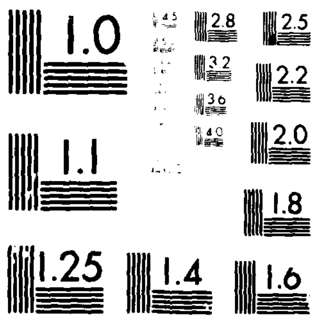
AD-A081 966 NAVAL SURFACE WEAPONS CENTER DAHLGREN VA F/G 8/5
ACCURACY OF MEAN EARTH ELLIPSOID BASED ON DOPPLER, LASER, AND A--ETC(U)
JAN 80 R J ANDERLE
UNCLASSIFIED NSWC/TR-80-4 NL

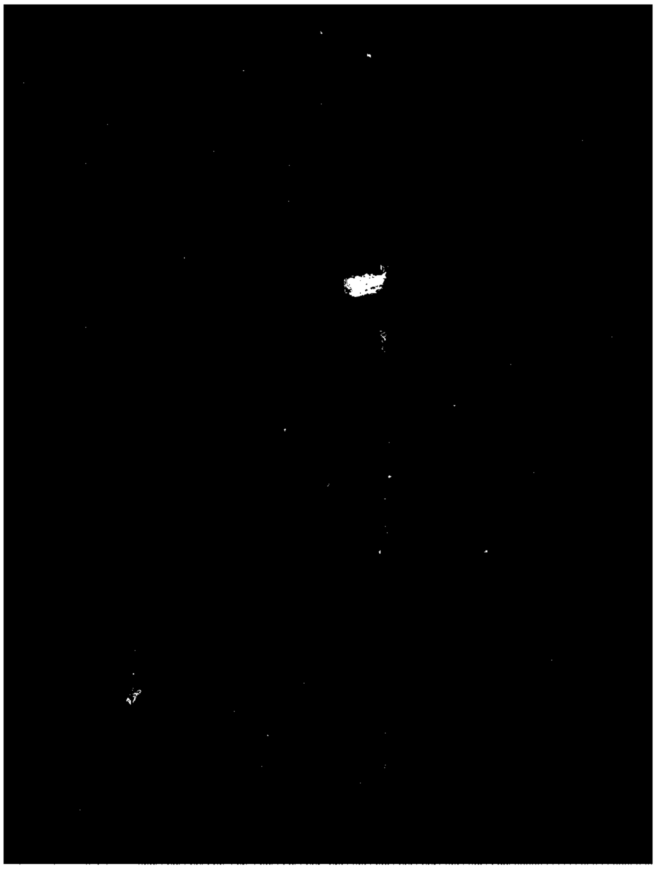
1 OF 1
AD
A081966

END
DATE
FILMED
4-80
DTIC



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963-A



REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NSWC/TR-80-4	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): ACCURACY OF MEAN EARTH ELLIPSOID BASED ON DOPPLER, LASER, AND ALTIMETER OBSERVATIONS	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Richard J. Anderle	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Surface Weapons Center (K10), Dahlgren, VA 22448	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Other DoD–DMAHTC
11. CONTROLLING OFFICE NAME AND ADDRESS: Defense Mapping Agency, Hydrographic/Topographic Center, Washington, DC 20390	12. REPORT DATE: Jan[redacted]80
	13. NUMBER OF PAGES: 29
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	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)

satellite observations
doppler coordinate system
earth's semimajor axis
best fitting ellipsoid
gravitational constant

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

The error in the mean earth ellipsoid computed on the basis of Doppler or laser observations of artificial earth satellites or radar altimeter observations of the ocean surface from a satellite depends upon instrument precision, on uncertainties in the specification of the earth's gravity field at both long and short wavelengths, on uncertainties in the origin of the coordinate system, on modeling errors in ionospheric (except laser) and tropospheric refraction, and, for altimetry, on oceanographic effects. The magnitude of the uncertainty in the computed ellipsoid will vary,

(back)

(20) (Continued)

depending on the size of these errors and on the number and distribution of observation stations. Review of computations based on various data sets indicates that differences in the computed ellipsoids are consistent with those expected, due to the various error sources and that the best-fitting ellipsoid has a semimajor axis of 6378136 ± 2 m.

FOREWORD

This report was presented at the Seventeenth General Assembly of the International Union of Geodesy and Geophysics in Canberra, Australia, in December 1979. The report reviews the determinations of the semimajor axis for best fitting ellipsoid to the earth and recommends a value of 6378136 m be adopted as a standard value corresponding to an earth's gravitational constant (with atmosphere), GM, of 398600.5 km^3/sec^2. During the assembly, Dr. David Smith of Goddard Space Flight Center presented recent results for the semimajor axis obtained from laser observations of the LAGEOS satellite; the values, which corresponded to a smaller GM, were somewhat smaller than those quoted in this report. The assembly adopted a value of 6378137 m as a standard for a new reference system on the basis of somewhat different weighting of the various results for the earth's semimajor axis. This adopted value is consistent with that recommended in this report, considering the 2-m uncertainty in the determination.

This report was prepared under Defense Mapping Agency Hydrographic Topographic/Center Work Order DMATC 75-005.

Released by:

R. T. RYLAND, JR., Head
Strategic Systems Department

CONTENTS

INTRODUCTION

The earth's semimajor axis has been calculated from the distance from the center of mass of the earth to mean sea level defined by:

1. Station locations determined from Doppler satellite observations

2. Station locations determined from laser satellite observations

3. Satellite altimeter observations of the ocean surface

The following sections review the solutions and discuss random and possible bias errors in the solutions.

DOPPLER SOLUTION FOR EARTH'S SEMIMAJOR AXIS

BACKGROUND OF DOPPLER COORDINATE SYSTEM

Calculations of positions of Doppler receivers have been in the NWL9D coordinate system during the period 18 Oct 1971 to 15 Jun 1977 and in the NWL9Z system from 15 Jun 1977 to date. The difference in designation of the system indicates that small adjustments were made in the positions of some base stations used to determine the precise position of the satellites; the NWL9D and NWL9Z coordinate systems are intended to be the same in scale, orientation, and origin. A change in the gravity field (from NWL9B to NWL10E) used in computing the satellite ephemeris was made 2 Jan 1973. This change was not intended to affect the scale, orientation or origin either. However, regional biases of the order of a meter or two can be expected, due to systematic differences in orbits computed with the two fields, and reported pole positions would have had a discontinuity of about a half meter if pole positions computed with the NWL10E first were not first corrected for the difference in pole positions obtained in control tests with the two fields.

