R-CATS - A NEW METHOD FOR CALIBRATING GLOBAL POSITIONING SYSTEM (GPS) REMOTE SITES

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INTRODUCTION

Historically, precise time has been transferred between two sites by means of a method using portable atomic clocks. The method entails the carrying of an active frequency standard and its associated clock from site A to site B. Personnel from the United States Naval Observatory (USNO), Bendix Field Engineering Corporation (BFEC), Naval Research Laboratory (NRL), and others have made portable clock trips by airplane and surface vehicles for the past 15 years. The accuracy obtained using this method for the transfer of time ranges from a few nanoseconds (on a short surface trip) to hundreds of nanoseconds (on an extended overseas trip). Typically the origin of the portable clock trip is a major time keeping observatory, such as USNO, where the portable clock is initially synchronized as close as possible to the master clock (MC) time at that observatory. Prior to departure a stationary rate is determined between the two clocks. Upon return to the originating observatory, closure is again made with the master clock and a rate of the portable clock against the master clock is measured. These two rates (before and after) are then compared. Assuming no major difference occurs, the time accumulation between the two clocks is estimated and linearly applied to results obtained from each location on the trip. The important thing to note in such a method is that the portable clock must be kept running during the entire trip; that is, transported "hot". Many logistics problems and additional costs result from this necessity.

A new method called Remote Calibration And Time Synchronization (R-CATS), allows a Global Positioning System (GPS) single frequency clear acquisition (C/A) code time transfer receiver (TTR) to be used instead of the portable clock. This "portable" TTR can be shipped or carried as luggage with no continuous power requirements. R-CATS performs three major technical functions: 1) calibration of existing GPS TTR; 2) time transfer; and 3) precise positioning/navigation. The procedure is similar to the portable clock method. The portable TTR is first calibrated against the originating observatory's master clock by making GPS time transfer observations at the originating observatory. These measurements are made with the antenna of the transportable TTR located near the antenna of the GPS receiver currently in use at that observatory. The portable TTR to be used in the R-CATS method is driven by the same clock that is used by the permanent TTR. In the event that a remote site does not have a GPS TTR the R-CATS method can be used to perform time transfer and coordinate positioning.

During December 1984, a team from NRL performed the first R-CATS trip using a Stanford Telecommunications Incorporated (STI) Model 502B GPS TTR. The trip included closure with major European time observatories and the USNO. Table 1 presents a list of participants in the first R-CATS trip.

TABLE 1

PARTICIPANTS

UNITED STATES NAVAL OBSERVATORY	(USNO)
OBSERVATORIE DE PARIS, PARIS, FRANCE	(OP)
VAN SWINDEN LABORATORY, DELFT, NETHERLANDS	(VSL)
PHYSIKALISCH-TECHNISCHE BUNDESANSTALT, BRAUNSCHEIG, GERMANY	(PTB)
TECHNICAL UNIVERSITY OF GRAZ, GRAZ, AUSTRIA	(TUG)
UNITED STATES NAVAL RESEARCH LABORATORY	(NRL)

The permanent GPS time transfer receivers currently in use at both the USNO and the TUG sites were manufactured by STI, the same type TTR as that transported in the R-CATS trip. At the OP, PTB and VSL sites a receiver either built at the National Bureau of Standards (NBS) or of similar design was being used.

The first consideration in using R-CATS at a site having a permanent TTR is the calibration, including the measurement of all cable delays, pulse trigger levels and pulse widths to determine quantitatively the hardware associated influences on overall system delay biases. After the delays are measured, data from NAVSTAR satellites is taken from each site over a period of three to four days to gain confidence in the resulting set of observations.

The time synchronization portion of the R-CATS involved the near common view tracking of multiple NAVSTAR satellites between each remote site and the USNO. Results will be presented on both the calibration and time synchronization aspects of the project.

The third technical objective of the trip was the precise positioning/navigation and coordinate determination of each remote site. Data was taken over an eight hour span, using all NAVSTAR space vehicles (SV), in a Kalman filter solution. Accurate positions of each GPS antenna were determined in an earth fixed XYZ coordinate frame on the WGS72 datum and then transformed to latitude, longitude and height coordinates. Results of the navigation determination will also be presented.

Figure 1 presents a schematic showing the R-CATS method. Measurements are first obtained using the transportable TTR, STI025, driven by the USNO master clock (USNO MC), and then driven by the MC at each remote site. Simultaneously, measurements are made by a permanent GPS receiver at each site. For discussion later, let the observations from the permanent receiver at the USNO site receiver be designated R1, the observations from the transportable R-CATS receiver be RT, and the first remote site observations be R2.

CALIBRATION

Figure 2 shows a simplified block diagram of a typical station hardware configuration. Care was taken to accurately measure each component of the system which could introduce any delay in the calibration. The results of these measurements, for each participating observatory, are presented in Table 2.

TABLE 2
R-CATS CALIBRATION PARAMETERS

STATION	1 pps Level(v)	1 pps Rise Time (ns)	1 pps Pulse Width (μs)	5 MHZ Level	5 MHz Wave-form	1 pps Cable Delay (ns)	REC + RF Cable Delay (ns)	Receiver Calibration (ns)
A. With respect to STI025 TTR								
USNO	0-5	4	10	1.0v rms 50Ω	sinewave	56	144	88
OP	0-8	150	20	1.0v rms 50Ω	sinewave	441	144	-297
VSL	0-2	40	10	3.0v p-p 50Ω	sinewave	677	144	-533
PTB	0-10	4	1	3.4v p-p 50Ω	sinewave	13	144	131
TUG	0-5	4	10	1.0v rms 50Ω	sinewave	38	144	106
B. With respect to permanent TTR								
USNO	0-5	4	10	1.0v rms 50Ω	sinewave	56	155	99
OP	0-8	150	20	1.8v rms 50Ω	sinewave	350	204	-146
VSL	0-2	40	10	3.0v p-p 50Ω	squarewave	15	746	731
PTB	0-10	4	.050	3.4v p-p 50Ω	sinewave	-50	259	309
TUG	0-5	4	10	1.0v p-p 50Ω	sinewave	38	82	44

These values have been recorded and in the event components are either repaired, replaced, or levels changed, a recalibration should be performed. All pertinent measurements are believed to be accurate to 1-2 nanoseconds. It was recommended to each participating site that they keep complete calibration records of any changes in configuration and that additional calibrations be performed on a yearly basis. A yearly check could determine if aging of system components affects system calibration at the nanosecond level.

The complete calibration procedure, referring to the notation in Fig. 1, includes the initial offset between observations RT and R1 then the offsets at each remote site (the difference between RT and R2 . . . RN). To combine these two offsets the following derivation is presented.

Measurements made at site 1 using the permanent receiver (STI011) and the transportable receiver (STI025) yield the observations of R1 and RT respectively. These measurements could be (local clock - GPS time) or (local clock - SV time). For this R-CATS trip, local clock-GPS time was used. Equation 1 shows the offset.

$$RT - R1 = \Delta 1 \tag{1}$$

The TTR is then transported to site 2 and similar measurements are made. As the transportable receiver is moved from site to site during the R-CATS, phase differences are determined between it and each site ($\Delta 1$, $\Delta 2$, . . . ΔN). The offset calibration of one site to another site can then be determined. For example:

$$\begin{aligned} RT - R2 &= \Delta 2 \\ (-)\underline{RT - R1} &= \underline{\Delta 1} \\ R1 - R2 &= \Delta 2 - \Delta 1 \\ R1 &= R2 + (\Delta 2 - \Delta 1) \end{aligned}$$

If each individual station offset is maintained, then any station calibrated during the R-CATS trip can easily be referenced against any other station, rather than only being compared back to the originating observatory (i.e., R1 + $\Delta 1$, R2 + $\Delta 2$, . . . RN + ΔN).

