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FINAL REPORT

INTERFEROMETRIC TRACKING SYSTEM FOR THE TRACKING AND DATA RELAY SATELLITE

For NASA SBIR Contract NAS 5-30313

(NASA-CR-193274) INTERFEROMETRIC TRACKING SYSTEM FOR THE TRACKING AND DATA RELAY SATELLITE (Interferometrics) 22 p

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TABLE OF CONTENTS

LIST OF FIGURES

1.0 EXECUTIVE SUMMARY

This report documents construction and testing of the Interferometric Tracking System project developed under the NASA SBIR contract NAS 5-30313. Manuals describing the software and hardware, respectively entitled: "Field Station Guide to Operations" and "Field Station Hardware Manual" are included as part of this final report.

All requisite hardware was constructed and all software was written that was required for data acquisition. A regional deployment of the system, which determined the consistency of the data using domestic satellites, was successfully completed. Interferometric fringes were obtained from the three field stations and consistency of the delay observables was verified for the two satellite case. Although the station geometry was far from ideal, the overall delay residual RMS was 3.4 ns, and we fully expect residuals in the range of 1-2 ns for the proposed station configurations in the southwest. Results using NASA's orbit determination program GEODYN are similar, with residuals for a short data set under 1 meter.

Experience in operating the system remotely was gained, so that we can be confident of success in deployment in the TDRS downlink beam in the southwest US.

The regional network was dismantled, an inspection tour was made of all the southwest station sites, and we are prepared to proceed to the next phase, which is actual measurements of the TDRS by deploying the system in the Southwest. The hardware is currently stored at Goddard under the auspices of Mr. Phil Liebrecht.

2.0 INTRODUCTION

Interferometric systems, which are physically separated networks of antennas and receivers, can provide highly accurate orbital tracking data, since resolving power, and hence the precision, scales with the separation between the antennas. A number of studies were performed to determine the practicality of such a system for the TDRS satellite system. Connected element interferometers (CEI), where the phase for all antennas is obtained from a common reference clock that is physically connected to each station, were studied using natural radio sources[1] and GPS satellites[2] as calibrators. The calibrators are required to resolve the phase ambiguity between the elements. A different interferometer approach, which allows arbitrarily long baselines, is the very long baseline interferometer (VLBI) system, which potentially can provide dramatically higher accuracy than CEI systems, was also studied. A VLBI system is distinguished from a CEI system because the former has separate clocks at each antenna. The phase of these clocks must be calibrated and studies were conducted using natural radio sources[3] and GPS satellites[4] to perform this calibration. Using multiple satellites to calibrate the clocks in a VLBI system was also studied[5] and that is the underlying approach that was used for this project, as presented in the SBIR Phase I study [6,7].

The objective of this contract was to design, build, and operate a system of three ground stations using VLBI techniques to measure the TDRS orbit. The ground stations receive signals from normal satellite traffic, store these signals in co-located computers, and transmit the information via phone lines to a central processing site which correlates the signals to determine relative time delays. Measurements from another satellite besides TDRS are used to determine clock offsets. A series of such measurements will ultimately be employed to derive the orbital parameters, yielding positions accurate to within 50 meters or possibly better.

3.0 HARDWARE

3.1 Hardware Constructed

This section provides a brief summary of the hardware. More detail is available in the accompanying report entitled "Field Station Hardware Manual".

Three field stations consisting of antennas, RF and analog electronics, digital storage buffers, and computer controllers were constructed during this project. The antennas were commercially available, 1.8 meter offset reflectors with hour-angle mounts purchased from Northern satellite. The mounts were modified by adding computer control to the existing hour angle axis as well as adding a computer controlled declination axis to allow tracking of high inclination satellites such as TDRS-East. Dual-band front-ends were constructed for each station to receive signals from either the TDRS downlink band (13.4-14.1 GHz) or the domestic Ku-band (11.7-12.2 GHz). Indoor equipment was constructed consisting of baseband converters, which accepted the 500-1000 MHz IF signals from the front-ends and converted a 16 MHz band to a digital bit stream. Digital buffer boards were built to store the one-bit sampled data streams simultaneously at all three stations.

3.2 Reliability

The station hardware was generally reliable during the regional deployment phase but several problems did occur. The GORF station antenna limit circuit became intermittent and the problem was traced to a cable that rubbed when the outdoor unit door was opened. At Vienna, intermittent metrology data was traced to bad solder joints that were located on screw-down type wire connections for the analog buffer card. The power supply voltage for the 500-1000 MHz synthesizer was only at 4.8 V, but the synthesizer required at least 4.9V for reliable operation.

A Computer Products 5V supply in the clock unit at GORF failed. The telephone lines at GORF became unreliable during the experiment and were repaired after about one week.

At Green Bank, control of the declination axis was lost which prevented the antenna from pointing closer than 0.25 degrees in declination to one of the observed satellites, SBS-5. The experiment was still successful because the system was designed with considerable SNR margin so the large pointing error caused little degradation in correlation coefficient.

4.0 SOFTWARE

This section only gives a brief summary of the software. More detail is available in the accompanying report "Field Station Guide to Operations".

The field station software points the antennas at a satellite, acquires data simultaneously at all three stations, catalogs and stores the data, and automatically down loads the data to a central computer that determines the satellite orbits. The software uses the Unix operating system to take advantage of its strengths in multiprocessing and mail facilities. The latter is extensively used to move data between computers. A scheduling facility is also available to automate the data acquisition and downloading procedures.

The central site computer, which receives the data files from the field stations, also runs under Unix. Data files were moved from the central site computer to a Novell network server where the actual satellite orbit determination was performed using DOS-based programs.

4.1 Reliability

The software operated well during the regional deployment phase. Some minor bugs were found and corrected. After expending considerable effort, a reliable technique was found for remotely setting the station clocks to the correct second. This synchronization is required so that the buffer cards at each tracking station, which are triggered from the one second tick of the frequency standard, commence data acquisition on the same second from all three stations.

5.0 REGIONAL DEPLOYMENT

Regional deployment of the three ground stations to observe two satellites was completed. The purpose of the regional deployment was to gain experience with the equipment and data analysis in a mode of operation as close to the operational mode as possible, and to examine the variations in the measured delays to verify the predicted accuracy of the delay measurements.