SCALE CORRECTION OF NWL9D AND NWL9Z COORDINATE SYSTEMS

The satellite observations used in computing the orbits and in positioning the stations are made to an antenna on the satellite, which is 1 m below the center of gravity of the satellite. The offset between the antenna and center of gravity positions was not considered in the derivation of coordinates in the NWL9D and NWL9Z systems. The computed satellite orbits are not expected to be affected by the neglect of the offset, because the satellite height is controlled by the measured orbit period and the earth's gravitational constant, GM, through Kepler's law for computations based on observations during many orbit revolutions from well-distributed ground stations. That is, the computed ephemeris will be that of the satellite center of gravity. However, station positions computed neglecting the antenna offset will be wrong in height, not by the full 1-m offset but, according to experiments, only .7 m too high. Similarly, the value of GM used in the computation (398601.0 km^3/sec^2), which is .5 larger than the current best estimate of 398600.5, yields orbital positions that are 3.0 m too high but affects station heights computed from these orbits by only 1.7 m. Therefore, NWL9D and NWL9Z station heights should be reduced by (0.7 + 1.7) = 2.4 m to correct for neglect of satellite antenna offset from the center of mass of the satellite and to correspond to the best current estimate of GM. Experiments conducted with the offset and revised GM indicate the correction is valid to within the accuracy of the test (-.1 m) and that no effect on other components of position could be detected.

A summary of test results obtained by C. A. Malyevac of the Naval Surface Weapons Center is given in Table 1 (Appendix A) while test results obtained by K. Murphy of the Defense Mapping Agency Hydrographic/Topographic Center are given in Table 2.

EVALUATION OF DOPPLER SCALE

Comparisons of computed Doppler positions, reduced by 2.4 m in height, with other systems indicate no scale bias larger than the accuracy of the tests (about one part in 10^7). Langley et al[1]* find Doppler minus VLBI differences between sites in California, Canada, and England to be .12 ± .1 ppm. Hothem[2] finds corresponding differences between VLBI sites in California, Massachusetts, and West Virginia to be below .1 ppm. He also finds the differences for the radius vector of the McDonald lunar laser to be -.08 ppm and differences for the spin axis distance of the Goldstone Deep Space station to be .1 ppm. Although Hothem reports similar agreement between Doppler and satellite laser determination of the distance between Massachusetts and California, laser determinations of the radius of these stations are 2.8 ± .2 m higher than the Doppler determinations.

DOPPLER VALUES FOR THE EARTH'S SEMIMAJOR AXIS

The adopted ellipsoid for the DoD WGS 72 has a flattening of 1/298.26 and semimajor axis of 6378135 m. Corrections to the semimajor axis found corresponding to a GM of 398600.5 are as follows:

---

*Raised numbers refer to similarly numbered items in the list of references on page 8.

1. Huber,[3] using coordinates of 106 Doppler stations in the northern hemisphere and 95 in the southern hemisphere (Appendix B, Figure 1), obtained, in meters:

Solution	Potential	dx	dy	dz	da	rms
1	GEM10B	1.2 ± 2	-.2 ± .2	2.2 ± .2	1.0 ± .1	2.3
2	GEM10	1.2 ± .2	-.6 ± .2	2.0 ± .2	1.0 ± .1	3.2

2. Grappo, of the Defense Mapping Agency Hydrographic/Topographic Center, found, using Doppler positions and the GEM10 gravity field:

Solution	No. Stations	dx	dy	dz	da
1	1100	–	–	–	-1
2	1100	+.7	+.2	+4.7	0
3	711 (Balanced)	–	–	–	0
4	(Balanced)	+.9	+.6	+3.8	0
5	300 (Balanced)	+.7	-.3	+4.4	-.6

3. The author, using Doppler positions for 27 of the 35 sites shown in Table 3 and Figure 2, obtained a value of a = 6378136.5, 1/f = 298.258 for the same GM.

EVALUATION OF DOPPLER SOLUTION FOR EARTH'S SEMIMAJOR AXIS

Tropospheric Refraction Correction Effect

In some instances, surface weather data is obtained for use in modeling the troposphere, and in some of these cases, the modeled troposphere is held fixed, while in others a tropospheric scale parameter is determined. When surface weather is not obtained, the scale parameter is used. A short test was conducted to determine if the solution was significantly different, particularly when the ephemeris is changed to reflect the revised GM and include satellite antenna offset. Joseph Anderson of the Naval Surface Weapons Center found any differences were below the meter level (Table 4).

Z Bias

Hothem[2] found a bias between the z coordinates of three Doppler and laser stations in the United States, as referred to earlier. Grappo, as shown earlier, found that a large number (1100) stations or as few as 300 stations balanced between northern and southern hemisphere yield the same semimajor axis (within a meter). The author selected 27 moderately balanced stations, and inspection of the height residuals in Table 3 reveals a possible z bias as large as 9 m. Application of a 9-m z bias increases the semimajor axis based on the 27 sites to 6378138.5 ± 8 and reduces the rms residuals for the 27 sites from 5.8 to 4.1 m. Such an increase does not occur with a larger number, better distributed set of sites.

LASER SOLUTION FOR EARTH'S SEMIMAJOR AXIS

LASER RESULTS FOR EARTH'S SEMIMAJOR AXIS

In 1977, laser data was used by Gaposchkin[4] to obtain a semimajor axis of 6378136 ± 1 corresponding to GM = 398600.5. Rapp[5] quotes Gaposchkin as currently quoting his best estimate as 6378138 and Lerch's estimate of 6378139 ± 1 when LAGEOS data is included. The author, using laser positions for 13 sites at 11 geographic locations given in Table 5 and Figure 3, provided by J. Marsh of Goddard Space Flight Center, obtained a = 6378138.7 ± .9, 1/f = 298.258 for GM = 398600.5, in reasonable agreement with the values cited by Gaposchkin and Lerch.