Figure 3 presents the series of NAVSTAR tracks performed at each site using the R-CATS STI025 and the local TTR. Each plot in the figure presents the calibration offset, in nanoseconds, between R-CATS STI025 and the individual TTR being used at each site as determined by observing multiple GPS satellites over a period of 3-4 days. The statistics of each station offset are shown below each plot. The mean offset, X is the number used by the remote site to calibrate against the R-CATS transportable receiver. At the conclusion of the R-CATS trip, the transportable TTR is returned to site 1 (the originating observatory) and additional measurements are made to insure that no offset occurred during the trip. In the traditional portable clock trips, a closure was made to determine the drift of portable clock in frequency between the PC and the master clock. No such drift is possible with the R-CATS method. Figure 4A shows that indeed a 10 ns shift, from +1ns before departure to -9ns on return, did occur. To have such a closure (10ns) after a three week European trip is an order of magnitude or so better than a typical portable clock closure. Since it is virtually impossible to determine when or how the shift occurred the best offset number to use is the average of the initial offset with the final offset at site 1. It is anticipated that closure in the 1-2 nanoseconds will be realized as additional R-CATS trips are performed. Table 3 presents a summary of the mean results from the calibration offset at each site during the first R-CATS trips.

TABLE 3

(STI025 - SITE) Calibration Offset

SITE	DATE	REC	NO.PTS	MEAN OFFSET (ns)	RMS (ns)
USNO	11-15-84	STI011	20	+1	7.8
OP	12-02-84	NBS06	13	-31	5.7
VSL	12-07-84	NBS01	13	4	8.9
PTB	12-12-84	NBS	14	-29	12.9
PTB1	12-12-84	NBS	18	-30	8.3
TUG	12-17-84	STI004	17	14	5.6
USNO	12-24-84	STI011	49	-9	5.6

It can be seen from the plots in Fig. 3 that for the three sites where the NBS type receivers were used (OP, VSL, PTB), a bias exists between the offset determined from NAVSTAR space vehicle (SV)11 and the offset determined from the other GPS SVs. No such bias exists in the TUG data where another STI TTR is used as the station receiver in the solution. From these results it was concluded that a difference existed between the algorithm used in the STI receivers and the one used in the NBS type receivers. A software bug was found to exist in the NBS algorithm where the term which corrected for the relativity had been "jumped over" in the execution of the software. The bug was a function of both the orbital eccentricity of the SV and its placement in its orbit (mean anomaly). For the observation times from the European observatories, the bug had the most effect on the SV11 satellite results. Therefore, in the mean offset calculated in Fig. 3 involving NBS type TTRs, all SV11 data was removed from the data base before the calculations were performed. NBS was notified and the bug in the algorithm has been removed. New programs have been installed at OP, VSL and PTB at the direction of NBS.

As a consequence of the NBS software modification, a second R-CATS trip was performed during January 1985 from USNO to the National Bureau of Standards (NBS), Boulder, Colorado and return by the same team from NRL using the same STI025 TTR as was used in the first R-CATS trip. Closure to 1 nanosecond was achieved, as shown in Fig. 4B. Also shown, in Fig. 4C, is the calibration of the local NBS on-site receiver (NBS03) with respect to STI025.

In an attempt to conclusively determine what closure accuracy is to be expected on a R-CATS trip a third trip was made from NRL to USNO using STI025 TTR in April 1985 and results again closed to 1 nanosecond with STI011 at USNO. Results are shown in Fig. 4D and in Table 4.

TABLE 4

(STI025 - SITE) Calibration Offset

SITE	DATE	REC	NO. PTS	MEAN OFFSET (ns)	RMS (ns)
USNO	12-24-84	STI011	49	- 9	5.6
USNO	02-07-85	STI011	24	- 8	7.7
USNO	04-01-85	STI011	41	-10	5.9

TIME TRANSFER

Another aspect of an R-CATS trip is to perform a time transfer (TT) between two sites after calibration has occurred. Figure 5 presents the time transfer from the participating sites involved in the first R-CATS trip, namely (USNO, OP, VSL, PTB, and TUG). Since the NRL team originated the trip from USNO each participating European observatory is referenced back to USNO, although this technique applies between any two tracking sites. The time transfer results were obtained from all passes observed by both the USNO GPS TTR (STI011) and corresponding passes taken at the European sites. The results are "near common view" but not exactly common view to the minute. To include the calibration portion of the R-CATS trip, corrections were made in the following way before the results in Fig. 5 were determined:

$$\text{Time Transfer (TT)} = (R1 + \Delta 1) - (R2 + \Delta 2)$$

where R1 corresponds to the observations made at USNO and R2 are similar measurements made at each remote European site with Δ1 and Δ2 being the calibration offset for each site as previously described. A summary for each European site is listed in Table 5.

TABLE 5

Time Transfer Between USNO and Remote Sites
TT(USNO - RMT)

Remote Site	Epoch (MJD)	Time Transfer (μs)	No. PTS	RMS (ns)
OP	6036.0	2.340	13	20
VSL	6042.0	3.563	13	14
PTB	6046.0	4.286	9	17
TUG	6050.5	-1.404	13	11

PRECISE POSITIONING/NAVIGATION

Another important aspect of the R-CATS trip is the accurate position determination of each site using the portable receiver (STI025). During this step of the R-CATS procedure, the GPS antenna coordinates are determined with respect to the World Geodetic Survey of 1972 (WGS 72). Figure 6 presents a typical phase 1 GPS constellation satellite coverage for the USNO and European observatories during December 1984. Included on the figure are the periods of time that each GPS satellite was tracked and used in the navigation solution.

A time history of satellite ground tracks are shown in the azimuth - elevation presentation. The concentric circles are elevation rings from the horizon to 90 degrees. Each existing satellite is plotted with respect to the GPS receiver antenna position. Since the four European observatories were relatively close this figure can be roughly applied to each. Continuous solutions were obtained using the GPS satellites shown in the figure. The final solution was compared with coordinates supplied by each of the observing sites. For USNO, results are compared against survey markers obtained from the Defense Mapping Agency (DMA) doppler satellite survey team. For the OP site, an approximate position had been obtained from the NBS06 receiver averaging results over 3 months of solutions. For the remaining three European sites (VSL, PTB and TUG) initial coordinates were supplied from the Institut Fur Angerwandte Geodasie (IFAG) European doppler campaign.

For the European sites, the TTR STI025 positioning solution used observations for a period from 10 PM local time to 6 AM local time on a single night. During this period the effect of the ionospheric uncertainties is minimized. This is important because the STI TTR is a single frequency receiver using a model to predict and correct for ionospheric effects. In addition no observations were made for any elevation angle less than 20 degrees, which also minimized the effect of the troposphere in the navigation solutions. Table 6 presents the R-CATS navigation solution for each site as compared against the initial coordinates supplied by the host observatory.

Figure 7A presents, in graphics form, the results tabulated in Table 6. It can be seen that the USNO position solution agrees with the DMA supplied coordinates to within 2 meters in all three axis. For the three sites referenced to the same IFAG doppler campaign solutions, a definite longitudinal bias of approximately 7 meters (.35 arc sec) exist, with the latitude results being less than a meter and a height bias of 2-3 meters. Many factors could contribute to the large longitudinal bias. It is understood that the IFAG campaign originally solved for the European coordinates in the NWL-9D (NSWC 9Z-2) datum and transformed to WGS72. The transformation matrix is such that shift occurs on the order of approximately 5 meters (.260 arc sec) in performing the transformation. In addition a change of approximately 4 meters is applied to the height coordinate. Another possibility is the method of data collection used in the R-CATS navigation solution. An on-line real-time Kalman filter was used in the STI025 TTR with NAVSTAR SVs being switched in 30 minute intervals over the 8 hours total track time. Subsequent solutions at the NRL site have shown that, if an optimum Geometric Dilution of Precision (GDOP) term is predetermined and satellites are switched every three minutes, a solution can be obtained that converges to a steady state over a one hour period (reference to Fig. 7 right plot). More detailed analysis is needed before it is recommended that new European site coordinates be adopted at the meter level.

