GPS Orbit Determination at the National Geodetic Survey

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Abstract

The National Geodetic Survey (NGS) independently generates precise ephemerides for all available Global Positioning System (GPS) satellites. Beginning in 1991, these ephemerides have been produced from double-differenced phase observations solely from the Cooperative International GPS Network (CIGNET) tracking sites. The double-difference technique combines simultaneous observations of two satellites from two ground stations effectively eliminating satellite and ground receiver clock errors, and the Selective Availability (S/A) signal degradation currently in effect. CIGNET is a global GPS tracking network whose primary purpose is to provide data for orbit production. The CIGNET data are collected daily at NGS and are available to the public. Each ephemeris covers a single week and is available within one month after the data were taken. Verification is by baseline repeatability and direct comparison with other ephemerides. Typically, an ephemeris is accurate at a few parts in 10^7. This corresponds to a 10 meter error in the reported satellite positions. NGS is actively investigating methods to improve the accuracy of its orbits, the ultimate goal being one part in 10^8 or better. The ephemerides are generally available to the public through the Coast Guard GPS Information Center or directly from NGS through the Geodetic Information Service. An overview of the techniques and software used in orbit generation will be given, the current status of CIGNET will be described, and a summary of the ephemeris verification results will be presented.

CIGNET

The Cooperative International GPS Network, or CIGNET, was created to make available reliable and continuous GPS tracking data from a global network of fiducial stations. The tracking site positions are defined in the International Earth Rotation Service (IERS) reference frame, and the sites are maintained for crustal motion studies and as a common starting point for GPS satellite ephemerides generation. The National Geodetic Survey (NGS) has been an active participant in CIGNET since its inception and serves as the CIGNET Information Center (CIC). Figure 1 shows the distribution of CIGNET tracking sites. Facilities at each site are provided and run by the sponsoring organizations. All sites are equipped with a personal or mini computer and power backup systems for automated routine operation. External frequency standards are available at most sites providing superior receiver clock performance. Data are taken continuously at 30 second intervals and surface meteorological measurements taken hourly. A minimum satellite observation elevation of 10 degrees is imposed. Many sites are equipped with high speed modems making possible remote receiver control. Table I contains a list of the CIGNET locations displayed in Figure 1 with their

Table 1: CIGNET DEVELOPMENT

STATION		INSTALLED	RECEIVER	SPONSOR
MOJAVE CA	USA	NOV 1986	MiniMac 2816AT	NATIONAL GEODETIC SURVEY (NGS)
YELLOWKNIFE	CANADA	JAN 1987	ROGUE	GEOLOGICAL SURVEY OF CANADA (GSC)/EMR
WETTZELL	GERMANY	NOV 1987	ROGUE	INSTITUT FUR ANGEWANDTE GEODASIE
TROMSO	NORWAY	DEC 1987	ROGUE	STATENS KARTWERK
ONSALA	SWEDEN	DEC 1987	ROGUE	ONSALA SPACE OBSERVATORY
RICHMOND FL	USA	FEB 1988	MiniMac 2816AT	U.S. NAVAL OBSERVATORY
KOKEE PARK HI	USA	APR 1988	TRIMBLE 4000SST	CDP/GSFC/NASA
TSUKUBA	JAPAN	JUL 1988	MiniMac 2816AT	GEOGRAPHICAL SURVEY INSTITUTE (GSI)
HOBART	AUSTRALIA	DEC 1989	MiniMac 2816AT	UNIVERSITY OF TASMANIA
WELLINGTON	NEW ZEALAND	JAN 1990	TRIMBLE 4000SST	DEPT. OF SURVEY AND LAND INFORMATION
TOWNSVILLE	AUSTRALIA	MAR 1990	TRIMBLE 4000SST	DIV. OF GEOGRAPHIC INF/DEPT. OF LANDS
HARTEBEESTHOCK	S. AFRICA	JAN 1991	ROGUE	CNES/IGN FRANCE
ANKARA	TURKEY	JAN 1991	MiniMac 2816AT	TURKEY ARMY
VICTORIA/PENTICTON	CANADA	APR 1991	ROGUE	PACIFIC GEOSCIENCE CENTRE/GSC/EMR
METSAHOVI	FINLAND	MAY 1991	ASHTECH	FINNISH GEODETIC INSTITUTE
TAI-SHI	TAIWAN	JUL 1991	MiniMac 2816AT	INSTITUTE OF EARTH SCIENCE
HERSTMONCEUX	GREAT BRITAIN	JUN 1991	ROGUE	UNIVERSITY OF NEWCASTLE UPON TYNE
KOOTWIJK	NETHERLANDS	JAN 1991	ROGUE	DELFT UNIVERSITY OF TECHNOLOGY
PLATTEVILLE CO	USA	AUG 1991	TRIMBLE 4000SST	UNAVCO
MATERA	ITALY	JAN 1991	ROGUE	ITALIAN SPACE AGENCY
ORRORAL	AUSTRALIA	JAN 1991	TRIMBLE 4000SST	AUSTRALIAN SURVEYING & LAND INFORMATION
FORTALEZA	BRAZIL	(FUTURE)	ROGUE/TRIMBLE	BRAZILIAN SPACE AGENCY
BRASILIA	BRAZIL	(FUTURE)	TRIMBLE	*BRAZILIAN INS. OF GEOGRAPHY & STATISTICS*
PORT HARCOURT	NIGERIA	(FUTURE)	TRIMBLE 4000SST	RIVERS STATE U. OF SCIENCE & TECHNOLOGY
BADARY	USSR	(FUTURE)	MiniMac 2816AT	USSR ACADEMY OF SCIENCES

