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THE EFFECT OF WGS-72 GEOPOTENTIAL IN THE NAVY NAVIGATION SATELL--ETC(U)
AUG 77 B B HOLLAND, A EISNER, S M YIONOULIS N00017-72-C-4401
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Technical Memorandum

THE EFFECT OF WGS-72 GEOPOTENTIAL IN THE NAVY NAVIGATION SATELLITE SYSTEM ON STATION SURVEYS

B. B. HOLLAND
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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

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(14)

REPORT DOCUMENTATION PAGE

1. REPORT NUMBER
APL/JHU/TG-1311

2. GOVT ACCESSION NO

3. RECIPIENT'S CATALOG NUMBER

(6) 4. TITLE (and Subtitle)
THE EFFECT OF WGS-72 GEOPOTENTIAL IN THE NAVY NAVIGATION SATELLITE SYSTEM ON STATION SURVEYS.

(9) 5. TYPE OF REPORT & PERIOD COVERED
Technical Memo~~randum~~

6. PERFORMING ORG. REPORT NUMBER

(10) 7. AUTHOR(s)
B. B. Holland, A. Eisner ~~and~~ S. M. Yionoulis

(15) 8. CONTRACT OR GRANT NUMBER(s)
N00017-72-C-4401

9. PERFORMING ORGANIZATION NAME & ADDRESS
The Johns Hopkins University Applied Physics Laboratory
Johns Hopkins Road
Laurel, MD 20810

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Task S1L0

(12) 35p.

11. CONTROLLING OFFICE NAME & ADDRESS
Strategic Systems Project Office, SP-243
Washington, DC

(11) 12. REPORT DATE
August 1977

13. NUMBER OF PAGES
39

14. MONITORING AGENCY NAME & ADDRESS
Naval Plant Representative Office
Johns Hopkins Road
Laurel, MD 20810

D D C
OCT 21 1977
C

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
WGS-72
Geopotential Transit
Survey
Navigation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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1. INTRODUCTION

WGS-72 is a geopotential coefficient set generated by the Naval Weapons Laboratory (NWL) in 1970 and shortly thereafter adopted by the Department of Defense to replace WGS-66. Nearly coincidental with this event, the Transit Improvement Program (TIP) satellites were being developed. One feature of the TIP satellites is a drag compensation system, similar to the Disturbance Compensation System* (DISCOS) proven on the Triad satellite (Ref. 1).

The two events precipitated an evaluation of the then current operational program for orbit determination and ephemeris prediction that had been in use since 1965 with only two significant modifications. The first modification was the inclusion of a significantly larger geopotential model (APL 4.5) in 1968; the second was compensation for Chandler wobble (more commonly referred to as polar motion) in 1974. Both modifications had been made in the environment of short-arc (1-day) ephemeris prediction. Since longer prediction arcs would be used with the TIP satellites, a major aim of the evaluation was to investigate the long-arc (7-day) prediction capability of the operational programs (called OIP-II). In addition to the geodesy and station coordinate changes (to WGS-72 and NWL-10D, respectively), the solar radiation program was improved, and models for the sun- and moon-induced earth-body tides were included in OIP-II (Ref. 2).

The revised operational computing program (OIP-II MK5MOD2) was placed in candidate status at the Navy Astronautics Group (NAG) where its evaluation under operational conditions was undertaken. Their studies produced some surprising results. First, station-navigated positions exhibited significant shifts when navigated with WGS-72 ephemerides and compared with navigations performed with APL 4.5 ephemerides. Second, a direct comparison of the ephemerides showed satellite position differences as large as 90 m.

---

*In fact, DISCOS compensates for all nongravitational forces acting on the satellite.

Ref. 1. Space Department Staff (APL) and Staff of Guidance and Control Laboratory (Stanford Univ.), "A Satellite Freed of All But Gravitation Forces: TRIAD I," AIAA 12th Aerospace Sciences Meeting, Washington, DC, 30 January-1 February 1974.

Ref. 2. H. D. Black et al., "The TRANSIT System 1975," APL/JHU TG 1305, December 1976.

The major impact of these results is best stated in the following question: If I have determined my position on the earth's surface using the Navy Navigation Satellite System (NNSS), what position shift, if any, will be evident if I redetermine my position using the same data but with the newly determined (WGS-72) ephemeris? It was this question we addressed.

2. BACKGROUND

STATION NETWORKS

There are two station networks involved in our studies. First is the set of four operational stations (300-series) located in Maine, Minnesota, California, and Hawaii, and referred to as OPNET. The second set is TRANET, which consists of a variable number of worldwide stations. Figure 1 shows the OPNET and the subset of TRANET used.

NAVIGATION

In general, navigation is a means of determining an estimate of position. Users of NNSS fall into two general categories: moving and fixed. The moving users are now almost exclusively ships at sea. The fixed-site users are generally attempting to survey the location of their sites by collecting a large set of passes and determining the mean of the navigated positions.

In editing the doppler data prior to orbit determination in OIP, each pass is navigated, and all the known (significant) error sources are modeled to within the state of the art. As a result, the "navigation errors" are representative of the orbit and/or station position errors. If we trust the station coordinates, the navigation errors are interpreted as orbit errors, and the orbit is adjusted accordingly. If the ephemeris is correct, the navigation errors are interpreted as station coordinate errors. In this study we used ephemerides only within the span over which they were fit; thus, they are the best attainable. We therefore interpret fixed-site movement as station coordinate shifts.

Individual results of pass navigation are affected by the relative geometry (station-satellite) during the pass, but such biases can be nearly eliminated by including equal numbers of passes from (a) north heading, (b) south heading, (c) eastward, and (d) westward. Pass elevation that also affects navigation quality is normally limited to between 15 and 75°, but there is generally no attempt to assure uniform elevation distribution.

Under these conditions we have found that the mean navigated position of a fixed site is stable if 30 or more passes are used in the determination of that mean. Recall that our interest is in obtaining a measure of how these positions are affected by ephemerides derived using different geopotential coefficient sets.

