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GPS Satellite-to-User Range Accuracies: A Calibration Experiment

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ABSTRACT

From 20 October to 17 November 1986, three Contracting and three Government institutions took part in a cooperative evaluation of the accuracy of the Global Positioning System (GPS). In effect, acting as independent GPS users employing C/A-code single-frequency or P-code dual-frequency receivers, each organization computed satellite-to-user range prediction errors.

Each institutional user computed statistical summaries of these User Range Errors (URE). The root-mean-square (rms) of the URE's across all satellites, and over all 30-days of the test, as reported by each user ranged from a high of 4.8 meters to a low of 3.1 meters. The C/A-code users experienced the largest rms URE. The GPS is required to provide 6 meter rms URE.

For the same test period, the GPS Operational Control System (OCS) computed URE performance measures of 2.0 meters (rms) and 2.5 meters (rms). This suggests that these GPS performance measures might be improved.

Throughout the 30 day test, users reported that the daily rms URE were approximately steady-state. However, just prior to the test, the rms URE did appear correlated over several days with rms values near 6 meters. This URE degradation appeared to improve as NAVSTARS 3, 6, and 10 were less and less eclipsed by the Earth shadow.

INTRODUCTION

At the request of the U.S. Air Force, a cooperative effort involving The Aerospace Corporation, General Dynamics Corporation, IBM Corporation, the

National Bureau of Standards, the Naval Surface Weapons Center, the U.S. Naval Observatory and other international GPS users (Figure 1) assessed the accuracy of the GPS satellite navigation messages and the accuracy of the broadcast satellite-to-user pseudo range predictions. This test period spanned 30 days, from 20 October to 27 November 1986.

GPS transmits satellite ephemeris predictions in a Defense Mapping Agency, earth-fixed, coordinate system and satellite clock time predictions relative to "U.S. Naval Observatory Time." Such GPS transmissions are to provide DoD-authorized users with 16 meter* navigation position accuracy, 0.1 meter/second (rms) velocity accuracy, and 103 nanosecond (rms) UTC-to-user time transfer accuracy.[1]

Although the navigation and time transfer functions operationally overlap in that both require that predictions of satellite position and clock offsets be broadcast to the user, the effect on the user of URE differs depending upon the user's application. A navigator, primarily interested in position or velocity determinations, achieves the navigation accuracy required as long as the uncorrelated URE across the observed satellites is less than 6 meters (rms). That portion of the URE that does correlate across the satellites is aliased into the

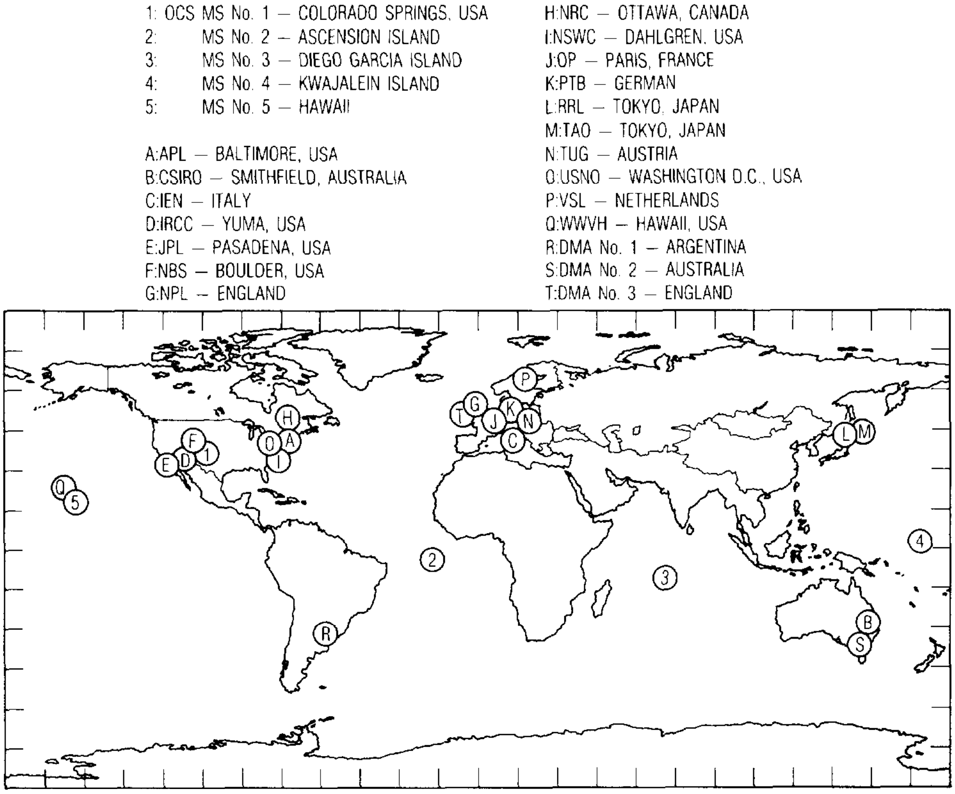


Fig. 1—Global Stations Involved in User Range Error Assessment.

(Spherical Error Probable, SEP = 50% probability that the error vector will be within a sphere of radius SEP.)

navigator's clock phase offset solution. Similarly, a time transfer user will alias the uncorrelated URE into the position determination and will alias the correlated URE into the time solution. However, if the time transfer user assumes his position known, the error in the satellite-to-user time transfer is sensitive to both the correlated and uncorrelated URE.

That GPS is required to deliver such navigation and time transfer accuracy implies that the total URE, correlated and uncorrelated components, not exceed 103 nanoseconds (rms) and that the uncorrelated URE not exceed 6 meters (rms). Since the first is of interest to the timing community, it is presented in units of nanoseconds while the second, a navigation requirement, is presented in meters.

Over the 30 day test period, rms UREs were computed for 24 hour and 30 day intervals. During the test period, for continental U.S. users that standardized their processing of GPS pseudo range (Figure 2), the above GPS accuracy requirements were demonstrated to be satisfied. In fact, the 30 day rms total URE, correlated and uncorrelated components combined, was less than 3.1 meters as reported by the P-code, dual-frequency, receiver users.

Examination of the U.S. Naval Observatory (USNO) UREs prior to the test period, from July 1984 to 20 October 1986, reveals that the URE dispersion is not steady-state (Figure 3). Over this extended period, about two-thirds of the daily rms UREs exhibited values below 6 meters and about one-third of the time the values were in excess of 6 meters. The degraded URE performance seems to occur when the angle between the orbit plane of a satellite and the sun-Earth line is below twenty degrees.

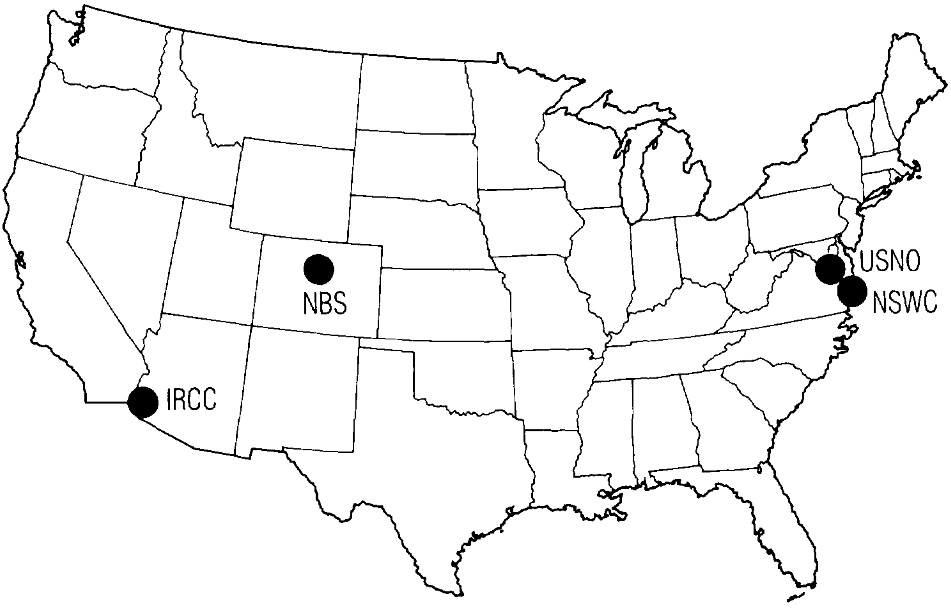


Fig. 2—Users Involved in Standardized User Range Error Assessment.