dates of installation, current receivers, and sponsors. Four future sites, indicated with crosses in Figure 1, are also listed.

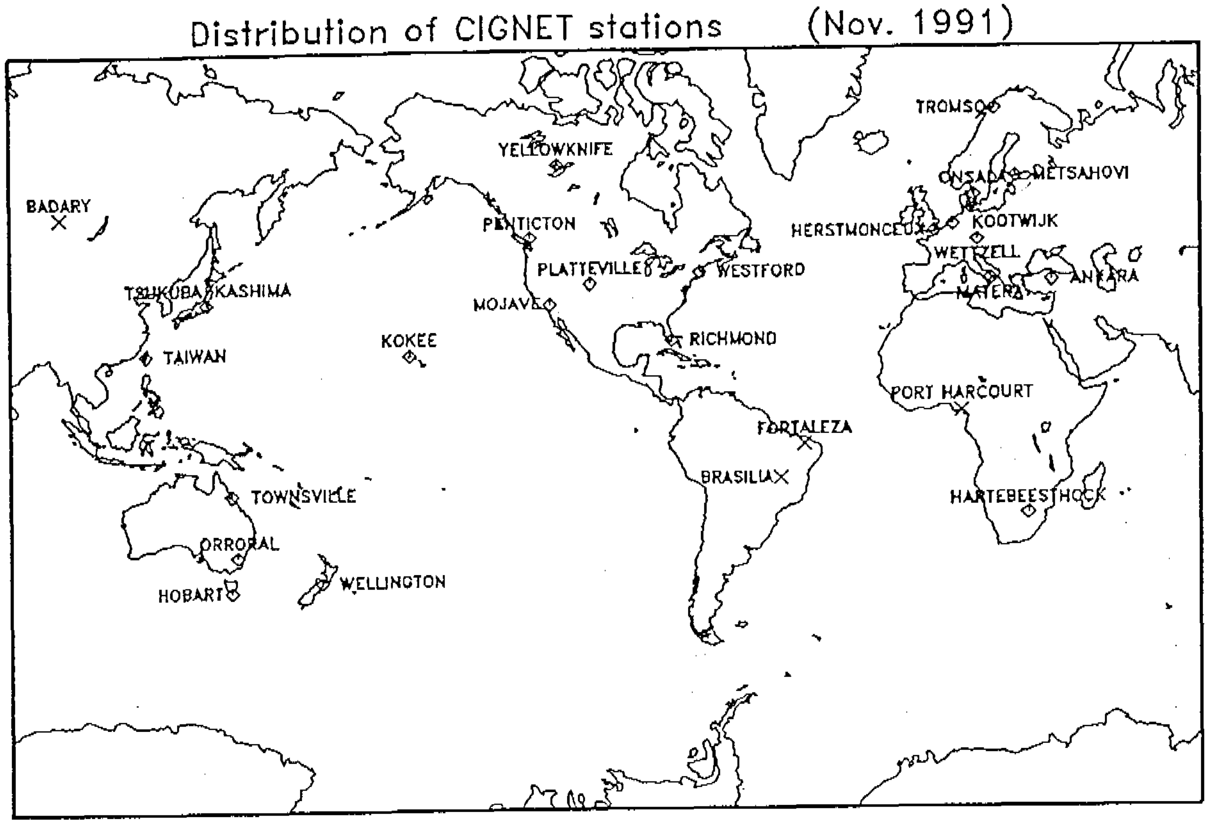

Figure 1

Data retrieval at the CIC is accomplished, where possible, via modem or computer network. Upon receipt, the raw data are converted into an ASCII exchange format. The reformatted data are then processed to provide receiver health, station clock health, satellite coverage, Selective Availability (S/A) status, cycle slip evaluation, and meteorological summary information. The entire operation is fully automated and completed each morning before 7:00 AM Eastern Time. The raw and reformatted data are archived on 9-track tape or magneto-optical disk. Occasionally, situations require the data to be copied onto floppy disks at each site and shipped to the CIC via express mail services. Upon receipt these data are processed manually and are typically available within one week.

The reformatted ASCII and raw data files are available through the CIC. The most recent data may be accessed directly through ARPAnet from an HP9000/825 computer with UNIX operating system. The network address is gracie.grdl.noaa.gov or 192.64.68.199; the system guest login name and password are anonymous. Individual data files are stored in subdirectories branching off /users/ftp/dist/cignet. The subdirectories are named d###a or d###b where ### is the day-of-year of the data. d###a contains the reformatted ASCII, and d###b, original binary files. Large quantities of data are transferred on 9-track, 6250 bpi tapes. Smaller requests may be sent via IBM compatible floppy disks or 9-track tape at