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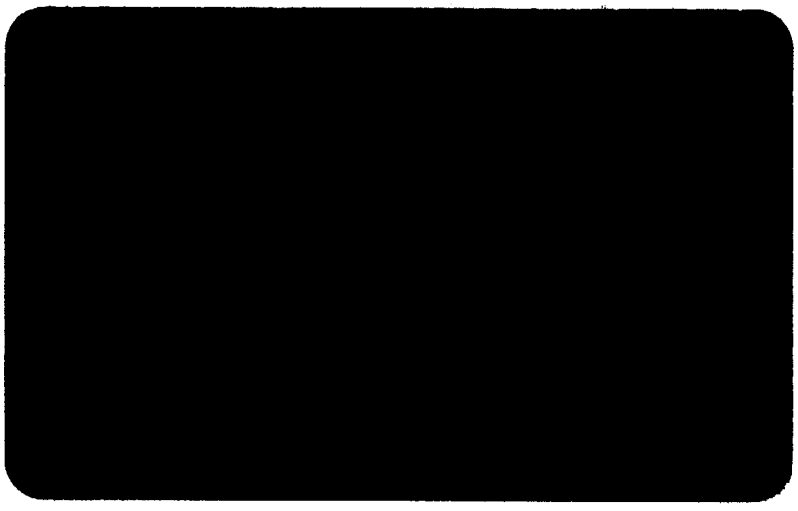

Memorandum M-464

ERS-1 ORBIT DETERMINATION FROM LASER, TRANET AND PRARE TRACKING DATA

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Summary

The significance of orbit determination error analyses heavily depends on the quality of the geometric and dynamic error models applied in the computations. For ERS-1 a realistic error model has been derived both from detailed studies on the accuracy with which forces and geometric parameters can be modeled and from a deterministic simulation approach.

This deterministic method yields orbital differences which arise when, in processing a set of simulated observations, a particular geometric or dynamic phenomenon is modeled in two different ways. Orbital differences were computed for 4 gravity models, 3 atmospheric models and 2 earth albedo models. In addition, the full orbital effects of solid earth tides, solar radiation pressure, earth infrared radiation pressure, station coordinate errors and polar motion were determined. The simulations are based on the nominal 778 km mean-altitude orbit and a 3-day arc consisting of laser tracking data acquired from a global 14-stations network.

The derived error model, which was subsequently used for orbit determination covariance analyses, intends to represent the residual errors after an accurate model for the satellite's geometry and a tailored gravity model, derived from tracking data acquired during the first months in orbit, are available and if in the actual orbit determination process suitable scaling factors, like the satellite's drag and reflection coefficients,are adjusted.

The covariance analyses were performed for 3-day, 2-revolution and 15-minute data arcs. For the 3-day and 2-revolution arcs laser range and TRANET-II range-rate tracking concepts were studied. Two global laser networks, consisting of 14 and 6 stations have been considered. In addition, the effects of laser station dropout due to maintenance or weather problems and of lowering the mean orbital altitude to 670 km have been analyzed. For TRANET tracking three networks, consisting of 45, 16 and 5 stations were considered. For the 45-station network the effects of solving for 12 selected gravity coefficients have been investigated.

The 15-minute arc represents a pass from Northern-Africa over Western-Europe and the North-East Atlantic. Both laser and PRARE range tracking concepts have been studied. The laser network consists of 9 stations; for the PRARE systems 5 locations were selected. A tracking network consisting of 3 laser and 2 PRARE stations was also considered.

The main conclusions are:
- To enable the computation of accurate orbits a tailored gravity model should be developed from ERS-1 tracking data acquired during the first months in orbit. This requires an intense tracking campaign involving many globally distributed tracking systems.
- For the 3-day arc the full 14-stations laser network leads to essentially the same orbit accuracy as the 45-stations TRANET network. In both cases the rms radial and cross-track orbit errors amount to about 58 cm and are dominated by the gravity field model errors.
- If the force model errors could be reduced significantly, the laser network would be superior, because the TRANET systems lead to larger orbit errors due to tropospheric and ionospheric refraction uncertainties.
- For the error model considered a reduction of the number of tracking stations to about 5 hardly deteriorates the radial orbit accuracy.

This paper presents the results of one phase of research carried out under ESOC contract no. 5227/82/D/IM (SC).

To derive these accurate dynamic models, however, a dense tracking network is required during the initial phase of the mission.

- Adjusting simultaneously with the orbit a subset of 12 selected gravity model coefficients leads for the 3-day arc to significant improvements of the radial and along-track orbit accuracy. The rms radial orbit error decreases to 47 cm.
- Lowering the orbit from the nominal mean altitude of 778 km to a mean altitude of 670 km yields an increase of the rms radial orbit error from 58 cm to 92 cm. This increase is mainly due to the larger effects of gravity model errors.
- For the 2-revolution arc the 14-stations laser network is inferior to the 45-stations TRANET network as far as the effects of force model errors are concerned.
- For the 2-revolution arc of TRANET tracking data the orbit errors due to gravity model errors are significantly smaller than for the 3-day arc, while the effects of surface force model errors are negligible. The rms radial orbit error is about 32 cm.
- With laser tracking from 9 stations during the 15-minute arc over Europe, rms radial, cross-track and along-track orbit errors of less than 17 cm are achieved. For the center part of this arc the radial orbit errors are even less than 10 cm.
- For this short arc the 5-stations PRARE network and the combined network of 3 laser and 2 PRARE stations yield larger orbit errors. The results are, however, strongly dependent on the actual locations of the tracking systems and on the accuracy with which their positions are known.

