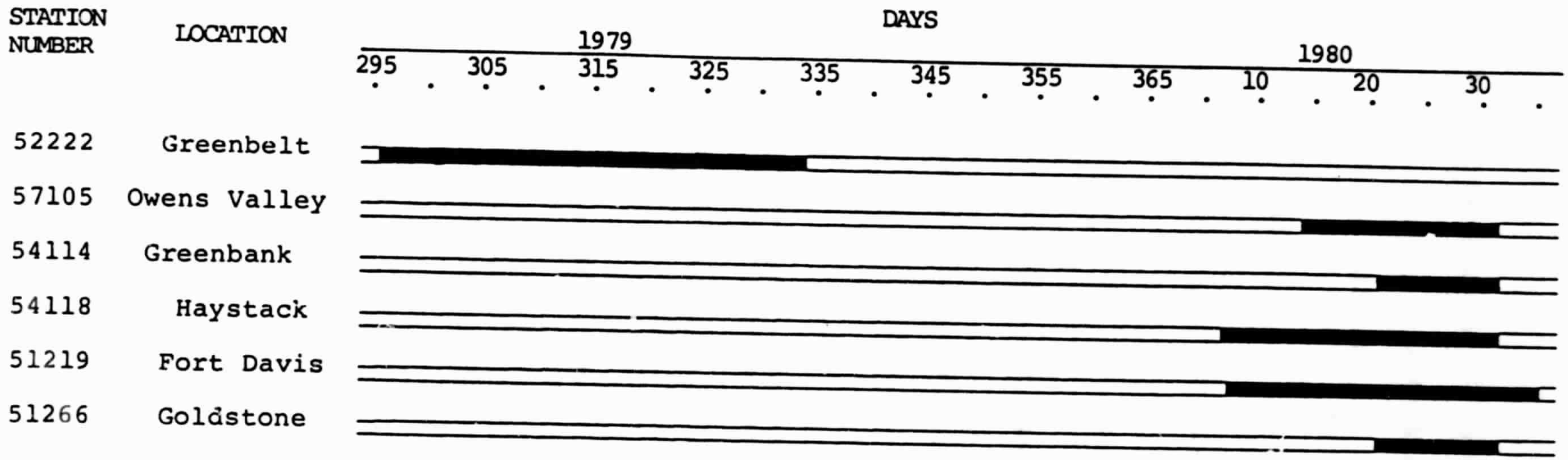


FIGURE 6-1

TABLE 1 -- SUMMARY OF DOPPLER STATION CARTESIAN COORDINATES

JUNE 20, 1981

STAT. NO.	OCCUPATION PERIOD (DAYS/YR)	NUM. OF PASS	SD DV (1)	DATE REDUCED	CARTESIAN COORDINATES X (M)	Y (M)	Z (M)	REMARKS
*** GOLDSTONE ***								
51266	21- 32/80	81	10	4-80	-2350913.97	-4655539.36	3660980.75	5 3
*** GREENBANK ***								
54114	21- 32/80	84	16	4-80	883204.96	-4924450.75	3944064.66	5 3
*** GREENBELT ***								
52222	296-334/79	329	17	9-80	1130713.50	-4831331.11	3994134.87	4 3
*** HAYSTACK ***								
54118	7- 32/80	163	14	4-80	1492394.13	-4457299.38	4296816.88	6 3
*** MCDONALD-FT. DAVIS ***								
51219	8-035/80	165	12	4-80	-1324224.58	-5332068.67	3232022.89	6 3
*** OWENS VALLEY ***								
57105	14- 32/80	112	11	4-80	-2409662.30	-4478362.64	3838521.40	6 3

REMARKS:

1. STANDARD ERROR OF UNIT WEIGHT IN CENTIMETERS FOR THE OBSERVATION RESIDUALS.
3. DOPPLER DATA WERE REDUCED WITH NGS VERSION OF PROGRAM "DOPPLR" AND "PRECISE" EPHEMERIDES, 1976 VERSION, 10 DEGREE CUTOFF, NO TROPOSPHERIC SCALE PARAMETER, NO EARTH ROTATION CORRECTION. COORDINATES ARE REFERRED TO NWL-9D OR NSWC 9Z-2 COORDINATE SYSTEMS.
4. GEOCEIVER I, FREQUENCY STANDARD: CRYSTAL
5. GEOCEIVER I, FREQUENCY STANDARD: RUBIBIUM
6. GEOCEIVER I, FREQUENCY STANDARD: HYDROGEN MASER

TABLE 6-1

DOPPLER OCCUPATION INFORMATION

Space System Validation and Intercomparison Experiments

LOCATION	SESSION II				SESSION IV			
	PERIOD OF OCCUPATION	TOTAL DAYS	SATELLITES	TOTAL PASSES	PERIOD OF OCCUPATION	TOTAL DAYS	SATELLITES	TOTAL PASSES
HAYSTACK	5- 55/1978	51	68,77	367	7- 32/1980	26	59,60	163
OWENS VALLEY	5- 55/1978	51	68,77	359	14- 32/1980	19	59,60	112
GOLDSTONE	6- 55/1978	50	68,77	371	21- 32/1980	12	59,60	81
GREENBANK	5- 51/1978	47	68,77	351	21- 32/1980	12	59,60	84
MCDON/FTDAV	6- 55/1978	50	68,77	367	8- 35/1980	28	59,60	165
GODDARD/GSFC	226-256/1978	31	68,77	132	296-334/1979	39	59,60,68	329

TABLE 6-2

NGS 1/26/81

Comparison of DOPPLR Solution Statistics - Sessions II vs. IV

Space System Validation and Intercomparison Experiments

LOCATION	TOTAL PASSES		OBSERVATIONS						σ_o	
	II	IV	II			IV			II	IV
			INPUT/USED	%	PER PASS	INPUT/USED	%	PER PASS	(cm)	(cm)
Haystack	413	163	7266/6500	10.5	15.7	3027/2715	10.3	16.7	15.5	13.8
Owens Valley	359	112	6721/6261	6.8	17.4	2268/2020	10.9	18.0	11.0	10.8
Goldstone	371	81	6797/6535	3.9	17.6	1524/1468	3.7	18.1	10.8	10.4
McDon/FtDav	367	165	6248/5621	10.0	15.3	3069/2918	4.9	17.7	12.0	11.5
Greenbank	351	84	5996/5814	3.0	16.6	1653/1592	3.7	19.0	10.4	15.8
Goddard/GSFC	132	329	2765/2362	14.6	17.9	6148/5481	10.8	16.7	14.8	17.5

σ_o is the standard error of unit weight for the observational residuals.