The requirements for the station location were the availability of a stable frequency standard and the ability to locate the antenna in the VLBI reference frame. The stations were located at the Interferometer Control Building at Green Bank, WV, at the Goddard Optical Research Facility (GORF) which is a few miles north of the GSFC main site, and at Interferometrics' headquarters in Vienna, VA. Each site had acceptable frequency standards but the antenna location was not well known. Operational experience was obtained with data acquisition and processing techniques. After successfully collecting data, the field stations at all sites were removed.

The Vienna and GORF sites used HP 5061A cesium frequency standards. A Sigma-Tau hydrogen maser was used at Green Bank. The GORF site location was the best known since it was only 3 meters from a VLBI fiducial marker. The location of the Green Bank antenna was poorly known, because the nearby interferometer antenna that has been used for VLBI experiments and hence is known in the VLBI reference frame was not tied to any ground based fiducial markers. This made referencing the TDRS tracking antenna position to the axis crossing of the interferometer antenna extremely difficult and so locating this TDRS antenna was abandoned. The location of the Vienna antenna was obtained only from an Alexandria Drafting Corporation map book. The site positions were known with sufficient accuracy to recover fringes.

5.1 GORF Cesium Frequency Standard

The HP 5061A cesium frequency standard installed at GORF was compared to the USNO hydrogen maser on a daily basis by Bendix Field Engineering. Time transfer was via timing information in the signal of TV channel 5. Figure 1 is timing differences in the 1 PPS between GORF and the USNO.

5.2 Data Acquisition

Data acquisition was scheduled at all three sites for the time period 23 April 1991 1400 UT through 24 April 1991 1400 UT. A 32768 byte observation of SBS5 was scheduled at 2, 22, and 42 minutes past each hour, and a 32768 byte observation of SBS6 was scheduled at 5, 25, and 45 minutes past each hour. Thus the total data scheduled to be acquired was 4.72 Mbytes per station. The data were acquired and returned to Interferometrics Laboratories for processing.

5.3 Data Correlation

The approximate clock offset and clock rate offset were determined by a wide delay search procedure, then all three baselines of each observation were correlated in a single batch process. The time required to perform the correlation and fringe search on a single observation was just over 30 seconds using a 16 MHz i386SX processor. The extremely high signal to noise ratio (SNR) available in these observations permits program modifications which would approximately halve this time if implemented. Satisfactory correlation was obtained on substantially all of the scheduled observations. The fringe amplitude varied between approximately 0.2 and 1.0 depending on whether the satellite transponder was idle or active.

5.4 Data Analysis

The resulting interferometric group delays were analyzed using a weighted least squares processing program implemented in the desktop computer. Satellite initial conditions for a time close to the time of the observations were kindly supplied by Hughes Communications. The procedure employed was to integrate the initial conditions and partial derivatives for the time spanned by the observations, then use the least squares program to obtain differential corrections to the satellite initial conditions, and the clock offset and clock rate offset at two of the three stations. The orbital elements provided by Hughes Communications were:

```
SBS5 1991 day 111 07:55:00 UT
Semimajor Axis          42165.17        km
Eccentricity                0.0000953
Inclination                 0.01620     deg
Initial Mean Anomaly     -173.0762      deg
Argument of Perigee       -91.2800      deg
R.A. of Ascending Node    108.9924      deg

SBS6 1991 day 115 09:53:22 UT
Semimajor Axis          42164.78        km
Eccentricity                0.0002307
Inclination                 0.01677     deg
Initial Mean Anomaly     -136.5441      deg
Argument of Perigee       171.1986      deg
R.A. of Ascending Node   -132.4501      deg
```

The elements of SBS6 were used to generate initial conditions before the time of the observations, which were then used in a forward integration to provide the reference trajectory. These initial conditions were:

```
SBS6 1991 day 111 09:53:22 UT
X      -8582.987458     km
Y     -41287.180217     km
Z          4.167075     km
Vx          3.0100589   km/s
Vy         -0.6252168   km/s
Vz          0.001065144 km/s
```

The station locations used for both correlation and data analysis were:

	X(m)	Y(m)	Z(m)
Ilabs:	1098708	-4846359	3985201
GORF:	1130686	-4831353	3994110
Green Bank:	882327.5	-4925138.9	3943398.1

The GORF position is that of the mobile VLBI van. The SBIR receiving antenna was within a few meters of this position. The Green Bank position is that of the 85-3 antenna. The SBIR antenna was within about 50 meters of this position. The Ilabs position was determined by measurement of the location of Interferometrics Headquarters on the ADC map of the area and is estimated to be within 100 meters of the correct position. Considering the limited goals of the experiment, we judged that it was not worth the expense to obtain more accurate station positions.

Note that the baseline GORF-Ilabs has about one fifth the length of the baseline Ilabs-Green Bank, and the two baselines are within eight degrees of being parallel. This leads to a degeneracy in the simultaneous solution for all the satellite orbital parameters as well as the station clock parameters. For this reason, plus the fact that the station coordinates were not known well in all cases, the orbit determination results are incomplete and lack physical significance. The residuals, however, do indicate the performance of the system in the field. The delay residuals to a solution for four out of the six elements of both satellites plus the clock parameters at GORF and Green Bank are shown in Figures 2-4 below. The overall residual RMS was 3.4 ns. The RMS for each baseline is shown on the baseline plot. The residuals for the two satellites are connected by a line in Figure 4 to emphasize the fact that they are far from random. We fully expect to reduce the residual RMS to the range 1-2 ns in the southwest deployment.

5.5 Analysis Using GEODYN

5.5.1 Purpose

During the period April 8-11, 1991 a series of observations of SBS-5 was made. These observations involved all three baselines, and were scheduled 10 minutes apart. The purpose of these observations was to verify that the system as a whole worked, and to examine variations in the measured delays to verify the predicted accuracy of the delay measurements.

An additional purpose was to verify that we could successfully process the data using GEODYN on the Goddard computer.

5.5.2 Data Correlation

The data was correlated in batch mode using a program called SBIRCALC which searched a window 10 microseconds wide around the *a priori* delay. Satisfactory correlation was obtained on virtually all the data.