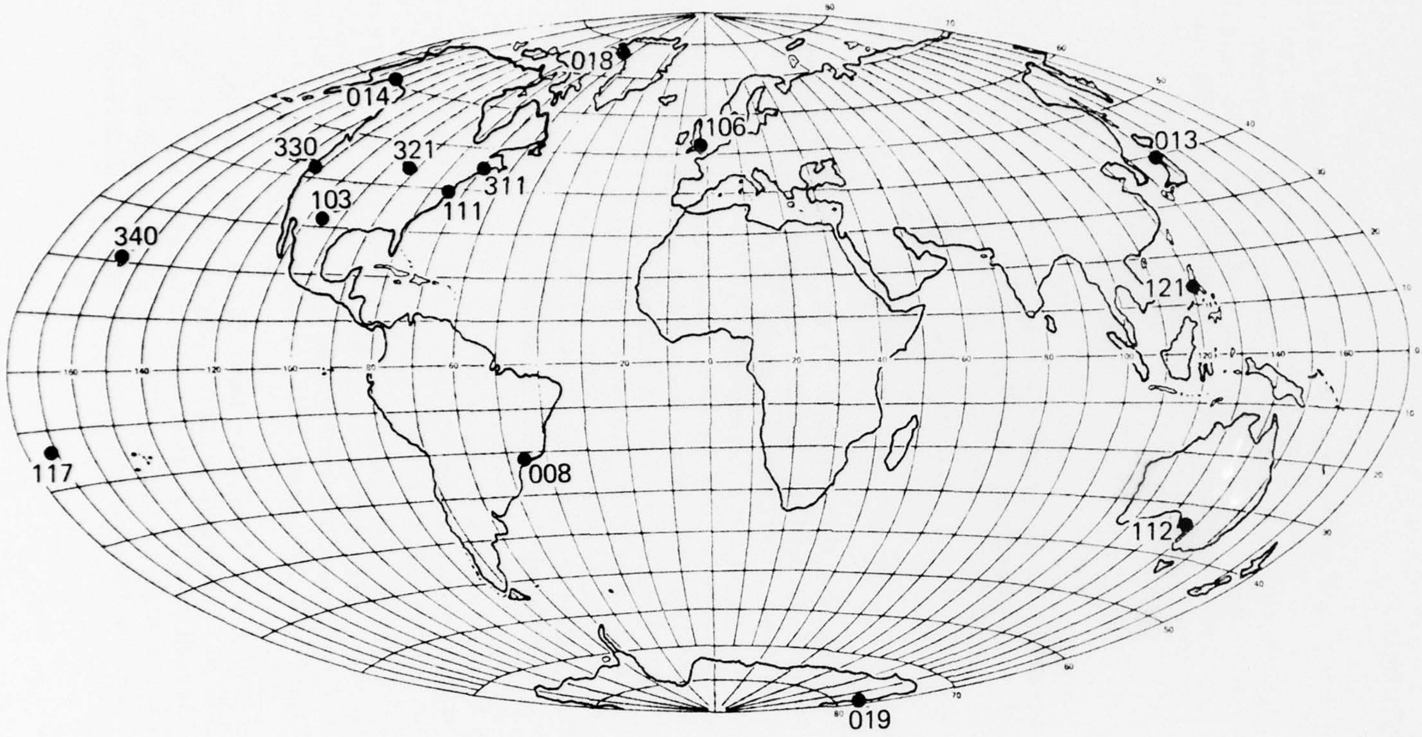


Fig. 1 OPNET and TRANET Station Sites

OIP NAVIGATION

In OIP the quality of the tracked* ephemerides is judged on how well they fit the doppler data. This is accomplished by navigating each pass using the full precision, tracked ephemerides. Tropospheric refraction is removed using Hopfield's model (Ref. 3). Two position parameters and a frequency correction are solved for at the time of closest approach of the satellite to the station. The two position parameters are ECA(ℓ) and ECR(ρ), which are, respectively, the error (relative to some input position) in the satellite velocity vector direction and the station-satellite range vector direction.

TRACKING AND NAVIGATION ACCURACY

One measure of orbit quality is a comparison of the final satellite ephemerides and the data used in their generation. It is well known that navigation errors, relative to the true station position, are excellent representations of the satellite ephemeris errors. Thus the rms of the pass errors can be used as a summary measure of orbit quality.

The rmst† using the APL 4.5 geodesy is about 15 m while for the WGS-72 geodesy it is 8 m. These are typical when using data within the tracking span; when the data are taken over the 24-h span immediately following the tracking span, the rmst's generally increase. This is almost exclusively due to atmospheric drag errors and does not occur when DISCOS operates.

Navigation accuracy depends on the ephemeris span (tracking or prediction) and the program used. Restricting ourselves to fixed-site navigation, the expected navigation rms's are:

---

*"Tracked" in this context means that the ephemerides are produced using initial conditions that have been least-squares fit to a set of doppler data passes. We have uniformly used ephemerides only within this span.

†Rmst is the rms of the total error $\left[(ECA^2 + ECR^2)^{\frac{1}{2}}\right]$.

Ref. 3. H. S. Hopfield, "Tropospheric Effects on Signals at Very Low Elevation Angles," APL/JHU SDO-4279, November 1975.

OIP-II*

Span	WGS-72 (m)	APL 4.5 (m)
Tracking	6-8	14-16
Prediction†	6-10	14-17

GEODESY COMPARISON

A convenient method of comparing geopotential coefficient sets is to compare the equipotential surfaces they define. Over a worldwide 5 × 5° grid, APL 4.5 and WGS-72 geoid differences have an rms of 11 m with peaks as large as 39.1 m. This is approximately the level of differences found no matter which coefficient sets are being compared. The conclusion can be drawn that our knowledge of the absolute location of the true geoid is no better than 11 m. Figure 2 is a zero-difference contour map of the APL 4.5 minus WGS-72 geoid height comparison; it is typical of all such comparisons.

Another characteristic of a geopotential coefficient set is where it locates a satellite in inertial space, i.e., its ephemerides. When comparing ephemerides produced using APL 4.5 and WGS-72 we found that:

1. Differences in position at a given time were as large as 90 m, and

2. The observed differences were geographically correlated, particularly in ℓ, which is the along-track component.‡

The second point surprised us; it quite obviously voids our previously held assumption that errors from one pass to another were uncorrelated.

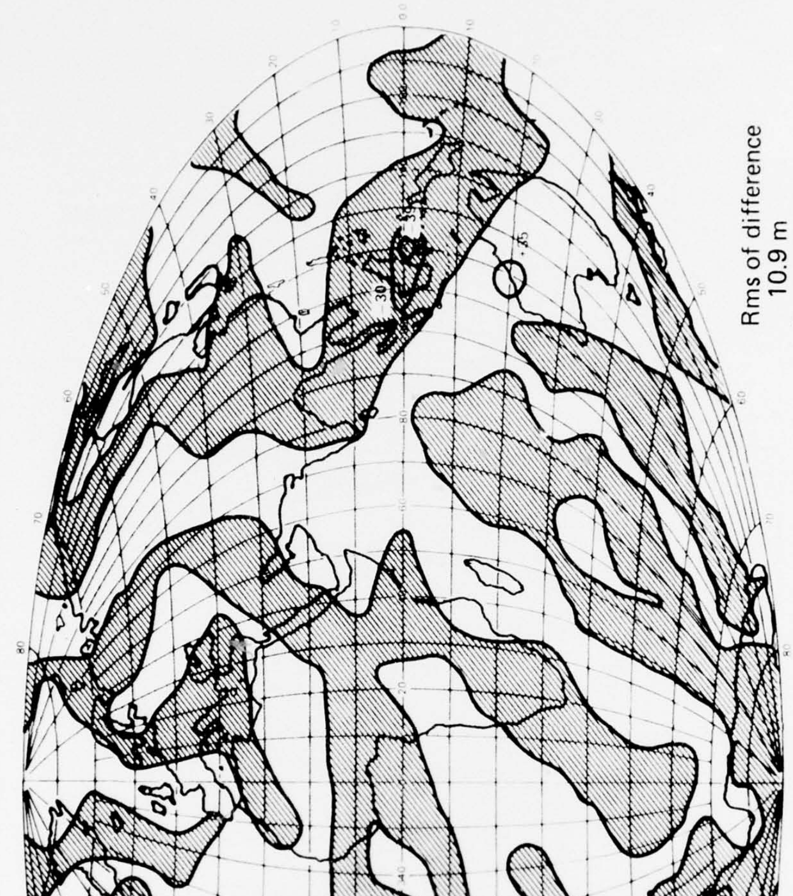
The geographic correlation noted above is dramatic as illustrated in Fig. 3, which shows a composite of the ℓ versus time

---

*Results are satellite-dependent; thus a range is given.