TABLE 6
R-CATS
NAVIGATION SOLUTION

	OP			VSL		
	INITIAL COORD	NAV SOLUTION	Δ	INITIAL COORD	NAV SOLUTION	Δ
X(m)	4202786.052	4202778.419	-7.633	3923530.712	3923529.422	-1.290
Y(m)	171348.005	171348.389	.384	300581.710	300573.287	-8.423
Z(m)	4778651.164	4778648.877	-2.287	5002832.933	5002830.062	-2.871
LAT	48°50'8.921"	48°50'9.058"	.137"	51°59'58.870"	51°59'58.862"	- .008"
LONG(E)	2°20'4.782"	2°20'4.816"	.034"	4°22'51.142"	4°22'50.707"	- .435"
HT(m)	122.840	116.110	-6.730	66.550	63.100	-3.45
	PTB			**TUG**		
	INITIAL COORD	NAV SOLUTION	Δ	INITIAL COORD	NAV SOLUTION	Δ
X(m)	3844066.050	3844062.995	-3.055	4194425.806	4194427.329	1.523
Y(m)	709642.380	709636.383	-5.997	1162693.455	1162686.063	-7.392
Z(m)	5023113.780	5023114.202	.422	4647242.417	4647240.093	-2.324
LAT	52°17'45.898"	52°17'46.011"	.113"	47°04'01.608"	47°04'01.569"	- .039"
LONG(E)	10°27'34.046"	10°27'33.764"	- .282"	15°29'36.082"	15°29'35.725"	- .357"
HT(m)	121.190	119.025	-2.165	537.604	535.564	-2.040

CONCLUSION

The R-CATS method has been proven, and initial absolute calibration has been completed for a series of major European observatories as well as the USNO and NBS sites in the USA. The R-CATS method is both cost effective and technically more accurate than a traditional portable clock trip. Navigation solutions (to the 10 meter level) have been performed. USNO is continuing to investigate this method and will begin replacing the current method of portable clock trips.

R-CATS METHOD

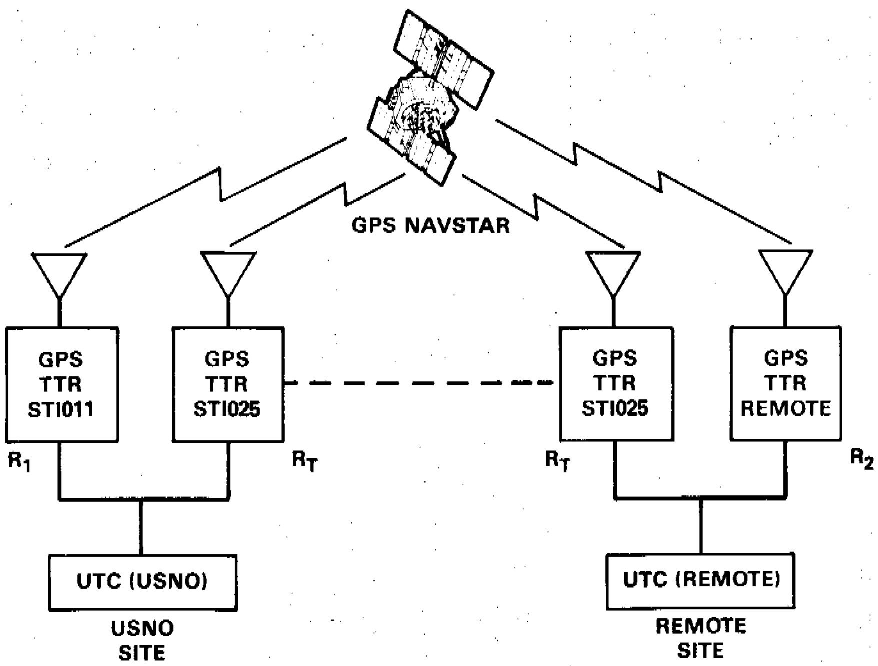


Figure 1

TYPICAL R-CATS STATION CONFIGURATION

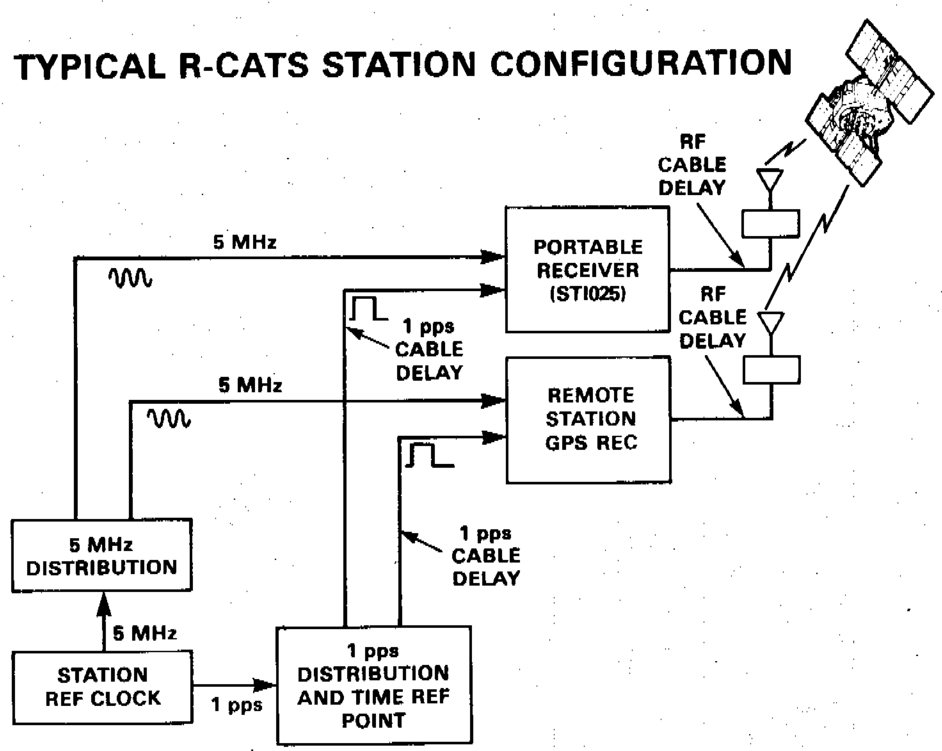
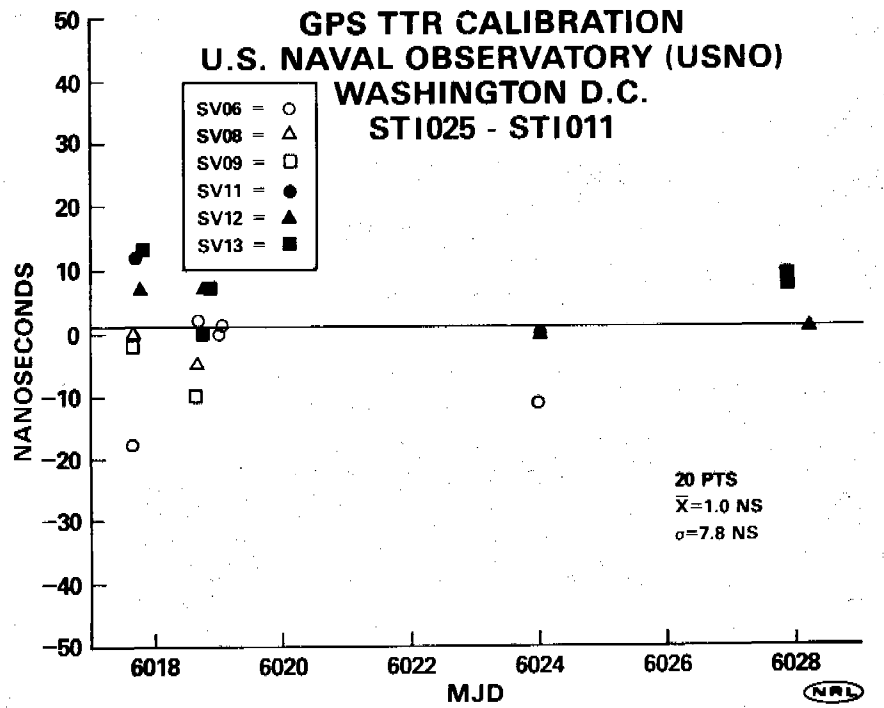
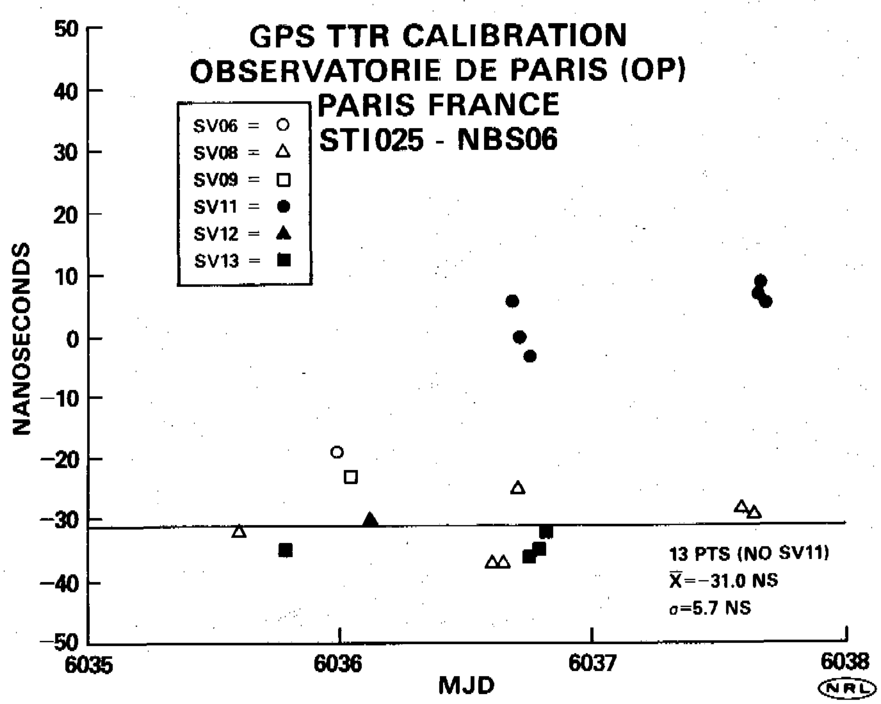