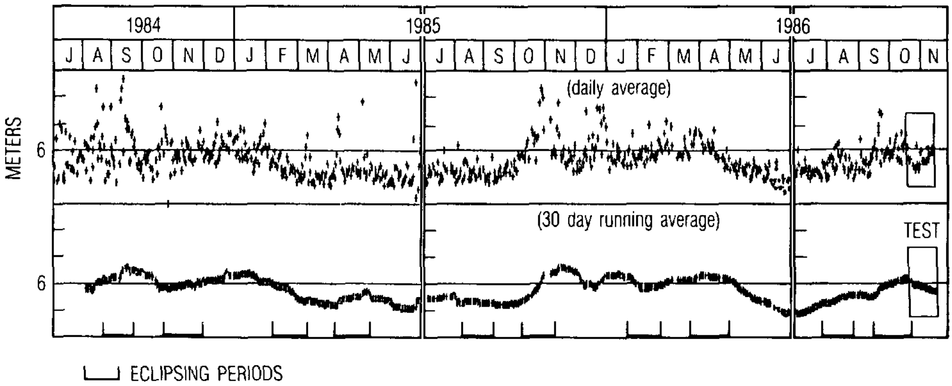


Fig. 3—U.S. Naval Observatory Two-Year History of Inferred RMS User Range Error.

USER RANGE ERROR FORMULATIONS

The consistency of GPS performance is continuously monitored by the Operational Control System (OCS). One measure, the observed range deviation (ORD), compares the pseudo range (PR) observed at each OCS monitor station (MS) against that PR computed for the MS using the Space Vehicle (SV) navigation message (NM).

$$\begin{aligned} \mathrm{ORD} &= \mathrm{PR}_{\mathrm{obs}} - \mathrm{PR}_{\mathrm{comp}} \\ &= \mathrm{PR}_{\mathrm{obs}} - [R + C \cdot \{\phi_{\mathrm{MS}} - \phi_{\mathrm{SV}}\}] \end{aligned} \tag{1}$$

where:

$\mathrm{PR}_{\mathrm{obs}}$ = the observed PR at the OCS MS corrected for ionospheric and tropospheric delays and periodic relativistic effect.

$\mathrm{PR}_{\mathrm{comp}}$ = the PR computed for the MS

R = the SV to MS geometric range

$R = \begin{vmatrix} X - x \\ Y - y \\ Z - z \end{vmatrix}$ with (X,Y,Z) derived from the SV broadcast NM and (x,y,z) the known coordinates of the MS

ϕ_{SV} = the SV clock phase offset (with respect to GPS time) as defined by the SV NM

ϕ_{MS} = the MS clock phase offset with respect to GPS time

C = speed of light

The ORD is computed by the OCS every fifteen minutes whenever an SV is tracked by an MS. However, if a satellite is not tracked by a monitor station, then no ORD calculation is performed. The second performance measure computed by the OCS, the estimated range deviation (ERD), is defined as the difference between the predicted pseudo range based on the OCS Kalman filter estimates as reflected in the current SV NM and current estimate of pseudo range defined by the current time filter estimation. ERDs are computed every fifteen minutes for each SV relative to that subset of 32 globally distributed locations contained in the OCS database for which the SVs are visible.

$$ERD = PR_p - PR_o \tag{2}$$

where

PR_p = the OCS computed PR using the SV predicted position (Z_p, Y_p, Z_p) and SV clock phase (ϕ_p) that is defined in the current SV NM

PR_o = the PR computed by the OCS using the OCS Kalman filter current estimates of SV position (X_o, Y_o, Z_o) and SV clock phase (ϕ_o)

ORD and ERD measure the consistency of OCS performance quite well but do not necessarily show GPS accuracy performance since modeling errors tend to cancel in the computation of these indices.

The GPS performance as defined by the ideal user who knows his position, clock time, tropospheric and ionospheric group delays, and receiver biases, and who need not consider multipath could formulate the SV-to-user PR error, the PR residual, as

$$\Delta PR = PR_{obs} - PR_{comp} \tag{3}$$

where

$$PR_{obs} = \text{the user observed PR}$$

$$PR_{obs} = C \cdot (T_{GPS} - t_{GPS}) \tag{4}$$

and where T_{GPS} is defined as the GPS time associated with the SV transmission of the PRN (pseudo random noise code) and t_{GPS} is defined as the GPS time associated with the user reception of the PRN.

PR_{comp} is the user computed PR using the SV NM[2] and the user's assumed perfect knowledge of user position and clock. The PR_{comp} must take into account the one-way-light-time (OWLT) of the SV-to-user propagation in the Earth rotating coordinate system, the satellite clock phase error or offset with respect to GPS time, the relativistic frequency change that the SV clock experiences as the satellite dips into and climbs out of the Earth's gravitational field, and ionospheric and tropospheric refractions. Equation (5) defines PR_{comp}:

$$PR_{comp} = R - [A_o + A_1 \cdot (T_{GPS}) + A_2 \cdot (T_{GPS})^2] \cdot C - PR_{rel} + PR_{iono} + PR_{tropo} \tag{5}$$

where

R = OWLT · C

A_o = the SV clock phase offset relative to GPS time

A_1 = the SV clock frequency offset relative to the GPS master clock frequency

A_2 = the SV clock frequency-rate offset relative to the GPS master clock frequency-rate

PR_{rel} = the periodic relativistic phase change that is a function of orbital eccentricity

PR_{iono} = the ionospheric refraction

PR_{iono}, as computed by a user equipped with a dual frequency GPS receiver, to first order is:

$$PR_{iono} = \Gamma \cdot (PR_{L1} - PR_{L2})$$

with

$\Gamma = 1/(1 - f_1/f_2)^2$

f_1 and f_2 = 1.57542 Ghz and 1.2276 Ghz, respectively.

PR_{L1} and PR_{L2} = pseudo range measurements at the f_1 and f_2 frequencies, respectively.

PR_{iono}, computed using dual frequency PR measurements, has an rms uncertainty at the sub-decimeter level.[2] PR_{iono}, computed by GPS users employing single frequency receivers, is not as accurate. Reference 2 provides an algorithm that the single-frequency user can use to estimate the ionospheric refraction at f_1. The algorithm uses coefficients which are broadcast in the SV NM and relate to solar flux predictions. Feess[3] evaluated the algorithm's accuracy as a function of user geomagnetic latitude, time-of-day, topocentric elevation angle, time of year, and with the solar flux level. To summarize the conclusions of Reference 3, the rms delay in PR, as a consequence of ionospheric delay, was about 5 meters and the rms algorithm calibration error was of order 2 meters for the solar flux conditions that existed in 1986.

PR_{tropo} is the tropospheric refraction.

PR_{tropo}, for all users, depends on a model. The OCS uses a modified 1969-Hopfield model[4] augmented with environmental measurements of pressure, temperature, and relative humidity. The Naval Surface Weapons Center (NSWC) also uses a Hopfield model, but with standard atmospheric parameters. The Inverted Range Control Center (IRCC) uses the Chao model[5,6] driven with measures of temperature, pressure, and relative humidity. The USNO and National Bureau of Standards (NBS) use the standard GPS user algorithm defined in Reference 2. Primarily due to the difference in the treatment of the PR refraction due to water vapor, the Chao and Hopfield models have an rms difference of 2%. The models are not significantly different in this test application. The rms difference between models and reality is about 3% or 40 centimeters for PR observed at an elevation angle of 10 degrees.

Apart from ionospheric and tropospheric refractions, (3) and (5) relate to the "ideal" user. Real world users have uncertainties in their local time, location survey, receiver bias, and multipath assumptions. If it were possible for the user to define these effects, additional terms should be added to (3) and (5).

It was with these considerations in mind that the users involved in this test attempted to standardize their models and their assumptions.

USER STANDARDIZATION

The implementation of some user standardizations was deemed impractical: NSWC and the IRCC employed P-code dual-frequency receivers that track up to four SV's simultaneously. The USNO and NBS used C/A-code single-frequency receivers that tracked SVs serially. The dual-frequency users model ionospheric group delay to ~ 4 centimeters (rms), while the single-frequency user is forced to employ a global ionospheric model that provides a calibration ranging in accuracy from 2 meters (rms) during quiet solar activity periods and up to 10 meters (rms) during active solar activity periods.[3] Accordingly, user URE is a function of user instrumentation.