†The results are for a span of time when solar activity (and hence drag) is near a minimum.

‡Satellite position vectors are differenced and then resolved into components along the orthogonal directions $\hat{H}$, $\hat{C}$, $\hat{\ell}$, where $\hat{H}$ is along the satellite radius vector (from the earth's center), $\hat{C}$ is along the negative angular momentum vector, and $\hat{\ell}$ is $\hat{H} \times \hat{C}$.



Rms of difference
10.9 m
Peak differences
+35.4 m
−39.1 m

Fig. 2 Geoid Height Difference, APL 4.5 Minus WGS-72, 1974

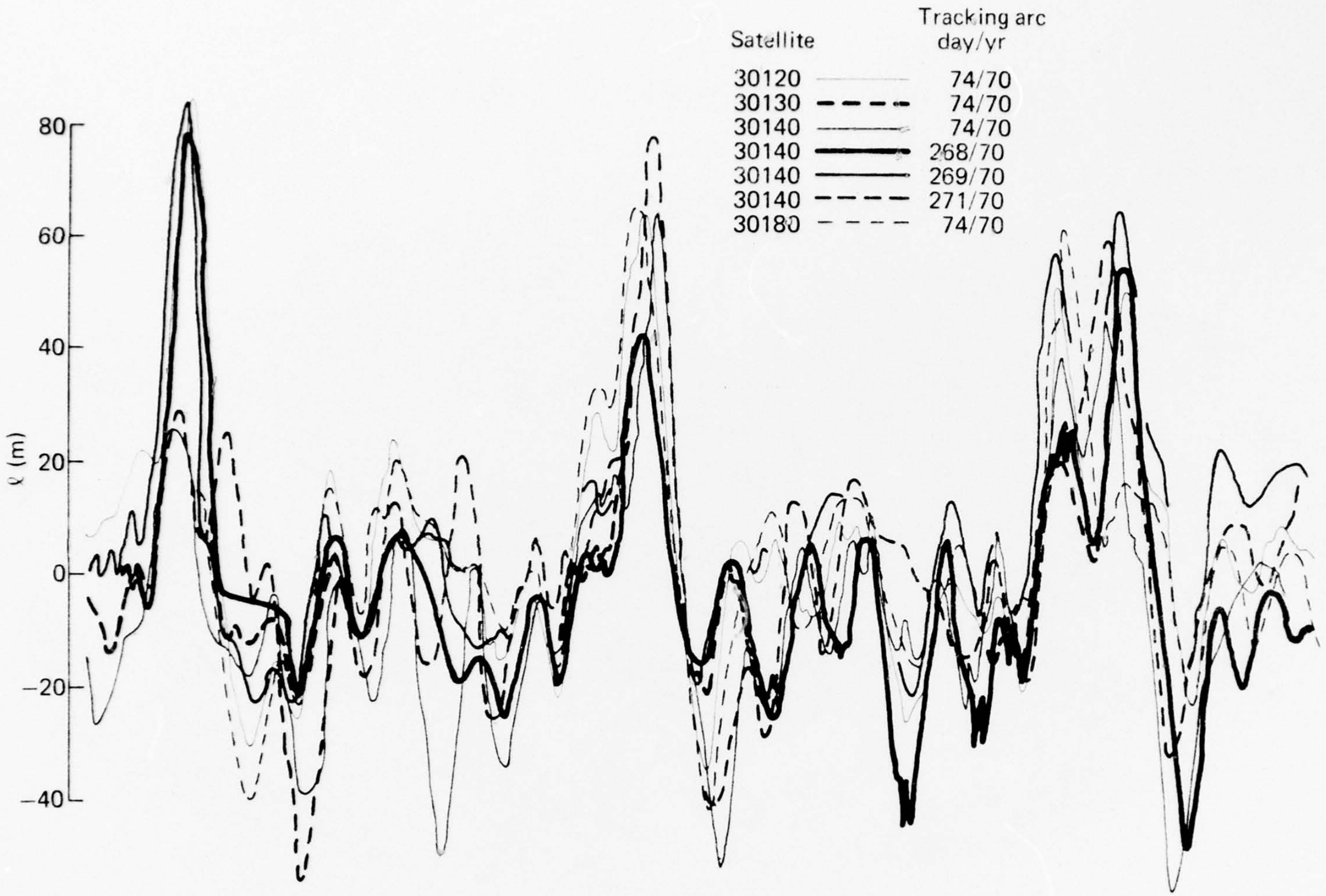


Fig. 3 Along-Track Difference Due to Geodesy Change (APL 4.5 to WGS-72), Resolved to Same Geographic Location for Various Satellite Arcs

plots from four different satellites over eight different arcs (see the key on the figure). It was generated in the following manner.

Ephemerides were generated from tracks using the WGS-72 and APL 4.5 geodesies. The ephemerides were then differenced (point-by-point) and the differences resolved in H, ℓ, C coordinates. The along-track difference, ℓ, and its earth-fixed position (φ,λ) were plotted versus time. Finally, the ground tracks were aligned so that the effect of geodesy difference could be observed as a function of earth-fixed location. The abscissa is time, since the satellite subtrack was at a base earth-fixed longitude while heading north; since the satellite is polar, each revolution samples longitudes that are 180° apart. The prominent positive peaks are about 12 h apart and are located over longitude bands centered on 90 and 270° (see Fig. 6b). The station location shifts, discussed in the next section, result from such biases.

STATION SHIFTS

NAG performed a series of simulated navigations as part of their evaluation of OIP-II. The fixes that use the broadcast ephemerides and have no tropospheric refraction correction were combined to produce the mean position for each station for each geopotential coefficient set. The station coordinate differences (WGS-72 minus APL 4.5) were then removed from the mean position differences to obtain the absolute mean navigated-position differences shown in Table 1.

The large shifts exhibited by stations 013, 111, 112, 115, and 121 caused some concern, particularly station 115. Knowing the simulation errors, we used the OIP-II Editor results (from the tracks used to produce the ephemerides used for the navigations) to estimate $\Delta\varphi$.* These numbers are shown in parentheses for the given stations.

---

*For polar satellites, the latitude error ($r\Delta\varphi$) is nearly equivalent to the along-track error (ECA).

Table 1

Coordinate and Simulated Navigated Station Position Differences, WGS-72 Minus APL 4.5 (NAG)

Station No. and Location	Coordinate Difference (m)			Mean Navigated-Position Difference (m)		
	$r\Delta\varphi$	$r\cos\varphi\,\Delta\lambda$	Δr	$\Delta\varphi$	$r\cos\varphi\,\Delta\lambda$	No. of Passes
008 Brazil	1.7	-1.3	-11.9	- 3.9	-13.0	30
013 Japan	5.4	-2.9	6.5	8.6(5.3)	- 4.5	44
014 Alaska	-3.2	1.2	10.6	- 4.7	- 6.1	74
018 Greenland	-1.9	0.4	5.6	2.0	1.2	142
019 Antarctica	3.2	-2.8	1.0	- 6.2	- 3.4	78
103 New Mexico	-3.4	-6.5	3.7	- 6.8	-15.7	31
106 England	-1.4	-5.5	0.3	5.5	- 3.7	48
111 Maryland	0.2	20.9	9.2	-11.2(-2.8)	- 4.3	27
112 Australia	13.9	4.2	- 8.3	10.0(5.3)	12.7	43
115 S. Africa	14.9	4.8	- 0.2	-22.4(0.7)	-13.3	38
117 Samoa	5.7	-8.1	11.0	0.5	-13.1	38
121 Philippine Islands	18.7	-6.8	6.2	-10.0(-7.4)	-20.3	31

NOTE: Numbers in parentheses are equivalent latitude differences taken from corresponding Editor runs.