5.5.3 Data Analysis

In all there were 451 observations during this period. The system was down for 1/2 day on April 8. Apart from this, the coverage is fairly uniform.

Hughes communication provided the following orbital elements for SBS5:

SBS5.		
Epoch	91/04/02 19:55	
Semi-Major Axis	42166460.770	km
Eccentricity	0.0001888000	
Inclination	0.01699	deg
Mean Anomaly	-178.4013508	deg
Argument of Perigee	-153.8711692	deg
RA of Ascending Node	-21.322144500	deg

These elements were propagated forward through the measurement period by GEODYN. Figures 5-7 display the delay residuals. There appears to be at least one break in the delay residual curves at roughly day 9.4. This may be caused by station keeping maneuvers.

When GEODYN attempted to fit a single orbit over the entire period of observation, the solution rapidly diverged. This is consistent with the satellite changing orbit in the middle of these measurements.

When GEODYN was run on a shorter data set, the solution converged fairly rapidly, and gave residuals which are well under 1 M for all three baselines. Figures 6-10 display the residuals for a six hours of data. Further iterations did not substantially reduce the residuals.

In short, we have used GEODYN to analyze data from the local deployment. For short periods of data, the results are as expected. For a long period, the solution does not converge, but this was due to a station keeping maneuver in the middle of data acquisition.

6.0 INSPECTION OF SITES FOR THE SOUTHWEST DEPLOYMENT

To ultimately test and operate the system, the TDRS field stations need to be deployed in the K-band downlink of the TDRS A satellite, which is located at 41 degrees west longitude. The requirements for each field station are the availability of 5 MHZ and 1 PPS from at least a cesium frequency standard, that the site location is known in the VLBI reference system, and that the site be in the main beam of the TDRS K-band downlink. The following sites satisfy these requirements: The Fort Davis, TX and Pie Town, NM VLBA sites and the University of Texas Applied Research Lab (ARL) at Austin.

The installations at the two VLBA sites appear to be straight forward, because installation of the antenna pole, which is the most time consuming task, will be performed by others. Antenna installation in Austin, which will be on the roof of the ARL, will require considerable effort. For that site, a wooden frame must be constructed on an existing steel mounting platform on the roof. ARL has also requested that we locate the TDRS tracking antenna in the VLBI reference frame by helping them make differential GPS measurements against a VLBI fiducial marker that is 2 miles away.

The National Radio Astronomy Observatory (NRAO) runs the VLBA sites. NRAO is concerned about stray signal radiation from the TDRS ground station front ends and has requested that we measure them for leakage from 100 MHz to 43 GHz. This requires test equipment that Interferometrics doesn't own and we are exploring different approaches to meeting this requirement.