the user's discretion. All users are urged to retrieve the data over the computer networks if possible. Requests, questions, or problems can be directed to Miranda Chin, N/OES13, NOAA/NOS/OES, Room 418, 11400 Rockville Pike, Rockville, MD 20852, USA; phone: 301-443-8798 or 301-443-0139; FAX: 301-443-5714; ARPAnet: ernie@gracie.grdl.noaa.gov.

GPS SATELLITE EPHEMERIDES

The growing use of GPS has motivated NGS to take an active interest in the production GPS satellite ephemerides. In addition, NGS agreed in April 1990 to be responsible for providing GPS ephemerides through the Civil GPS Service. The participation in CIGNET has made possible an effort to produce these ephemerides at NGS. Typically, the NGS ephemerides are available one month after the data were taken. These ephemerides can be gotten, via modem and free of charge, through the Civil GPS Service Interface Committee (GPSIC) bulletin board operated by the United States Coast Guard. Only the most recent ephemerides will be available because of space limitations. The GPSIC bulletin board may be reached by dialing 703-866-3890 for 300 - 2400 bps modems, or 703-866-3894 for 9600 bps modems. The communication parameters are asynchronous, 8 data bits, 1 start bit, 1 stop bit, no parity, full duplex, and XON/XOFF. Both Bell And CCITT protocols are recognized. In addition to the GPSIC bulletin board, all NGS ephemerides are available through the NGS Geodetic Information Branch. There is a $50 (US) charge for each week requested plus a 25% surcharge for distribution outside the United States. For additional information, the Information Branch may be telephoned directly at 301-443-8631.