Figure 2

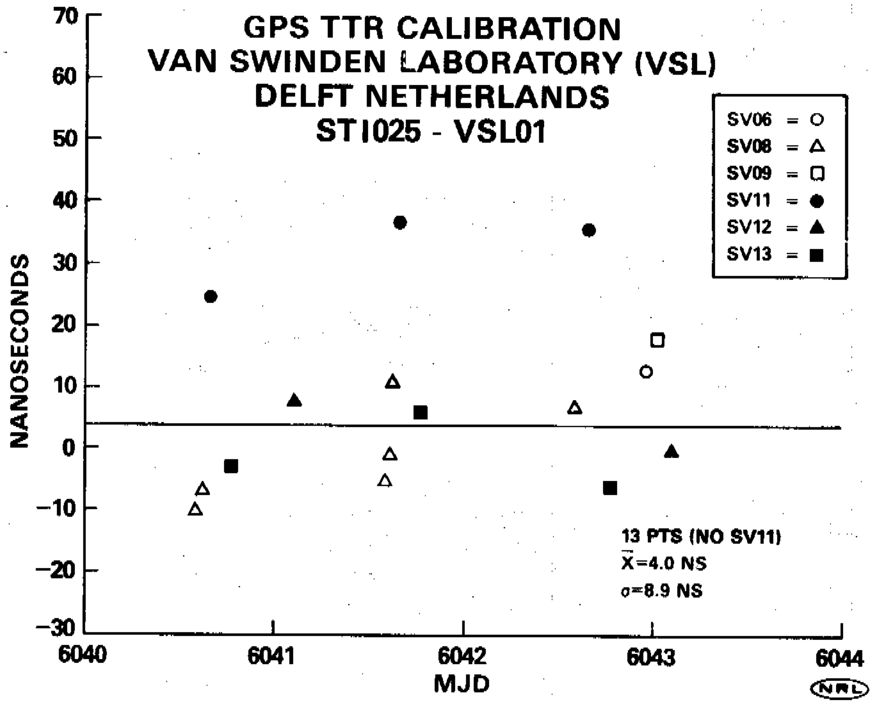


GPS TTR CALIBRATION
U.S. NAVAL OBSERVATORY (USNO)
WASHINGTON D.C.
STI025 - STI011
SV06 = ○
SV08 = △
SV09 = □
SV11 = ●
SV12 = ▲
SV13 = ■
NANOSECONDS
20 PTS
X̄=1.0 NS
σ=7.8 NS
MJD



GPS TTR CALIBRATION
OBSERVATORIE DE PARIS (OP)
PARIS FRANCE
STI025 - NBS06
SV06 = ○
SV08 = △
SV09 = □
SV11 = ●
SV12 = ▲
SV13 = ■
NANOSECONDS
13 PTS (NO SV11)
X̄=−31.0 NS
σ=5.7 NS
MJD

Figure 3



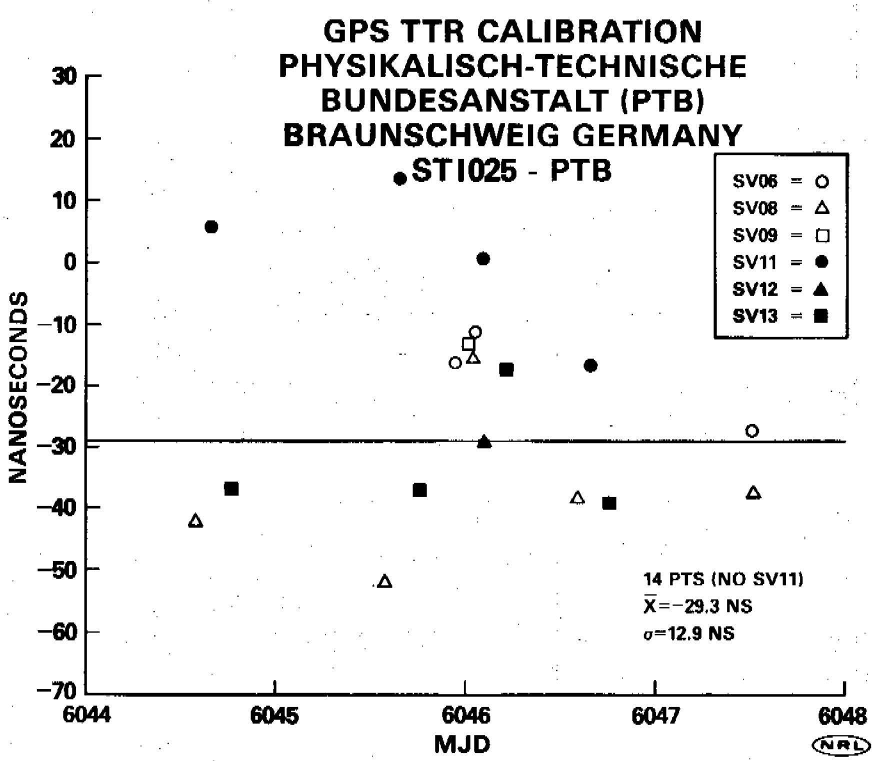
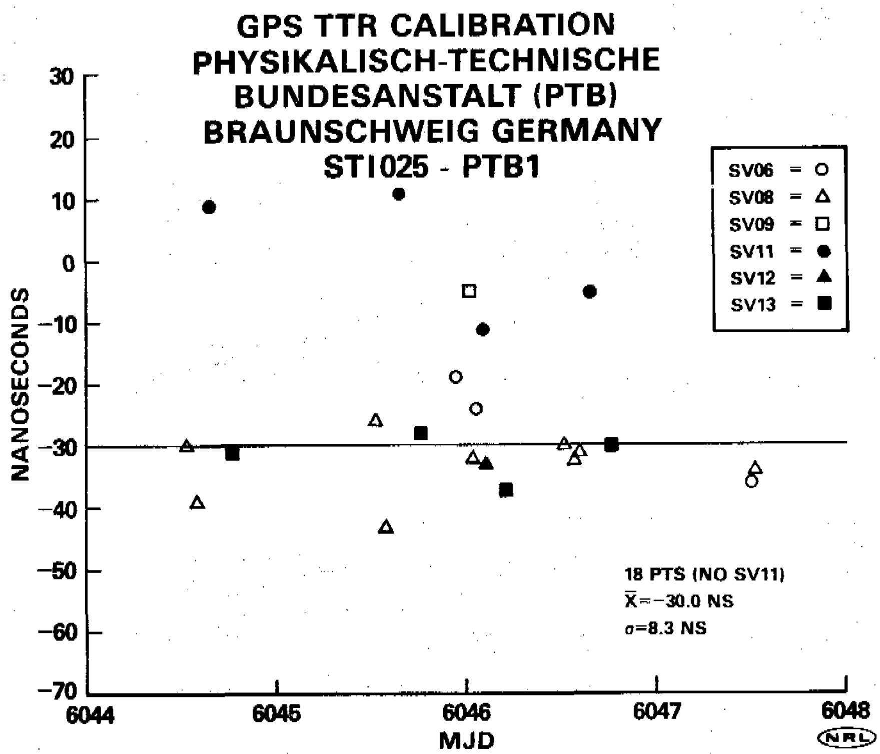