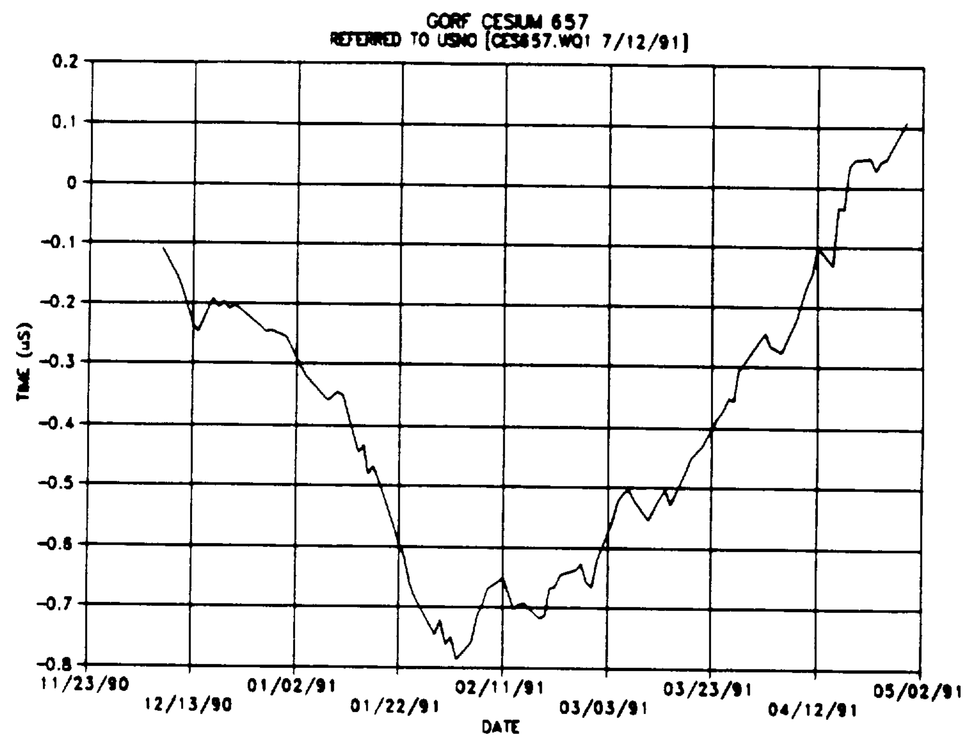

Figure 1: Cesium Performance at GORF

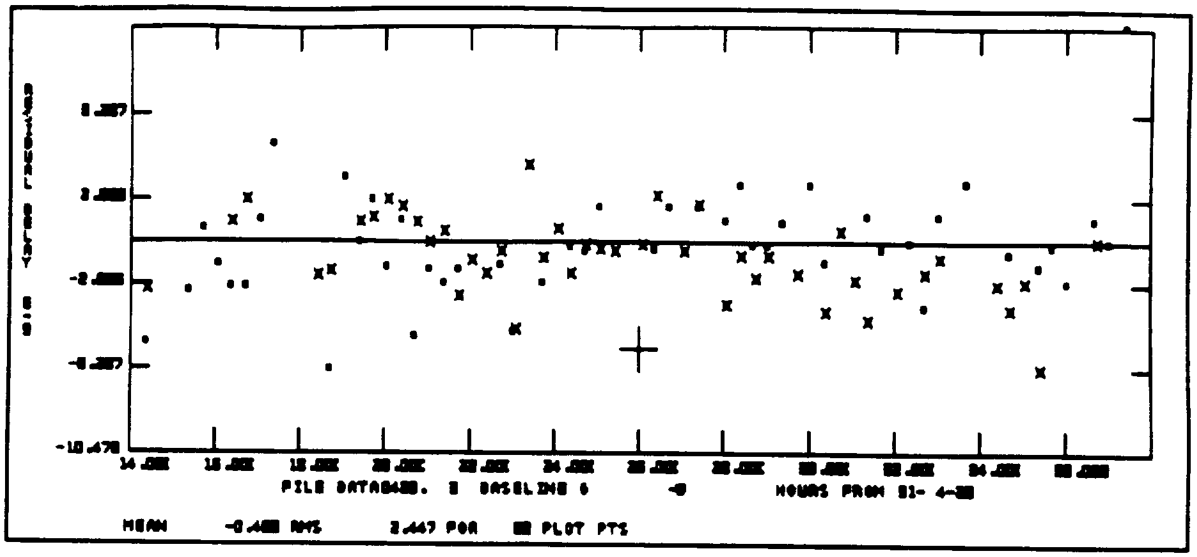

Figure 2: Residuals for the Baseline GORF-Green Bank

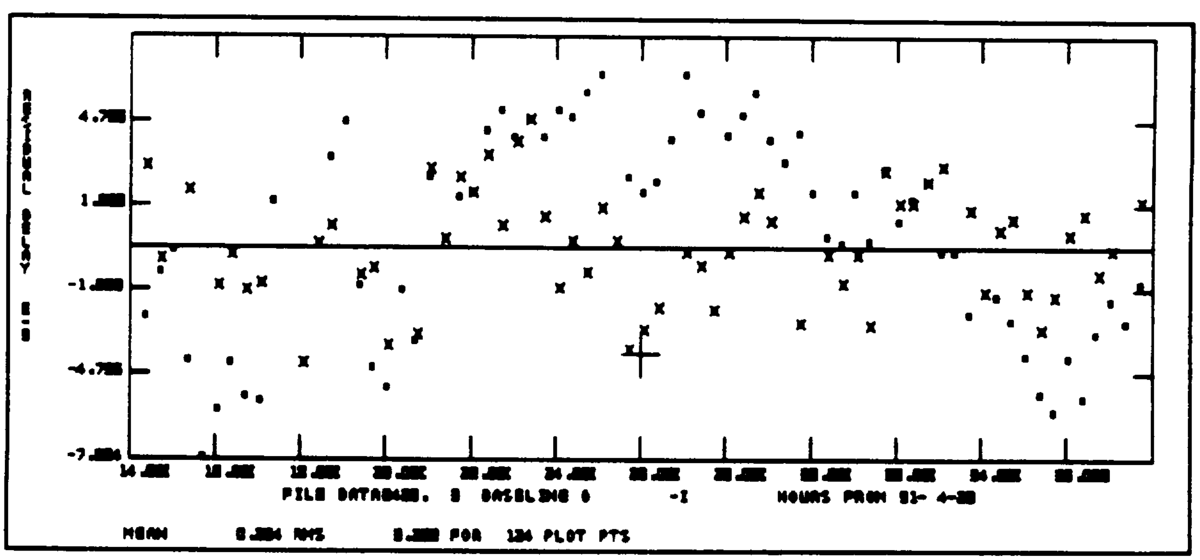

Figure 3: Residuals for the baseline GORF-Ilabs

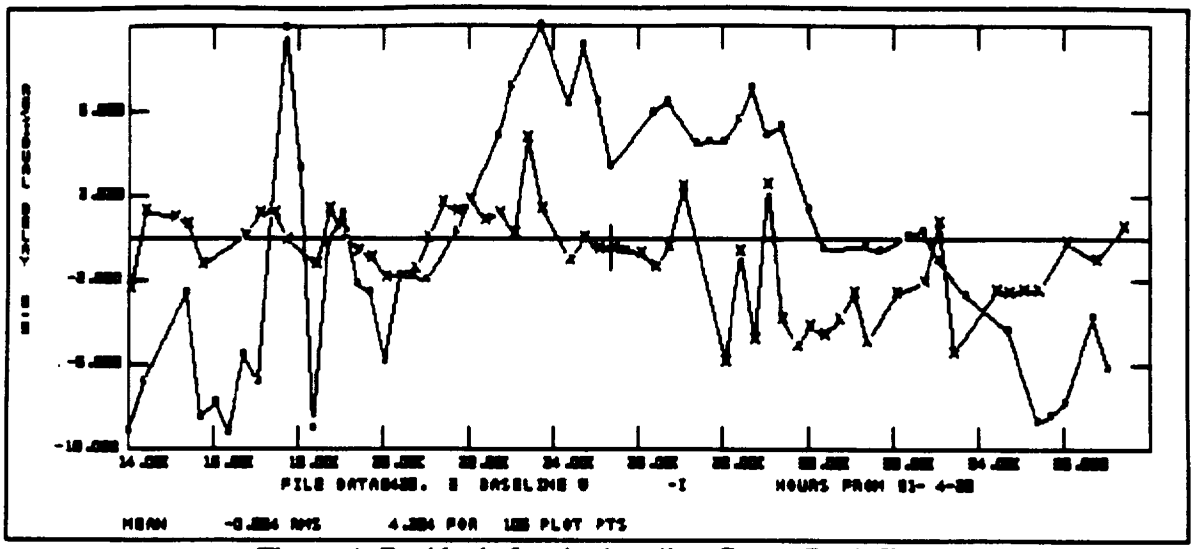

Figure 4: Residuals for the baseline Green Bank-Ilabs

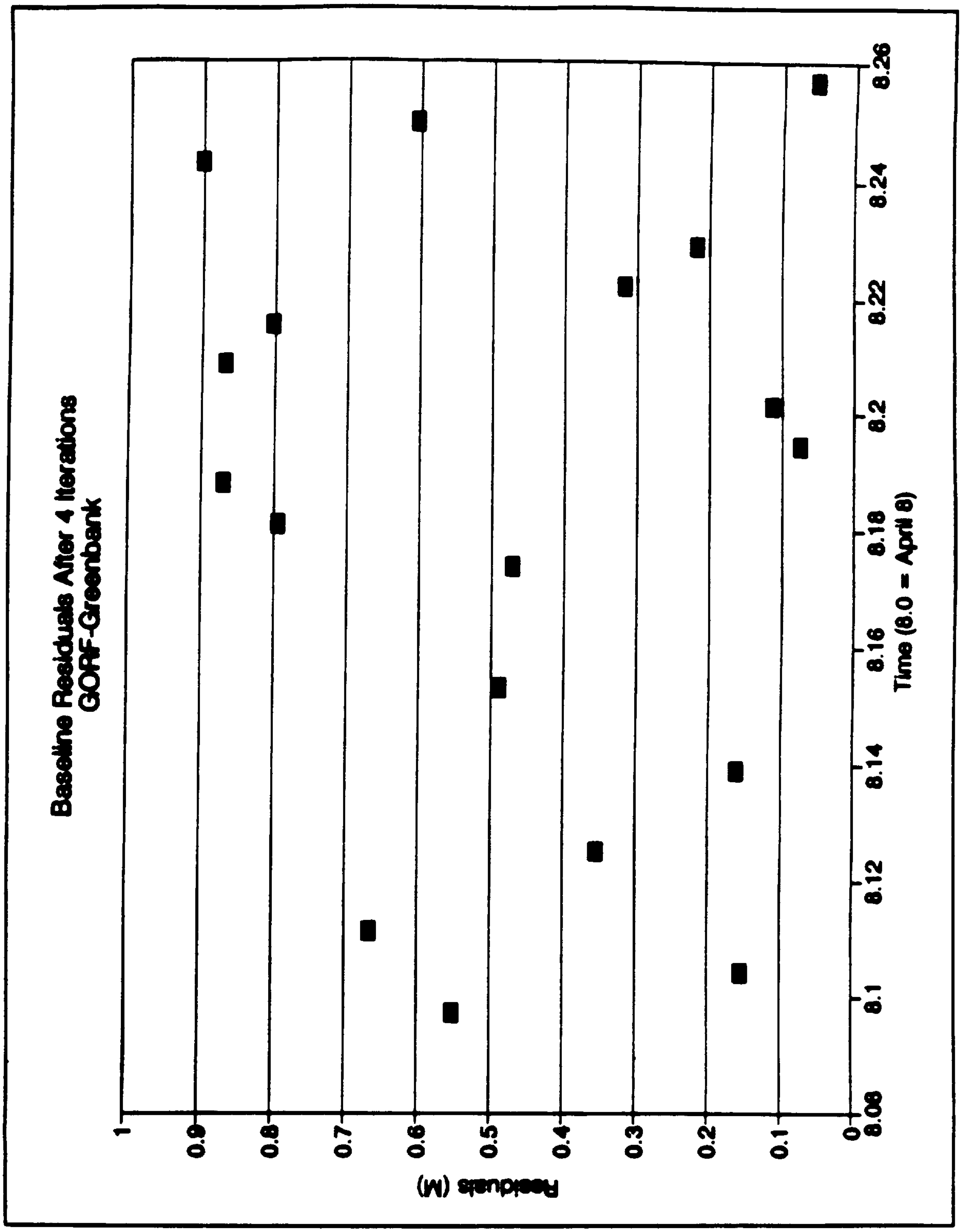

Figure 5: GEODYN Results - GORF-Green Bank Residuals

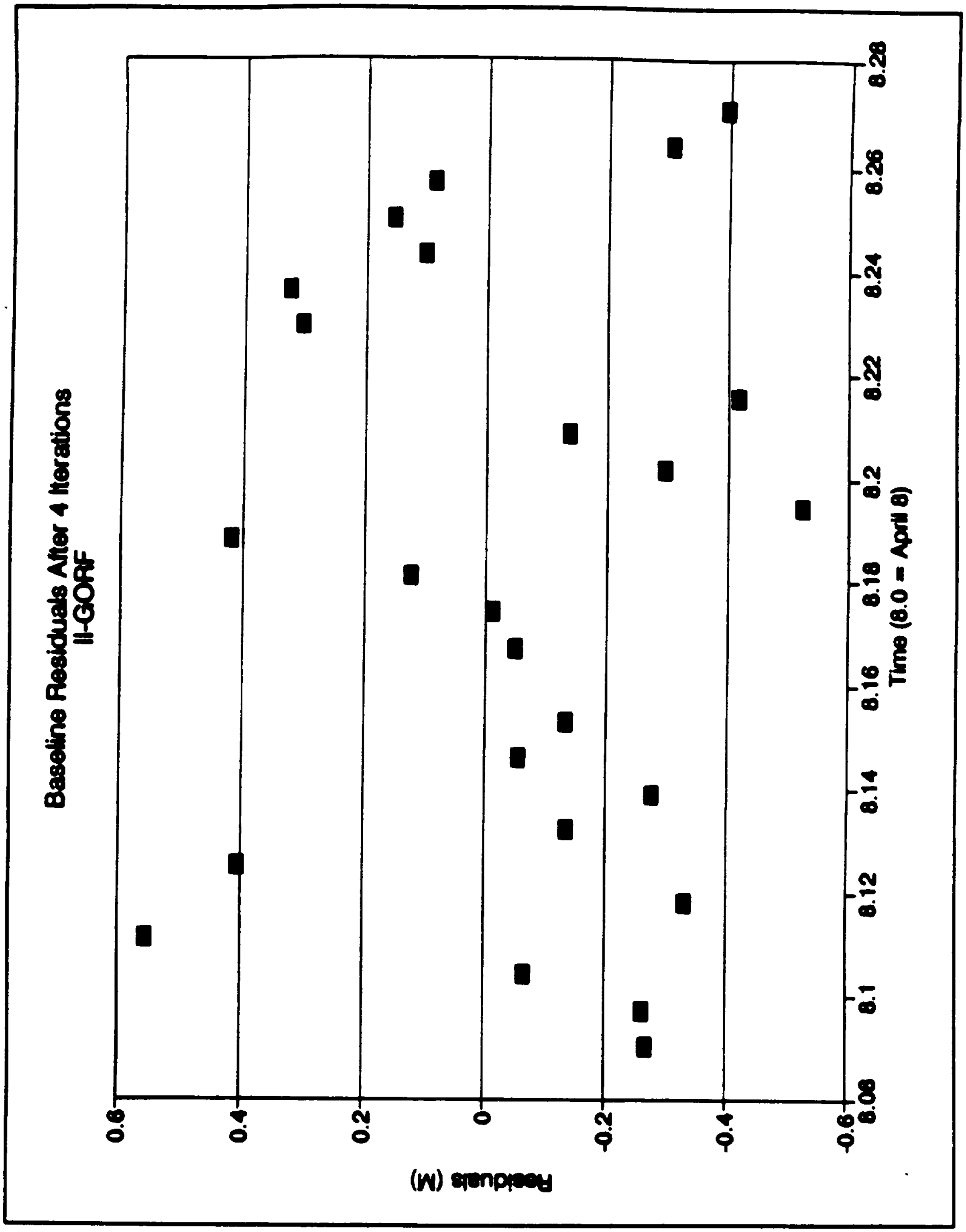

Figure 6: GEODYN Results - GORF-Ilabs Residuals