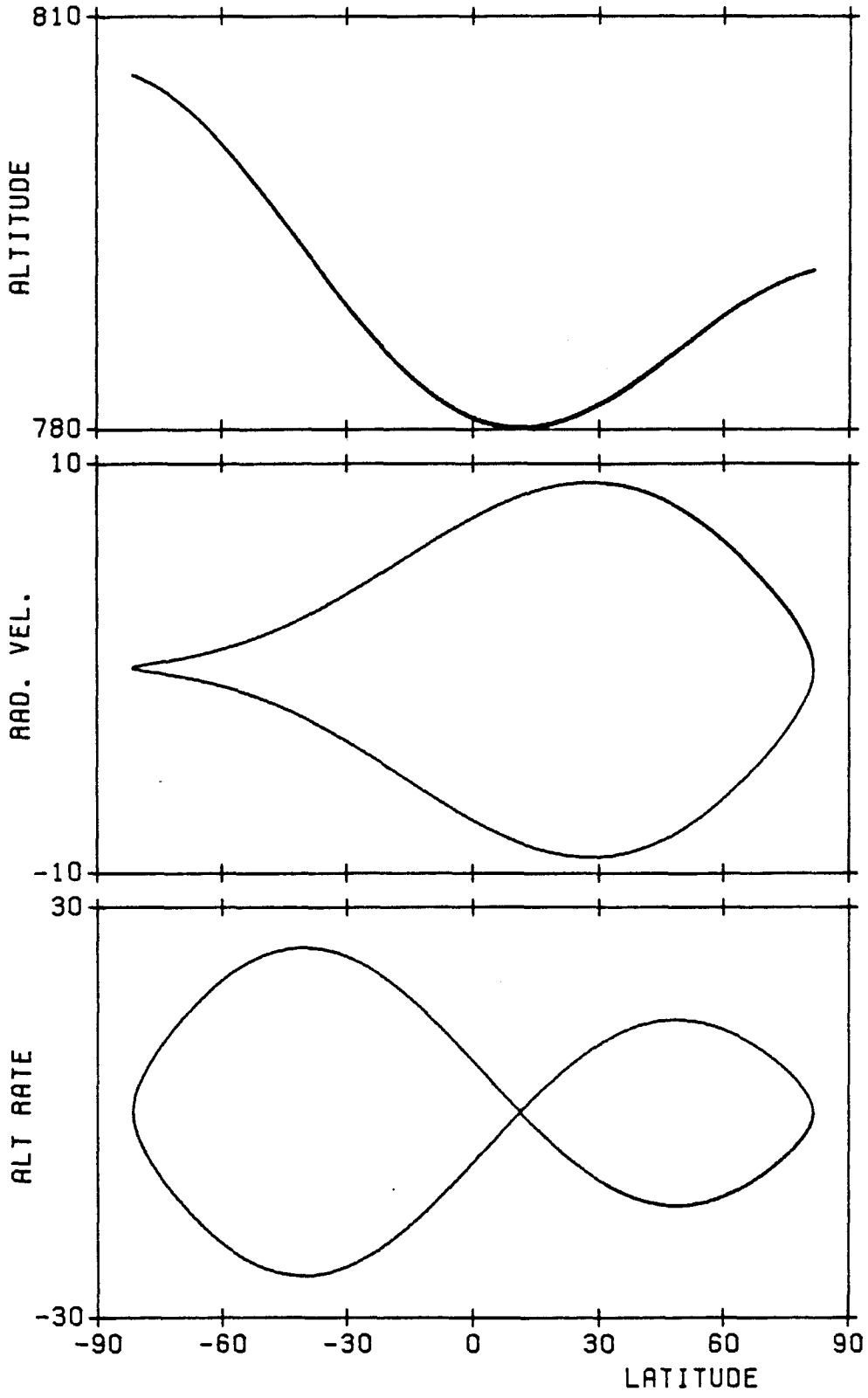
ERS-1 nominal mean and osculating orbital elements.

	Mean elements	Osculating elements
Epoch (UT)	1987/06/21	$12^h0^m0^s$
a (km)	7153.1439	7144.0753
e	0.0010000	0.0006588
i (deg)	98.52146	98.52689
Ω (deg)	247.069	247.069
ω (deg)	90.00	270.00
M (deg)	0.00	180.00

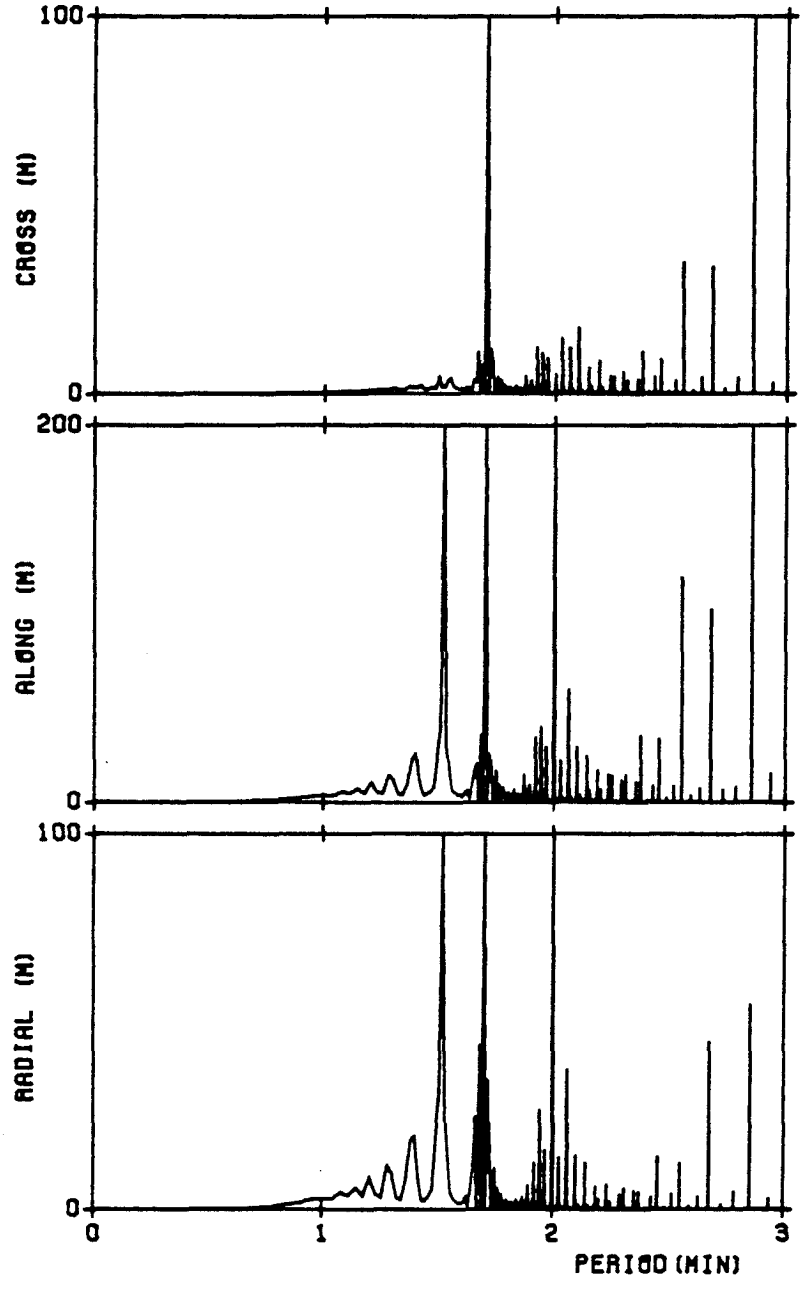
Derived parameters of ERS-1 nominal orbit.

Osculating orbit	
Perigee altitude (km)	780
Apogee altitude (km)	806
Mean Keplerian orbit*	
Perigee altitude (km)	771
Apogee altitude (km)	785
Rates of mean orbital elements (deg/day)	
Ω	0.988
ω	0.49
M	5167.6
Number of nodal revolutions per day	14 1/3
Orbital nodal period (min)	100.46
Local solar time at descending node (hr)	10.4
Ground track repetition period (day)	3
Equatorial spacing of successive tracks (km)	2803
Equatorial spacing of adjacent tracks (km)	934

* relative to a spherical Earth with a radius of 6375 km



The variation of altitude (in km), radial orbital velocity (in m/s) and altitude rate (in m/s) with latitude (in deg).