TABLE 6-3

NGS 1/26/81

DOPPLER DATA

DIFFERENCES: SESSION II minus SESSION IV

Space System Validation and Intercomparison Experiments

LOCATION	STATION DIFFERENCES					
	GEOCENTRIC			SPIN-AXIS DISTANCE (cm)	RADIUS VECTOR (cm)	LONGITUDE (sec)
	X (cm)	Y (cm)	Z (cm)			
HAYSTACK	- 73	9	42	- 32	- 52	- 0.029
OWENS VALLEY	12	20	- 62	- 24	- 56	0.000
GOLDSTONE	107	97	-125	-135	-182	0.021
GREENBANK	- 12	- 15	14	13	19	- 0.006
MCDON/FTDAV	23	103	-105	-106	-144	- 0.001
GODDARD/GSFC	- 52	6	-106	- 18	- 80	- 0.021
MEAN	1	37	- 71	- 50	- 82	- 0.006
σ	± 64	± 50	± 52	± 72	± 57	± 0.018

Positions scaled by -0.4 ppm.

TABLE 6-4

NGS 1/23/81

DOPPLER DATA

DIFFERENCES: SESSION II minus SESSION IV

Space System Validation and Intercomparision Experiments

		B A S E L I N E D I F F E R E N C E S		
STATIONS FROM - TO	LENGTH (KM)	VECTOR BASE LINE (CM)	EQUATORIAL ALTITUDE (SEC)	EQUATORIAL AZIMUTH (SEC)
HAY - OVRO	3930	- 82	0.000	-0.005
HAY - NRAO	845	- 54	-0.090	(0.151)
HAY - GSFC	602	21	(0.211)	0.068
HAY - GOLD	3900	(-168)	0.059	-0.042
HAY - HRAS	3140	- 91	-0.065	-0.043
OVRO - NRAO	3325	- 17	0.048	-0.024
OVRO - GSFC	3561	36	0.024	-0.011
OVRO - GOLD	237	12	(0.604)	(-1.265)
OVRO - HRAS	1500	- 22	-0.078	0.108
HRAS - NRAO	2360	- 18	-0.114	-0.010
HRAS - GSFC	2623	- 89	-0.020	-0.066
HRAS - GOLD	1294	- 76	-0.009	-0.070
NRAO - GSFC	269	- 63	(0.845)	(0.296)
NRAO - GOLD	3258	- 97	0.094	-0.078
GSFC - GOLD	3502	(-151)	0.020	-0.059
MEAN σ		- 42 ± 46	-0.011 ±0.065	-0.019 ±0.056