Production is composed of three primary tasks or stages: the creation of a priori ephemeris, data pre-processing, and orbit adjustment. The a priori ephemerides are created with ARC, an orbit integrator program, provided by the Massachusetts Institute of Technology. ARC employs an eleventh order Adams-Moulton predictor-corrector to produce satellite positions and partial derivatives to the initial conditions at 22.5 minute intervals. The constants used in the program were defined in the IERS standards (McCarthy, 1989) with an 8x8 gravity field taken from the GEM-T2 model (Marsh et al. 1989). A simplified ROCK4 model (Columbo, 1989) for the satellite radiation pressure, ad hoc Y-bias, and the related partial derivatives are currently in use. Conversion between inertial and Earth-centered fixed coordinates uses polar motion and UT1-UTC values determined from VLBI observations, and nutation values generated from IAU 1980 Theory of Nutation (Seidelmann, 1982; Wahr, 1981). In routine production, initial conditions taken from the previous week's adjusted ephemeris are used although any precise or broadcast ephemerides can provide these.

Pre-processing involves the creation of databases, and the identification and removal of cycle slips. Both tasks are accomplished with the OMNI software developed at NGS; however, human intervention is required to verify and complete the cycle slip removal. Cycle slip correction, being the most intensive and time consuming task, is the current limiting factor in ephemeris production.

The program PAGE2 combines the a priori ephemerides from ARC with the tracking data in a least-squares adjustment to produce the corrected ephemerides. Designed for background or batch operation, PAGE2 can process observations of 24 satellite from 20 sites. Dual frequency data are combined to produce an ionosphere-free, double-differenced observable. Double-differencing effectively removes all clock errors. S/A, which manifests itself a satellite clock error, is therefore also removed with this technique. A neutral atmosphere path length correction derived from the Saastamoinen dry atmosphere (Saastamoinen, 1972) plus the Chao wet atmosphere (Chao, 1972) zenith corrections combined with the Center for Astrophysics 2.2 mapping function (Davis et al., 1985), and an Earth tide correction (Melchion, 1978) for the tracking sites are applied. Data from a GPS week plus one day before and after are used to create the weekly ephemerides. The two additional days are included to help smooth discontinuities between subsequent ephemerides. Typically, adjustments to all satellite positions and velocities, scale factors for the radiation pressures, Y-biases, and tropospheric delays, and phase bias values are determined. The site coordinates are not adjusted in normal operation. Currently, time and physical limitations allow only sub-networks in the U.S., Europe, and Australia to be processed for orbit determination. Planned software and hardware improvements, and the continued growth of CIGNET will allow other sites to be included in the near future.

Ephemeris verification is performed using two methods. The first is direct comparisons with independently produced ephemerides. Through the advent of continuous S/A in the Block II satellites, agreement between all sources has been at a few parts in 10^7. Although this method is valuable for long term improvement of the techniques and models used in the ephemerides adjustment, it does not satisfy the strict time constraints of routine production. To address the problem in a timely fashion, a repeatability study using tracking sites not included in the orbit solution was proposed. Three permanent tracking sites equipped with P-code receivers in southern California were used in the example shown here. The three sites, designated JPLMESA, PIN1, and SIO1, are part of the Permanent GPS Geodetic Array, a NASA pilot project operated by the Scripps Institution of Oceanography and the Jet Propulsion Lab with the assistance of the California Institute of Technology, the Massachusetts Institute of Technology, and the University of California at Los Angeles. The relative positions of these sites is shown if Figure 2. Data from August 18 through September 28, 1991 were processed. These data span GPS weeks 606 - 611, days-of-year 230 - 271. The position of SIO1 was held fix as the reference position. The variation of the estimated positions for the other two sites could then be used to judge the quality of the input ephemerides. The resulting baseline lengths were 171.2 km for JPLMESA to SIO1, and 110.9 km for PIN1 to SIO1. Consistency required that similar observing scenarios be used each day. If substantial data were missing from more than one site, the day was eliminated from consideration. Thus, days 236, 239, 257, 258, and 267 are not included in the subsequent discussion. In addition, PIN1 data were unavailable for most of GPS week 611. The week 611 results for PIN1 are included for completeness and should not be considered a reliable diagnostic for that ephemeris. Ionosphere-free, double difference phase measurements of the baselines were made using the OMNI software and NGS generated ephemerides. Hourly tropospheric path length scaling factors were estimated to minimize tropospheric modelling errors. The data were edited automatically, but only down to the few cycle level. Examination of randomly selected days revealed that several small cycle slips remained in the data after the editing. Undoubtedly cycle slips of this magnitude exist in each set of data. Although these cycle slips will worsen the repeatability, in essence giving a worst case evaluation, the slips are not large or frequent enough to prevent an evaluation of ephemeris quality. A single set of coordinates for all three sites were adopted to simplify comparisons.