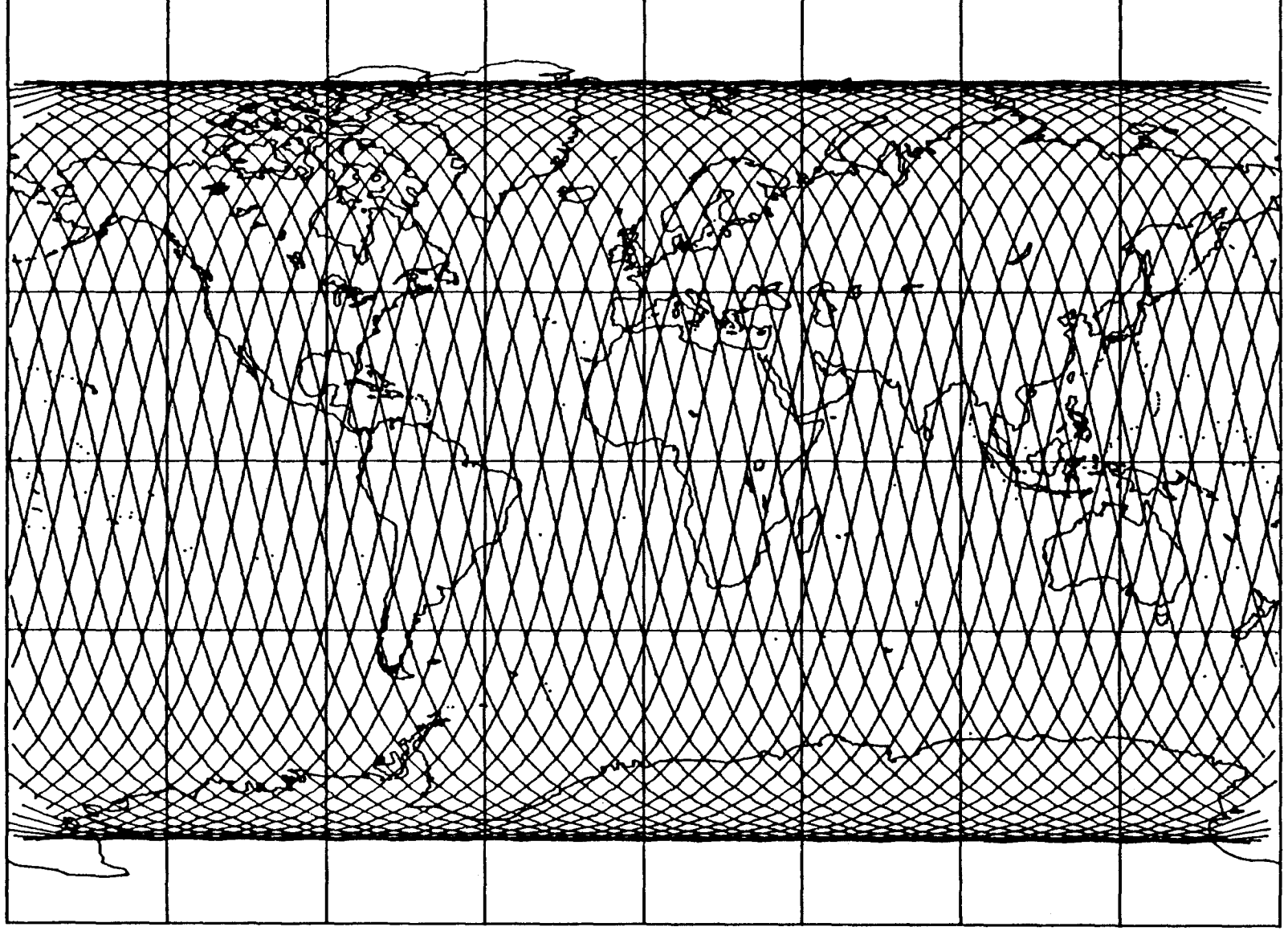
Amplitude spectrum of the radial, cross-track and along-track gravity field perturbations. The horizontal scale ranges from 10^{0} to 10^{3} minutes.

Survey of the maximum magnitudes per unit mass and the directions of the various surface forces acting on ERS-1.

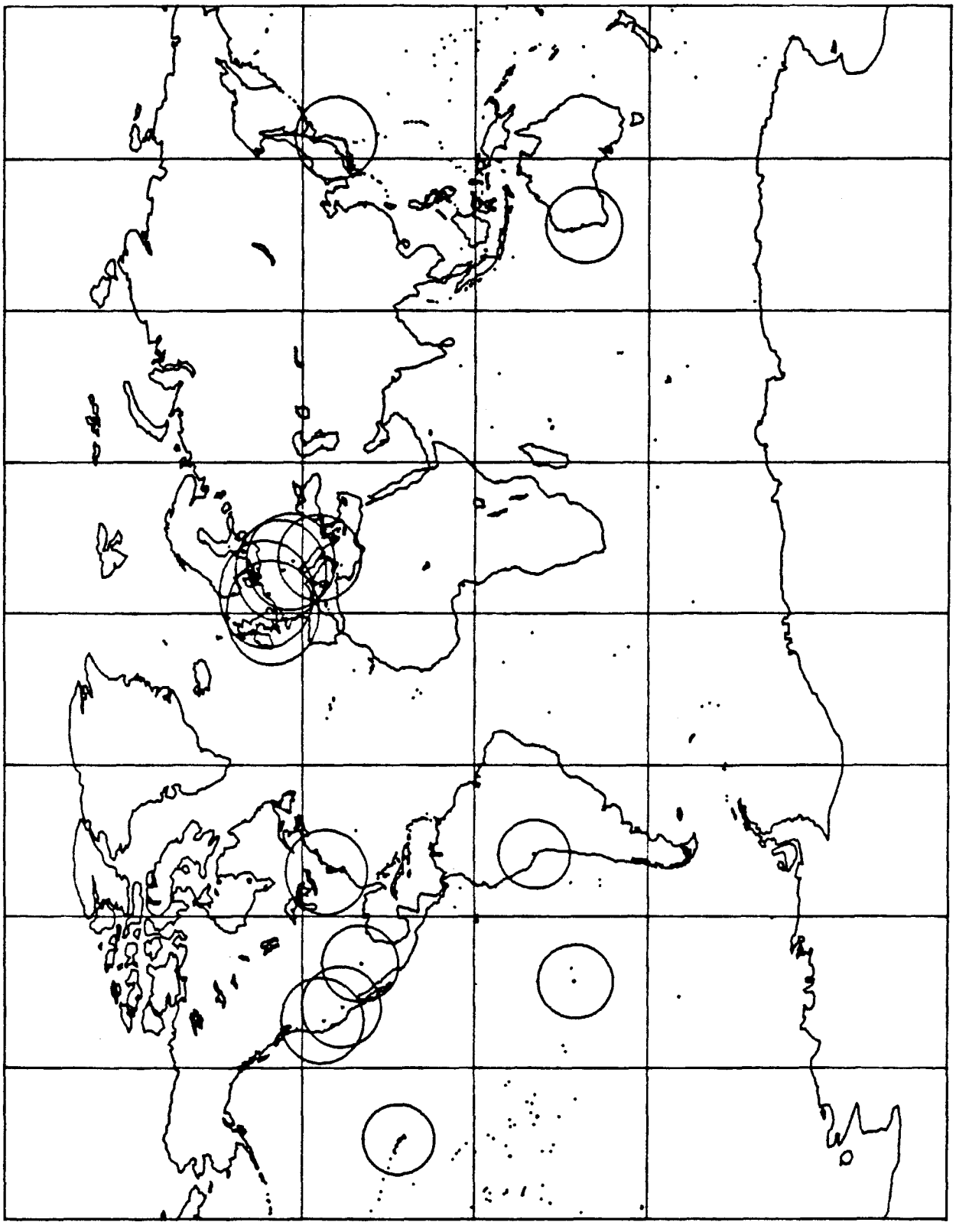
Force	Magnitude (m/s^2)	Direction
Atmospheric drag		
low solar activity	$6.3 * 10^{-9}$	along-track
high solar activity	$1.4 * 10^{-7}$	along-track
Direct solar radiation pressure	$8.7 * 10^{-8}$	sun
Albedo radiation pressure	$2.0 * 10^{-8}$	radial
Infrared radiation pressure	$9.8 * 10^{-9}$	radial
Photonic thrust	$6.0 * 10^{-9}$	sun

Orbit, satellite and tracking parameters for the deterministic dynamic model errors simulation.