TABLE 6.5

NGS 1/26/81

Fig. 2 -- LATITUDE VARIATION - UKIAH

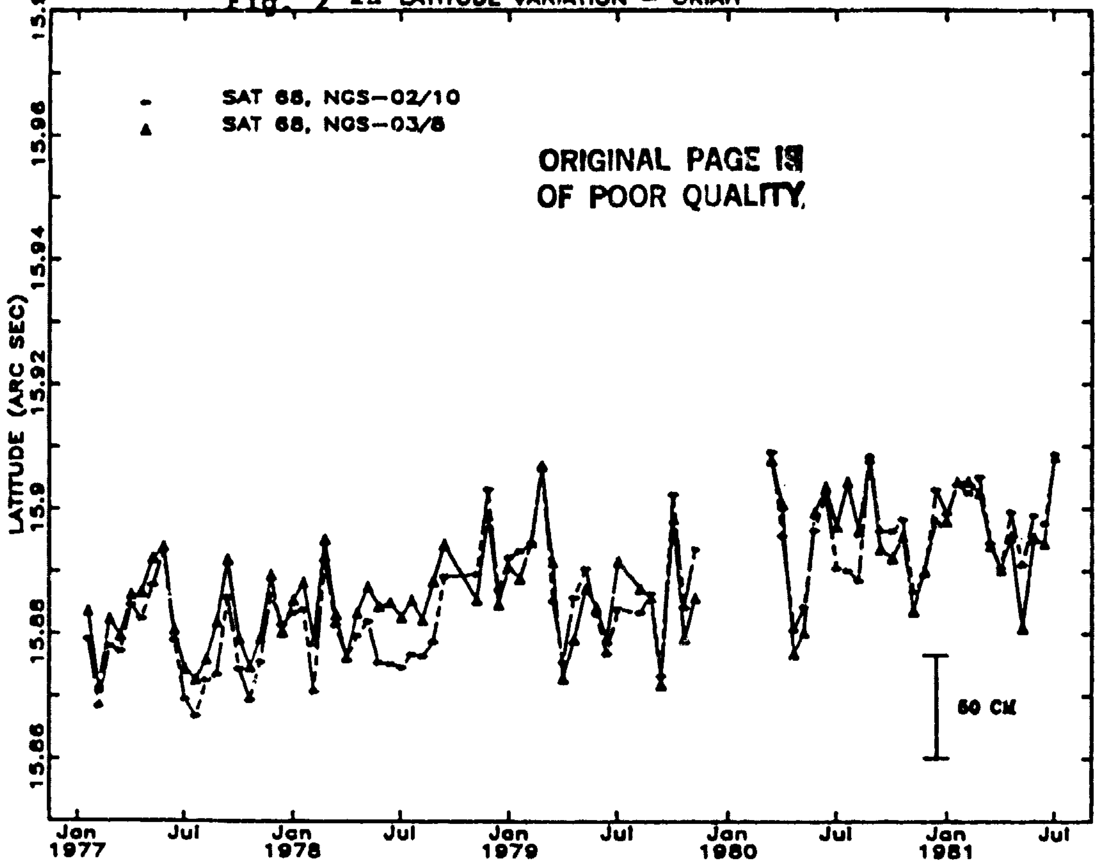


Fig. 3 - LONGITUDE VARIATION - UKIAH

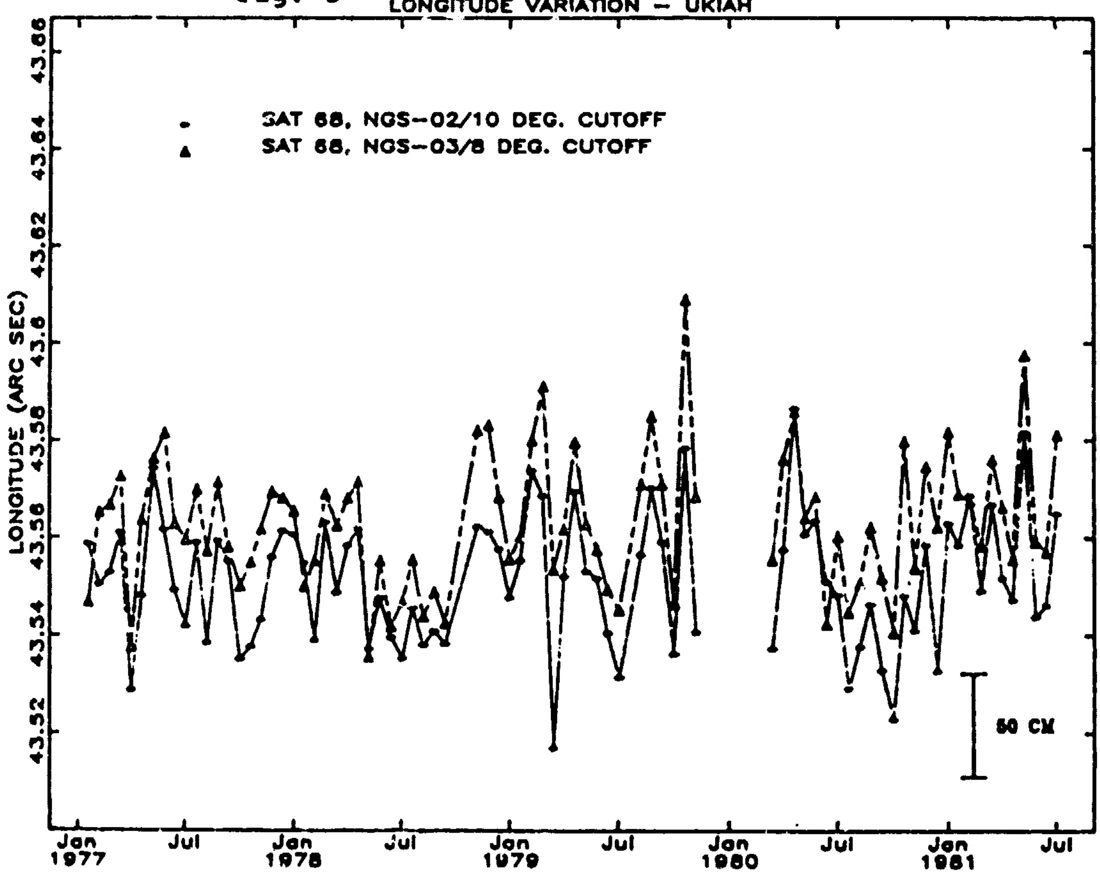


Fig. 4 --

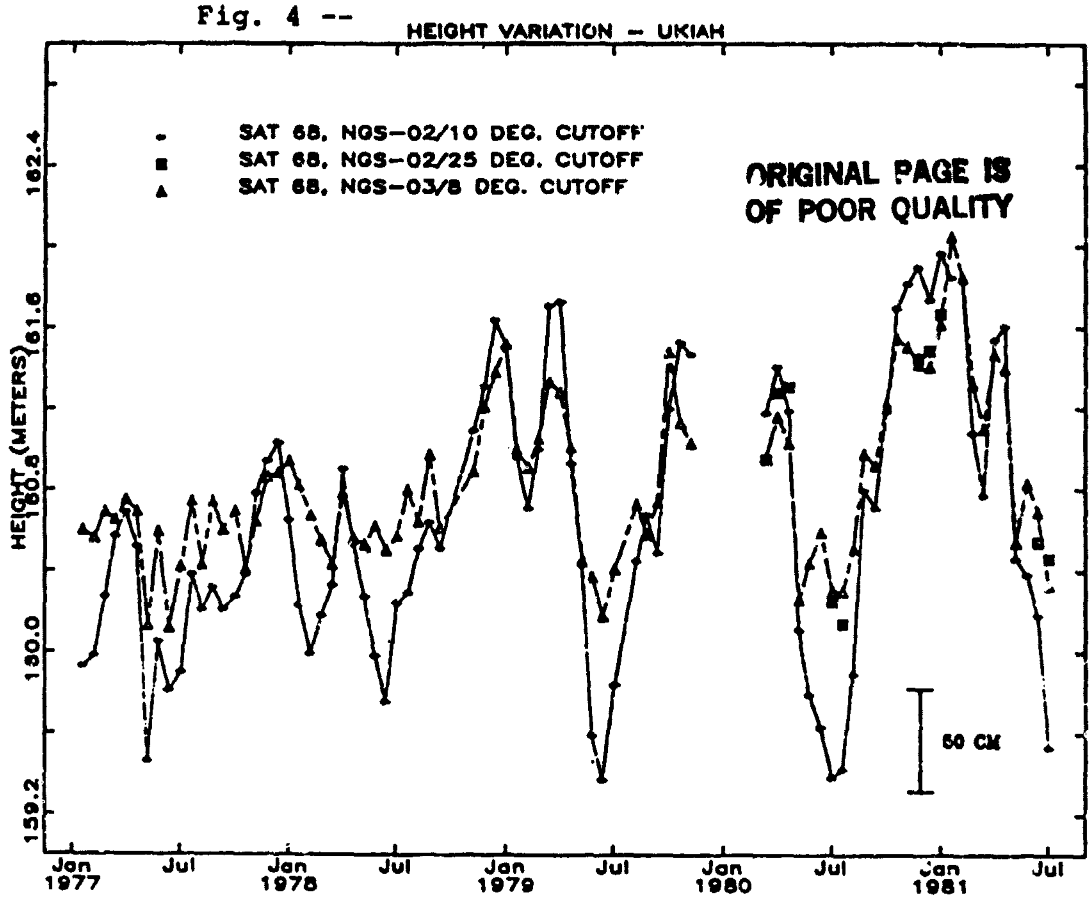

HEIGHT VARIATION — UKIAH
SAT 68, NGS-02/10 DEG. CUTOFF
SAT 68, NGS-02/25 DEG. CUTOFF
SAT 68, NGS-03/8 DEG. CUTOFF
ORIGINAL PAGE IS
OF POOR QUALITY
HEIGHT (METERS)
162.4
161.6
160.8
160.0
159.2
50 CM
Jan 1977
Jul
Jan 1978
Jul
Jan 1979
Jul
Jan 1980
Jul
Jan 1981
Jul