A second influence on URE perception is the user observation schedule which is in part dictated by the SV rise/set patterns that are unique to each user.

Three user test standardizations were adopted to different degrees.

(1) Observations are to be distributed over each day, but PR acquired at topocentric elevation angles below 10 degrees are not to be included in the rms URE.

(2) Users are to assume Defense Mapping Agency (DMA) World Geodetic Survey of 1972 locations for receiver sites. WGS '72 documented[7] uncertainties are 1 meter (rms) in the latitude and longitude coordinates and 2 meters (rms) in the height coordinate.

(3) Users are to calibrate PR residuals for the user-GPS time scale offsets. Specifically, the phase and frequency offsets of the user clock relative to the GPS master clock are to be estimated and removed from the user PR residuals. This clock offset estimate takes the form of a first order polynomial fit ($\alpha + \beta \cdot T^{GPS}$) where α is the user phase offset and β is the frequency offset. Hence (5) becomes

$$PR_{comp} = R - [A_0 + A_1 \cdot (T_{GPS}) + A_2 \cdot (T_{GPS})^2] \cdot C - PR_{rel} + PR_{iono} + PR_{tropo} + (\alpha + \beta \cdot T_{GPS}) \cdot C \quad (6)$$

For convenience, the definition of α and β acquired two forms:

(a) The IRCC re-estimated α every 54 seconds whenever four or more SVs were simultaneously tracked. The re-estimate of α was computed as the mean PR residual at each 54 second point. β was not estimated. Every 54 seconds with a new α, the IRCC used (6) to compute that component of the PR residual that was uncorrelated across the SVs. This is the IRCC definition of the URE.

(b) The NSWC solved for α and β using all PR residuals computed each calendar day. The NBS and the USNO also solved for α and β each day; however, the USNO and NBS first order polynomial fits were to 3 day spans of PR residuals where the line-of-regression was only interpolated for the middle day. The PR residual with the line-of-regression removed is the definition of the URE used by the NSWC, USNO, and NBS.

For comparative purposes, the IRCC PR residuals were post-processed at The Aerospace Corporation using technique (b).

The sections that follow contain assessments for the GPS URE by the OCS, the IRCC, the NSWC, and the USNO, respectively. Finally, a summary of results for the OSC, IRCC, NSWC, and USNO assessments is provided along with those offered by the 18 other global stations shown in Figure 1.

OCS USER RANGE ERROR ASSESSMENT BY THE IBM CORPORATION

From 20 October to 17 November 1986, the Operational Control System (OCS) of GPS was undergoing a performance evaluation. The IBM Corporation participated in that test by compiling OCS performance statistics. Table 1 shows

Table 1—OCS Root-Mean-Square ORD and ERD (meters)

NAVSTAR	RMS ORD	RMS ERD	RMS "Maximum ORD"	RMS "Maximum ERD"
3	3.1	2.8	4.1	4.2
6	2.7	2.1	3.2	3.7
8	1.8	1.3	2.2	2.0
9	2.2	1.6	2.7	2.3
10	2.7	2.2	3.4	3.4
11	2.3	1.8	3.2	2.9
combined	2.5	2.0	3.2	3.2

four different rms compilations of the ERDs and ORDs computed by the OCS. All four techniques show the OCS rms URE to be appreciably below the 6 meter, 30 day rms requirement.

Column 1 shows the actual rms ORD computed for the MSs over the test period. The ORDs were computed using the satellite broadcast NMs. NMs, which represented SV orbit and clock state predictions, were on average 4 hours old since all SVs were uploaded with new navigation messages typically every 8 hours.

Column 2 displays the rms ERD computed for the average global user over the test period. The ERDs are computed using Equation (2).

Column 3 shows the rms of the maximum ORD in each upload period for the ensemble of all uploads in the test period.

Column 4 shows the rms of the maximum ERD in each upload period for the ensemble of all uploads.

The OCS computed ORDs and ERDs, coupled with the user computed UREs discussed elsewhere in this paper, indicate that the OCS satisfied the rms URE 6 meter requirement for the 20 October to 17 November 1986 test period.

However, it is also of interest to note that the OCS ORD and ERD performance measures indicated a comparable URE performance for October 1986 (Figure 4). This was at a time when the USNO assessed the URE 30 day rms to be larger than 6 meters (Figure 18). The NBS also reported the URE rms to be above 6 meters (Figure 18). From this apparent discrepancy, it is possible that the OCS might benefit from augmenting the ORD and ERD performance measures with a new measure that is more consistent with the URE computations offered by the time transfer users.

Speculative Cases of URE Degradation

The USNO two-year-plus history suggests a weak correlation between rms URE growth and satellites being eclipsed by the Earth's shadow. An independent analysis performed at the IBM Corporation shows, in the instance of NAVSTAR 3, that there is a strong correlation between OCS MS predicted pseudo range residuals and SV clock temperature (Figure 5). Whether such correlations exist for other GPS satellites is yet to be demonstrated. However, it is known from the Rockwell pre-flight calibration of the Block I SV rubidium clocks that the clock frequency does change with temperature ($\Delta f/f/^{\circ}C = 5 \cdot 10^{12}$). The frequency change per degree Centigrade for cesium atomic standards is an order of magnitude less. From SV telemetry it is known that on-orbit

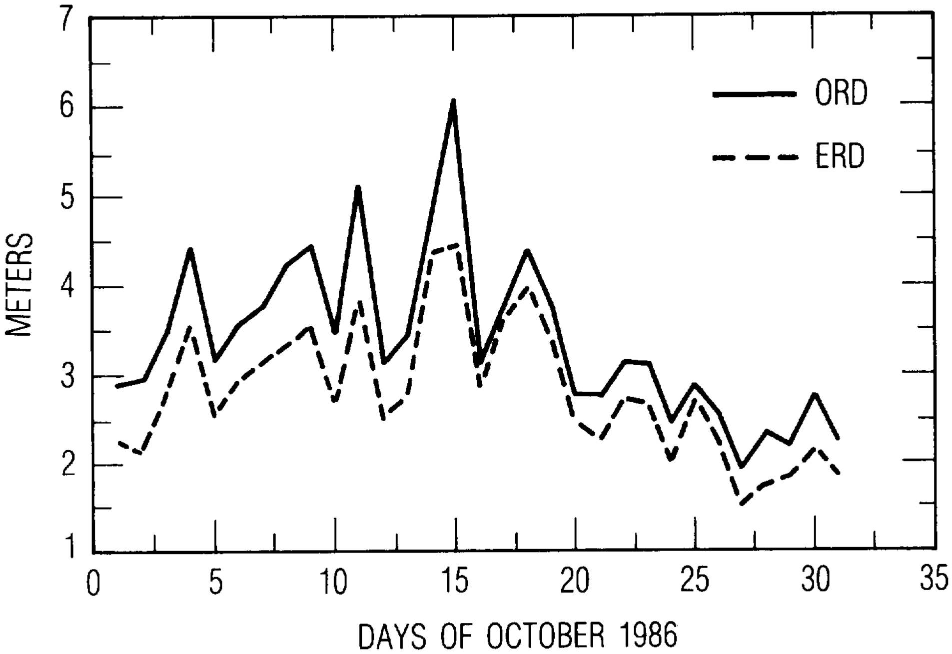
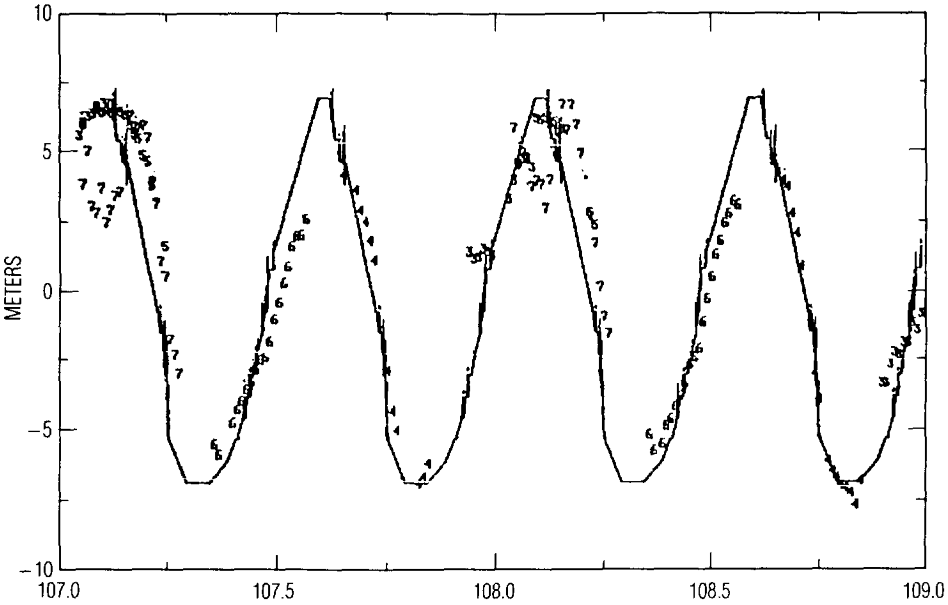


Fig. 4—Operational Control System Daily RMS Observed and Estimated Range Deviations, ORD and ERD.