ORBIT	Epoch : 76/6/21 , $12^h0^m0^s$
	Elements: a = 7144.1 km ; e = 0.000659 ; i = 98.527 deg
	Ω = 247.069 deg ; ω = 270 deg ; M = 180 deg
SATELLITE	Area-to-mass ratio = 0.01 m^2/kg
	Drag coefficient = 2.3
	Solar and albedo reflectivity = 1.5
TRACKING NETWORK	14 globally distributed laser stations
OBSERVATIONS	Arc length : 3 days
	Type : laser range
	Repetition rate: 1 measurement per 30 s
	Cut-off angle : 30 deg



The ERS-1 ground traces for a 3-days period.



The locations of the 14 laser tracking stations and the visibility contours for an elevation of 30 deg.

Effects of various types of model errors on the solved-for state-vector at epoch and the atmospheric drag coefficient.

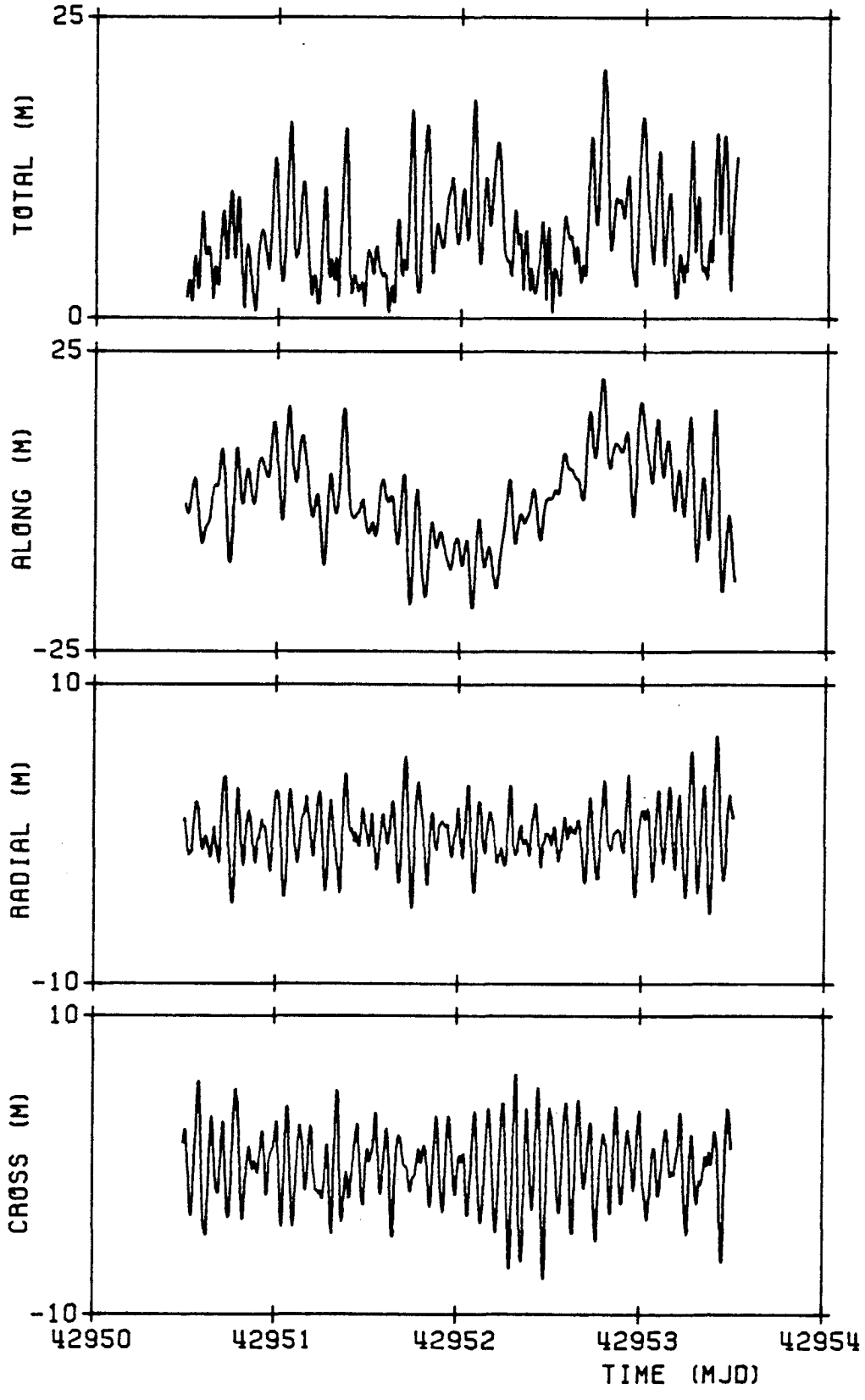
Error source	Observ.generated with	Observ.processed with	Adjusted minus a-priori values C_D	$\|\Delta\bar{r}\|$ (m)	$\|\Delta\bar{V}\|$ (cm/s)
Gravity field	GEM-10	GEM-10B	-0.88	1.81	0.27
	PGS-S4	GEM-10B	0.01	18.35	1.36
	PGS-S4	PGS-S3	-0.25	20.98	1.80
Solid Earth tides	$k_2 = 0.29$	unmodeled	0.32	5.01	0.03
	$\phi_2 = 2.5^o$	$\phi_2 = 0$	-0.02	0.34	0.02
Atmospheric drag	Jacchia 1971	unmodeled	-	30.98	3.19
	Jacchia 1971	Jacchia 1977	-0.41	0.30	0.03
	Jacchia 1971	MSIS	-0.57	0.26	0.03
	$A_p = 3,3,4,16$	$A_p = 3,3,8,16$	-0.12	0.75	0.08
Solar rad. pressure	modeled	unmodeled	-0.11	8.04	0.82
Albedo and infrared rad. pressure	unmodeled	full model	-0.02	0.42	0.04
	unmodeled	simple model	0.00	0.40	0.04
	unmodeled	only infrared	-0.00	0.01	0.00
Station coordinates	nominal coord.	with 20 cm 1σ noise	-0.01	0.04	0.01
Polar motion	modeled	unmodeled	-0.02	3.19	0.45

The effects of applying different models for various dynamic and geometric phenomena on the orbit solution. Listed are maximum/rms values of position differences.