Fig. 5 --

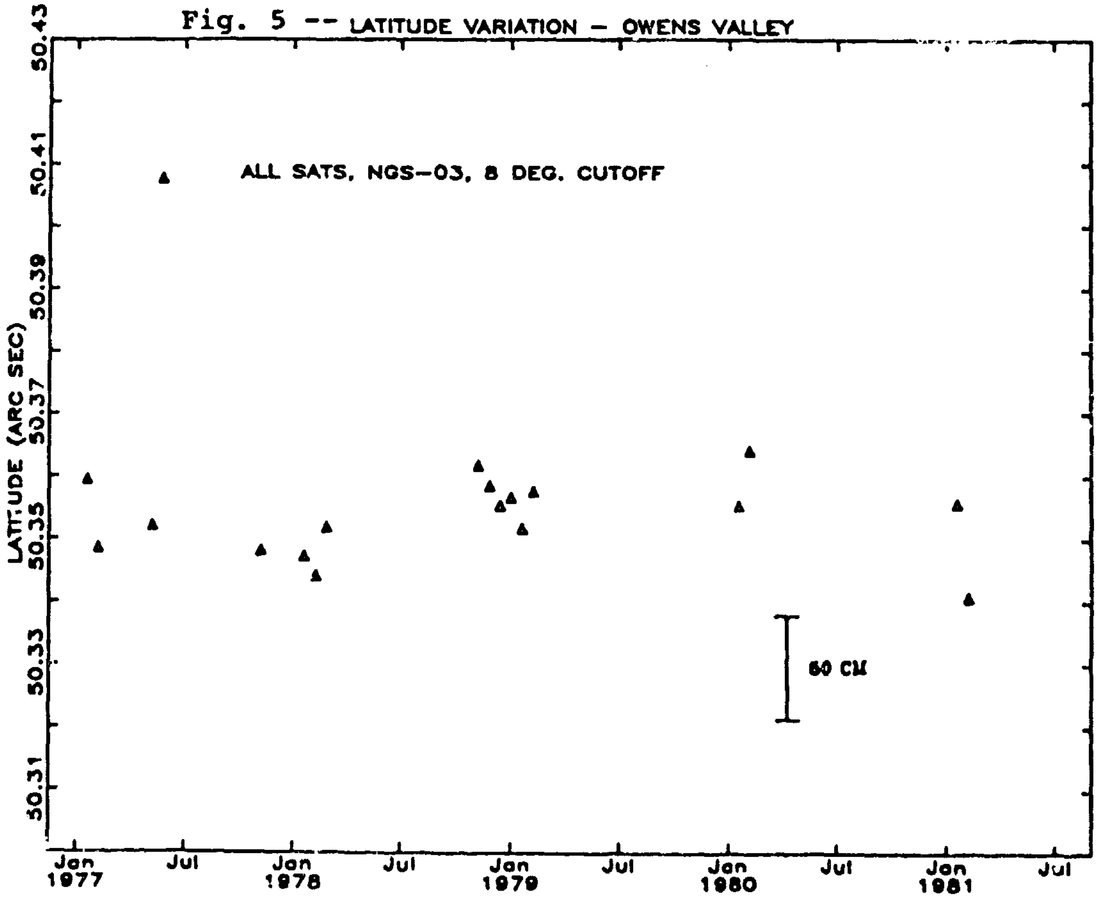

LATITUDE VARIATION — OWENS VALLEY
ALL SATS, NGS-03, 8 DEG. CUTOFF
LATITUDE (ARC SEC)
50.43
50.41
50.39
50.37
50.35
50.33
50.31
50 CM
Jan 1977
Jul
Jan 1978
Jul
Jan 1979
Jul
Jan 1980
Jul
Jan 1981
Jul

Fig. 6 -- LONGITUDE VARIATION - OWENS VALLEY

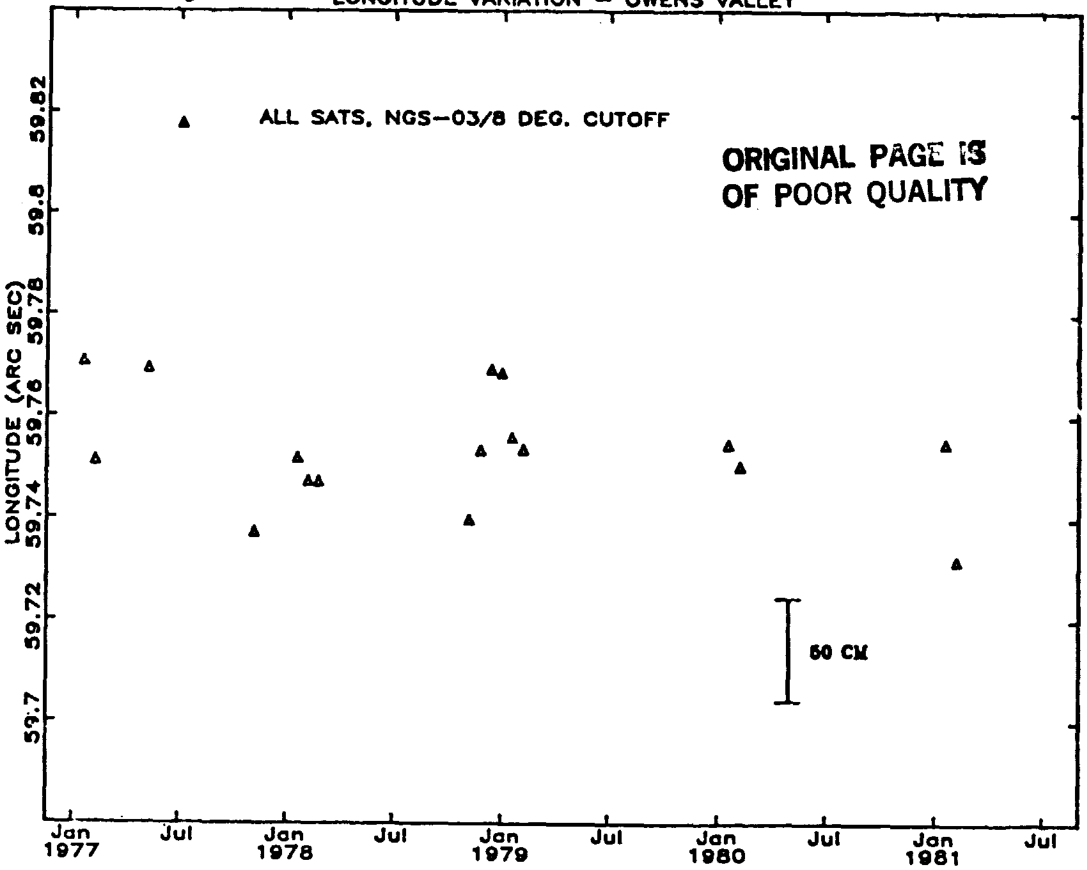
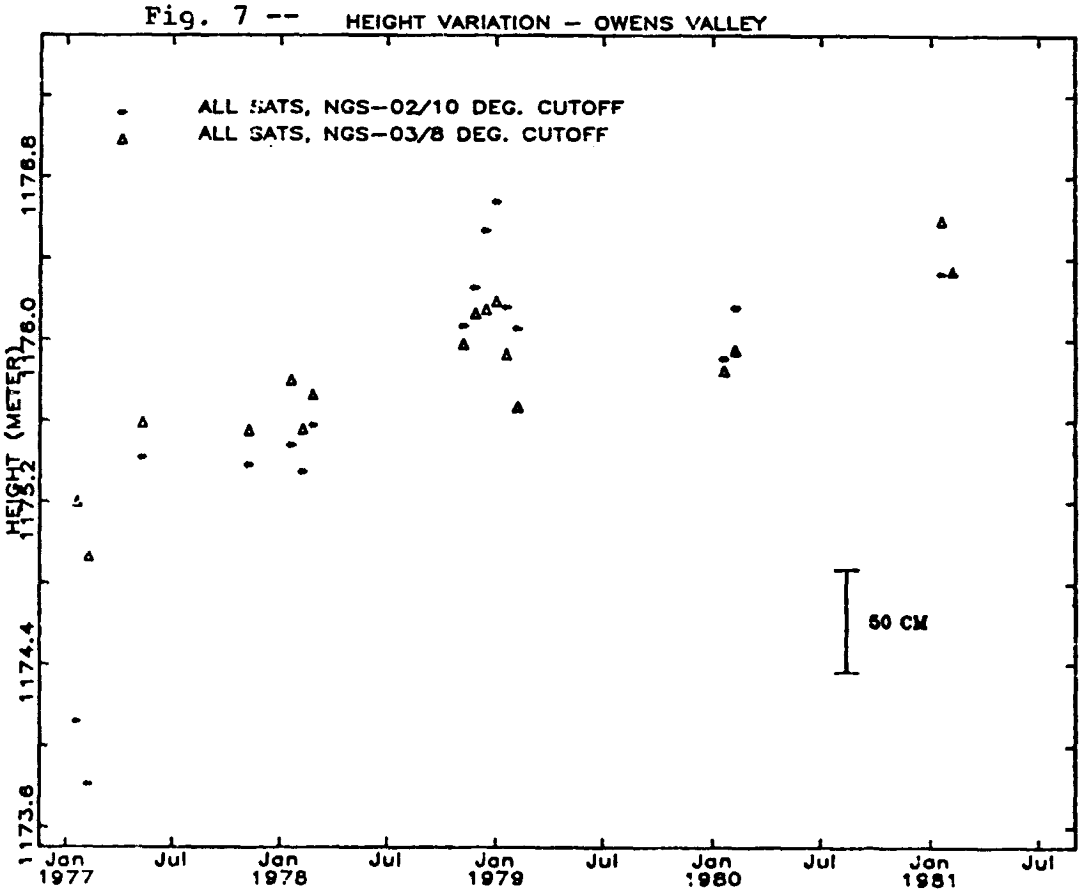