EVALUATION OF LASER SOLUTION

Medium-Long Wavelength Effects

An upper limit for the long wavelength effect may be estimated from the relatively independent gravity fields GEM10B and WGS 72. At the 11 geographic locations of the laser sites, the mean difference in the two fields is 1.7 m in the direction that would reduce the difference between laser and Doppler solutions. At 10 latitudes equally spaced along the 0° and 90° meridians, the mean differences are 1.6 and 1.2 m, respectively, in a direction that would resolve the discrepancy, while at a meridian of 270° (the approximate mean longitude of most of the laser sites) the mean difference is 2.5 m in a direction that would exasperate the laser-Doppler difference. Since these mean differences are larger than the standard error of the mean semimajor axis based on laser data, the result implies either that the GEM10B gravity field is more accurate than the difference between the WGS 72 and GEM10B fields (not unreasonable) or that the laser locations (Figure 3) are not sufficiently dispersed to sense errors in the medium wavelength field (also not unreasonable).

Short Wavelength Effects

The GEM10B geoid does not represent wavelengths shorter than 5°, and the question of the averaging of high-frequency effects is particularly pertinent with only 11 locations represented. Of these, Utah, GSFC, Patrick, and Australia appear to be in relatively benign areas. Bermuda is the site of a high-frequency anomaly evident either in surface gravimetry (Figure 4) or altimetric geoids (Figure 5) in a direction that would reduce the discrepancy between Doppler and laser values of "a." The California sites, the Grand Turk site, and possibly the Australian site are also in disturbed areas but in unknown direction. The remaining sites either have inadequate high-frequency data for evaluation and/or are in mountainous regions that may produce anomalies.

Statistical Significance

The standard error of the laser semimajor axis will reflect the long and short wavelength uncertainties referred to above to the extent that the sites are sufficiently dispersed. However, even for a random process, the standard error of the solution itself is uncertain to 43% at 95% confidence when only 11 independent samples are available[6].

In the discussion of the Doppler results above, it was shown that reduction of the station set from 300 to 27 led to a larger apparent z bias that would increase the semimajor axis for the reduced network. Table 4 shows the effect of assuming a z bias of 3 m in the laser sites is to increase the rms residuals from 2.9 to 3.5 m and to decrease the semimajor axis by 1 m.

Geographic Limitations

Huber[3] shows limiting the station coverage gives the following results:

Southern Hemisphere	6378138.5 ± .5 (95 sites)
Equatorial Belt	6378139.2 ± .6 (76 sites)
Contiguous United States	6378134.4 ± .2 (110 sites)
Canada	6378133.7 ± .1 (177 sites)

This is another statement of the long wavelength effect referred to above and gives a result consistent with Lachapelle[7] for Canadian sites.

ALTIMETRIC SOLUTIONS FOR EARTH'S SEMIMAJOR AXIS

BACKGROUND

Since the radius to the GEOS-3 and SEASAT-1 satellites is known from ground observations of the spacecraft motion, an ellipsoid can be fit to the ocean geoid defined by the altimeter observations from the satellite to the ocean surface. The ellipsoid solutions discussed below are not completely independent of Doppler data, since the satellite orbits used in the computations were based on Doppler observations. However, the mean radius to the satellite is controlled by the satellite orbit period, which is well defined by Doppler tracking.

GEOS-3 ALTIMETRIC CONTRIBUTION TO SOLUTION FOR EARTH'S SEMIMAJOR AXIS (TANENBAUM)

Mark Tanenbaum, fitting an ellipsoid radius and origin to 5X5° mean geometric geoid heights based on the DMAAC 1977 GEOS-3 altimeter geoid[8], found that for a GM = 398600.5 the corrections to an ellipsoid with a = 6378135 m were:

Solution	Gravimetric Field	dx	dy	dz	da
1	NWL10E	.1	.6	2.4	-.5
2	A10H01	.2	.6	2.7	-.5
3	B10H01	-.1	.5	2.5	-.5
4	C10H01	-.2	.5	2.6	-.5
5	A10H01	.5	.7	2.7	-.5
6	GEM10B	.0	.3	2.6	-.5

The gravity field for solution 1 is based purely on satellite data. Fields 2, 3, and 4 have gravimetry and altimetry added to the satellite data with successively increasing weights. The field for solution 5 is based on the same data as that used in solution 2 but was developed with a different suppression of gravity parameters. (In developing the WGS 72 model, Tanenbaum found that an increase of 2.5 km^3/sec^2 resulted in a +11-m shift of the z coordinates of the stations, so that the change from 398601 in GM, on which NWL9D and 9Z coordinates are based, to 398600.5, on which the above ellipsoid calculations are based, might be expected to change the z coordinates by 2.2 m.) However, zonal coefficients were free in the WGS 72 experiment and fixed in the above calculations. (Recomputation of Doppler positions using orbits based on the latest GM value did not exhibit a bias in z.) It should be noted that 2.5 m was subtracted from the DMAAC altimetric geoid heights before the above calculations were performed to account for correction of the equipment delay used in the calculation and for the GM used in the ephemeris generation. This correction differs from the recommended value of 1.15 m given by West[9] who provided an incorrect GM correction.

GEOS-3 ALTIMETRIC VALUE FOR THE EARTH'S SEMIMAJOR AXIS (RAPP)

Richard Rapp of Ohio State University used the same GEOS-3 altimetric geoid source data as Tanenbaum to determine a value for the earth's semimajor axis based solely on the altimetric data. His result of 6378137 m is 2.5 m higher than Tanenbaum's value, which was based on a somewhat different statistical treatment of the data.