Figures 3 through 6 show the estimated offsets from the a priori positions. Lines connect points that belong to the same GPS week. Table II summarizes the weekly and overall RMS deviations from the mean for these offsets. Two extreme cases appear in the weekly results. GPS week 608 shows a large variation in the east component for the PIN1 - SIO1 baseline. This variation is not seen in the JPLMESA - SIO1 baseline and probably results from missing or improperly edited data from the PIN1 site. GPS week 607 is more troubling. Both baselines show similar large variations. Again, missing or improperly edited data, this time from the common reference station SIO1, is the likely source. Although an ephemeris error can not be completely ruled out, the north components do not show a similar variation which implies a specific event rather than a more global ephemeris error. Weekly RMS variations are typically 1 - 3 cm in the horizontal, 4 - 6 cm in the vertical

Southern California

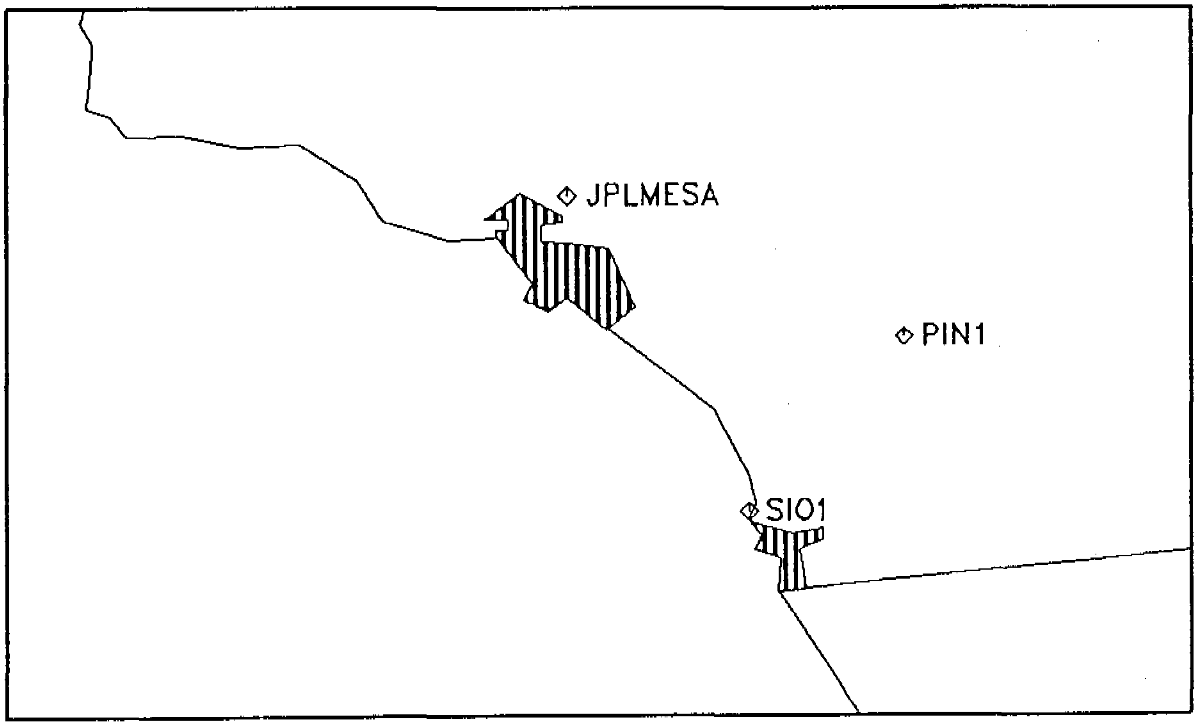

Figure 2: Relative location of sites used in the repeatability study.