Block I SV clock environments have peak-to-peak thermal swings of 5°C when the orbit plane is near or contains the Earth's shadow and that thermal swings of 3°C occur for orbit planes nearly normal to the sun-Earth line. But there is an indication that SV clock phase dependence on temperature is not the source of the problem. NAVSTAR 8, which utilized a rubidium atomic standard that was thermally controlled to 0.1°C, also produced UREs that were degraded when NAVSTAR 8 was near or in eclipse.

The question of temperature dependence of SV clock phase needs to be resolved. In the very near future, two eclipse seasons will occur (February–March 1987 and March–April 1987). An intensive SV data collection and analysis effort is planned by the authors of this paper. SV telemetered temperatures and UREs will be compared.

A second analysis effort at IBM considered the fact that when the URE is degraded, all reporting users see nearly the same URE time correlation as if the frequency of the GPS master clock had a 24 hour periodic fluctuation or as if all SV clocks have a 24 hour frequency fluctuation. A comparison of UREs computed for an IBM/Gaithersburg GPS receiver with those computed for the nearby USNO receiver showed that the URE signatures matched. Accordingly, the frequency and phase stabilities of the OCS Kwajalein MS clock were examined when it was the GPS master clock. For the 7 day period analyzed, the Kwajalein MS clock frequency excursions with time and temperature do not correlate with the user reported URE signature (Figure 6).



——— = 2 (temperature − 30)
3 = ASCENSION; 4 = DIEGO GARCIA; 5 = HAWAII;
6 = KWAJALEIN; 7 = COLORADO SPRINGS

Fig. 5—Correlation of NAVSTAR 3 Clock Temperature and Pseudorange Residuals.

URE STATISTIC COMPUTED AT THE AF INVERTED RANGE CALIBRATION CENTER (IRCC)

The IRCC, located at the Army Proving Ground in Yuma, Arizona, consists of a dual-frequency four-channel Magnavox X-set receiver with its internal oscillator phase locked to a Hewlett Packard cesium frequency standard. At a 54 second sample rate, the receiver simultaneously samples P-codes on both L_1 and L_2 frequency carriers when four SVs are in view. Four SVs are simultaneously in continuous view of the IRCC approximately 6 hours per day. The IRCC tracked the GPS constellation on 19 of the 30 days of the test period.

At the IRCC, the P-code observations are processed using two ground-truth assumptions. First, corrected pseudo range (CPR) residual histories are computed relative to GPS time, where time is estimated by effecting a time transfer to the IRCC. The time transfer is computed as follows. The observed pseudo range is corrected for tropospheric and ionospheric delays and IRCC receiver biases. The PR is further corrected for the SV-to-IRCC one-way-light-time (OWLT), the SV clock phase offset relative to GPS time, and the periodic relativistic effect as computed from SV NM parameters. The IRCC assumed the DMA WGS '72 site location survey[7] for the IRCC in the calculation of the OWLT. The mean CPR obtained from the 4 SVs tracked in any 54 second interval represents the IRCC—GPS time offset. The IRCC uses the mean CPR computed at the start of the tracking period as its estimate of the time offset. Hence, subsequent CPR samples minus the IRCC—GPS time offset scaled by

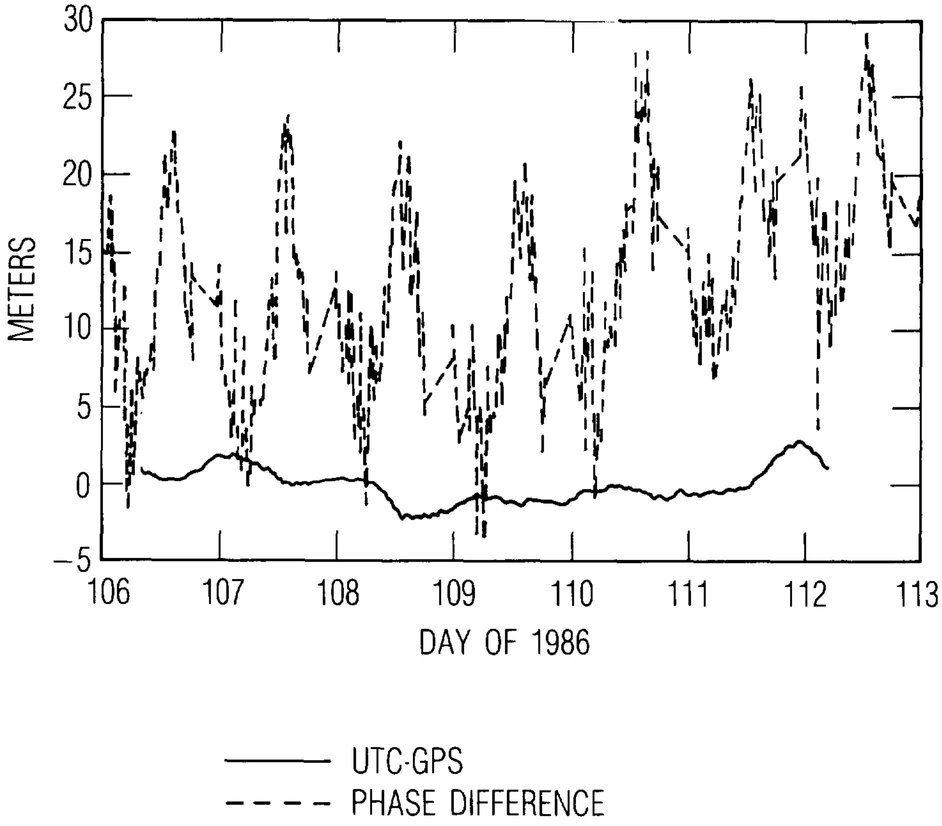


Fig. 6—Kwajalein Clock Phase Correlated with UTC (USNO)—GPS.

the speed of light defines the CPR residual history. This CPR history, which can be thought of as URE history, is placed in the IRCC computer database which can be accessed by other telecommunication systems. It is in effect a time transfer URE.

If a line-of-regression estimate of the IRCC clock phase offset and phase drift is removed from the above CPR residuals, as was done at The Aerospace-Corporation, the 30-day rms is below 3.9 meters (Figure 7). Figure 8 provides an example of UREs relative to the IRCC mean daily clock over a tracking pass: Date of pass is 20 October 1986: The URE sample rate is 4.5 minutes.

The second IRCC post-process redefines the IRCC—GPS time for each 54 second interval. In effect, that component of the URE that was correlated across the SVs in each interval has been removed. It is the URE that is uncorrelated across the SVs at any time that drives the navigation solution. Figure 9 shows the daily rms statistic of the CPR residuals using the second process, which has removed the correlated portion of the URE. The rms over the 19 day sample is 3.1 meters. Figure 10 shows the URE daily rms values resulting from this navigation application.