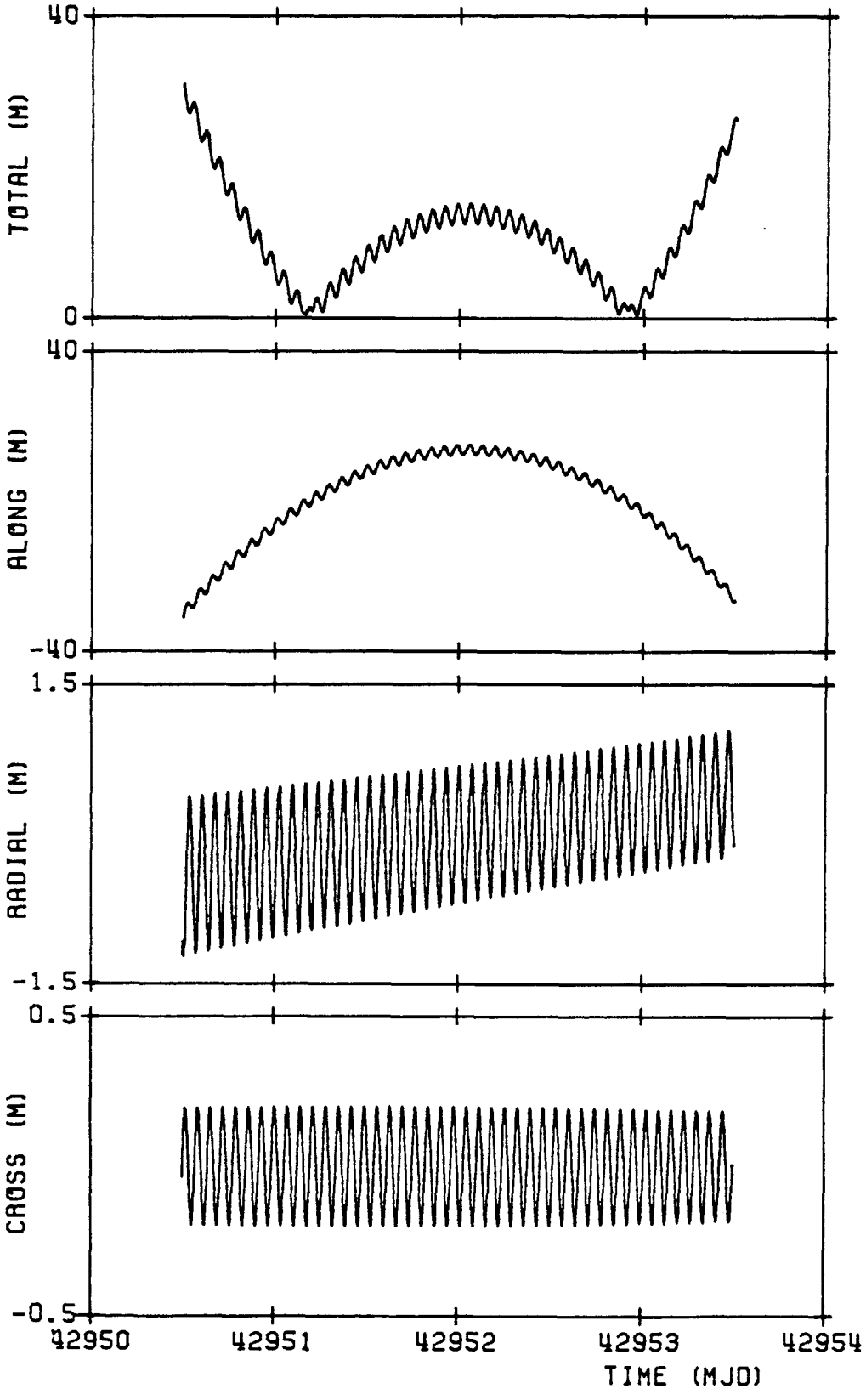
Error source	Comparison	Orbital differences (cm)		
		Radial	Cross-track	Along-track
Gravity field	GEM-10 vs. GEM-10B	657/196	757/245	2054/754
	PGS-S4 vs. GEM-10B	1912/518	1020/402	6264/1650
	PGS-S4 vs. PGS-S3	1487/444	1125/376	4799/1433
Solid Earth tides	modeled vs. unmodeled	8/3	500/184	45/15
	$\phi_2 = 2.5^o$ vs. $\phi_2 = 0$	1/0	68/23	9/2
Atmospheric drag	Jacchia 1971 vs. unmodeled	123/56	20/14	3099/1257
	Jacchia 1971 vs. Jacchia 1977	3/1	0/0	55/15
	Jacchia 1971 vs. MSIS	8/2	0/0	63/15
	A_p = 3,3,4,16 vs. 3,3,8,16	3/1	1/0	77/28
Solar rad. pressure	modeled vs. unmodeled	833/334	100/39	2136/722
Albedo and infrared rad. pressure	unmodeled vs. full model	45/18	2/1	116/40
	unmodeled vs. simple model	42/17	2/1	105/37
	unmodeled vs. only infrared	0/0	0/0	2/1
Station coordinates	nominal coord. vs. with 20 cm. 1σ noise	4/3	9/7	14/7
Polar motion	modeled vs. unmodeled	197/139	318/217	597/303

The reduction of the orbital effects of albedo and Earth's infrared radiation forces by adjusting also for C_R. Listed are the differences in the adjusted parameters and the resulting orbits for a tracking data reduction with vs. a data reduction without modeling the albedo and infrared radiation pressures.