components of the baselines. Limitations of satellite geometry and coverage, errors in tropospheric modelling, and signal multipathing generally manifest themselves most strongly as errors in the vertical component of a baseline solution. The weekly results are consistent with these effects. These results imply NGS ephemerides are internally consistent at 1 part in 10^7. The overall RMS values are significantly larger for the east and vertical components indicating possible week-to-week ephemeris variations. Such week-to-week variations are expected and efforts are taken to minimize them. The overall RMS values indicates the "worst case" accuracy of slightly better than 1 part in 10^6; however, the repeatability in the north component implies results an order of magnitude better.

Table II: RMS variations of the baseline components. All values are in meters.

	JPLMESA - SIO1			PIN1 - SIO1		
GPS WEEK	EAST	NORTH	UP	EAST	NORTH	UP
606	0.0184	0.0105	0.0252	0.0213	0.0090	0.0307
607	0.0861	0.0114	0.1345	0.0621	0.0259	0.1503
608	0.0435	0.0081	0.0345	0.1299	0.0099	0.0436
609	0.0278	0.0139	0.0534	0.0221	0.0122	0.0404
610	0.0081	0.0061	0.0460	0.0256	0.0104	0.0669
611	0.0160	0.0102	0.0308	0.1391	0.0148	0.0104
OVERALL	0.1350	0.0130	0.0910	0.0972	0.0183	0.0927

Conclusion

CIGNET is a global GPS tracking network whose data are generally available for geodetic and geophysical studies, and ephemeris generation. The data are retrieved and available through the CIGNET Information Center daily. In turn, these tracking data are used in GPS ephemeris generation at National Geodetic Survey. Each ephemeris covers a single GPS week and is available one month after the data were taken. Direct comparisons with independent sources and baseline repeatability studies indicate the accuracy of the NGS ephemerides to be roughly 1 part in 10^7.

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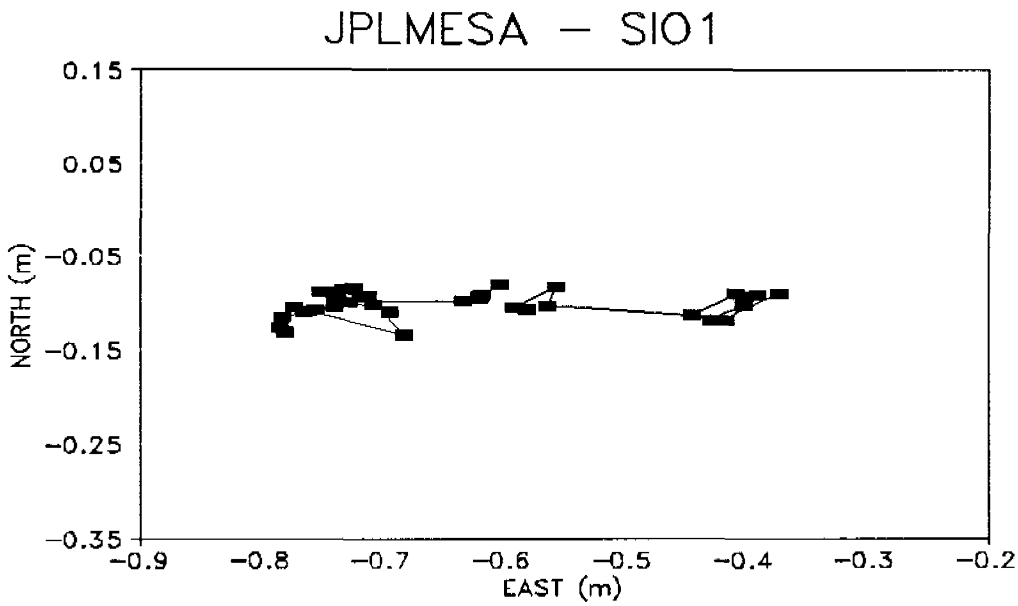

Figure 3: JPLMESA - SIO1 estimated daily horizontal offset from the a prior position.