USER RANGE ERRORS AT THE NAVAL SURFACE WEAPONS CENTER

During the OCS test period (20 October to 17 November 1986), GPS pseudo range was collected by the NSWC T14100, dual-frequency, four tracker, mul-

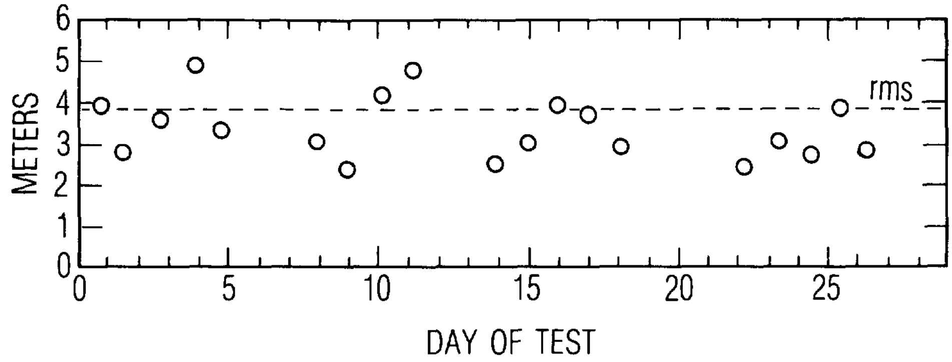


Fig. 7—Daily RMS User Range Error Relative to Inverted Range Control Center Mean Daily Clock Estimate.

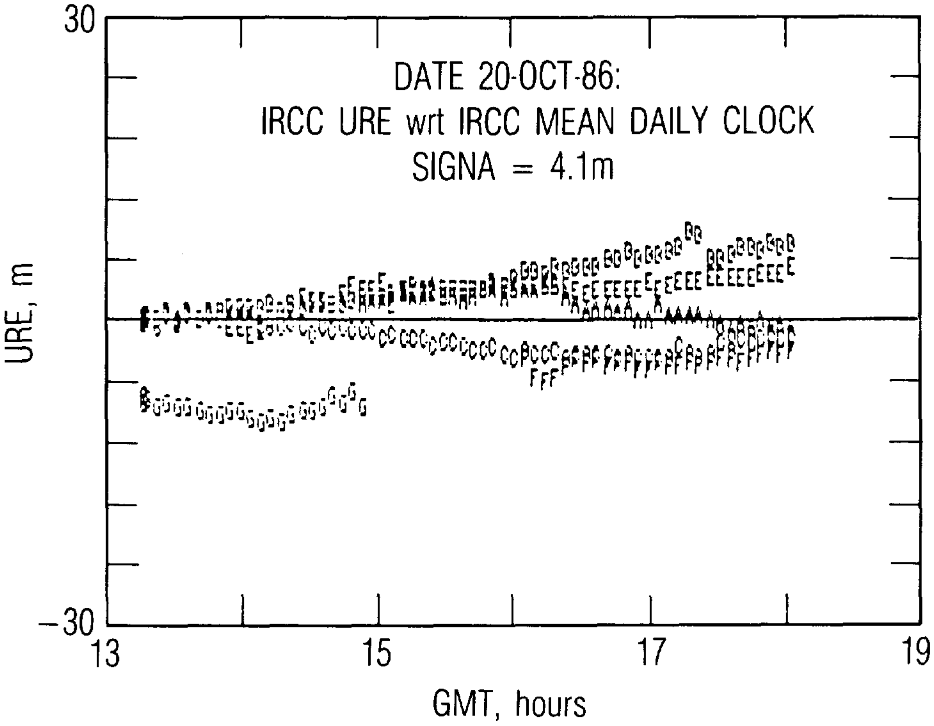


Fig. 8—Inverted Range Control Center User Range Errors for October 20, 1986 (Time Transfer Application).

tiplexed GPS P-code receiver. The receiver, located at Dahlgren, Virginia, was operated using the NSWC developed GESAR software and driven by an external Efratom rubidium oscillator. Both PR and integrated Doppler were recorded at 1 minute intervals for all satellites except NAVSTAR 4. The data were preprocessed by smoothing the PR to 5 minute intervals using the phases as range differences. The receiver also collected the SV broadcast navigation messages (NM). Each day of observations was processed independently. A day

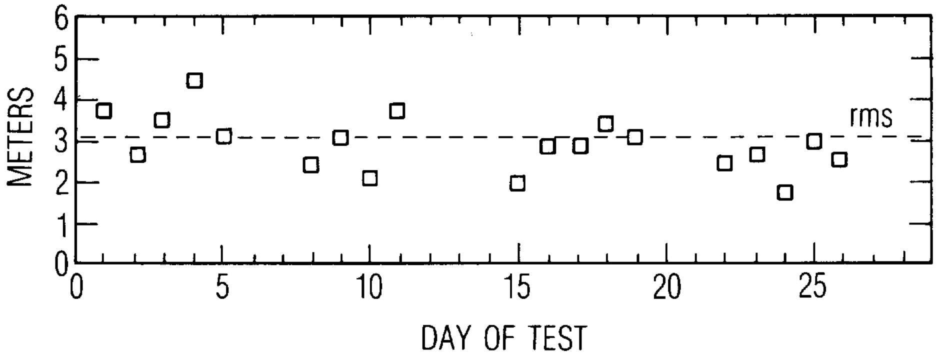


Fig. 9—Daily RMS User Range Error Relative to Inverted Range Control Center Running Clock Estimate.

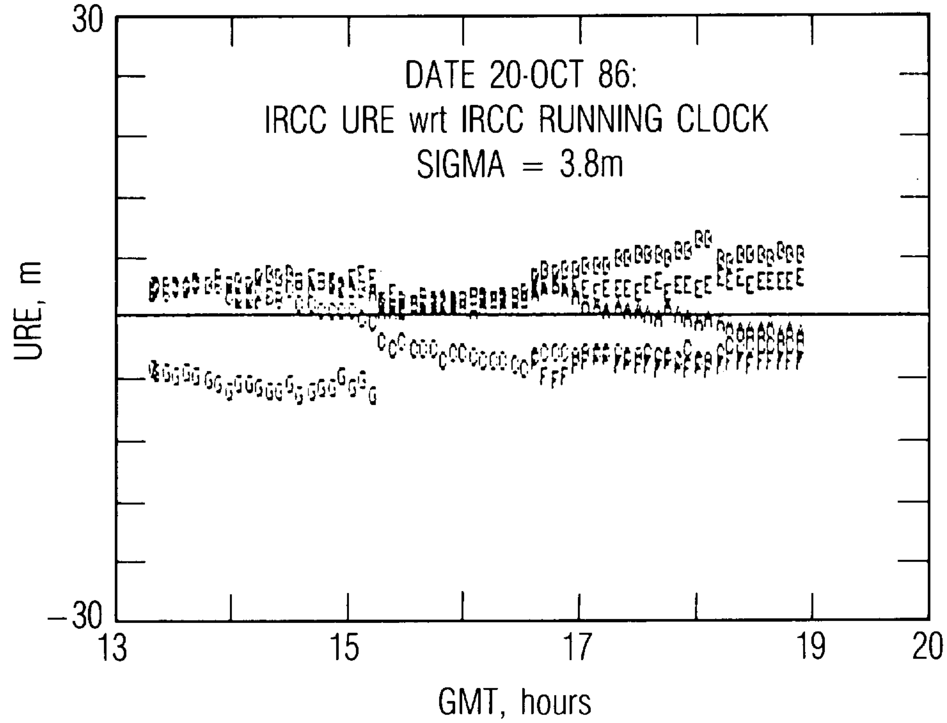


Fig. 10—Inverted Range Control Center Using Range Errors for October 20, 1986 (Navigation Application).

was defined to begin with the rising of NAVSTAR 11 in the west and to end with the setting of NAVSTAR 10 in the east. After NAVSTAR 10 set, there followed a period of about seven hours without any satellites being tracked.

Each smoothed PR observation was converted to a corrected range residual by removing the geometric range, the satellite clock phase offset, the ionospheric and tropospheric refractions, and the periodic relativity effect. The geometric range was computed using a satellite position derived from the SV NM and the station coordinates determined using GPS tracking data collected in the Spring 1985 Precision Baseline Test Period. All computations were done in the WGS '72 conventional terrestrial system.[7] The satellite clock correlation was also computed from the NM information. The ionospheric refraction correction was made to the raw PR and phase observations before smoothing using the dual-frequency PR measurements as discussed earlier. The tropospheric refraction correction was computed using standard weather conditions (static model). Observations acquired below 10 degrees elevation angle were omitted. The relativity correction was computed using the eccentric anomaly derived from the NM.