3. EXPERIMENTS AND RESULTS

There are two ways to determine how much a station's coordinates will shift due to a change in geodesy. The first and most obvious method is to generate satellite ephemerides with each geopotential coefficient model and, using actual data, determine the station's location both ways. The major disadvantage of this method is that shifts can be determined at only a few specific locations (i.e., stations from which the required data have been taken). The advantage is that a shift, once determined, is an excellent measure of the effect of the geodesy change in that region as well as at that location.

The second method is to perform pseudonavigation over a uniform, worldwide grid, thus producing numbers that are useful everywhere, not just at doppler tracking stations. However, devising a suitable pseudonavigation algorithm presents a problem.

Although both methods possess inadequacies they tend to be complementary, so we decided to try both and compare them. Thus, we produced the fixed-site shift numbers and, through the comparison, a measure of the quality of the worldwide shift numbers.

Both methods require satellite ephemerides that are generated by integrating the satellite equations of motion using initial conditions obtained from tracking. Since the initial conditions depend on the force models used, their determination must be performed twice for each arc, once with each of the geopotential coefficient models. To eliminate all other differences, the same program model (OIP-II MK5MOD2) was used for all runs. This program contains our latest force models (Ref. 2).

We chose, as part of our overall investigation, data from OPNET and TRANET (over the same time span) and performed separate tracks using APL 4.5 and WGS-72 geopotential coefficient models. Thus, each span was covered by four tracks:

Data Source	Geodesy Used
OPNET	APL 4.5
TRANET	APL 4.5
OPNET	WGS-72
TRANET	WGS-72

OPNET-GENERATED EPHEMERIDES IN THE SOUTHERN HEMISPHERE

Because the Transit System uses only the OPNET stations (all of which are in the northern hemisphere), the quality of the satellite ephemeris over the southern hemisphere is a recurring question. To investigate this question, we performed two satellite tracks, one using data from OPNET and the other using data from TRANET, and compared the ephemerides produced using the different sets of initial conditions.

Figure 4* is a plot of these ephemeris differences versus time, resolved into the H, ℓ, C coordinate frame. The differences in H are less than 1 m and can best be described as jitter; that is, the differences are below our threshold of interest. The amplitude and phase of the sinusoid exhibited by C indicate a slight difference in the nodes (4×10^{-7} rad) of the two orbits. The along-track (ℓ) secular component of the differences indicates a small period difference (about 2×10^{-5} s). The sawtooth-type envelope on both ends and the random spikes in the center are numerical in nature and are peculiar to the program used to produce the graphs. The structure results from differencing large numbers (the times, which have been truncated to millisecond significance) to get small differences; 1 ms translates to approximately 7 m in along-track for our satellites. The results shown are for the WGS-72 geodesy. When the APL 4.5 geodesy is used, the results are slightly worse (see Fig. 5*). H peaks at about 1 m and C peaks at about 7 m; ℓ exhibits slightly more structure but has the same amplitude.

Thus, the ephemerides are essentially identical worldwide independent of the tracking station network. This conclusion has been reached previously with similar experiments and can be regarded as firmly established.

EVALUATION STATION NAVIGATIONS

To test the quality of the ephemeris at stations not used in orbit determination, the data from three TRANET stations† (013, 112, and 121) were withheld from all the tracks. These data were then navigated with tracked ephemerides. Station 112 is in the southern hemisphere.

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*Scaled in kilometers.

†These were called "evaluation stations" because their data had no influence on the tracked ephemerides and thus their navigations served as an independent measurement of ephemeris quality.