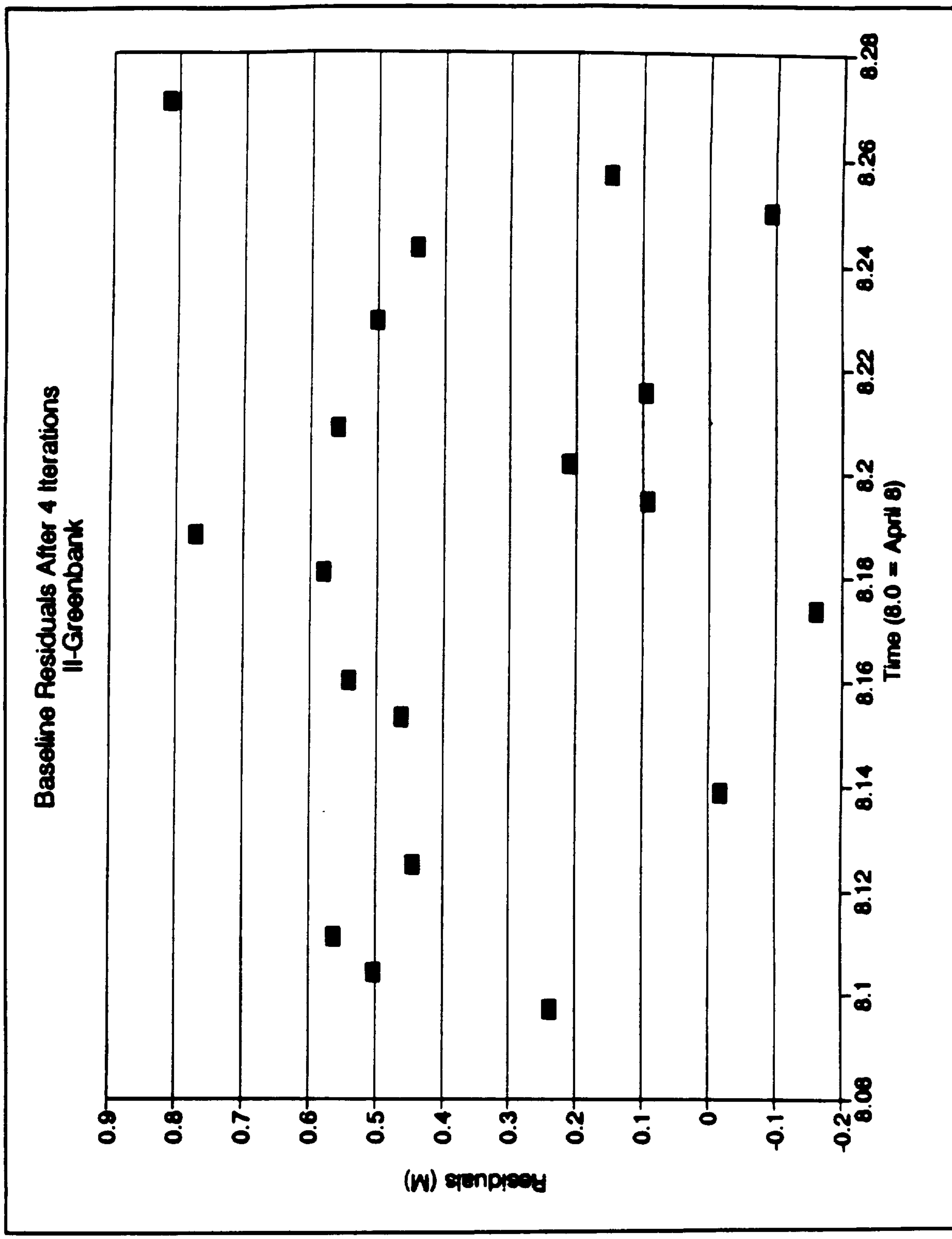

Figure 7: GEODYN Results Green Bank-Ilabs Residuals

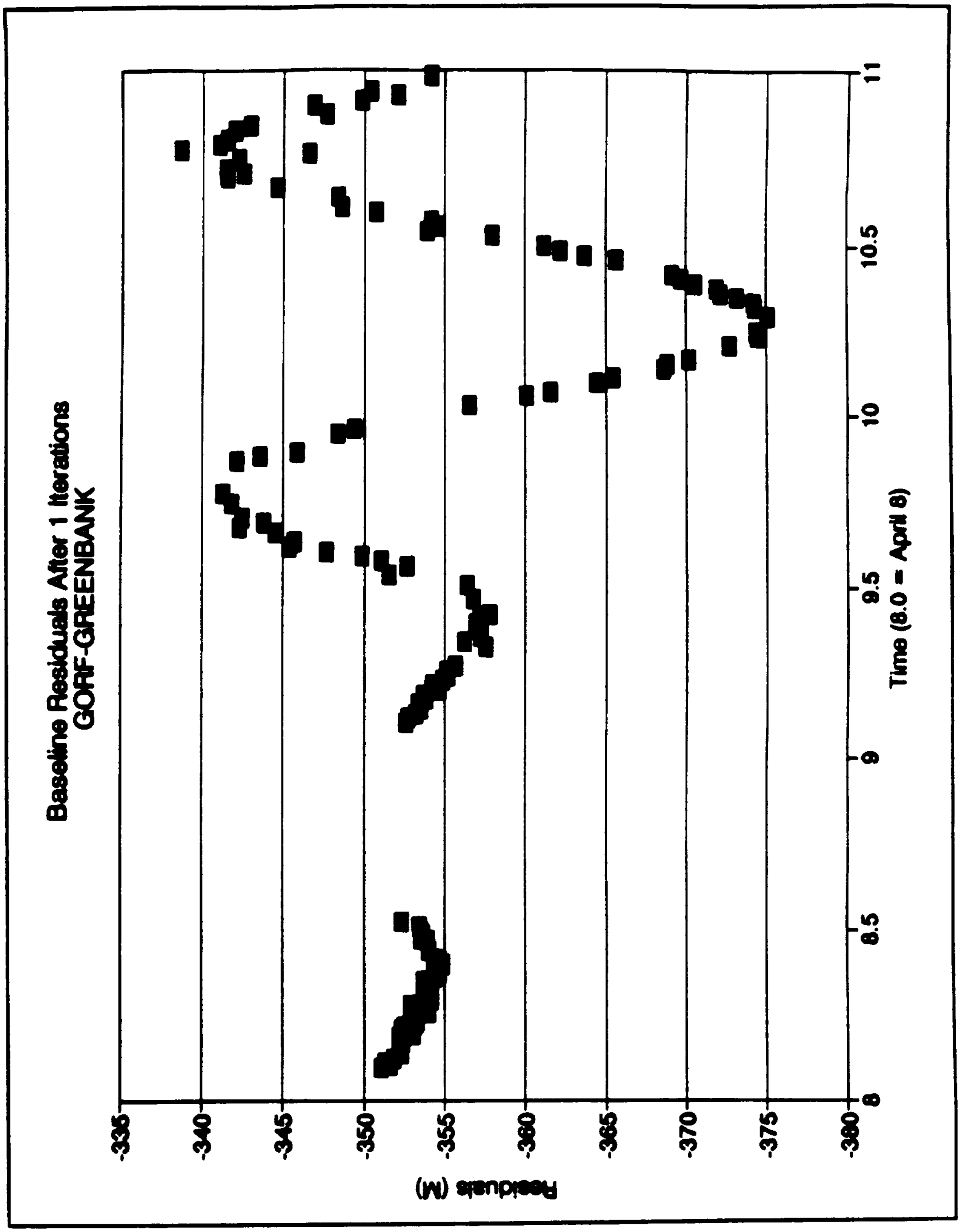

Figure 8: GEODYN Results: 6 Hours; GORF-Green Bank Residuals

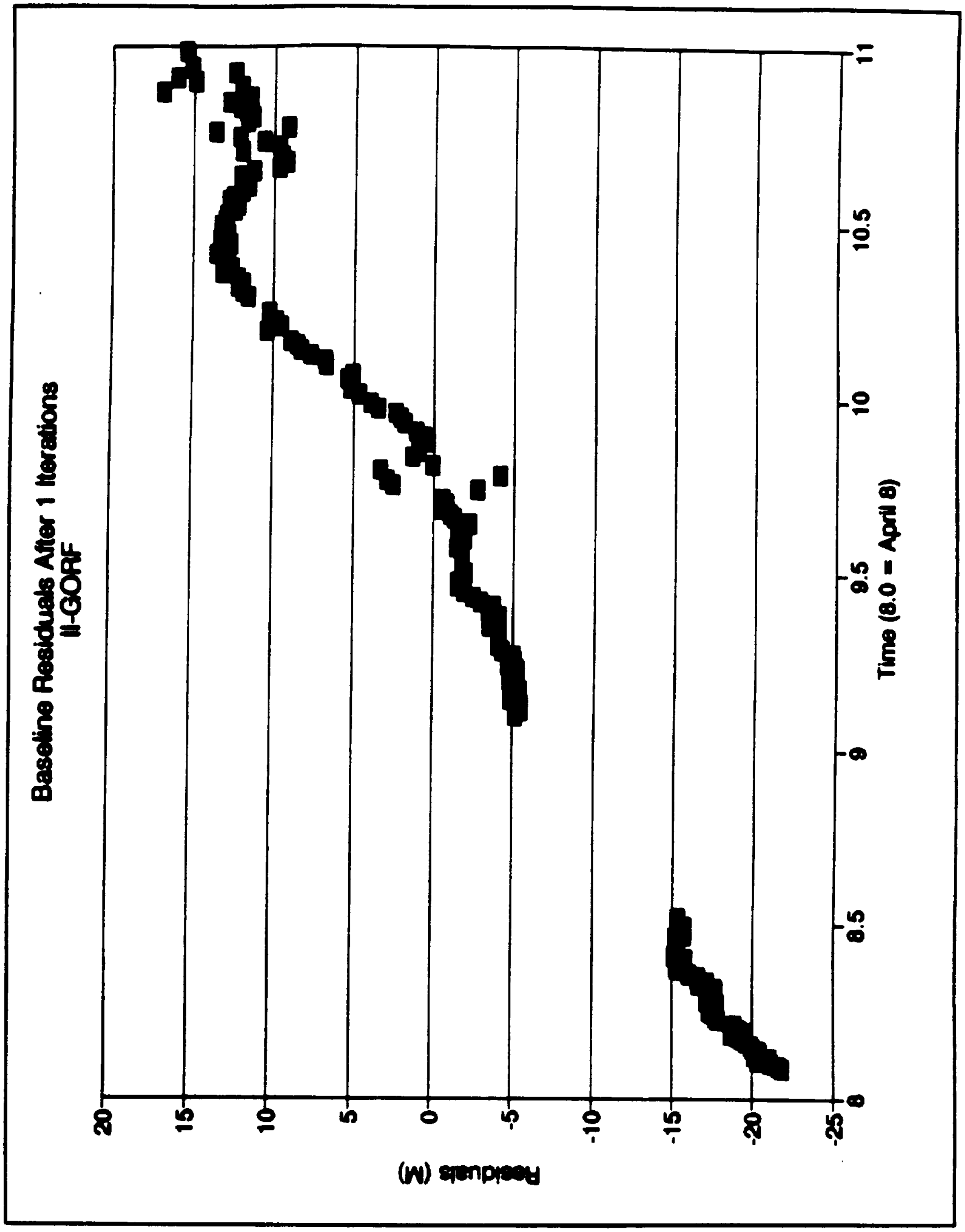

Figure 9: GEODYN Results: 6 Hours; GORF-Ilabs Residuals

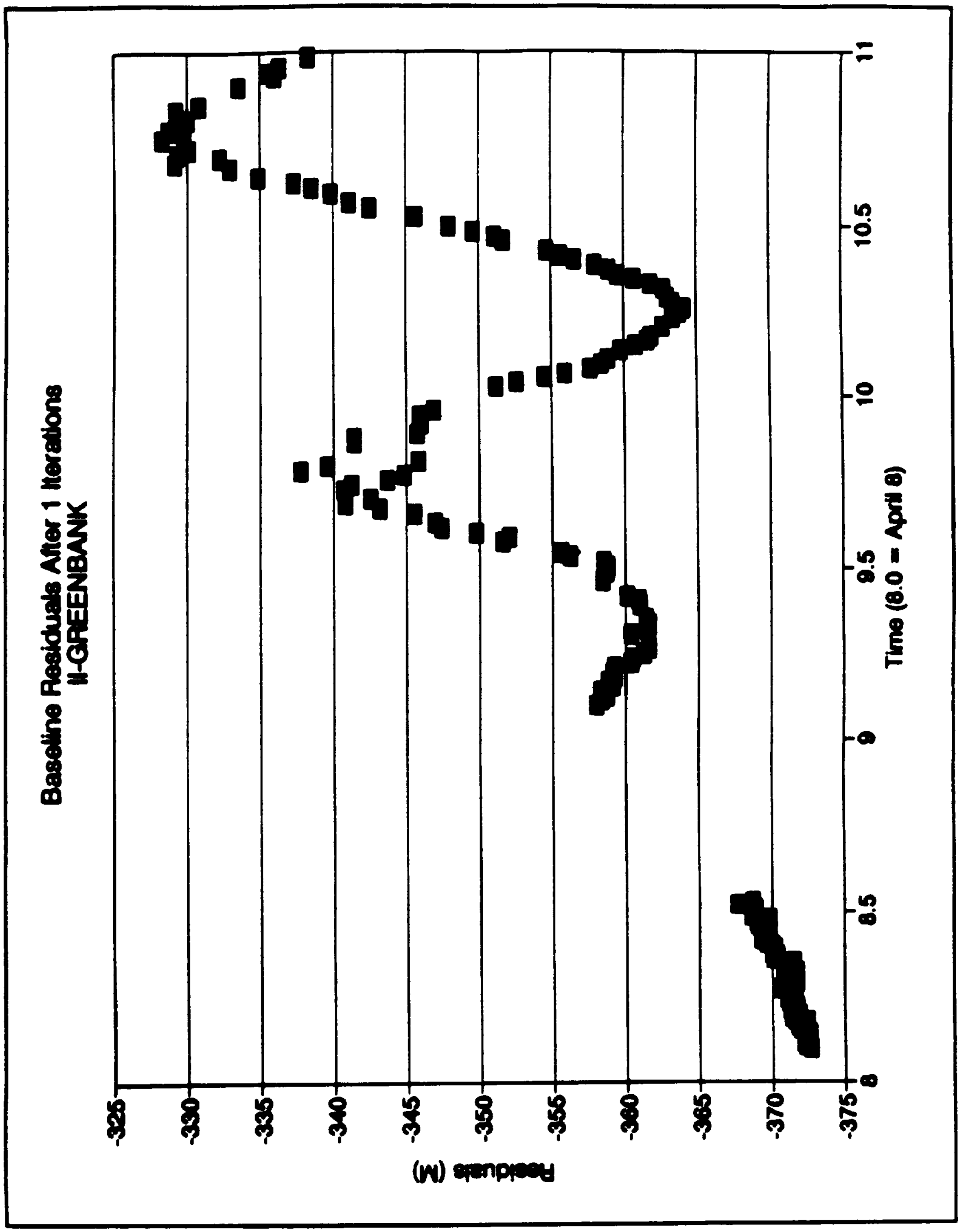

Figure 10: GEODYN Results: 6 Hours; Green Bank-Ilabs Residuals

REFERENCES

1 J. Ray, N. Zelensky, C. Knight, D. Shaffer, K Way, B. Schupler, "Specifications for a TDRS-Tracking System Using Interferometry: 1 