The resulting smoothed PR residuals still contained the effects of offsets between the local frequency standard and GPS time. To model these effects, a first order polynomial was fit to these PR residuals for all SVs simultaneously, and iterative editing was done. The residuals to this fit (Figure 11) were then summarized by computing the rms over all SVs. This overall rms is called the NSWC URE for this day. The combined rms URE over all days processed was 3.1 meters.

UREs at DMA Tracking Sites

The DMA currently has three fixed-site GPS tracking stations operating in Australia, England, and Argentina (Figure 1). Each site consists of a T14100 receiver integrated into a system that includes a PDP-11 mini-computer, a

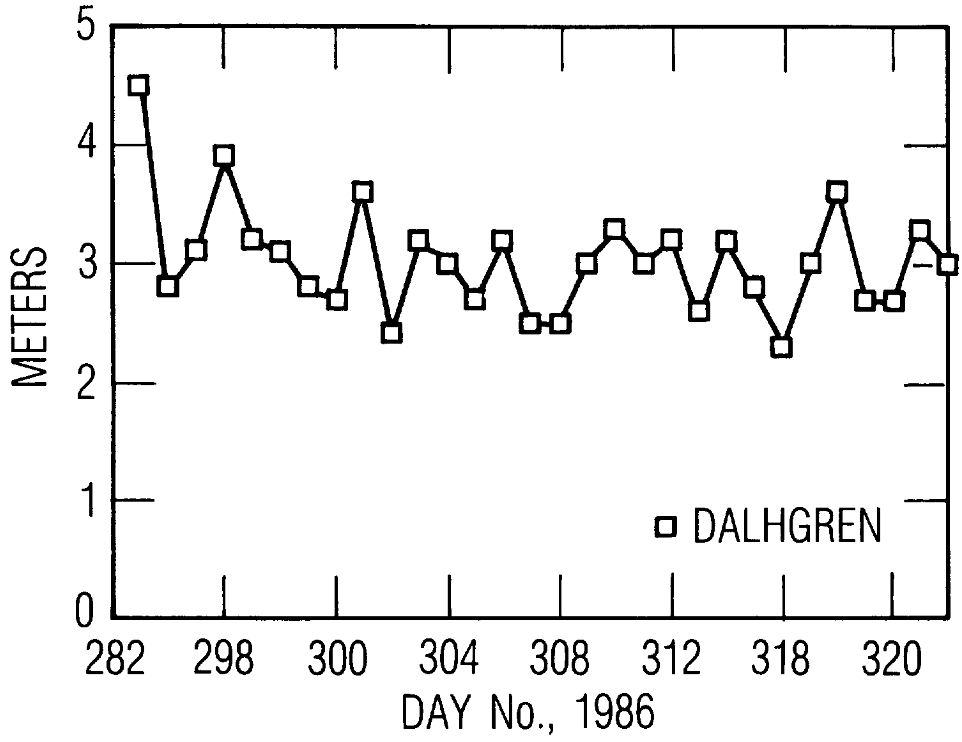


Fig. 11—NSWC at Dahlgren, VA: 24-Hour User Range Error (30-Day Test Period).

video display terminal, dual 8-inch floppy disk drives, a dot-matrix printer, a modem, and an automatic weather station. The receiver is driven by an external Hewlett-Packard cesium oscillator. Both PR and Doppler data are sampled at 1.5 second intervals. The DMA 1.5 second data is compressed to 15 minute samples. The weather station samples temperature, barometric pressure, and relative humidity every 15 minutes. The smoothed PR data and the weather data are formatted into ASCII code for transmission to NSWC via the GE MARK III network.

At NSWC, the smoothed PR data were corrected for tropospheric refraction effects, the periodic relativistic effect, and the SV-to-DMA site transmission one-way-light-time. Observations below 10 degrees elevation were deleted and residuals failing consistency tests were also deleted.

The navigation messages were received directly from the OCS on magnetic tape. For each SV the NM were converted into an Earth-fixed trajectory written at a 5 minute interval and a clock history written at a 15 minute interval. Each NM page was used starting at 2 hours before the TOE parameter for that page until a future page was found. The Earth-fixed trajectories were then converted from WGS '72 conventional terrestrial coordinates to the preliminary WGS '84[8] conventional terrestrial system by a Z-rotation (-0.24 of an arc second) and Z-shift (-4.5 meters). These Earth-fixed trajectories were then converted to the J2000/FK5 inertial reference frame using the DMA Earth orientation data with the most recent effectivity date (date on which a new coefficient set is first used by the OCS). Station coordinates for the DMA sites were obtained by transforming the WGS '72 coordinates derived from Transit surveys on each site to WGS '84.

During the OCS 30 day test period, the data from Argentina for the first two weeks were not received in time to be included in the processing. Other days were not processed due to missing data and various problems in converting the NMs. Each calendar day of data was processed independently. The trajectory, SV clock offsets, and station coordinates were held fixed and a linear clock model for each DMA station was fit to the corrected and edited PR residuals. The residuals to these fits were then summarized by computing the rms over all SVs for each DMA site for each day. Each daily rms for each site is called the URE for that site that day (Figure 12). The rms URE over all days processed were 2.8, 3.2, and 2.8 meters for Australia, England, and Argentina, respectively.

INFERENCE OF URE FROM USNO TIME TRANSFER DATA

The USNO has been monitoring the performance of GPS as it pertains to time transfer since 1980. Four different time transfer monitor receivers are used in various aspects of the USNO GPS monitoring program, i.e., routine monitoring, remote site installation, special programs, and experimental testing. The data used in this analysis are a subset of the data collected during routine monitoring. This data are available to all interested users through the USNO Automated Data Service (ADS).[9] The data reported to USNO by other international time-keeping laboratories is available through the G.E. Mark III Information System. The data is reported weekly. Information on GPS is updated daily.[10]

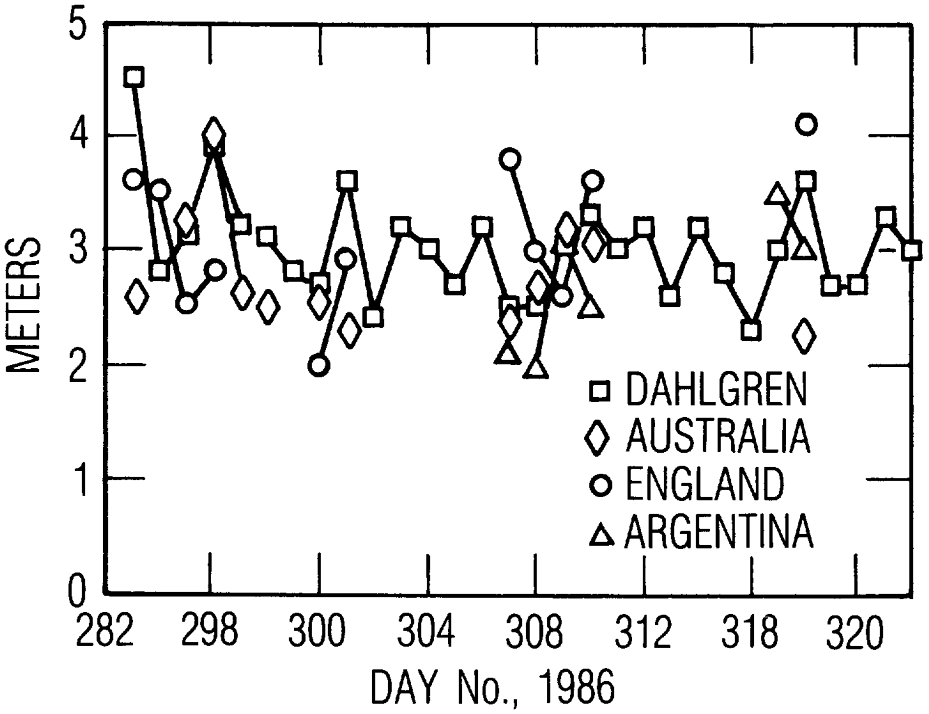


Fig. 12—NSWC at Dahlgren, Australia, England, and Argentina: 24-Hour RMS User Range Error (30-Day Test Period).