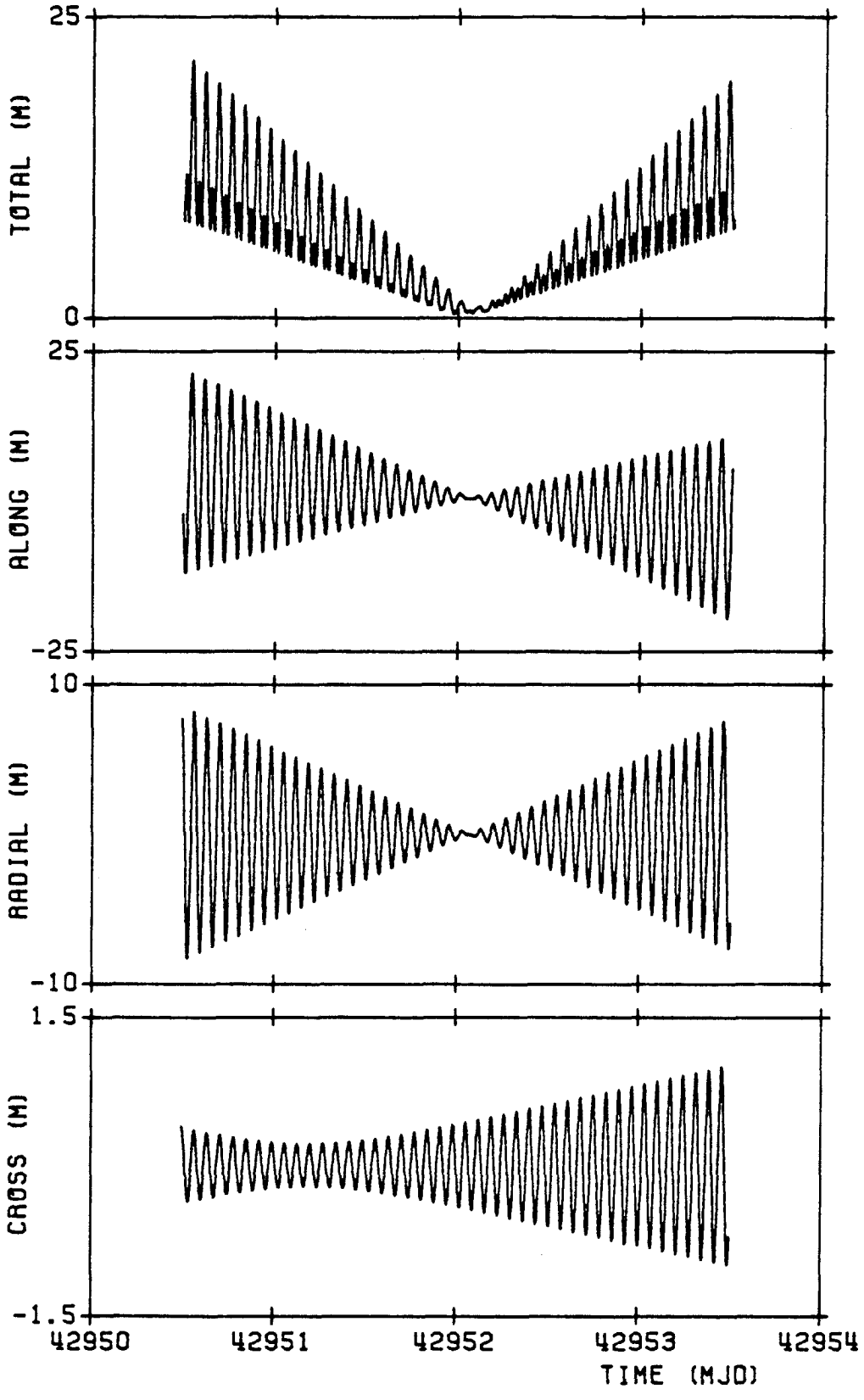
	C_D adjusted	C_D and C_R adjusted
C_D	-0.02	-0.01
C_R	-	0.08
$\|\Delta\bar{r}\|$ (m)	0.42	0.09
$\|\Delta\bar{V}\|$ (cm/s)	0.04	0.00
Rms orbit. diff. (cm)		
radial	18	3
cross-track	1	2
along-track	40	7



The radial, cross-track, along-track and total position differences for the GEM-10B versus the GEM-10 gravity models.



The radial, cross-track, along-track and total position differences for atmospheric drag according to the Jacchia 1971 model versus no atmospheric drag.



The radial, cross-track, along-track and total position differences for solar radiation pressure modeled versus no radiation pressure.

Orbit, satellite and tracking parameters for the 3-day and 2-revolution arcs analyses.

ORBIT	Epoch : 88/6/21 , $12^h0^m0^s$ UT Elements: a = 7144.1 km ; e = 0.00066; i = 98.527 deg; Ω = 247.069 deg; ω = 270 deg; M = 180 deg
SATELLITE	Area/mass ratio = 0.01 m^2/kg Drag coefficient = 2.2 Solar reflectivity = 1.5
LASER TRACKING	full 14-stations network, degraded 14-stations network or degraded 6-stations network
TRANET TRACKING	full 45-stations network, reduced 16-stations network or reduced 5-stations network
OBSERVATIONS	Type : laser range or TRANET range-rate Arc length : 3 days or 2 revolutions Repetition rate : 1 measurement per 30 s Cut-off elevation : 20 deg

The locations of the 45 TRANET tracking stations.

Tracking station	Latitude (deg)	Longitude (deg)
Barton	51.0	359.0
Herndon	39.0	282.7
Las Cruces	32.3	253.3
Mizusawa	39.1	141.1
Pretoria	-25.9	28.4
Smithfield	-35.0	137.0
Sao Paulo	-23.2	314.1
Uccle	50.8	4.4
Ottawa	45.4	284.3
Ukiah	39.0	236.6
Calgary	51.0	245.9
McMurdo	-77.8	186.7
San Miguel	14.3	120.0
Thule	76.5	291.2
Guam	13.5	144.7
Anchorage	61.2	210.2
Mahé	- 4.7	55.5
Tafuna	-14.3	189.3
Napier	-39.7	176.9
Quito	- 0.1	281.6
Townsville	-19.3	147.0
Bangkok	13.7	100.6
Diego Garcia	- 8.0	72.0
Shemya Island	52.7	174.1
Azores	38.7	332.9
Easter Island	-27.2	250.6
St. Helena	-15.9	354.3
Santiago	-33.0	289.0
Perth	-31.6	115.9
Bermuda	32.3	295.3
Kwajalein	8.7	167.7
Hawaii	22.1	200.3
Kourou	4.0	308.0
Canary Island	28.0	344.0
Tahiti	-17.5	210.0
Indonesia	- 8.0	115.0
Spitzbergen	77.5	16.0
Kiruna	67.9	20.2
Reunion	-22.0	55.0
St. Pierre	47.0	305.0
Kenya	0.0	37.0
Ouagadougou	12.4	358.5
Kerguelen Island	-49.1	70.2
Terade	-70.0	140.0
Ascension Island	- 7.5	345.0

The locations of the 14 laser tracking stations.

Tracking station	Latitude (deg)	Longitude (deg)
Arequipa	-16.5	288.5
Greenbelt	39.0	283.2
Goldstone	35.4	243.1
McDonald Obs.	30.7	256.0
Yaragadee	-29.0	115.3
Mauii	20.7	203.7
Quincy	40.0	239.1
Simosato	37.0	141.0
Easter Island	-27.2	250.6
Kootwijk	52.2	5.8
Wettzell	49.1	12.9
Herstmonceux	50.9	0.3
Graz	47.1	15.5
Matera	40.7	16.6

The reduced TRANET and laser stations networks.