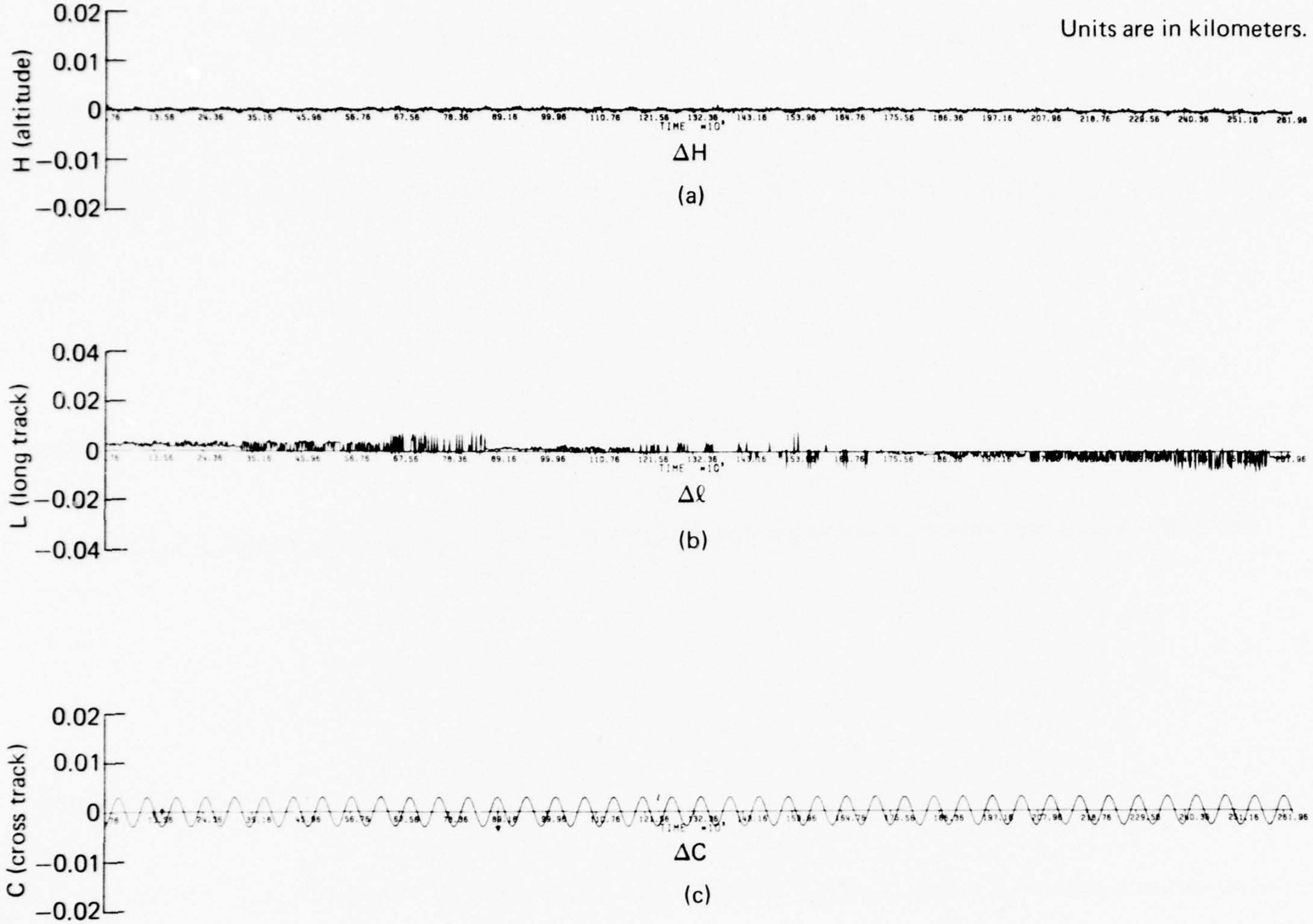
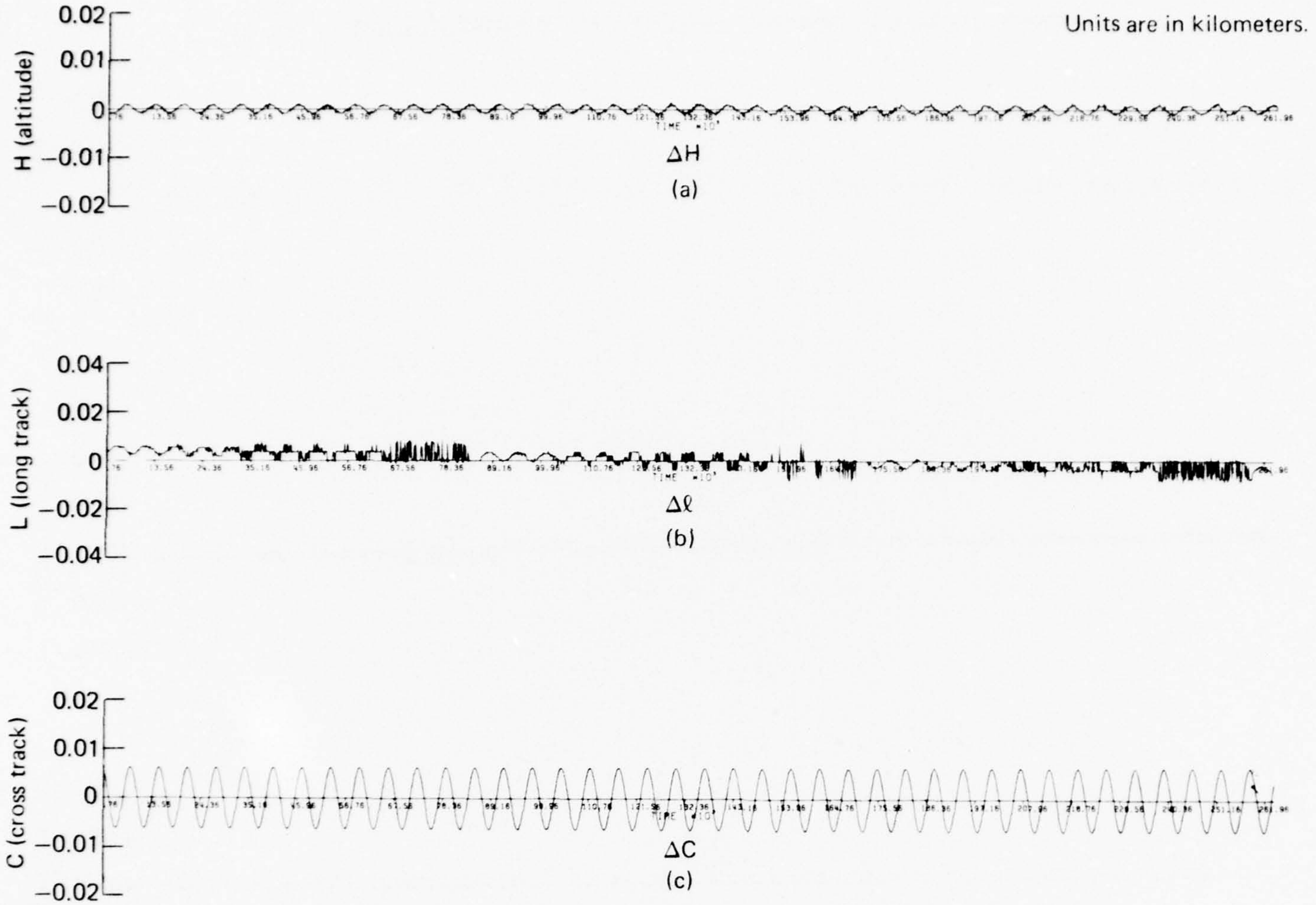


Fig. 4 OPNET Ephemeris versus TRANET Ephemeris with WGS-72 Geodesy



Units are in kilometers.

ΔH
(a)

Δℓ
(b)

ΔC
(c)

Fig. 5 OPNET Ephemeris versus TRANET Ephemeris with APL 4.5 Geodesy

As noted earlier, the values of three parameters are determined during navigation. The parameters are the frequency offset correction, and the station movement in the two coordinates, ρ and ℓ.

Sets of (ρ,ℓ) for a given station can be processed to determine the three-dimensional position fit presented in Table 2. The variables tabulated are $r\Delta\varphi$, $r \cos\varphi\ \Delta\lambda$, Δr (position errors in the latitude, longitude, and radius directions scaled to meters), the radial error, and the standard deviations of the input data σ_ℓ, σ_ρ. There are two points of note. First, significant differences occur for different geodesies but not for different station networks. This verifies what was evident when the ephemerides were compared. Second, WGS-72 solutions are uniformly better than APL 4.5 solutions; this is also true of the tracking errors. While too few passes are involved to get good absolute positioning of the stations, there are more than enough for adequate relative comparison.

NAVIGATION USING TRACKED EPHEMERIDES

We knew from the ephemeris comparison that station position shifts would occur. Therefore, we sought a measure of the shifts by looking at the tracking station position shifts for the passes used in the tracks themselves. There were enough pass results available over the various tracking spans to compare the relative station positioning between WGS-72 and APL 4.5.

To position the station, ρ and ℓ for all passes of that station are combined along with the station-satellite relative geometry for each pass to form a three-dimensional solution (λ,φ,r). We found that 30 passes of well distributed geometry were barely adequate to produce a stable solution.

We would like to make two points regarding the navigations: (a) They use full-precision ephemerides over the tracking span (i.e., not predicted), and (b) tropospheric refraction has been corrected (usually with default weather data since submission of actual weather data is rare). Incidentally, one should remember when comparing the Editor and simulated navigation solutions that these points are the two major error sources in simulated navigations. Additionally, while both types of navigation find two-dimensional solutions, they are resolved along different axes. Since the navigations are two-dimensional fits to a three-dimensional error, they absorb the third dimension differently; there exists no transformation between them.