A time transfer observation is the difference between GPS time and a local time reference. The local time reference for the USNO is UTC (USNO, MC). This is the time given by the USNO Master Clock which is the real-time representation of UTC (USNO), a time scale based on the average of about 25 selected cesium beam frequency standards. A single observation, as reported here, is a filtered average of between 120–130 six second data points. The filter is an iterative one which eliminates residuals greater than 6 times the sigma of a linear fit to the six second points over the 13 minute period. Standard corrections, as outlined in Reference 2 and reported in other sections of this article, are applied to the observations.

During the time period of the calibration experiment, the data obtained at the USNO indicated that GPS performed within the nominally specified limits which are mentioned earlier in this paper. Because specification requirements may be ambiguously written, two separate analyses of the USNO data are reported here in order to show that system performance was met regardless of the interpretation of the specified requirements. Figure 13 shows the daily average of the rms for all the 13 minute time transfer observation points. The 30 day rms is 14.8 nanoseconds. This gives an indication of the internal consistency (precision) of the observations from day to day. Figure 14 shows the daily rms of a linear fit through the daily values of GPS time minus UTC (USNO). This gives an indication of the external accuracy of the time transfer capabilities of GPS. The rms of the 30 day test interval is 16 nanoseconds. It is seen that both the internal (precision) and external (accuracy) measures of

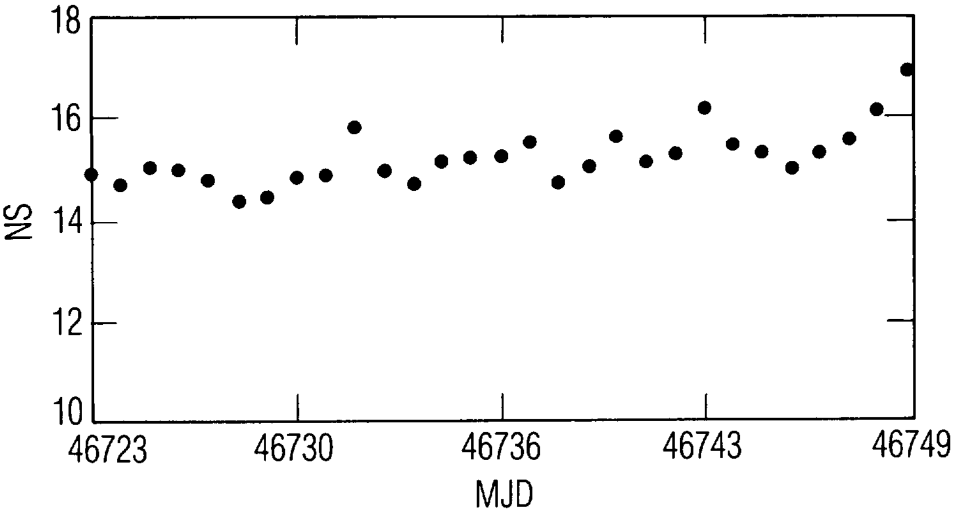


Fig. 13—Daily Mean of the RMS of 13-Minute Time Transfer Observation.

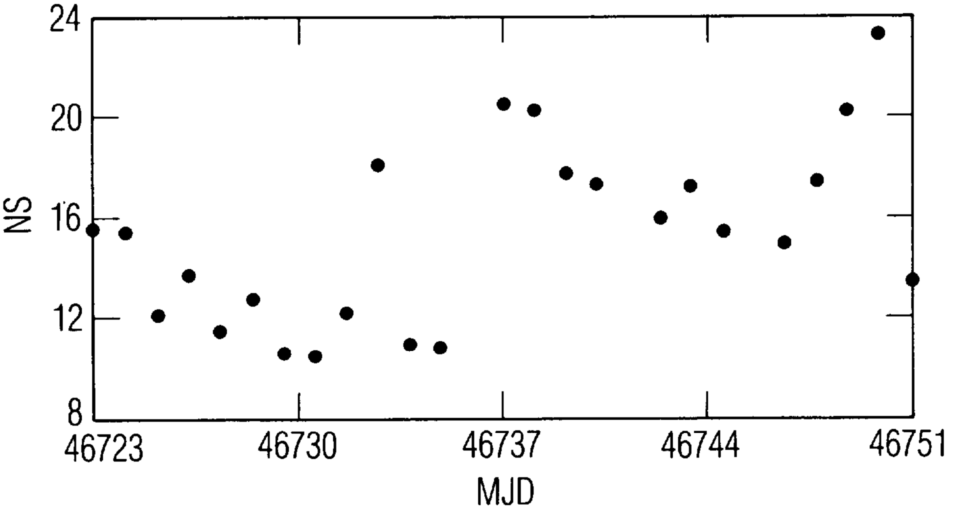


Fig. 14—RMS of Residuals to a Linear Regression to Daily 13-Minute Time Transfer Observations.

system performance are nearly equal. This indicates that the system performed well during this period and within the specified goals.

NATIONAL BUREAU OF STANDARDS

During the test period, the NBS data base contained GPS time transfer data from fifteen international timing centers. All of the receivers were C/A L_1, single channel sets. Whereas USNO and NBS track whenever satellites are above a 10° elevation angle mask, the other international timing centers were optimized for time and frequency transfer. Elevation angles were maximized for the GPS common-view technique and were usually above 30°.

The reference clocks at each timing center were of the highest quality and would only contribute a few rms nanoseconds to the rms URE. In the case of NRL there was a known coordinate error contributing to the rms URE. It is believed that a significant component of the rms URE at Hawaii was the result of L_1 ionospheric modeling errors. Figure 15 gives a summary of the 30 day rms URE for each global station. Figure 15 labels coincide with those of Figure 1.

SUMMARY OF RESULTS

Prior to this GPS URE test, the USNO and the NBS had been routinely using GPS in their time transfer applications for years. The NSWC, in cooperation with the DMA, accelerated their receiver deployments in order to support the URE evaluation test. GPS users located in Argentina, Australia, Canada, Holland, England, France, Germany, Italy, Japan, and the United States made available their URE observations in a cooperative effort with the NBS and the USNO. If the five OCS MSs are added to the sample, twenty-five ground stations distributed over the Earth (Fig. 1), provided daily rms assessments of URE.

Figure 16 shows the daily rms URE values for the NBS, the USNO, the

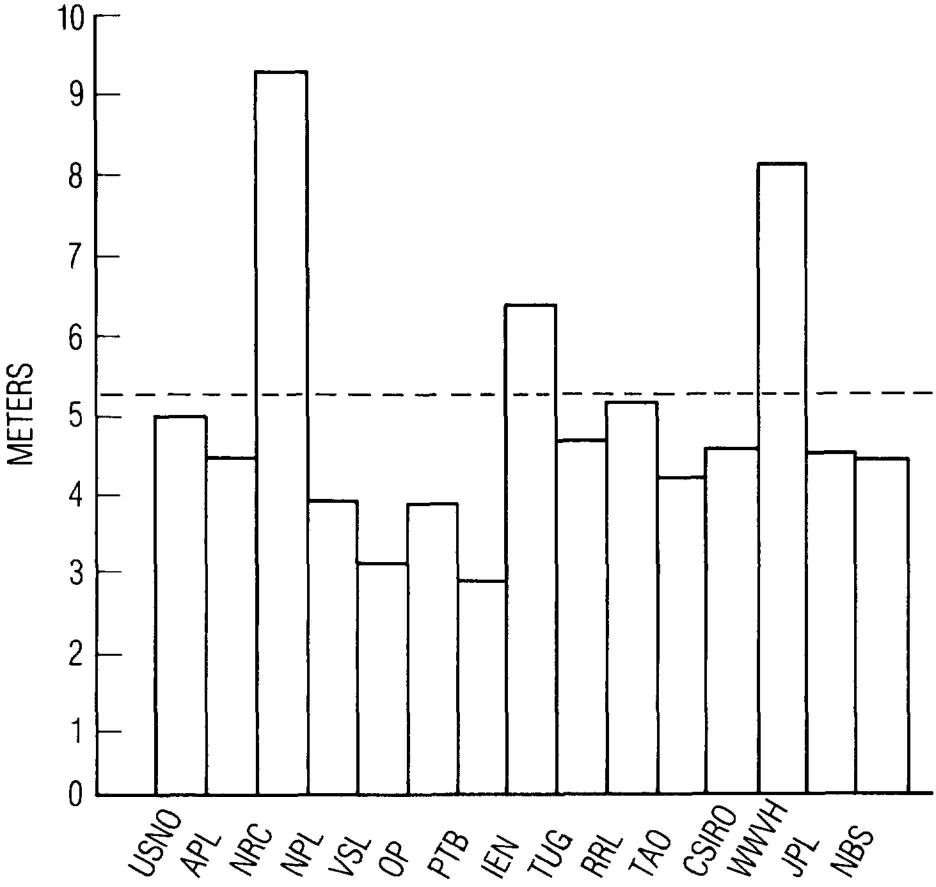


Fig. 15–RMS User Range Error from C/A Code Receivers, October 20 to November 17, 1986.