The reduced 16-stations TRANET network

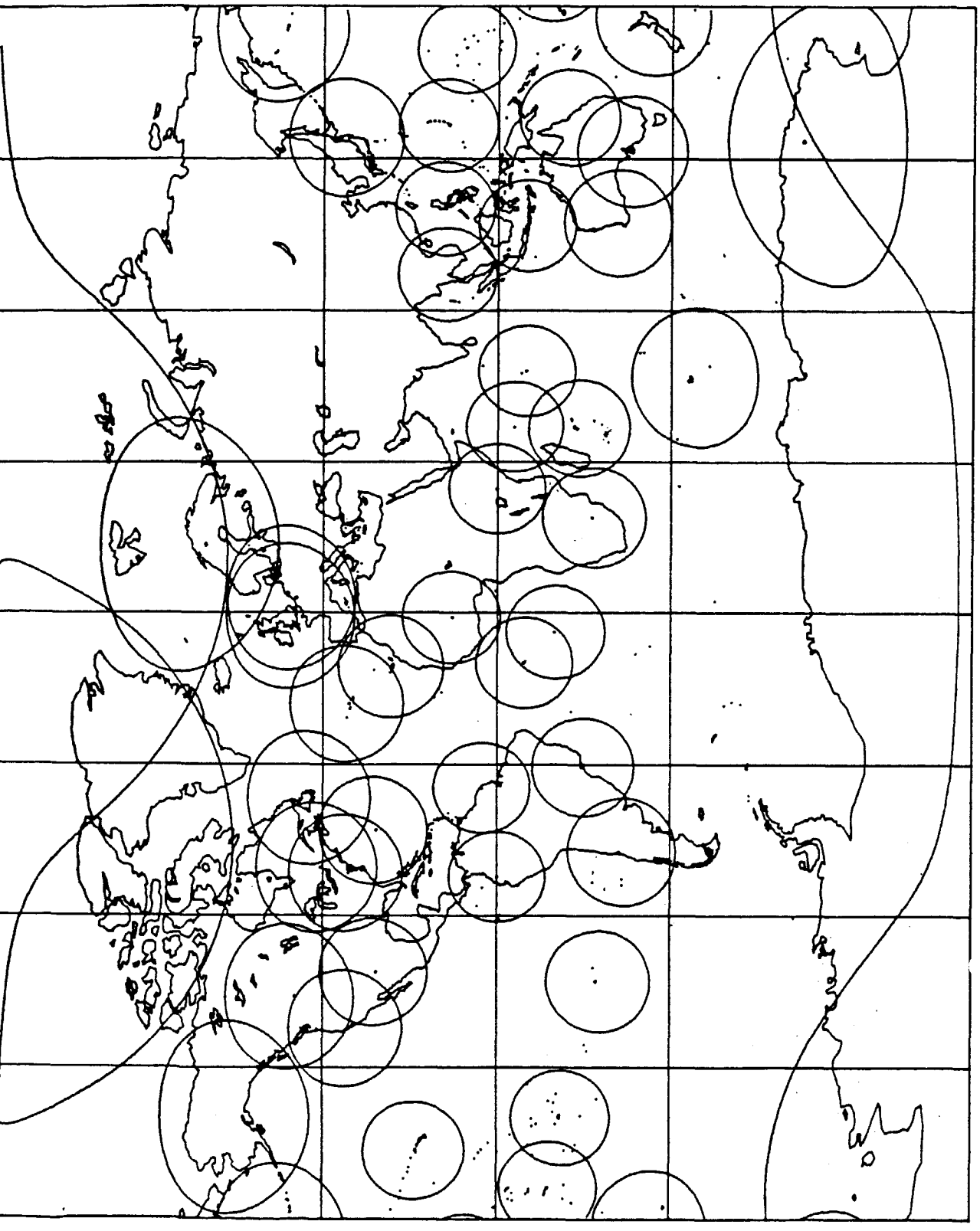
Mizusawa	Pretoria	Uccle
Ukiah	McMurdo	Anchorage
Townsville	Bangkok	Easter Island
Santiago	Perth	Kourou
Tahiti	Kiruna	Kenya
Ascension Isl.		