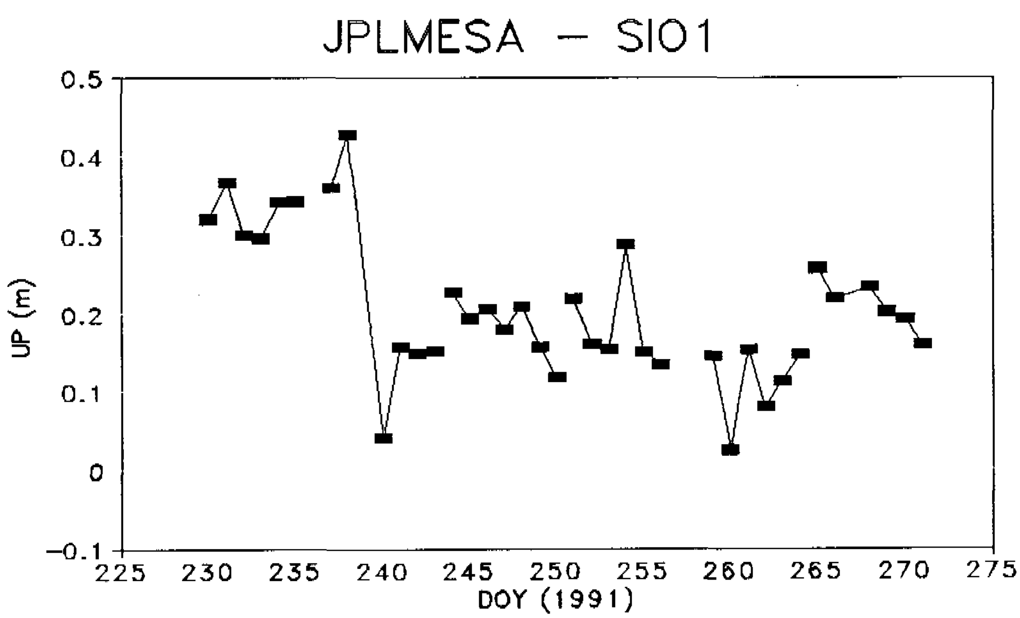

Figure 4: JPLMESA - SIO1 estimated daily vertical offset from the a priori position.