Fig. 7 -- HEIGHT VARIATION - OWENS VALLEY



Baseline Vector Repeatibility

Chi Square Test (12 Degrees of freedom)

$\sigma\Delta_L$ = difference between length components

$\sigma_L = \sigma\Delta_L/\sqrt{2}$ (assuming the two determinations are independent)

<u>Confidence Interval</u>

	$\sigma\Delta_L$	σ_L
.50	.47	.34
.99	.84	.60
Apriori Avg		.56

For Intercomparison σ_L= Baseline Apriori Avg. (Varies from .4 to .7M)

VALIDATION AND INTERCOMPARISON EXPERIMENTS

SESSION IV

SECTION 7

SITE SURVEY TIES

Larry Hothem

Table 7-1 contains the common reference points for the collocated systems used in the Session IV experiments.

Table 1 is a listing of the Cartesian coordinate differences in the ground survey ties between all reference points used in the Session II and IV Intercomparison Experiments.

Except for the station tie at Greenbank, the site surveys were adjusted 3-dimensionally with the NGS program HAVAGO. The adjustments for Goldstone, Ft. Davis, Haystack, and Owens Valley are considered final. The adjustment at Greeenbelt is preliminary. Plans have been made to perform additional surveys at Greenbeit and Greenbank for inclusion in a final adjustment.

The accuracy of the ties at all sites except Greenbank are estimated to be better than 2 centimeters, 1 sigma. Until the existing ties can be verified, the uncertainty at Greenbank may be an order of magnitude larger.

Except at Greenbank, the contribution of survey tie error to the Session IV intercomarison results is believed to be negligible.

DS13 and DS14 refer to intersection of axes for the VLBI antennae (VENUS and MARS, respectively) at Goldstone. NRAO, HAY, HRAS, and OVRO refer to intersection of axis for VLBI antennae at the Greenbank, Haystack, and Ft. Davis, and Owens Valley sites, respectively.

SLR, followed by a 4-digit number, refers to the monumented point in the ground that were occupied with the mobile laser ranging systems. STALAS is the x-axis of intersection for the laser system at Greenbelt.

The 5-digit Doppler number refers to the monumented point on the ground ocupied with the antenna. The point position coordinates are reduced to the mark. The second digit of the 5-digit number refers to the occupation number while the last 3 digits are unique to each station.

COMMON REFERENCE POINTS FOR COLLOCATED SYSTEMS

SESSION IV

LOCATION	COMMON REFERENCE POINT	DESCRIPTION
Ft. Davis	51123	Mark: McDonald 1942 No. 1
Greenbank	51114	Mark: T-007 1971 USA Topocom
Haystack	SLR 7091	Mark: GSFC Moblas No. 7091 1977
Greenbelt	51222	Mark: North GEOS GSFC/GORF
Goldstone	SLR 7115	Mark: GSFC Moblas No. 7115 1979
Owens Valley	51105	Mark: BP Aries 1 1977 (South Monolith)

TABLE 7-1

TABLE 1 -- CARTESIAN COORDINATE DIFFERENCES IN GROUND SURVEY POSITION
FEBRUARY 25, 1982
(TO TRANSFER COORDINATES FROM THE ONE STATION TO THE OTHER, ADD DIFFERENCES)