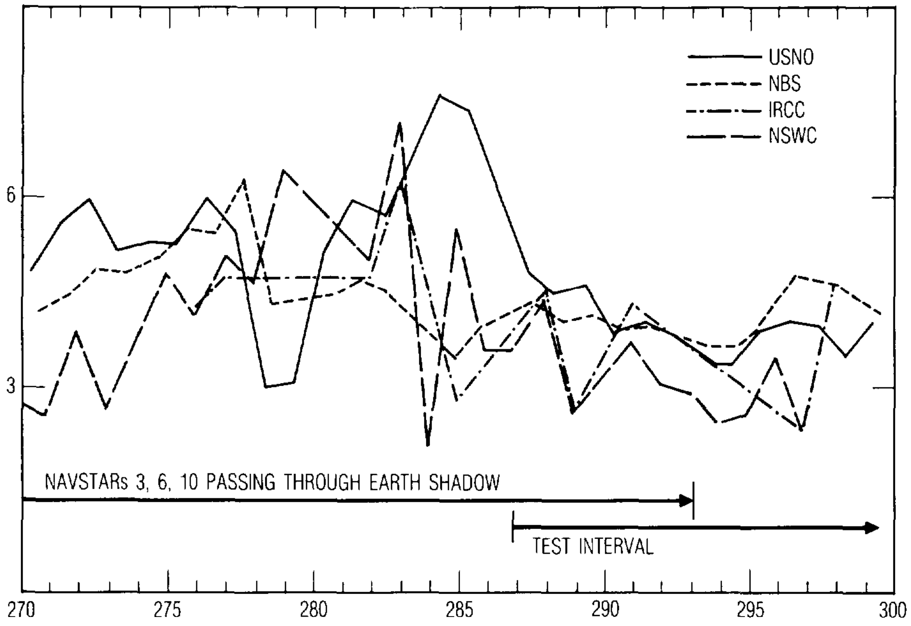


Fig. 16

NSWC and the IRCC. For these users, all daily rms URE values are below 6-meters. The rms URE over all 30-days for the NSWC, the IRCC, the USNO, and the NBS are 3.9, 3.9, 4.8, and 4.3 meters respectively (Figure 17). NSWC and the IRCC employ P-code dual-frequency receivers and hence are less sensitive to ionospheric refraction and multipath. The USNO and the NBS use C/A-code receivers.

For the same period, the OCS ORDs and ERDs provided 2.5 meters and 2.0 meters rms URE assessments (Figure 17). If the IRCC daily rms values are computed where only the SV-noncorrelated PR residuals define the URE (Figure 9), then the IRCC rms URE averaged over the 30-days is 3.1 meters (Figure 17).

Other GPS users provided similar evaluations of the quality of the GPS satellite-to-user pseudo range (Figure 15) for the 30-day test period.

Figure 16 suggests that the daily rms URE was relatively constant over the test period. Figure 18 shows that just prior to the 30-day test period the rms URE was significantly greater however. (Almost a factor of two larger.) Figure 18 shows a coincidence between the degraded URE performance and satellites passing through the Earth shadow. Preliminary analysis suggests that Block I SV clock phase or electrical phase path delays may be significantly dependent upon SV temperatures.

As shown in Figure 3, there have been other occasions, where for months at a time, the GPS user range error exhibited standard deviations in excess of 6-meters.

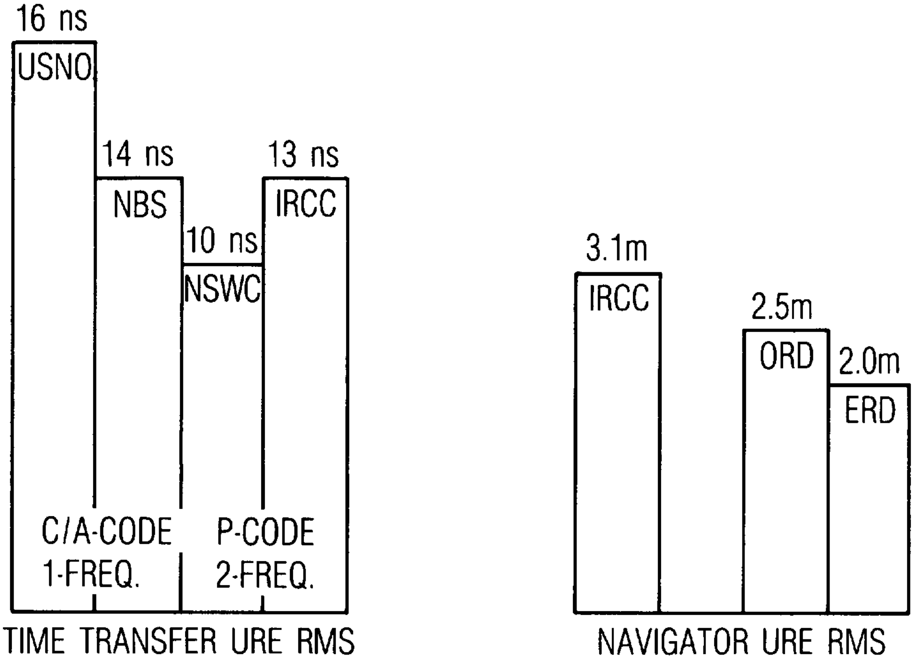


Fig. 17–RMS User Range Error over All Satellites and 30-Day Test Period.

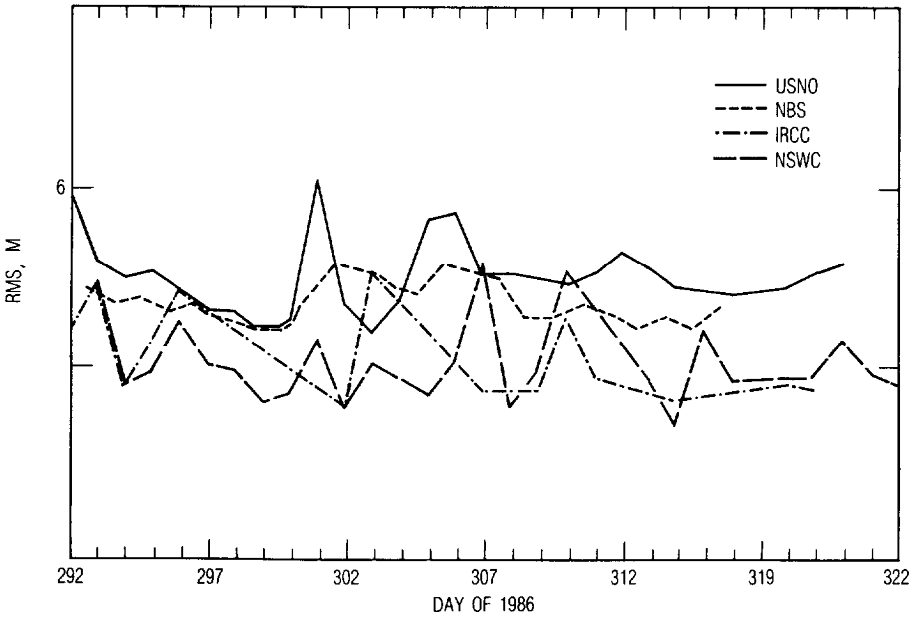


Fig. 18–Evidence of User Range Error Degradation with Eclipsing.

CONCLUSION

GPS is required to deliver satellite ephemeris and clock predictions via satellite transmission to end users.

From 20 October to 17 November 1986, the Aerospace Corporation, General Dynamics Corporation, IBM Corporation, the National Bureau of Standards, the Naval Surface Weapons Center, and the U.S. Naval Observatory independently tracked GPS satellites and demonstrated that the GPS predictions satisfied the GPS design requirements. Both single-frequency, clear/acquisition-code and dual-frequency, protected-code receivers were used in this test.

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