Table 2

Evaluation Station Position Fit (OIP)
(entries in meters)

Station 013 (13 passes)

Tracking Network	Geodesy	$r\Delta\varphi$	$r \cos\varphi \, \Delta\lambda$	Δr	Radial	σ_ℓ	σ_ρ
TRANET	WGS-72	-4.93	-6.79	-1.14	8.47	7.4	1.4
TRANET	APL 4.5	-9.52	-6.24	6.94	13.33	8.2	8.4
OPNET	WGS-72	-3.34	-4.08	-0.25	5.28	7.5	2.5
OPNET	APL 4.5	-5.45	-9.72	9.52	14.66	7.7	10.0
WGS-72	(TRA-OP)	-1.59	-2.71	-0.89	3.27	-	-
APL 4.5	(TRA-OP)	-4.07	3.48	2.58	5.94	-	-
Station 112 (18 passes)							
TRANET	WGS-72	-0.54	5.21	2.97	6.02	7.9	5.1
TRANET	APL 4.5	8.06	-3.85	-0.75	8.96	11.4	4.8
OPNET	WGS-72	-0.30	-5.32	-3.16	6.19	7.6	4.0
OPNET	APL 4.5	11.09	-7.83	-2.14	13.74	10.4	4.3
WGS-72	(TRA-OP)	-0.24	-0.11	0.19	0.33	-	-
APL 4.5	(TRA-OP)	-3.03	3.98	1.39	5.19	-	-
Station 121 (8 passes)							
TRANET	WGS-72	-1.23	-1.82	-4.59	5.09	7.3	4.9
TRANET*	APL 4.5	-3.28	-0.26	-2.02	3.86	17.0	17.0
OPNET	WGS-72	-0.41	0	-3.88	3.90	5.2	5.0
OPNET	APL 4.5	-2.00	-3.57	-3.53	5.40	17.0	17.6
WGS-72	(TRA-OP)	-0.82	-1.82	0.71	2.12	-	-
APL 4.5	(TRA-OP)	-1.28	3.31	-1.51	3.56	-	-

---

*Nine passes

Table 3 shows the tracking station shifts. The numbers in the table are the difference in the absolute position of the station as determined using (a) WGS-72 ephemerides against NWL-10D station coordinates, and (b) APL 4.5 ephemerides against APL 4.5 station coordinates, and then removing the difference in the station coordinates. The doppler data, program, and other force models were identical. Since the corrections are in meters, the entries are actually $r\Delta\varphi$, $r \cos\varphi \, \Delta\lambda$, and Δr rather than $\Delta\varphi$, $\Delta\lambda$, and Δr.

THE PSEUDONAVIGATION

A by-product of each orbit determination is the satellite ephemerides over the tracking span; these consist of satellite position and velocity at equal time steps, usually every minute. Ephemerides produced over the same span with the two different geodesies are differenced and transformed into H, ℓ, C. Additionally, the earth-fixed coordinates (φ,λ) are associated with each H, ℓ, C set.*

We are now ready to perform the pseudonavigation, which is based on the fact that navigation errors are equivalent to ephemeris errors over the satellite trajectory arc used in the navigation and vice versa. Thus we will simulate multiple navigations by averaging the ephemeris differences over an appropriate area.

All navigation satellites are at an altitude of approximately 1000 km, which places them in view of a station whenever they are within 30° (great circle) of that station. If the satellite is 12° above the station's horizon, the angle is reduced to 20°. Because low-elevation passes are generally eliminated for station survey work, we used data only within this distance of the point under consideration.

The earth was partitioned into equal areas of 40 × 40° at the equator with appropriate latitude compensation for areas not on the equator. We then calculated the average and standard deviation over all H, ℓ, and C in each area and assigned these values to the area midpoint. We did this for areas centered every 10° in both latitude and longitude. Maps showing these averages, which we refer to as predicted position shifts, are presented in Figs. 6a, 6b, and 6c.

Table 4 shows the pseudonavigation estimates for the TRANET and OPNET sites.

---

*We have these differences resolved into earth-fixed coordinates for 44 arc days from four different satellites.

Table 3

OIP Absolute Mean Navigated Position Using WGS-72 and APL 4.5 Geodesies

	Position Shift* (m)		
Station	$r\Delta\varphi$	$r \cos\varphi \, \Delta\lambda$	Δr
008	0.3	1.5	-5.8
013	4.1	-2.1	0.8
014	2.5	-4.7	0.6
018	0.7	-1.7	2.9
019	2.4	3.7	-7.7
103	4.9	4.1	0.8
106	2.9	-4.7	1.4
111	1.8	-11.0	1.4
117	5.4	-9.0	-1.7
311	2.1	-7.7	-1.5
321	4.5	-0.4	4.4
330	3.4	-3.0	-0.1
340	6.8	-3.5	-5.5
Mean	3.20	-2.95	-0.79
σ	3.68	5.31	3.53
σ_{mean}	1.81	4.42	3.44