Figure 3 (cont.)



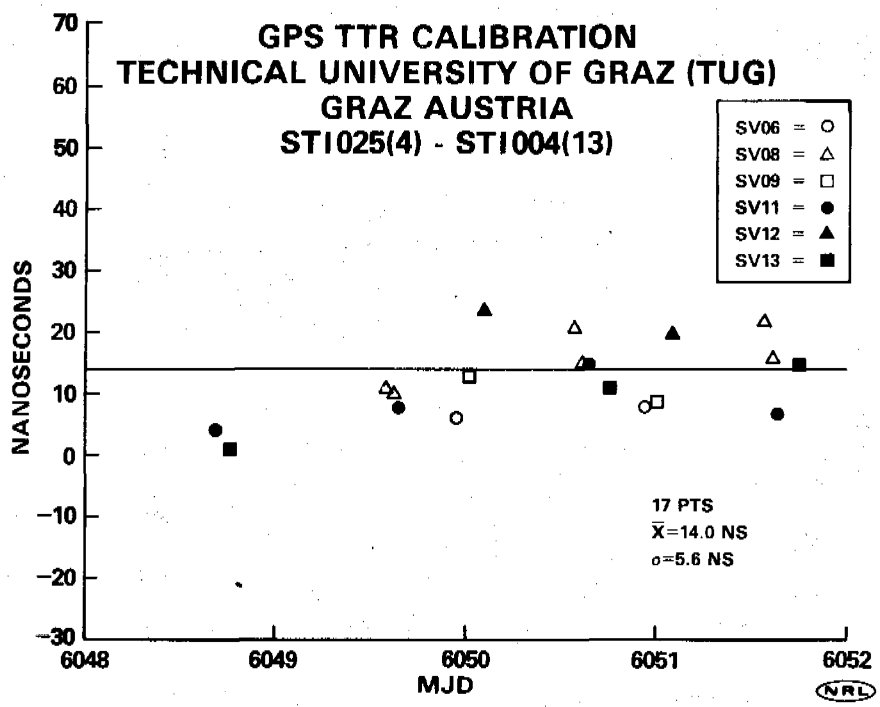


Figure 3 (cont.)