LOCATION	STATIONS FROM	TO	CARTESIAN COORDINATE DIFFERENCES DELTA X (M)	DELTA Y (M)	DELTA Z (M)	GEODETIC ADJUSTMENT DATE	REMARKS
GOLDSTONE	51065	DSS13	2267.338	-13968.124	-15968.892	1-14-82	3
GOLDSTONE	51065	DSS14	-242.687	167.322	126.600	1-14-82	3
GOLDSTONE	51065	SLR 7085	2.318	- 20.679	- 26.550	1-14-82	3
GOLDSTONE	51065	SLR 7115	2534.840	-14037.304	-15927.949	1-14-82	3
GOLDSTONE	51212	51065	- 58.612	34.372	6.989	1-14-82	3
GOLDSTONE	51212	DSS13	2208.726	-13933.752	-15961.903	1-14-82	3
GOLDSTONE	51212	DSS14	-283.299	201.694	133.589	1-14-82	3
GOLDSTONE	51212	SLR 7085	- 56.294	13.694	- 19.561	1-14-82	3
GOLDSTONE	51212	SLR 7115	2476.228	-14002.931	-15920.960	1-14-82	3
GOLDSTONE	51266	DSS13	-234.327	67.277	-25.929	1-14-82	3
GOLDSTONE	51266	DSS14	-2726.353	14202.723	16069.564	1-14-82	3
GOLDSTONE	51266	51065	-2501.666	14035.401	15942.963	1-14-82	3
GOLDSTONE	51266	51212	-2443.053	14001.029	15935.975	1-14-82	3
GOLDSTONE	51266	SLR 7085	-2499.348	14014.722	15916.414	1-14-82	3
GOLDSTONE	51266	SLR 7115	33.174	-1.903	15.014	1-14-82	3
GOLDSTONE	SLR 7085	DSS13	2265.020	-13947.445	-15942.342	1-14-82	3
GOLDSTONE	SLR 7085	DSS14	-227.005	188.001	153.150	1-14-82	3
GOLDSTONE	SLR 7115	DSS13	-267.502	69.179	- 40.943	1-14-82	3
GOLDSTONE	SLR 7115	DSS14	-2759.527	14204.625	16054.550	1-14-82	3
GOLDSTONE	SLR 7115	SLR 7085	-2532.522	14016.625	15901.399	1-14-82	3
GOLDSTONE	DSS14	DSS13	-2492.025	14135.466	16095.493	1-14-82	3
GREENBANK	51114	NRAO	-343.68	- 39.50	63.58	APRIL 1978	1
GREENBELT	51222	STALAS	- 16.107	- 47.429	- 47.164	12-14-81	6
HAYSTACK	51118	SLR 7091	43.695	11.544	- 3.256	SEPT. 1979	2
HAYSTACK	51118	HSTK	- 5.170	23.808	62.550	SEPT. 1979	2
HAYSTACK	SLR 7091	HSTK	- 48.865	12.265	65.805	SEPT. 1979	2
MCDON/FT DAV	51123	51219	6677.196	-3321.651	-3617.613	11-26-80	4
MCDON/FT DAV	51123	SLR 7086	755.312	220.297	507.625	11-26-80	4
MCDON/FT DAV	51123	HRAS	6669.726	-3276.256	-3524.238	11-26-80	4
MCDON/FT DAV	51219	HRAS	- 7.469	45.395	93.374	11-26-80	4
MCDON/FT DAV	51219	SLR 7086	-5921.884	3541.947	4125.237	11-26-80	4
MCDON/FT DAV	SLR 7086	HRAS	5914.416	-3496.552	-4031.863	11-26-80	4
OWENS VALLEY	51105	SLR 7084	-946.275	623.623	124.789	1-09-81	5
OWENS VALLEY	51105	SLR 7114	-778.252	566.372	162.431	1-09-81	5
OWENS VALLEY	51105	OVRO	43.308	19.245	79.115	1-09-81	5
OWENS VALLEY	SLR 7084	OVRO	989.583	- 604.378	- 45.674	1-09-81	5
OWENS VALLEY	SLR 7114	OVRO	821.561	- 547.127	- 83.317	1-09-81	5
OWENS VALLEY	SLR 7114	SLR 7084	-168.022	57.251	- 37.643	1-09-81	5

REMARKS:

1. VALUES ARE PRELIMINARY UNTIL SURVEY TIES CAN BE VALIDATED.
2. HAVAGO ADJUSTMENT, HAYSTACK-WESTFORD SURVEY, NOAA TM NOS NGS-21, SEPT. 1979.
3. HAVAGO ADJUSTMENT, HAVAGO VERSION 4-27-79, ADJUSTMENT DATE 1-14-82.
4. HAVAGO ADJUSTEMENT, "REPORT OF SURVEY FOR MCDONALD OBSERVATORY, HARVARD RADIO ASTRONOMY STATION, AND VICINITY'" NOAA TM NOS NGS-32, MAY 1981.
5. HAVAGO ADJUSTMENT, HAVAGO VERSION 4-27-79, ADJUSTMENT DATE 1-09-81.
6. HAVAGO ADJUSTMENT, HAVAGO VERSION 4-27-79, ADJUSTMENT DATE 12-14-81.

Table 7-2

APPENDIX A

INTERCOMPARISON VECTORS

1. BASELINE VECTORS:

   NRAO OVRO

   HAY OVRO

   HAY NRAO

   GBLT OVRO

   HAY GBLT

   GBLT FTDV

   NRAO FTDV

   HAY FTDV

   FTDV OVRO

   OVRO GDS

   HAY GDS

   GBLT GDS

   FTDV GDS

2. POSITION VECTORS

   OVRO

   HAY

   GBLT

   FTDV

   GDS

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : NRAO OVRO

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXP-6	Deg	EXP-6
MK III	3324620.12	± 0.03	172.285300	± 5	-1.819213	± 2
DOPPLER	3324619.94	± 0.60	172.285049	± 10	-1.819214	± 10

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
MK III-DOPPLER	0.19 ± 0.60	0.904 ± 0.041	0.006 ± 0.038

ORIGINAL PAGE IS
OF POOR QUALITY

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : HAY OVRO

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXP-6	Deg	EXP-6
MK III	3928974.79 ±	0.02	180.309673 ±	3	-6.698465 ±	2
SLR	3928974.91 ±	0.06	180.309629 ±	3	-6.698460 ±	2
DOPPLER	3928975.17 ±	0.50	180.309445 ±	9	-6.698467 ±	9

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
MK III-DOPPLER	-0.38 ± 0.50	0.821 ± 0.034	0.006 ± 0.032
MK III-SLR	-0.12 ± 0.06	0.158 ± 0.016	-0.019 ± 0.010
SLR-DOPPLER	-0.26 ± 0.50	0.663 ± 0.033	0.025 ± 0.033

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : HAY NRAO

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXP-6	Deg	EXP-6
MK III	844887.72 ± 0.03		217.481381 ±	6	-24.677468 ±	5
DOPPLER	844888.74 ± 0.60		217.481177 ±	45	-24.677430 ±	41

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
MK III-DOPPLER	-1.03 ± 0.60	0.732 ± 0.163	-0.137 ± 0.147

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : GBLT OVRO

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXP-6	Deg	EXP-6
SLR	3561327.10 ±	0.08	174.306733 ±	3	-2.504335 ±	1
DOPPLER	3561327.06 ±	0.50	174.306538 ±	10	-2.504356 ±	10

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
SLR-DOPPLER	0.03 ± 0.51	0.700 ± 0.036	0.076 ± 0.035

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : HAY GBLT

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXP-6	Deg	EXP-6
SLR	601969.00	± 0.07	225.959378	± 4	-30.186454	± 8
DOPPLER	601969.20	± 0.40	225.959213	± 66	-30.186355	± 57

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
SLR-DOPPLER	-0.20 ± 0.41	0.593 ± 0.238	-0.357 ± 0.208

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : GBLT FTDV

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXP-6	Deg	EXP-6
SLR	2623409.56 ±	0.06	191.424024 ±	2	-16.805589 ±	1
DOPPLER	2623409.84 ±	0.40	191.423867 ±	14	-16.805592 ±	13

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
SLR-DOPPLER	-0.28 ± 0.40	0.565 ± 0.050	0.013 ± 0.047

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : NRAO FTDV

BASELINES	LENGTH Meters	M	LONGITUDE Deg	EXP-6	DECLINATION Deg	EXP-6
MK III	2359573.09 ±	0.05	190.348423 ±	8	-17.471671 ±	4
DOPPLER	2359572.70 ±	0.60	190.348211 ±	15	-17.471654 ±	15

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
MK III-DOPPLER	0.39 ± 0.60	0.763 ± 0.062	-0.058 ± 0.035