SEASAT-1 ALTIMETRIC VALUE FOR THE EARTH'S SEMIMAJOR AXIS (WEST)

Gladys West of the Naval Surface Weapons Center solved for the radius the origin of an ellipsoid best fitting SEASAT-1 altimetric observations that had been averaged to two points per second. Her least-squares fit was based on mean geoid heights in 5° squares for satellite tracks on 11 days selected from the time period day 207 to 225 weighted by the number of observations in each square. She repeated the solution for data observed on 12 different days selected from the time period day 211 to 239 to evaluate the consistency of the results. The solutions were made using the DoD WGS 72 as the reference geoid, and the solution for the first span was repeated using GEM10B as the reference geoid. West's solutions were, in meters:

Solution	Reference Geoid	No. Points	Δx	Δy	Δz	a
1	WGS 72	910,074	.1	-.2	.2	6378134.7
2	WGS 72		.1	.0	.0	6378134.8
3	GEM10B		.2	-.4	.3	6378135.8

EVALUATION OF ALTIMETRIC SOLUTIONS

Although only altimetric data obtained over the ocean areas can be used for the computation of the earth's radius, the data is used to adjust a geoid defined by spherical harmonics in a manner similar to that followed in using Doppler or laser geometric determinations of geoid height. Since the low-frequency errors in the geoid defined by spherical harmonics are very small, little aliasing is expected due to the lack of data over land. On the other hand, the high density of altimeter observations can be expected to be considerably more effective in averaging out high-frequency variations in the gravity field than the averaging obtained using data at the relatively few ground tracking sites.

The three above solutions for the earth's radius differed in some way. Tanenbaum and Rapp both used GEOS-3 data and Doppler satellite orbits but gave different statistical treatment to the altimeter data. Tanenbaum's solution was based on mixed data types, although he tested solutions with varying data weights, while Rapp's solution was based solely on altimetry. West's solution was purely altimetric but used data from the SEASAT-1 altimeter rather than from GEOS-3. The SEASAT data included more ocean area than GEOS and would be subject to different altimeter biases. Although both GEOS-3 and SEASAT satellite orbits were based on Doppler observations, calculations for the former were based on NWL9Z station coordinates and required scaling to the currently accepted value for the earth's gravitational constant, GM, while the SEASAT orbits were based on

NWL11Z station coordinates, the current value of GM, and considered the Doppler antenna vertical offset from the center of mass of the satellite. Although the mean orbit radius is affected in a predictable way by these differences, orbital eccentricity can be affected due to unbalanced geographic distribution of stations, and therefore the mean earth's radius could be affected by unbalanced geographic distribution of altimetric data.

SUMMARY AND CONCLUSIONS

Various data sets have yielded the following results for the earth's semimajor axis:

Doppler Station Positions	6378136.0 ± .1
Laser Station Positions	6378139 ± 1
Satellite Altimetry	
GEOS-3 (Tanenbaum)	6378134.5
GEOS-3 (Rapp)	6378137
SEASAT-1	6378135.2

A semimajor axis of 6378136 ± 2 is consistent with the expected random and systematic errors of the various results.

REFERENCES

1. Langley, R. B., et al, "LBI and Satellite Doppler: Baseline Comparisons," ***Proceedings of the 2nd International Geodetic Symposium on Satellite Doppler Positioning***, University of Texas, Austin, Texas, January 1979.

2. Hothem, Larry D., "Determination of Accuracy, Orientation and Scale of Satellite Doppler Point-Positioning Coordinates," Ibid.

3. Huber, Donovan H., ***Estimation of the Equatorial Radius for the Mean Earth Ellipsoid from a Comparison of Geoid Heights***, Defense Mapping Agency Aerospace Center, St. Louis, Mo., in preparation.

4. Gaposchkin, E. M., "Gravity-field determination from laser observations," ***Philosophical Transactions of the Royal Society***, London, England A284, 1977, 515-527.

5. Rapp, Richard H., letter to Helmet Moritz, Ohio State University, Columbus, Ohio, 12 February 1979.

6. Greenwood, Joseph A., "Sample size required for estimating the standard deviation as a percent of its true value," ***Journal of the American Statistical Association***, June 1950, 257-264.

7. Lachapelle, Gerard, "Comparison of Doppler-derived and gravimetric geoid undulations in North America," ***Proceedings of the 2nd International Geodetic Symposium on Satellite Doppler Positioning***, University of Texas, Austin, Texas, January 1979.

8. Brace, Kenneth L., ***Preliminary Ocean-Area Geoid from GEOS-3 Satellite Radar Altimetry***, Defense Mapping Agency Aerospace Center preprint, St. Louis, MO., November 1977.

9. West, Gladys B., "Filtering of GEOS-3 Radar Altimeter Data at NSWC/DL," ***Journal of Geophysical Research*** (in press). Preprint of paper presented at meeting of GEOS-3 principal investigators, New Orleans, LA., November 18-19, 1977.

10. Mader, Gerald L., ***A revised 5' gravimetric geoid and associated errors for the North Atlantic calibration area***, NASA Contractor Report 156851, February 1979.

APPENDIX A

TABLES

Table 1. Effect on Computed Station Positions of GM Change and Satellite Antenna Offset

	Difference in Position 11Z-9Z		
	Latitude	Longitude	Height
Mean*	+.15 m	+.21 m	-2.17 m
Std. Err.	.09	.25	.11

*The test involved 20 days at observations of one satellite (days 269-288 of 1977) from 21 stations. Data filtering was not controlled to be the same in the two runs and data received in the computing center too late for the original solution was used in the recomputed solution.

Table 2. Effect at 11 Geoceiver Sites of GM Change and Satellite Antenna Offset

			Difference in Position 11Z-9Z		
Station	ϕ, deg	λ, deg	$\Delta\phi$, in.	$\Delta\lambda$, in.	ΔH, m
30126	-4	15	+.010	.001	-2.4
30203	-1	37	.004	.009	-2.5
30124	36	51	.009	-.006	-2.2
30121	0	282	-.009	.002	-2.3
30120	-17	292	-.003	.001	-2.2
20284	37	15	.005	-.004	-2.2
30414	51	246	.003	-.006	-2.2
30130	35	34	.011	-.004	-2.2
30188	21	202	.012	.001	-2.2
30122	-25	302	-.003	.000	-2.3
30800	14	100	.003	.000	-2.5
Mean			.003	-.001	-2.29
Std. Dev.			.006	.004	.12
Std. Err.			.002	.001	.03