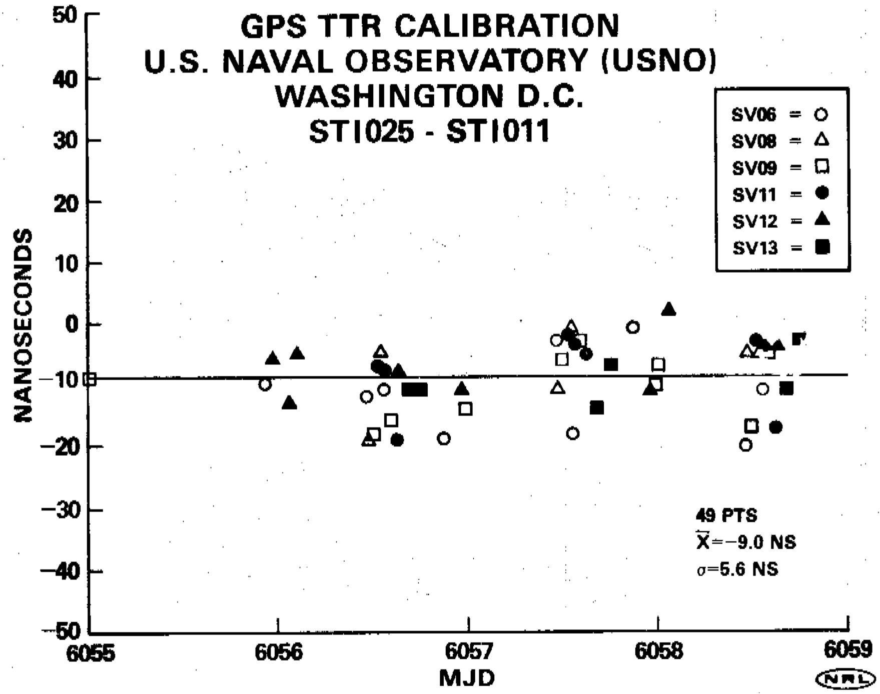


Figure 4A

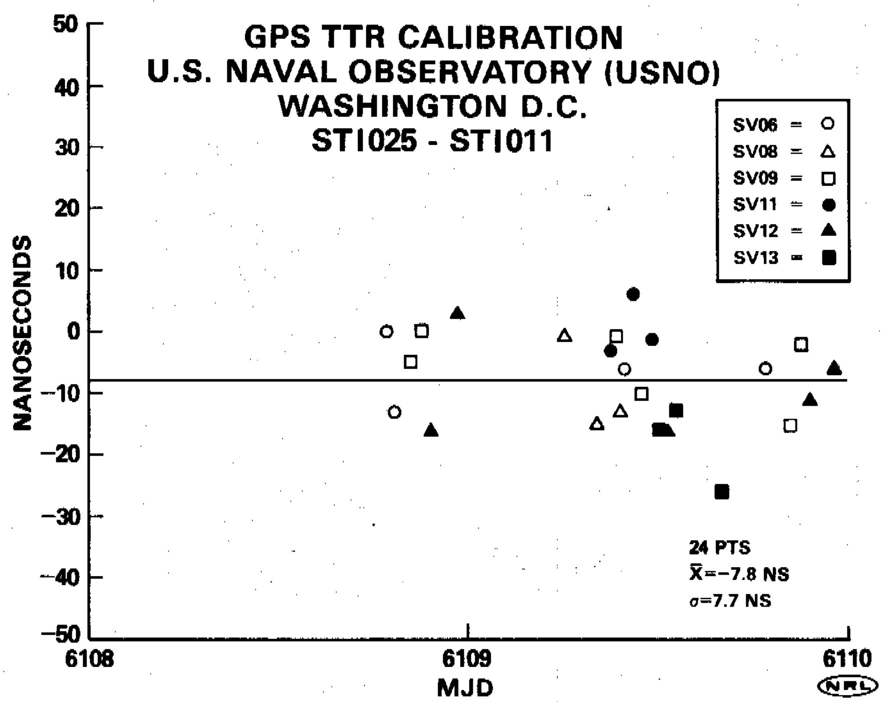


Figure 4B

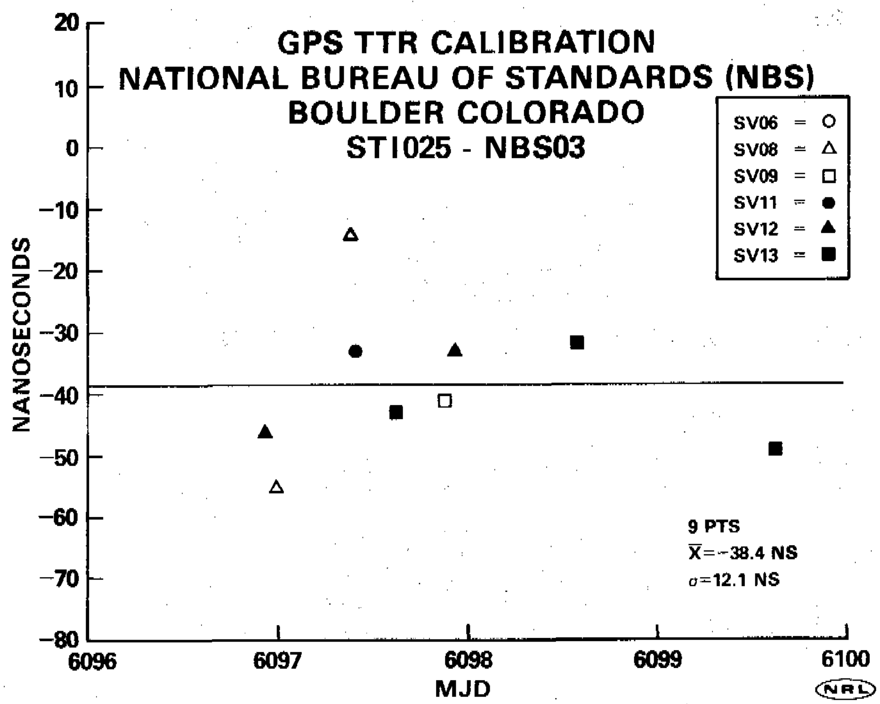


Figure 4C

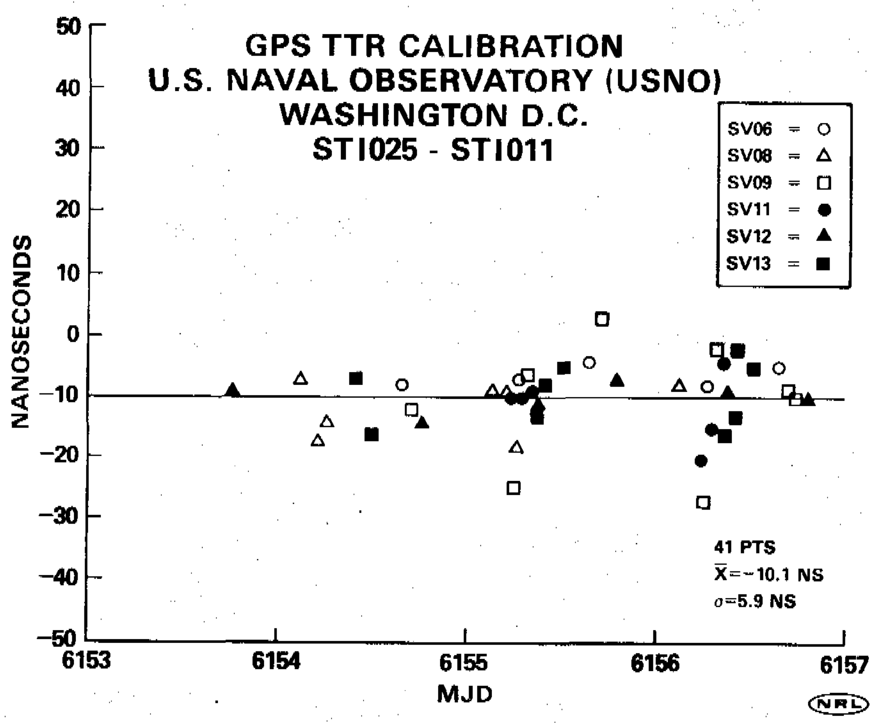
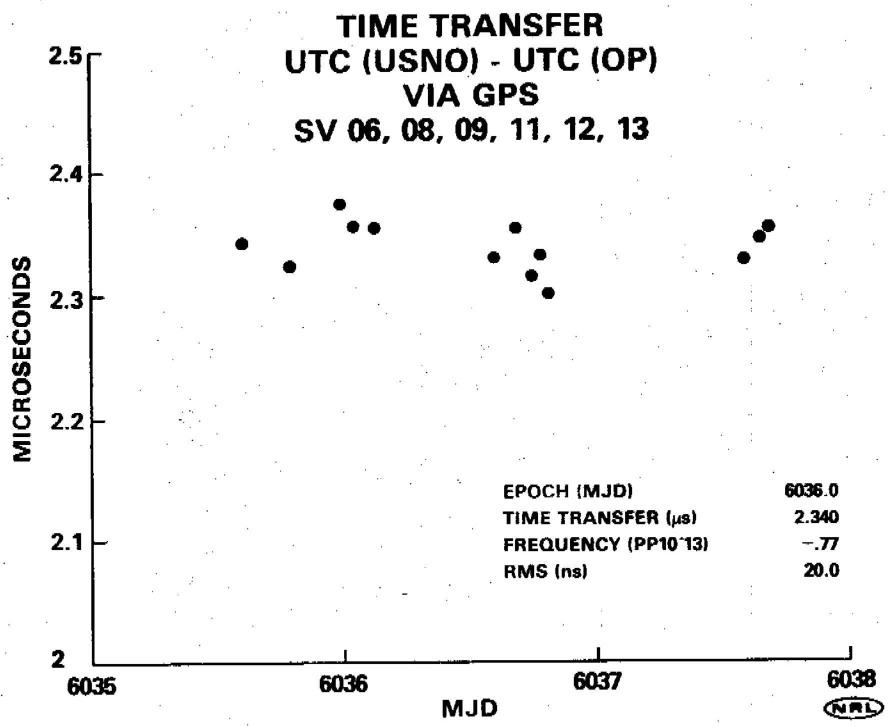


Figure 4D


TIME TRANSFER
UTC (USNO) - UTC (OP)
VIA GPS
SV 06, 08, 09, 11, 12, 13
MICROSECONDS
2.5
2.4
2.3
2.2
2.1
2
EPOCH (MJD) 6036.0
TIME TRANSFER (μs) 2.340
FREQUENCY (PP10^13) −.77
RMS (ns) 20.0
6035
6036
6037
6038
MJD
NRL