CEI Using Natural Rado Sources as Calibrators", part of the NASA RTOP Study entitled "VLBI Tracking of TDRS", November 1987.

2 R. Potash, A. Au, J. Ray, N. Zelensky, C. Knight, D. Shaffer, K Way, B. Schupler, "Specifications for a TDRS-Tracking System Using Interferometry: II CEI Using GPS Satellite Sources as Calibrators", part of the NASA RTOP Study entitled "VLBI Tracking of TDRS", November 1987.

3 R. Potash, J. Ray, N. Zelensky, C. Knight, K Way, B. Schupler, "Specifications for a TDRS-Tracking System Using Interferometry: II VLBI Using Natural Radio Sources as Calibrators", part of the NASA RTOP Study entitled "VLBI Tracking of TDRS", November 1987.

4 A. Au, J. Ray, N. Zelensky, C. Knight, K Way, B. Schupler, "Specifications for a TDRS-Tracking System Using Interferometry: II VLBI Using GPS Satellite Radio Sources as Calibrators", part of the NASA RTOP Study entitled "VLBI Tracking of TDRS", November 1987.

5 J. Ray, N. Zelensky, "Clock Calibration for Interferometric Tracking of Multiple TDRS Satellites", part of the NASA RTOP Study entitled "VLBI Tracking of TDRS", November 1987.

6 J. Ray, C. Knight, D. Shaffer, and C. Moore, "SBIR Phase I Report: Interferometric Tracking System for the Tracking and Data Relay Satellite (TDRS) Volume 1: System Overview", August, 1987.

7 J. Ray, C. Knight, D. Shaffer, and C. Moore, "SBIR Phase I Report: Interferometric Tracking System for the Tracking and Data Relay Satellite (TDRS) Volume 2: Detailed System Specifications", August, 1987.

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15. Supplementary Notes

16. Abstract

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