Table 3. Doppler Height Comparisons

Sta. No.	Location	Latitude		Longitude		hmsl	he*	GEM10B Gravimetric-Geometric
23	Guam	13°	26′	144°	38′	38.13 m	84.6 m	-6.1 m
30800	Thailand	13	48	100	35	15.34	-22.3	1.3
22	Philippines	14	59	122	4	11.5	49.2	-.0
30188	Hawaii	21	19	202	4	4.01	9.66	(-4.7)**
340	Hawaii	21	31	202	0	401.19	407.4	(-5.3)**
113	New Mexico	32	17	253	15	1205.84	1172.8	4.5
30967	Bermuda	32	19	295	10	24.30	-13.8	-7.9
330	California	34	7	240	56	461.56	402.2	(17.0)**
30130	Cyprus	35	0	33	44	101.90	118.43	7.6
30124	Tehren	35	45	51	23	1421.22	1415.74	1.6
20284	Sicily	37	24	14	56	20.83	53.53	-2.6
107	Virginia	38	60	282	41	118.60	76.84	1.4
27	Japan	39	6	141	8	82.6	114.1	(-6.9)**
30078	Massachusetts	42	37	288	31	140.551		3.0
641	Florence	43	48	11	14	100.30	137.4	4.6
311	Maine	44	24	291	59	25.88	-11.6	(9.4)**
128	Ottawa	45	24	284	5	86.08	40.57	7.7
320	Minnesota	44	44	266	55	299.5	259.7	(4.7)**
31	Uccle	50	48	4	22	115.8	148.2	8.3
30414	Calgary	50	52	245	42	1267.8	1238.2	8.6
116	England	51	11	358	37	78.928	116.0	(6.9)**
114	Alaska	61	17	210	10	67.6	67.3	9.3
118	Greenland	76	32	291	15	54.79	59.1	6.8
30121	Quito	-0	5	281	35	1682.59	2703.99	-10.6
30203	Kenya	-1	20	36	49	1677.31	1656.73	-2.7
30126	Zaire	-4	22	15	15	453.88	448.62	1.3
20	Seychelles	-4	40	55	29	592.5	546.1	-3.8
24	Samoa	-14	20	189	17	9.2	39.1	(-9.1)**
30120	La Paz	-16	32	291	50	4041.93	4085.44	-8.6
30793	Townsville	-19	16	146	45	6.41	58.13	1.1
8	Brazil	-23	1	314	8	612.68	605.3	-5.1
30122	Paraguay	-25	18	302	23	177.16	189.4	-3.6
30105	So. Africa	-25	57	38	21	1580.56	1600.9	-2.6
112	Australia	-34	40	138	39	34.44	30.3	-4.1
19	McMordo	-77	51	166	40	38.2	-17.8	-9.4

*NWL9Z heights with respect to a = 6378145, 1/f = 298.25.

**Not included in ellipsoid calculation either because of high-frequency geoid error near station (Japan and Hawaii), coordinates not available at time of least-squares fit, or to reduce number of NAD stations.

NOTE: Geometric positions in * scaled to GM = 398600.5 and corrected for satellite antenna offset give a = 6378136.5 ± 1.1, 1/f = 298.258.

Table 4. Tropospheric Refraction Parameter Test (Correction in Height to Meters)

Station	Location	ΔH(with Tropo. Parameter)	ΔH(w/o Tropo. Parameter)
	Ephemeris with GM = 398601.0, no satellite antenna offset		
20073	South Pole	0.7	-0.1
30188	Hawaii	+2.6	2.5
30144	Calgary	0.8	-0.3
	Ephemeris with GM = 398600.5, with satellite antenna offset; nominal station height decreased 2.4 m		
20073	South Pole	0.5	-0.1
30188	Hawaii	2.5	2.7
30144	Calgary	0.6	-0.2

Table 5. Laser Height Comparisons for 13 Sites at 11 Geographic Locations

Sta. No.	Location	Latitude		Longitude		hmse	he*	GEM10B Gravimetric-Geometric**	GEM10B Gravimetric–Geometric†
7051	Quincy	39°	58'	239°	4'	1087.08 m	1046.34 m	-2.45 m	-1.49 m
7062	San Diego	32	36	243	10	1025.57	975.00	-.57	.08
7063	GSFC	39	1	283	10	56.16	4.70	1.25	2.17
7065	GSFC	39	1	283	10	55.29	3.67	1.41	2.33
7067	Bermuda	32	21	295	21	13.44	-36.87	-4.97	-4.33
7068	Grand Turk	21	28	288	52	28.52	-32.36	-.80	-.67
7069	Patrick	28	14	279	24	9.96	37.24	2.80	2.25
7081	Patrick	28	14	279	24	5.24	-41.70	2.57	3.02
7082	Bear Lake	41	56	248	35	1980.29	1948.76	2.35	3.38
9907	Arequipa	-16	28	288	30	2452.27	2475.99	-4.44	-6.26
9921	Mt. Hopkins	31	41	249	7	2383.39	2334.76	4.64	5.25
9929	Natal	-5	56	324	50	45.6	22.70	1.48	.20
9943	Orroral	-35	37	148	57	929.53	932.45	-3.26	-5.98
								0 ± 2.90	0 ± 3.5

*a = 6378155 m, 1/f = 298.255, GM = 398600.64(?)

**Geometric positions in * scaled to GM = 398600.5 give 6378138.63 ± 0.9, 1/f = 298.258.

†Geometric positions in * scaled to GM = 398600.5 and translated 3. m in z (3.0 sin ψ) give 6378137.66 ± 1.1.