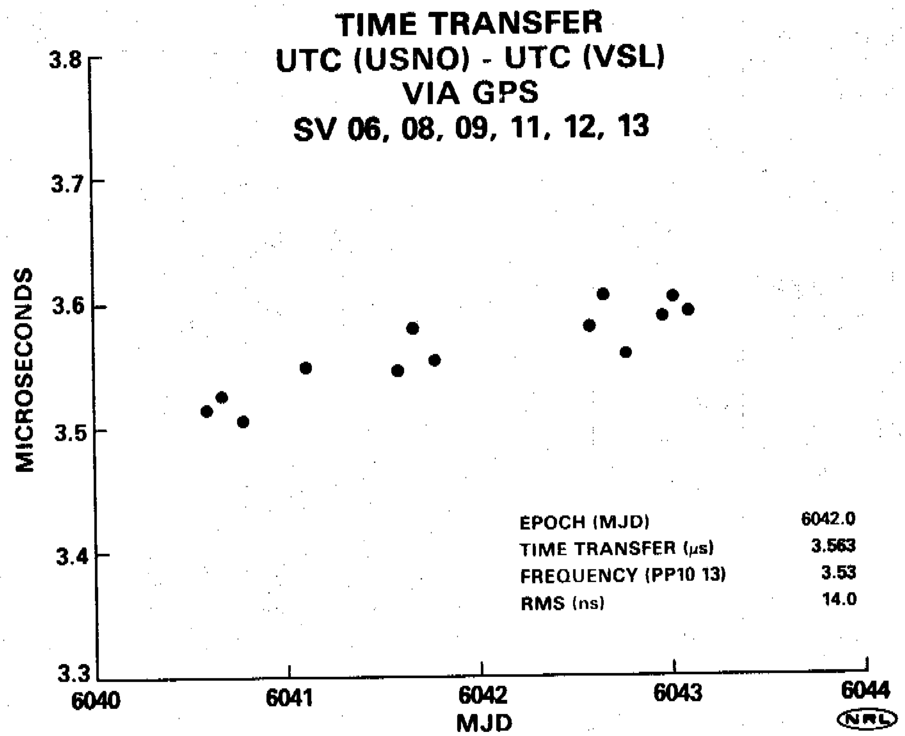
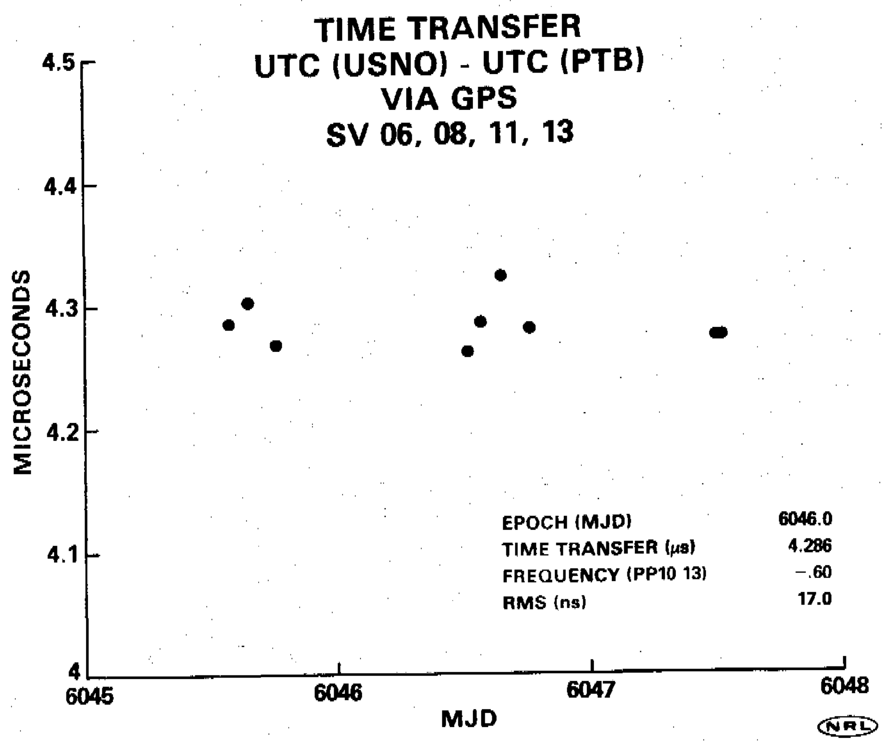

TIME TRANSFER
UTC (USNO) - UTC (VSL)
VIA GPS
SV 06, 08, 09, 11, 12, 13
MICROSECONDS
3.8
3.7
3.6
3.5
3.4
3.3
EPOCH (MJD) 6042.0
TIME TRANSFER (μs) 3.563
FREQUENCY (PP10 13) 3.53
RMS (ns) 14.0
6040
6041
6042
6043
6044
MJD
NRL

Figure 5



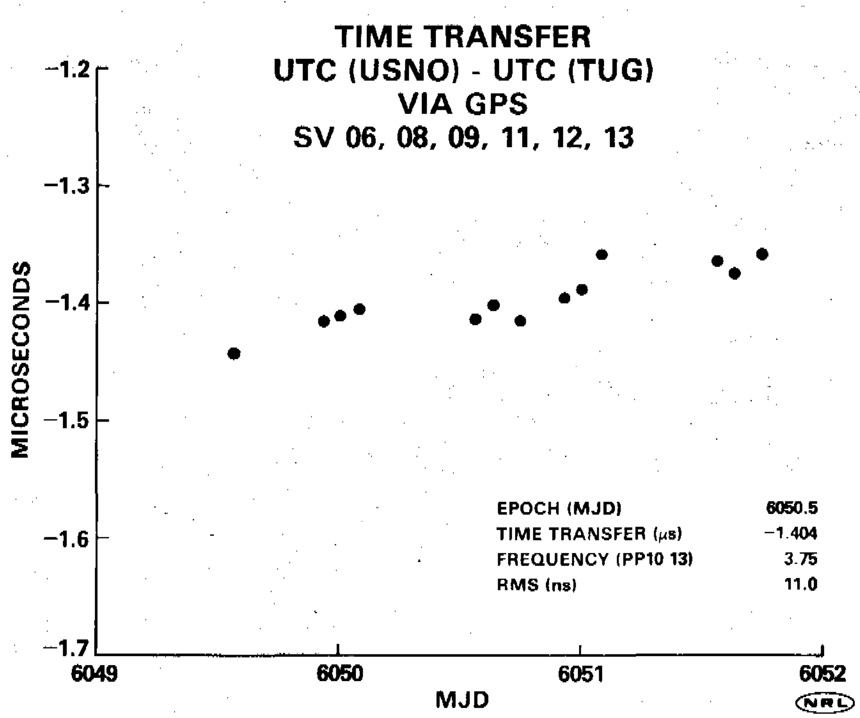
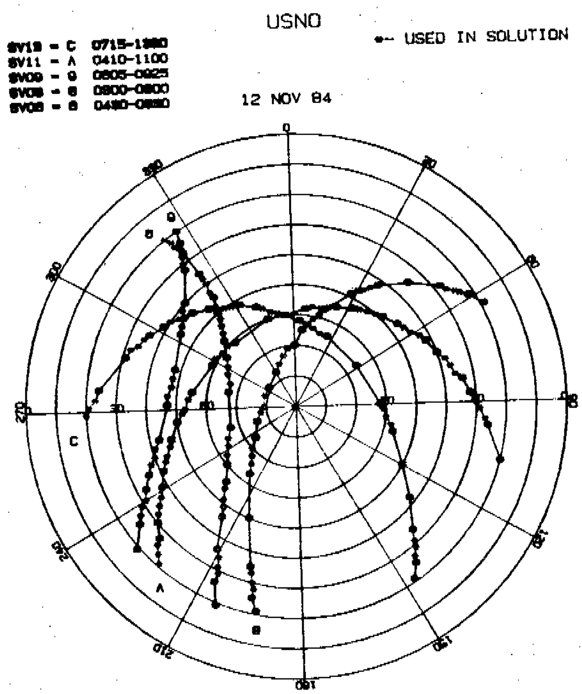
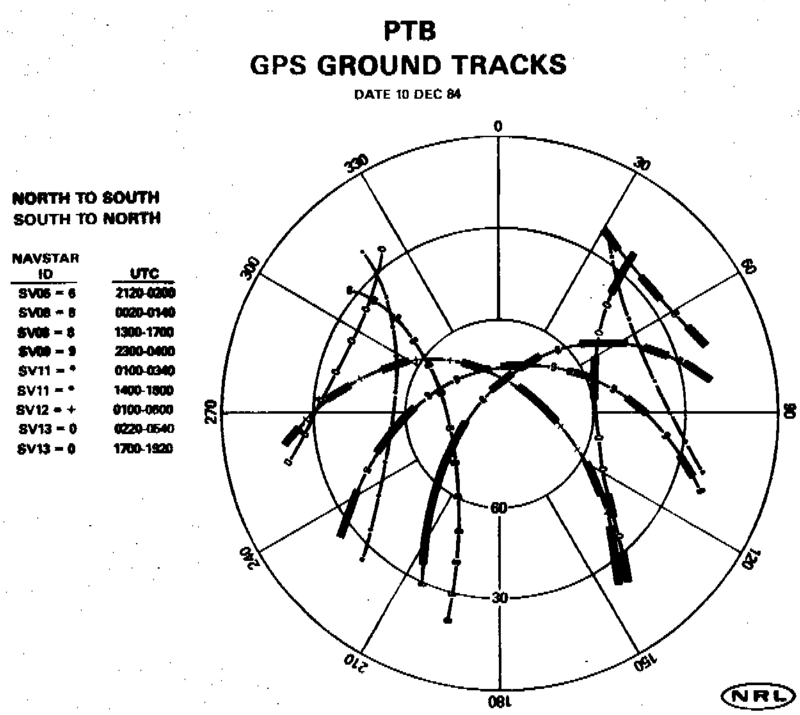


Figure 5 (cont.)