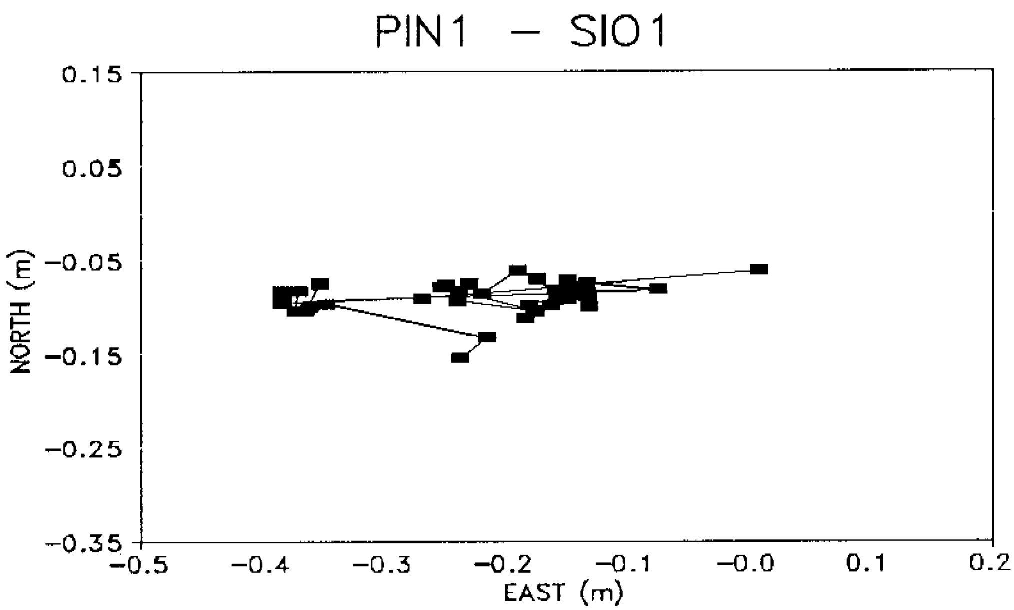

Figure 5: PIN1 - SIO1 estimated daily horizontal offset from the a priori position.

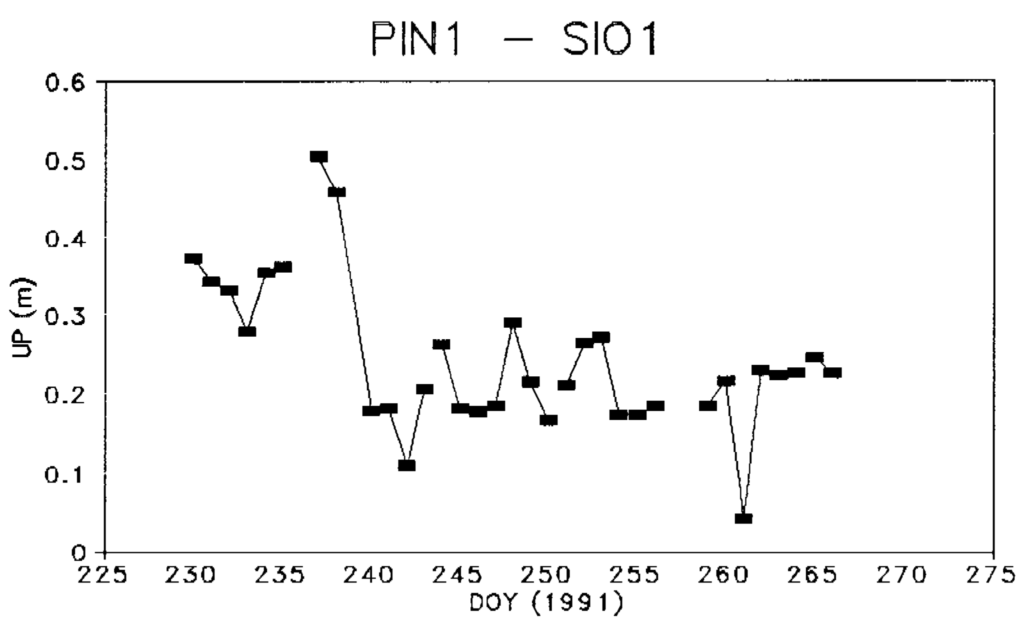

Figure 6: PIN1 - SIO1 estimated daily vertical offset from the a priori position.

QUESTIONS AND ANSWERS

G. Petit, BIPM: Is the processing to produce the ephemeris a global process? This means that all satellites are equivalent?

Mr. Schenewerk: At this point in time that is correct. I am sure that it is something that you can sympathize with and occasionally it is something that I am embarrassed about. A binding force in the universe is the establishment of a procedure for operations. We do have set procedures so that we have traceability of our ephemerides. We use equal weighting for all satellites and all stations that are involved. It varies of course from week to week depending on the availability of the data. Roughly, eight or ten stations, scattered around the globe, go into these ephemerides.

Mr. Petit: Did you get a chance to compare your three station network with the other positions? From VLBI or other?

Mr. Schenewerk: For this particular experiment, which is in actuality an attempt to establish a procedure for our verification project, all the sites, both in the orbit production and SIO for this experiment were held fixed. In other work that we have done, we have estimated the position of the tracking sites as well as the orbit when we do the solution. In those cases, we have fairly consistently got a correspondence with the VLBI and other locations at about one part in 10^8. Given the limitations of an incomplete constellation this is very good.