APPENDIX B

FIGURES

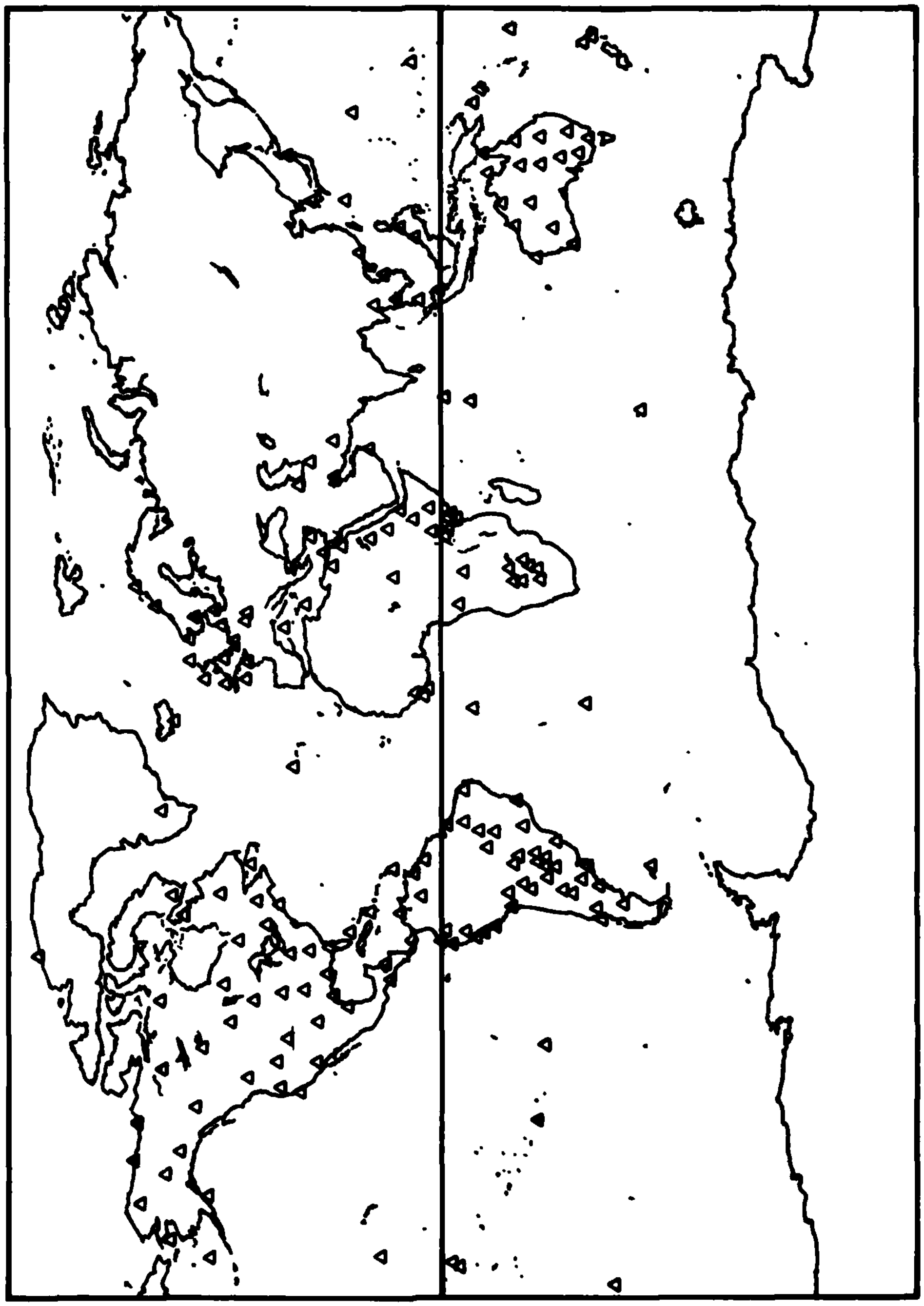


Figure 1. 201 Doppler Stations Used by Huber

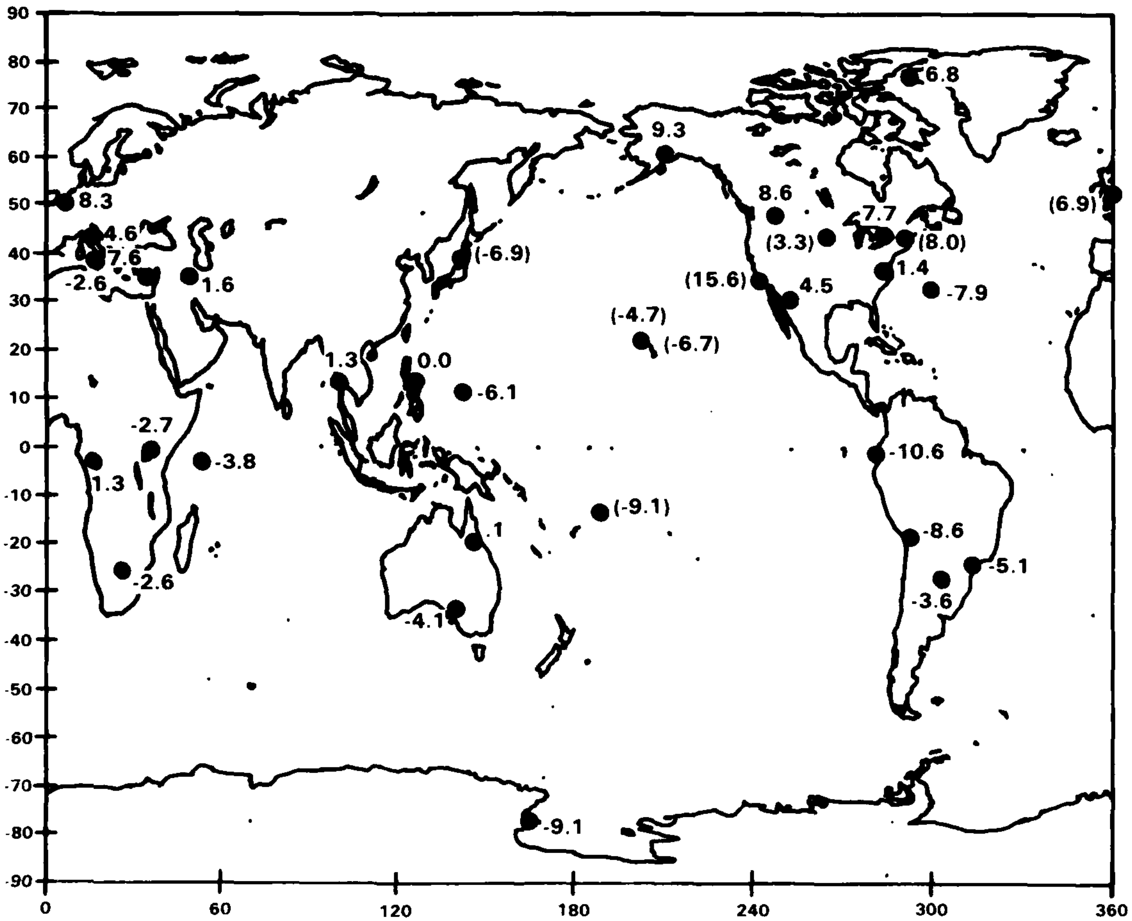


Figure 2. Height Residuals for 35 Doppler Locations Studied by Anderle

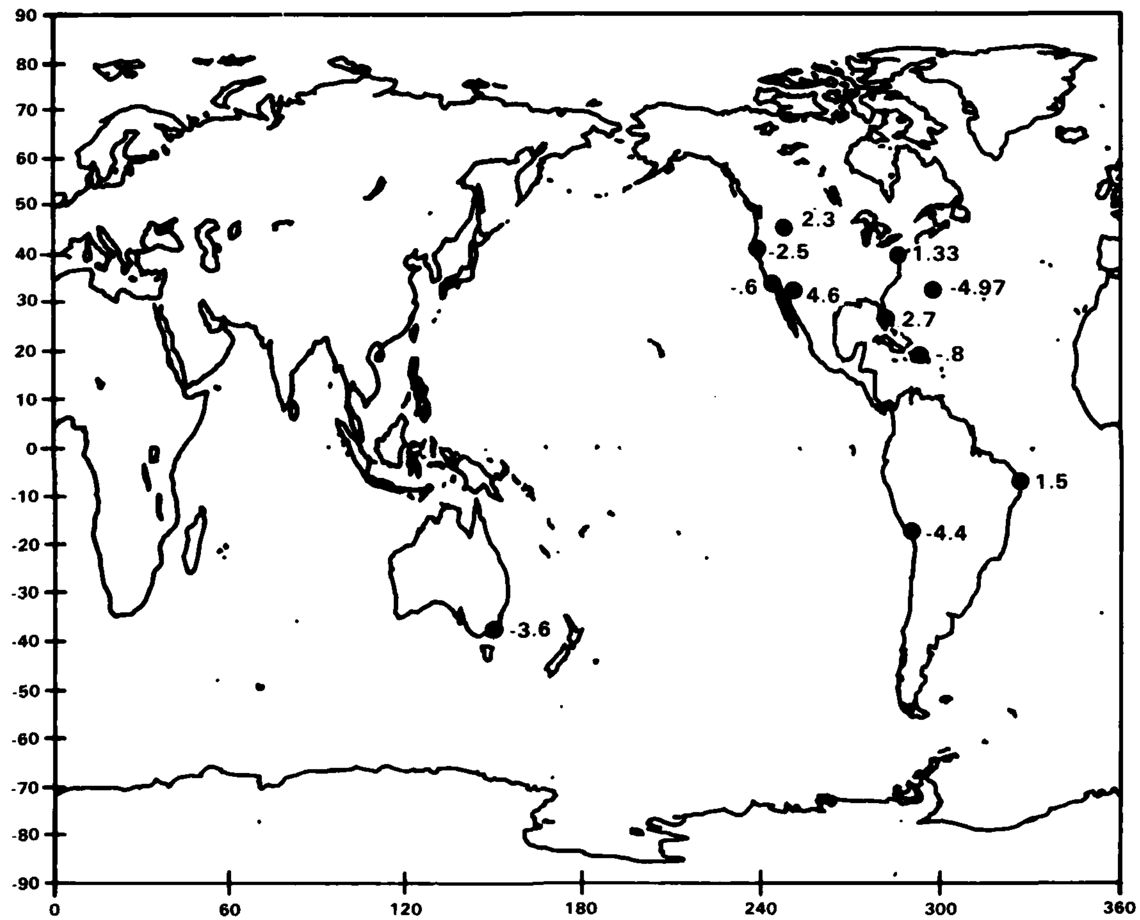


Figure 3. Height Residuals (m) for 11 Laser Locations Used by Anderle

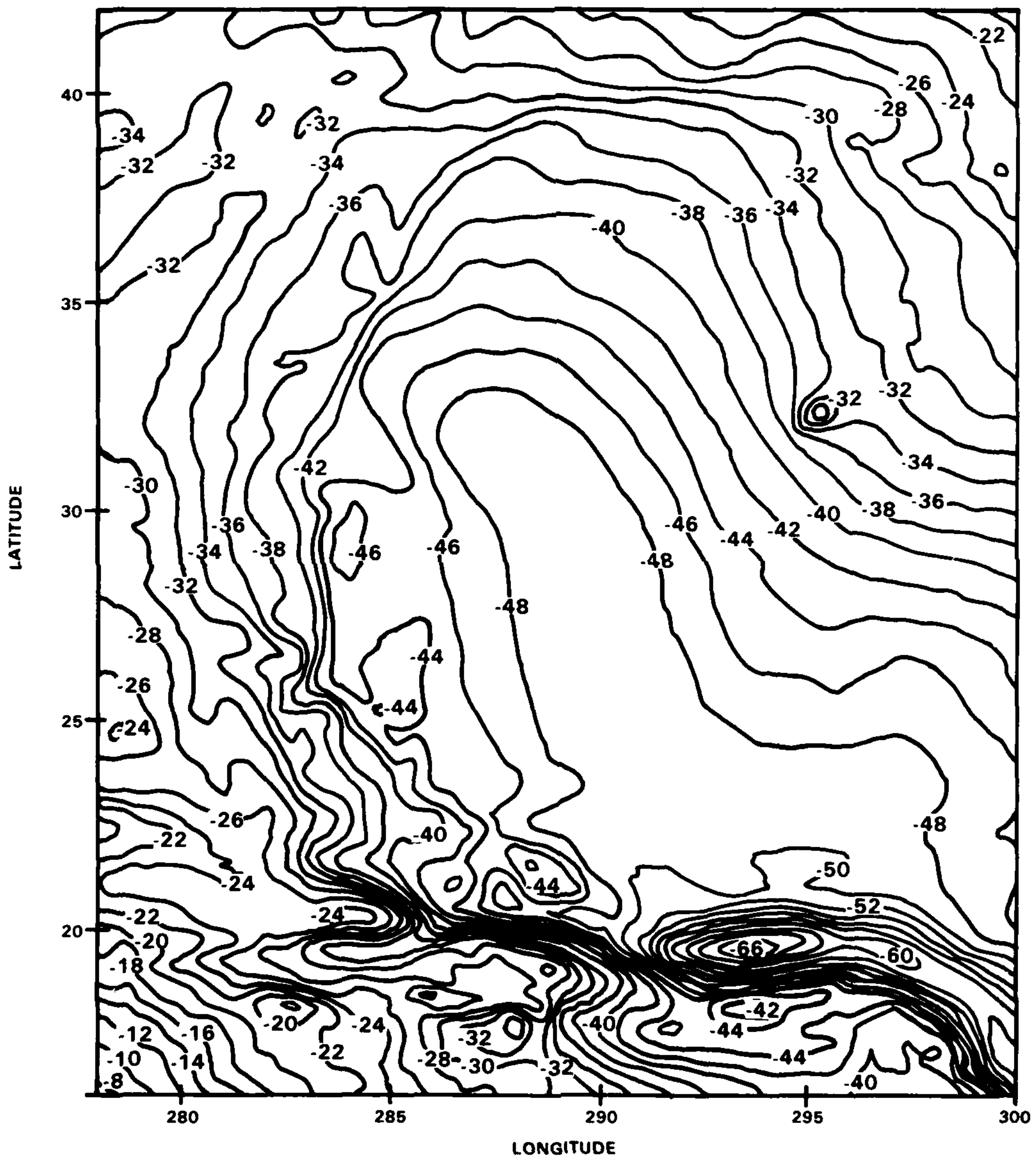


Figure 4. Geoid Undulations for the North Atlantic Calibration Area, Meters[10]

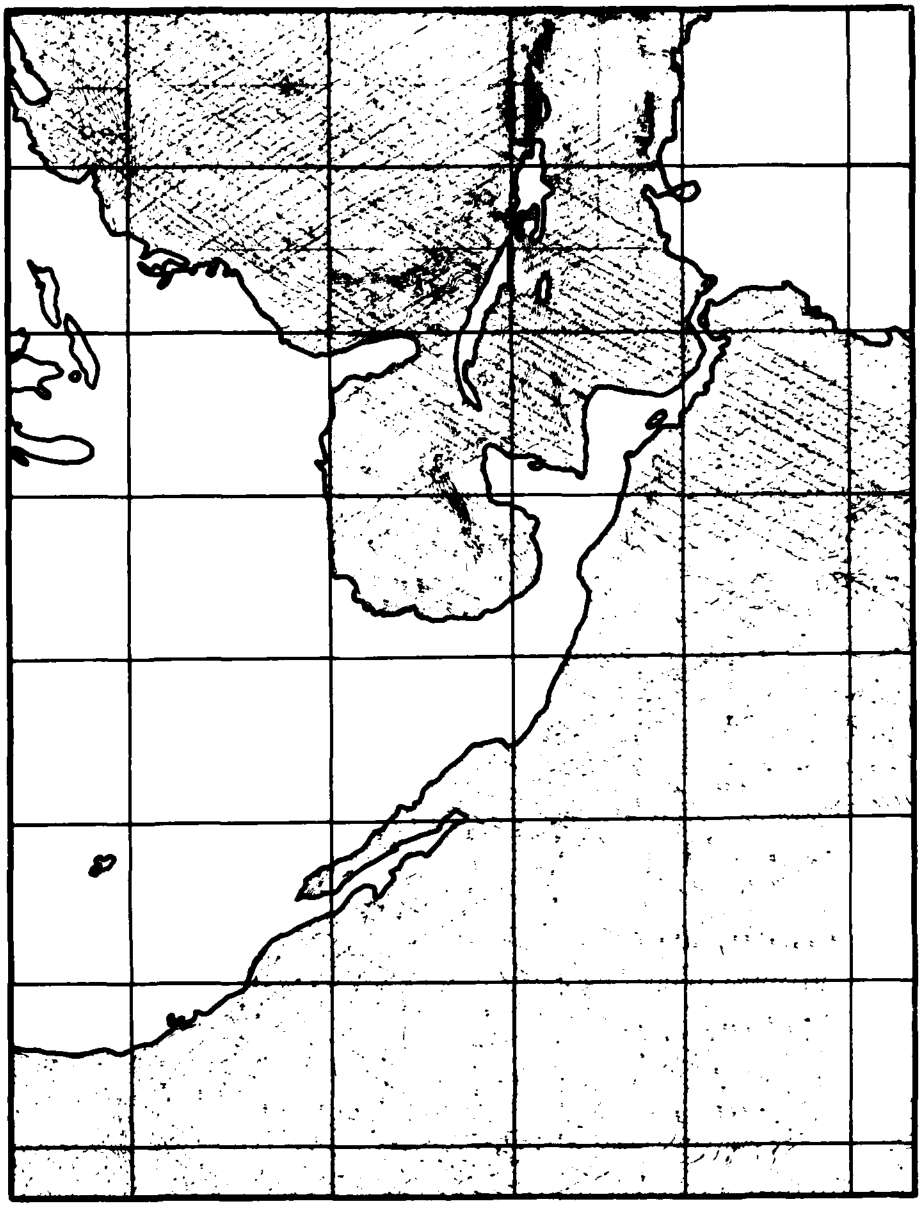


Figure 5. GEOS-3 Preliminary Altimetric Geoid[8]

DISTRIBUTION

Defense Technical Information Center Cameron Station Alexandria, VA 22314	(12)
Library of Congress Washington, DC 20540 Attn: Gift and Exchange Division	(4)
National Aeronautics and Space Administration Scientific and Technical Information Facility Box 5700 Bethesda, MD 20014 Attn: Technical Library	(2)
Director Defense Mapping Agency Washington, DC 20305	(3)
Director Defense Mapping Agency Hydrographic/Topographic Center Washington, DC 20390 Attn: Mrs. Carolyn Leroy	(3)
Director Defense Mapping Agency Aerospace Center St. Louis, MO 63118 Attn: Dr. Robert Ballew	(6)
National Oceanic and Atmospheric Administration National Ocean Survey Rockville, MD 20850 Attn: Dr. John Bossler	(5)
The Ohio State University Department of Geodetic Science 1958 Neil Avenue Columbus, OH 43210 Attn: Dr. Richard Rapp	(5)

Local:

E31 (GIDEP)	
E41	
K10	(30)
K11	(10)
K12	(5)
K13	(10)
X210	(2)
X211	(2)