USNO
•– USED IN SOLUTION
12 NOV 84
SV11 – A 0410-1100
0
30
60
90
120
150
180
210
240
270
300
330
C
A


PTB
GPS GROUND TRACKS
DATE 10 DEC 84
NORTH TO SOUTH
SOUTH TO NORTH
NAVSTAR ID
UTC
2120-0200
0020-0140
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2300-0400
SV11 – *
0100-0340
SV11 – *
1400-1800
SV12 – +
0100-0600
SV13 – 0
0220-0540
SV13 – 0
1700-1920
0
30
60
90
120
150
180
210
240
270
300
330
NRL

Figure 6

Δ NAV SOLUTION

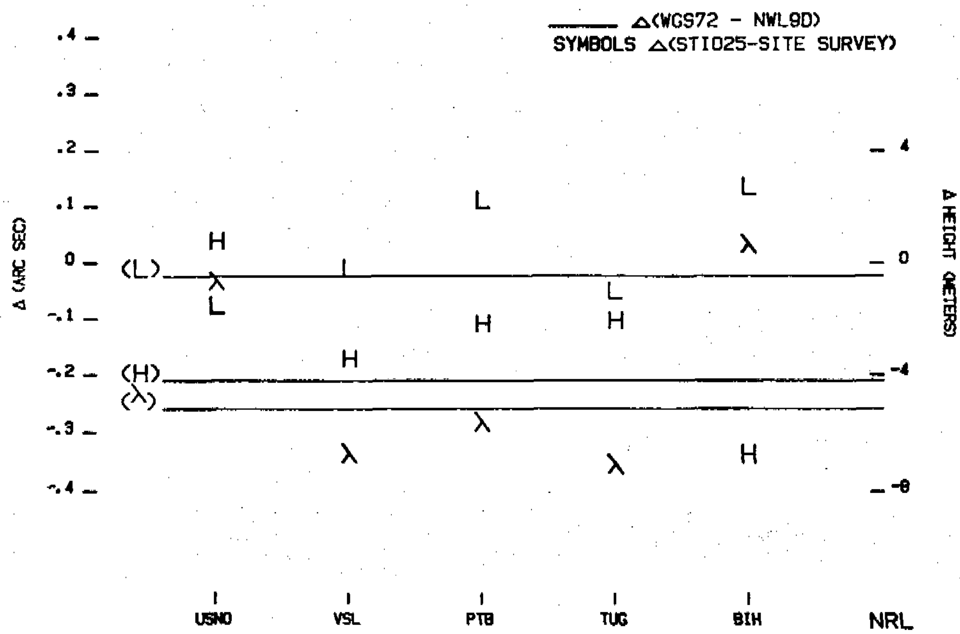

Figure 7A

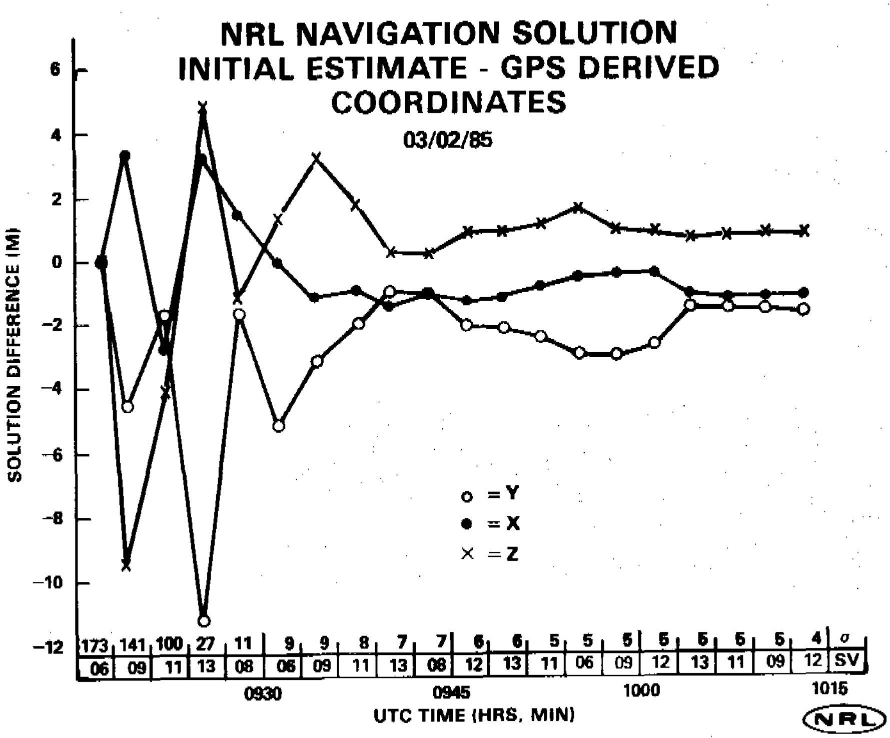

Figure 7B

QUESTIONS AND ANSWERS

ANDREW JOHNSON, NAVAL OBSERVATORY:
As you may know, I am the one responsible for the traveling clock trips for the Observatory. I am really interested in the use of the GPS receiver, but I wonder if the four day time frame is necessary at each site to make the calibration.

MR. LISTER:
Are you suggesting less time?

MR. JOHNSON:
I am asking if you need four days.

MR. LISTER:
You could probably do it in a shorter period of time. I am not sure why four days was selected. It was probably to gain some confidence in the measurements since this was the first R-CATS trip ever performed. The results reveal that you probably can do it in a lesser time.

MR. JOHNSON:
The next question is: at sites where there is no GPS receiver on a clock to be calibrated, how would your system work?

MR. LISTER:
What it would entail at such a site would be to calculate a time transfer and perform a navigation. There would be no reason to be concerned with calculating a calibration offset since they don't have a GPS receiver. We feel that GPS would give you a relatively good time transfer in that case.

SAM WARD, JET PROPULSION LABORATORY:
Is there any explanation that you know of for the bias that appears to be in Space Vehicle 11?

MR. LISTER:
The results of the investigation that was performed in close cooperation with Dave Allan and his group at the National Bureau of Standards revealed that the NBS algorithm was jumping over the correction for relativity, which is a function of orbital eccentricity as well as mean anomaly. It turned out that worst error occurred in the SV11 data. When that "bug" was found, new programs were sent out to each site containing an NBS receiver. One of the purposes for going to NBS in the second R-CATS trip was to be sure that no biases existed at that point.

DAVID ALLAN, NATIONAL BUREAU OF STANDARDS:
You've all heard of software bugs. We suffered from a bug in this case. We should mention that this technique is excellent and the work is outstanding. I would suggest that one think about putting fixed antenna sites so that you just leave the antenna there. If there are multi-path problems they would be minimized as well. You would then come back with a receiver and hook into the antenna to make the calibration.