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : HAY FTDU

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXP-6	Deg	EXP-6
MK III	3139548.16 ±	0.02	197.153694 ±	4	-19.755186 ±	2
SLR	3139548.09 ±	0.08	197.153650 ±	3	-19.755184 ±	2
DOPPLER	3139548.72 ±	0.50	197.153498 ±	12	-19.755169 ±	11

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
MK III-DOPPLER	-0.56 ± 0.50	0.705 ± 0.044	-0.059 ± 0.040
MK III-SLR	0.07 ± 0.08	0.158 ± 0.017	-0.005 ± 0.009
SLR-DOPPLER	-0.62 ± 0.51	0.548 ± 0.043	-0.054 ± 0.040

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : FTDV OVRO

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXP-6	Deg	EXP-6
MK III	1500113.05 ±	0.02	141.751649 ±	4	23.696427 ±	3
SLR	1500113.14 ±	0.11	141.751619 ±	4	23.696434 ±	4
DOPPLER	1500113.66 ±	0.50	141.751371 ±	25	23.696381 ±	23

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
MK III-DOPPLER	-0.60 ± 0.50	1.001 ± 0.091	0.164 ± 0.083
MK III-SLR	-0.08 ± 0.11	0.108 ± 0.021	-0.027 ± 0.017
SLR-DOPPLER	-0.52 ± 0.51	0.893 ± 0.091	0.190 ± 0.083

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : OVRO GDS

BASELINES	LENGTH Meters	M	LONGITUDE Deg	EXP-6	DECLINATION Deg	EXP-6
SLR	257609.71 ±	0.06	-71.645622 ±	10	-43.561210 ±	12
DOPPLER	257609.81 ±	0.60	-71.646009 ±	184	-43.560942 ±	133
MK II	257609.80 ±	0.05	-71.645617 ±	21	-43.561188 ±	16

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
SLR-DOPPLER	-0.10 ± 0.60	1.394 ± 0.664	-0.963 ± 0.482
SLR-MKII	-0.09 ± 0.08	-0.017 ± 0.084	-0.078 ± 0.072
DOP-MKII	0.01 ± 0.60	-1.411 ± 0.667	0.885 ± 0.484

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : GBLT GDS

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXF-6	Deg	EXP-6
SLR	3501909.31	± 0.08	177.109699 ±	2	-5.458832 ±	1
DOPPLER	3501909.53	± 0.60	177.109522 ±	10	-5.458840 ±	10

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
SLR-DOPPLER	-0.21 ± 0.61	0.637 ± 0.036	0.028 ± 0.036

SESSION 4 VALIDATION & INTERCOMPARISON

BASELINE : FTDV GDS

BASELINES	LENGTH		LONGITUDE		DECLINATION	
	Meters	M	Deg	EXP-6	Deg	EXP-6
SLR	1294019.85	± 0.09	146.574631	± 4	19.190405	± 4
DOPPLER	1294020.33	± 0.60	146.574422	± 28	19.190385	± 26

ORIGINAL PAGE IS
OF POOR QUALITY

BASELINE DIFFERENCES

	LENGTH (M)	LONG (SEC)	DEC (SEC)
SLR-DOPPLER	-0.48 ± 0.61	0.753 ± 0.102	0.070 ± 0.096

SESSION 4 VALIDATION & INTERCOMPARISON

STATION : OVRO

RAW VECTORS	X	Y	Z
SLR	-2410425.743	-4477800.843	3838686.660
DOPPLER	-2409661.095	-4478360.401	3838519.481

CORRECTED VECTORS	X	Y	Z
SLR	-2409647.491	-4478367.215	3838524.229
DOPPLER	-2409661.095	-4478360.401	3838519.481

	LENGTH (M)	AZ (DEG)	EL (DEG)
SLR	6371533.74	241.716912	37.045498
DOPPLER	6371531.23	241.716740	37.045461

VECTOR DIFFERENCES	X	Y	Z
SLR-DOPPLER	13.60	-6.81	4.75

	LENGTH (M)	AZ (SEC)	EL (SEC)
SLR-DOPPLER	2.51	0.62	0.13

SESSION 4 VALIDATION & INTERCOMPARISON

STATION : HAY

RAW VECTORS	X	Y	Z
SLR	1492450.415	-4457279.871	4296815.724
DOPPLER	1492393.384	-4457297.151	4296814.732

CORRECTED VECTORS	X	Y	Z
SLR	1492450.415	-4457279.871	4296815.724
DOPPLER	1492437.079	-4457285.607	4296811.476

	LENGTH (M)	AZ (DEG)	EL (DEG)
SLR	6368467.43	-71.487684	42.430989
DOPPLER	6368465.46	-71.487861	42.430953

VECTOR DIFFERENCES	X	Y	Z
SLR-DOPPLER	13.34	5.74	4.25

	LENGTH (M)	AZ (SEC)	EL (SEC)
SLR-DOPPLER	1.98	0.63	0.13

SESSION 4 VALIDATION & INTERCOMPARISON

STATION : GBLT

RAW VECTORS

	X	Y	Z
SLR	1130711.725	-4831370.925	3994089.159
DOPPLER	1130712.940	-4831328.691	3994132.876

CORRECTED VECTORS

	X	Y	Z
SLR	1130727.832	-4831323.496	3994136.323
DOPPLER	1130712.940	-4831328.691	3994132.876

	LENGTH (M)	AZ (DEG)	EL (DEG)
SLR	6369721.90	-76.827530	38.832836
DOPPLER	6369721.04	-76.827711	38.832803

VECTOR DIFFERENCES

	X	Y	Z
SLR-DOPPLER	14.89	5.20	3.45

	LENGTH (M)	AZ (SEC)	EL (SEC)
SLR-DOPPLER	0.86	0.65	0.12

SESSION 4 VALIDATION & INTERCOMPARISON

STATION : FTDV

RAW VECTORS	X	Y	Z
SLR	-1330129.323	-5328525.560	3236150.202
DOPPLER	-1324223.914	-5332066.004	3232021.274

CORRECTED VECTORS	X	Y	Z
SLR	-1330884.635	-5328745.857	3235642.577
DOPPLER	-1330901.110	-5328744.353	3235638.887

	LENGTH (M)	AZ (DEG)	EL (DEG)
SLR	6374650.52	255.976931	30.502742
DOPPLER	6374650.83	255.976761	30.502702

VECTOR DIFFERENCES	X	Y	Z
SLR-DOPPLER	16.47	-1.50	3.69

	LENGTH (M)	AZ (SEC)	EL (SEC)
SLR-DOPPLER	-0.31	0.61	0.14

SESSION 4 VALIDATION & INTERCOMPARISON

STATION : GDS

RAW VECTORS	X	Y	Z
SLR	-2350865.103	-4655544.495	3660997.881
DOPPLER	-2350912.795	-4655537.032	3660978.920

CORRECTED VECTORS	X	Y	Z
SLR	-2350865.103	-4655544.495	3660997.881
DOPPLER	-2350879.621	-4655538.935	3660993.934

	LENGTH (M)	AZ (DEG)	EL (DEG)
SLR	6372092.81	243.208037	35.067157
DOPPLER	6372091.83	243.207867	35.067120

VECTOR DIFFERENCES	X	Y	Z
SLR-DOPPLER	14.52	-5.56	3.95

	LENGTH (M)	AZ (SEC)	EL (SEC)
SLR-DOPPLER	0.97	0.61	0.13

Appendix B
Mathematical Definitions

$$\text{Mean Difference} = \text{Sample Mean} \pm \sqrt{\sum_{i=1}^{N} \frac{(x_i - x_m)^2}{N\,(N-1)}}$$

$$\text{STD Deviation} = \sqrt{\sum_{i=1}^{N} \frac{(x_i - x_m)^2}{N-1}} \qquad x_m = \text{Mean}$$