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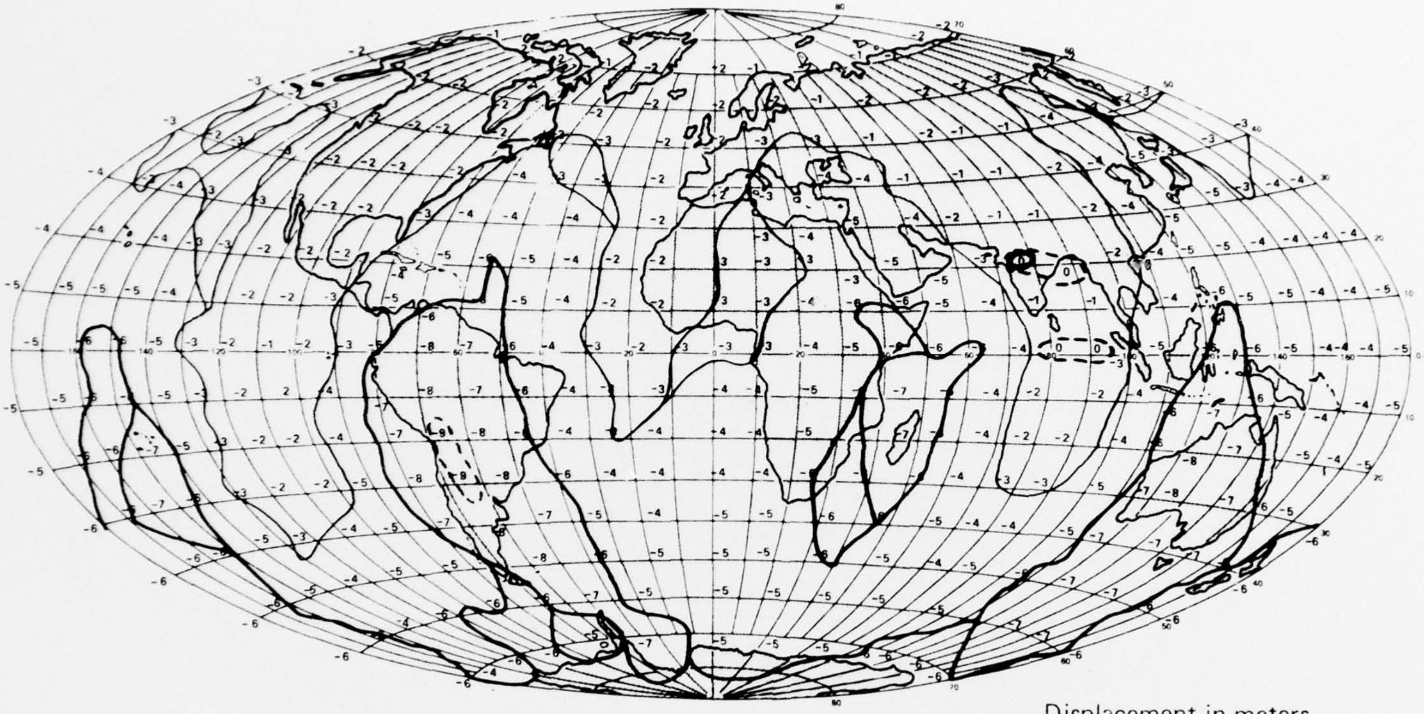
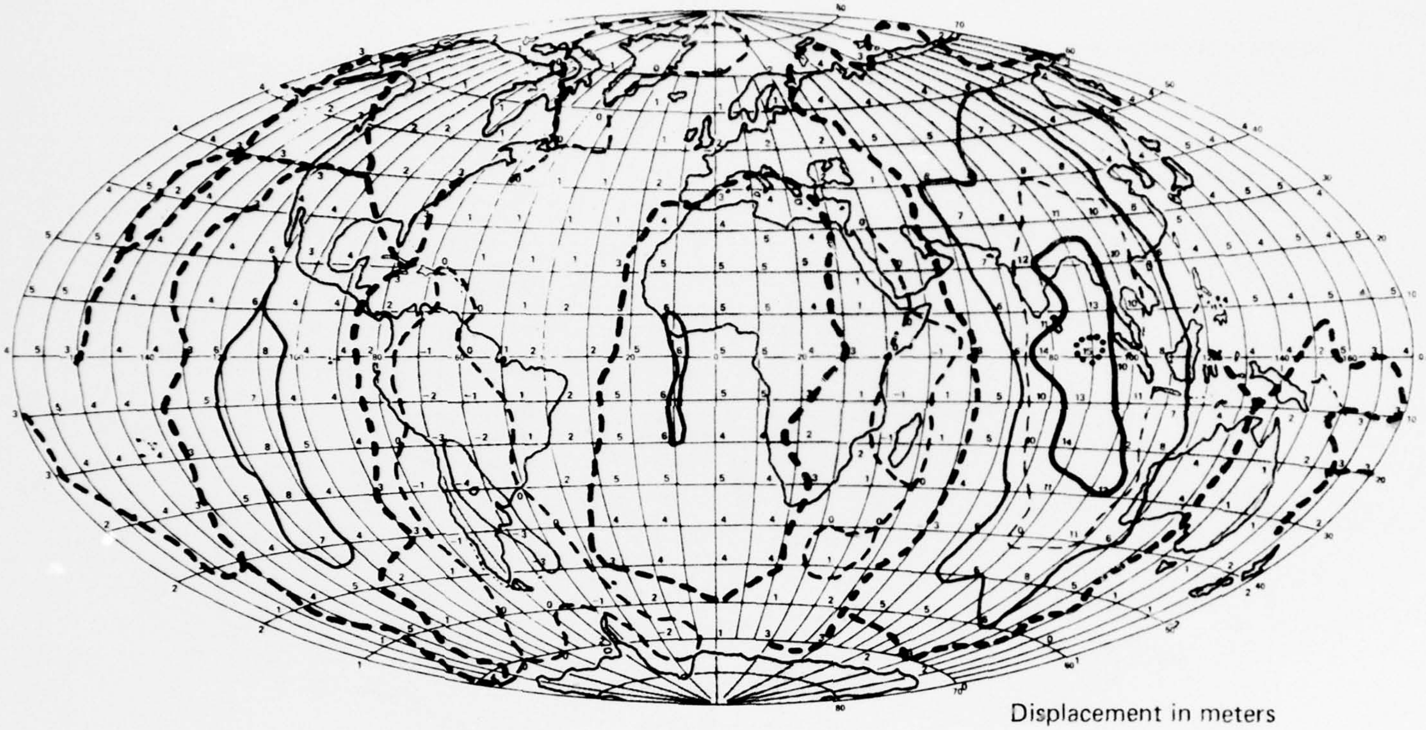
*Position shift = $\overline{NAV}_{WGS} - \overline{NAV}_{4.5} + \Delta STA$

ΔSTA = NWL-10D - APL 4.5 station coordinates



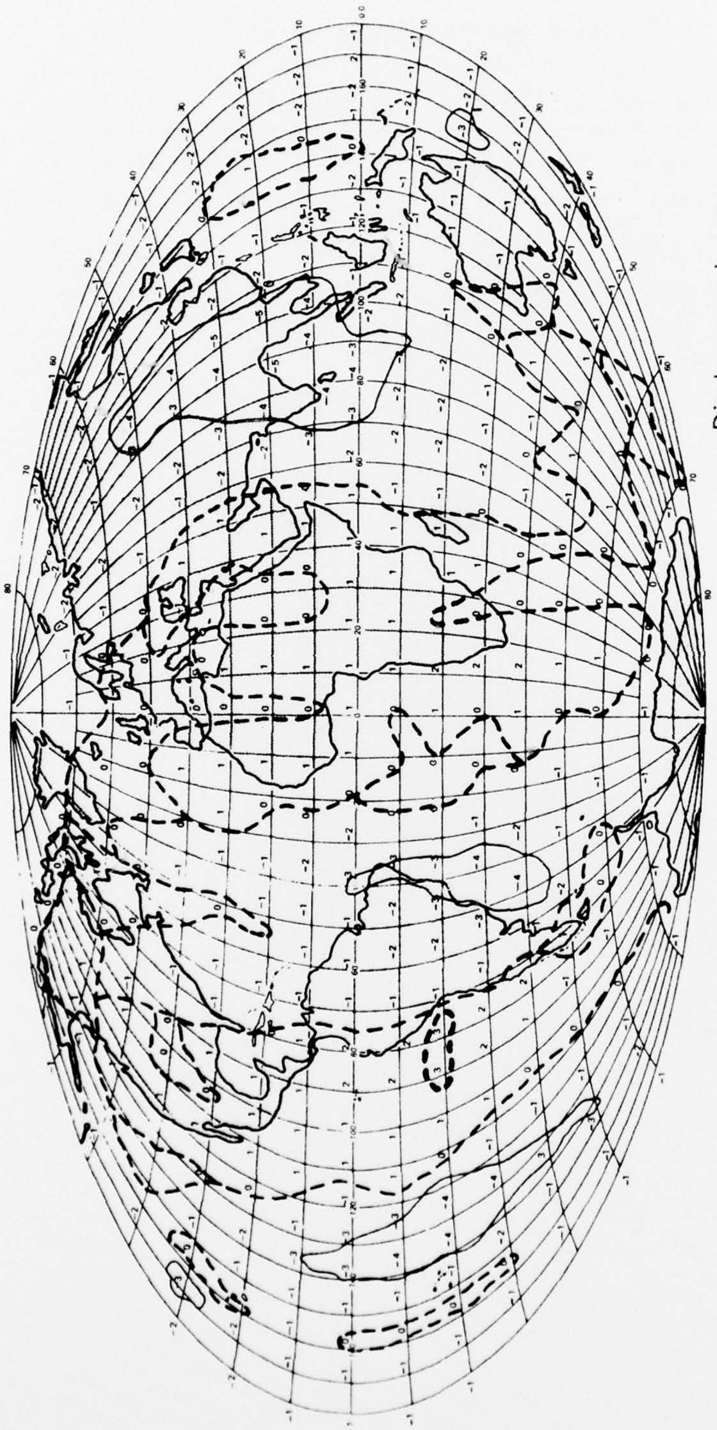
Displacement in meters

Fig. 6a Pseudonavigation Mean Altitude (H) Shift in Position of Multiple Pass Solution Due to Change from APL 4.5 to WGS-72 Geodesy



Displacement in meters

Fig. 6b Pseudonavigation Mean Longitude (λ) *Shift in Position of Multiple* Pass Solution Due to Change from APL 4.5 to WGS-72 Geodesy



Displacement in meters

Fig. 6c Pseudonavigation Mean Latitude (ϕ) Shift in Position of Multiple Pass Solution Due to Change from APL 4.5 to WGS-72 Geodesy

Table 4

Pseudonavigation Position Shifts (m)

Station	$r\Delta\varphi$	$r \cos\varphi \, \Delta\lambda$	Δr
008	1.0	-3.0	-7.0
013	4.5	-1.0	-5.0
014	3.0	-1.0	-2.0
018	-1.0	-1.0	-1.0
019	1.5	-1.0	-6.0
103	4.0	0	-2.0
106	2.0	0	-2.0
111	3.0	-1.0	-2.0
117	3.0	-1.0	-5.0
311	1.0	-1.0	-3.0
321	2.0	1.0	-2.0
330	3.0	1.0	-2.0
340	4.5	0	-5.0
Mean	2.42	-0.65	-3.38
σ	2.85	1.18	3.86
σ_{mean}	1.50	1.00	1.86

Table 5 compares the OIP navigation and pseudonavigation results. As to the quality of these measures as shift indicators, one is forced to accept the mean values from the OIP navigation as most precise, at least those that contain 30 or more passes. The passes are well distributed in elevation, azimuth, and direction. In the case of the Editor navigations (Table 6), all known significant error sources are modeled to the meter level, and full-precision, tracked ephemerides are used. We have included in the table the mean position relative to the station coordinates (in both APL 4.5 and WGS-72) as an indicator of data quality, the assumption being that the closer the better.

ERROR SOURCES

There are certainly errors associated with all the above results. The problem is to identify and quantify these errors to judge their effect on our conclusions.

Noise* is our constant companion and will not be discussed beyond what has been said regarding its magnitude. The effect of the tracking network has also been discussed.

It is categorically true that the station coordinates are in error (i.e., not exact). We have eliminated these errors by reducing our results to difference in absolute position, i.e., subtracting out the reference positions.

In our effort to believe that the pseudonavigations were more accurate than the station-fit results, we pursued a detailed investigation of the latter. One of our discoveries was that the compiled thresholds in the Editor navigation were not tight enough. Since the amplitude of the doppler decreases with elevation, sensitivity of the ECA, ECR fit also decreases. We found that the navigation was sometimes breaking out at false minima, especially on low-elevation passes. We examined parameter values at the end of various numbers of iterations (up to 20) to determine the stable value of each parameter for every pass (25 passes were investigated). We found that by reducing the breakout thresholds from 0.60 to 0.02 m, the breakout values were identical to the stable values.

We also investigated the effect of initial station position on final solution. The range of input coordinate error was 4 to

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*The words "noise" and "random" are used loosely to indicate sources of which we are ignorant, either because of the nature of the phenomena or the difficulty in analyzing them.

Table 5

Comparison of OIP-Navigated and Pseudonavigated Mean Station-Position Shifts (m)

	OIP-Navigated			Pseudonavigated			(OIP-Pseudo) Difference		
Station	$r\Delta\varphi$	$r\cos\varphi\,\Delta\lambda$	Δr	$r\Delta\varphi$	$r\cos\varphi\,\Delta\lambda$	Δr	$r\Delta\varphi$	$r\cos\varphi\,\Delta\lambda$	Δr
008	0.3	1.5	-5.8	1.0	-3.0	-7.0	-0.7	4.5	1.2
013	4.1	-2.1	0.8	4.5	-1.0	-5.0	-0.4	1.1	5.7
014	2.5	-4.7	0.6	3.0	-1.0	-2.0	-0.5	-3.7	2.6
018	0.7	-1.7	2.9	-1.0	-1.0	-1.0	-1.7	-0.7	3.9
019	2.4	3.7	-7.7	1.5	-1.0	-6.0	0.9	4.7	-1.7
103	4.9	4.1	0.8	4.0	0	-2.0	0.9	4.1	2.8
106	2.9	-4.7	1.4	2.0	0	-2.0	0.9	-4.7	3.4
111	1.8	-11.0	1.4	3.0	-1.0	-2.0	-1.2	-10.0	3.4
117	5.4	-9.0	-1.7	3.0	-1.0	-5.0	2.4	-8.0	3.3
311	2.1	-7.7	-1.5	1.0	-1.0	-3.0	1.1	-6.7	1.5
321	4.5	-0.4	4.4	2.0	1.0	-2.0	2.5	-1.4	6.4
330	3.4	-3.0	-0.1	3.0	1.0	-2.0	0.4	-4.0	1.9
340	6.8	-3.5	-5.5	4.5	0	-5.0	2.3	-3.5	-0.5
Mean	3.20	-2.95	-0.79	2.42	-0.65	-3.38	0.79	-2.18	2.61
σ	3.68	5.31	3.53	2.85	1.18	3.86	1.42	5.08	3.37
σ_{mean}	1.81	4.42	3.44	1.50	1.00	1.86	1.18	4.59	2.13

Table 6

OIP Mean Radial Navigated Position and Standard Deviation for Selected TRANET and OPNET Stations Using WGS-72 and APL 4.5 Geodesies (m)

Station No.	WGS-72			APL 4.5		
	No. of Passes	Mean Radial	σ	No. of Passes	Mean Radial	σ
008	40	1.83	5.36	43	8.59	9.76
013	27	4.08	5.01	24	4.95	9.50
014	51	3.36	5.54	58	12.03	9.31
018	70	4.31	7.99	77	1.51	14.81
019	42	3.34	12.70	38	11.07	19.15
103	36	3.66	8.31	37	15.47	11.04
106	42	5.78	5.13	41	6.19	8.50
111	63	6.25	6.16	63	11.12	10.42
117	38	4.62	4.26	40	8.94	7.05
311	64	6.10	4.80	70	6.67	11.50
321	44	3.72	3.81	50	5.34	8.09
330	36	2.53	2.59	39	4.73	8.54
340	40	4.63	3.36	51	8.59	6.79

$$\text{Mean radial} = (r\Delta\varphi^2_{\text{mean}} + r\cos\varphi\,\Delta\lambda^2_{\text{mean}} + \Delta r^2_{\text{mean}})^{\frac{1}{2}}$$

$$\sigma = (\sigma^2_{\text{along-track}} + \sigma^2_{\text{radial}})^{\frac{1}{2}}$$

22 m with resultant errors of 0.1 to 0.6 m. For this region, the error is linear at about 0.025 m/m.

Finally, we looked at the effect of including the frequency drift parameters in the Editor and found that this speeded convergence but the solution was not affected.

The tracking data for station 020 were systematically deleted from the tracks done with APL 4.5 geodesy because of poor coordinates for that station. The passes deleted amounted to a 9% difference in the data used in the track, which will certainly have an influence on the resultant ephemeris, but we did not know exactly what the size of the change would be. To find out, we reran two of the WGS-72 tracks without data from station 020, which had formerly been included. A comparison of the tracking results showed the effect to be less than 1 m.

4. CONCLUSIONS

The station navigation results are excellent measures of the position shifts that would be expected in the regions they occupy. From a comparison of the navigation and pseudonavigation results, we see that pseudonavigation gives only a fair measure of the shifts to be expected. Where one wishes to know the position shift to better than 5 m, he is advised to reposition that particular site.

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The work reported in TG 1311 was done under Navy Contract N00017-72-C-4401. This work is related to Task S1L0, which is supported by Strategic Systems Project Office (SP-243).

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