LMV (Linear Minimum Variance) Estimate

$$\text{EST} = \infty = \frac{1}{\sum_{i=1}^{N} \frac{1}{\sigma_i^2}} \cdot \sum_{i=1}^{N} \frac{X_i}{\sigma_i^2}$$

$$\text{Cov. } \Gamma = \frac{1}{\sum_{i=1}^{N} \frac{1}{\sigma_i^2}} = \sigma^2$$

$$\text{Assuming} \quad \text{Cov } \Gamma_x = \begin{bmatrix} \sigma_1^2 & & & 0 \\ & \sigma_2^2 & & \\ & & \cdot & \\ 0 & & & \sigma_n^2 \end{bmatrix}$$

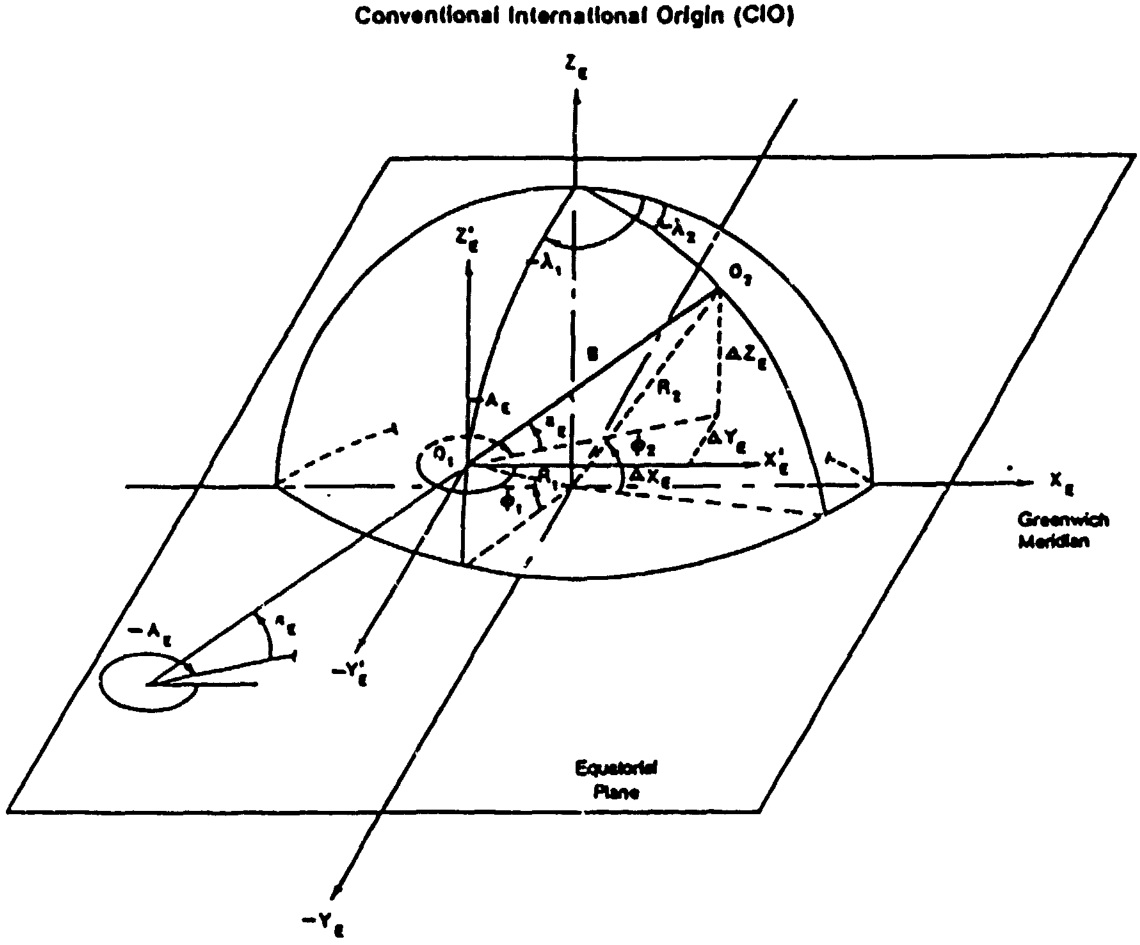
Range Estimate:

For small sample sizes an estimate of the standard deviation can be obtained from the sample range /d where d is dependent on the number of samples (n).

n	3	6	10
d	1.693	2.534	3.078

Reference: Page 176,
Probability and Statistics
for Engineers
Irwin Mille' & John E. Freun

APPENDIX C



- COMPONENTS OF BASELINE LENGTH AND ORIENTATION. O_1 = Observatory 1; O_2 = Observatory 2; B = Length of Vector Baseline $\overline{O_1O_2}$; a_E = Equatorial Altitude of Baseline $\overline{O_1O_2}$; A_E = Equatorial Azimuth of Baseline $\overline{O_1O_2}$; ΔX_E, ΔY_E, ΔZ_E = Components of Baseline $\overline{O_1O_2}$ in Geocentric Coordinate System X_E, Y_E, Z_E; ϕ_1 = Geocentric Latitude of Observatory 1; ϕ_2 = Geocentric Latitude of Observatory 2; λ_1 = Geocentric Longitude of Observatory 1; λ_2 = Geocentric Longitude of Observatory 2; R_1 = Radius Vector from Geocenter to Observatory 1; R_2 = Radius Vector from Geocenter to Observatory 2; X'_E, Y'_E, Z'_E = Topocentric Coordinate System centered at Observatory 1 and parallel to X_E, Y_E, Z_E Coordinate System; X_E, Y_E, Z_E = GEOCENTRIC COORDINATE SYSTEM.

In this report, equatorial altitude is also referred to as declination and equatorial azimuth is also referred to as longitude.

REFERENCES

1. P. Liebrecht, "Session IV, Validation and Intercomparison Experiments 1979-1980", March 1980, GSFC.

2. L. Hothem, T. Vincenty and R. Moose, "Relationship Between Doppler and other Advanced Geodetic System Measurements Based on Global Data", Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, New Mexico, February 8-12, 1982.