The reduced 5-stations TRANET network

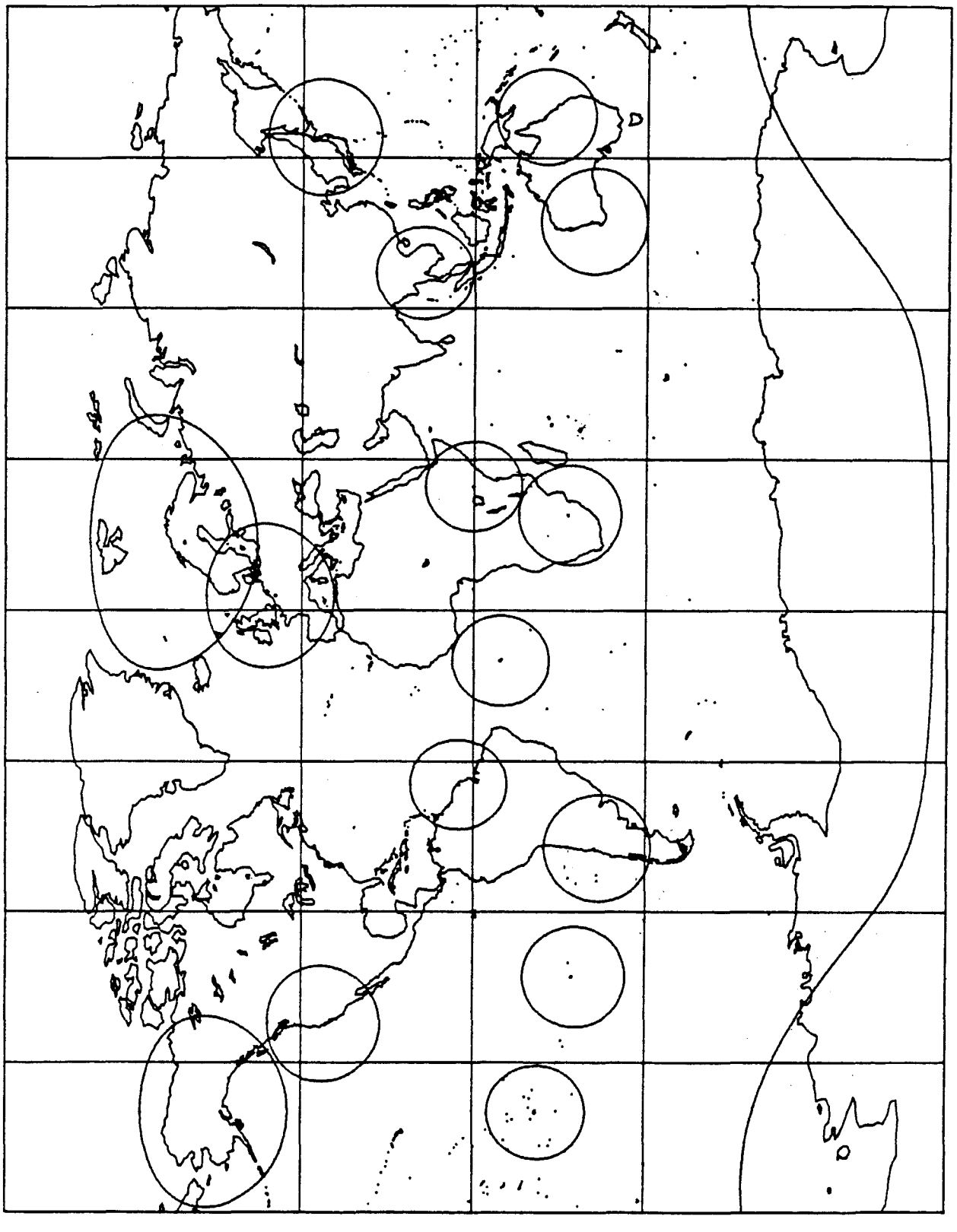
Mc.Murdo	Thule	Guam
Easter Island	Kenya	

The reduced 6-stations laser network

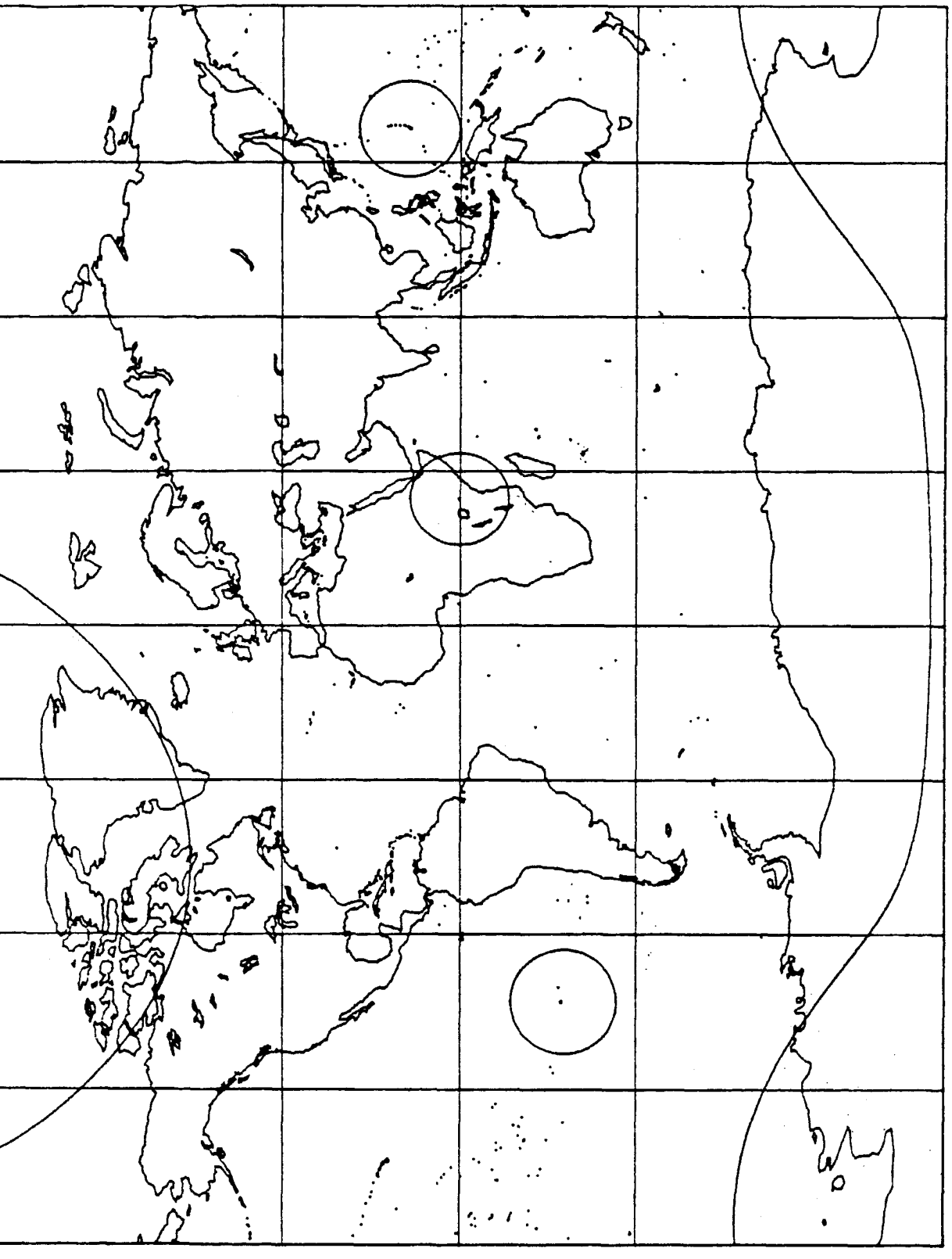
Arequipa	Greenbelt	Yaragadee
Quincy	Kootwijk	Graz



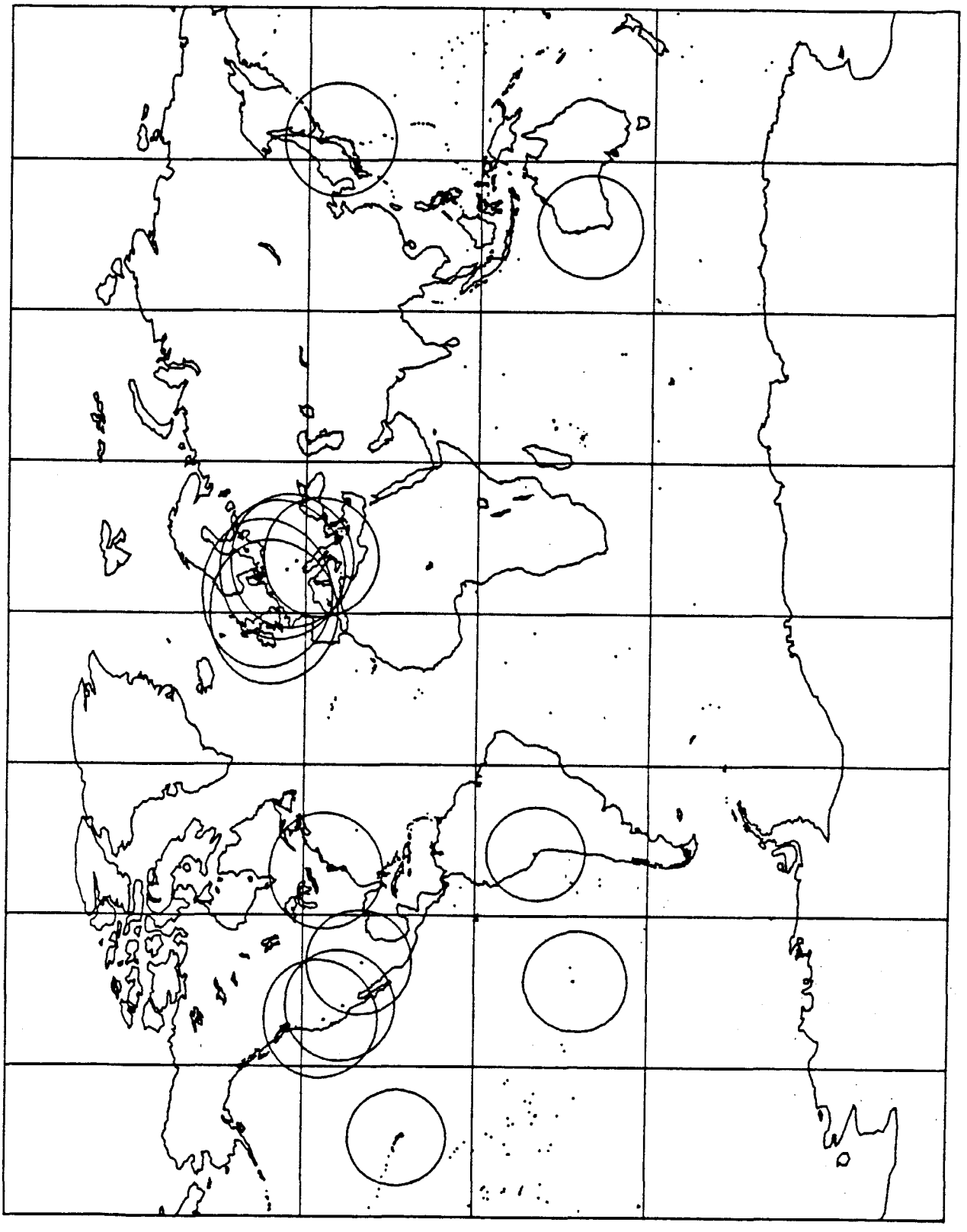
The network of 45 TRANET tracking stations and the visibility contours for a 20-deg cut-off elevation.



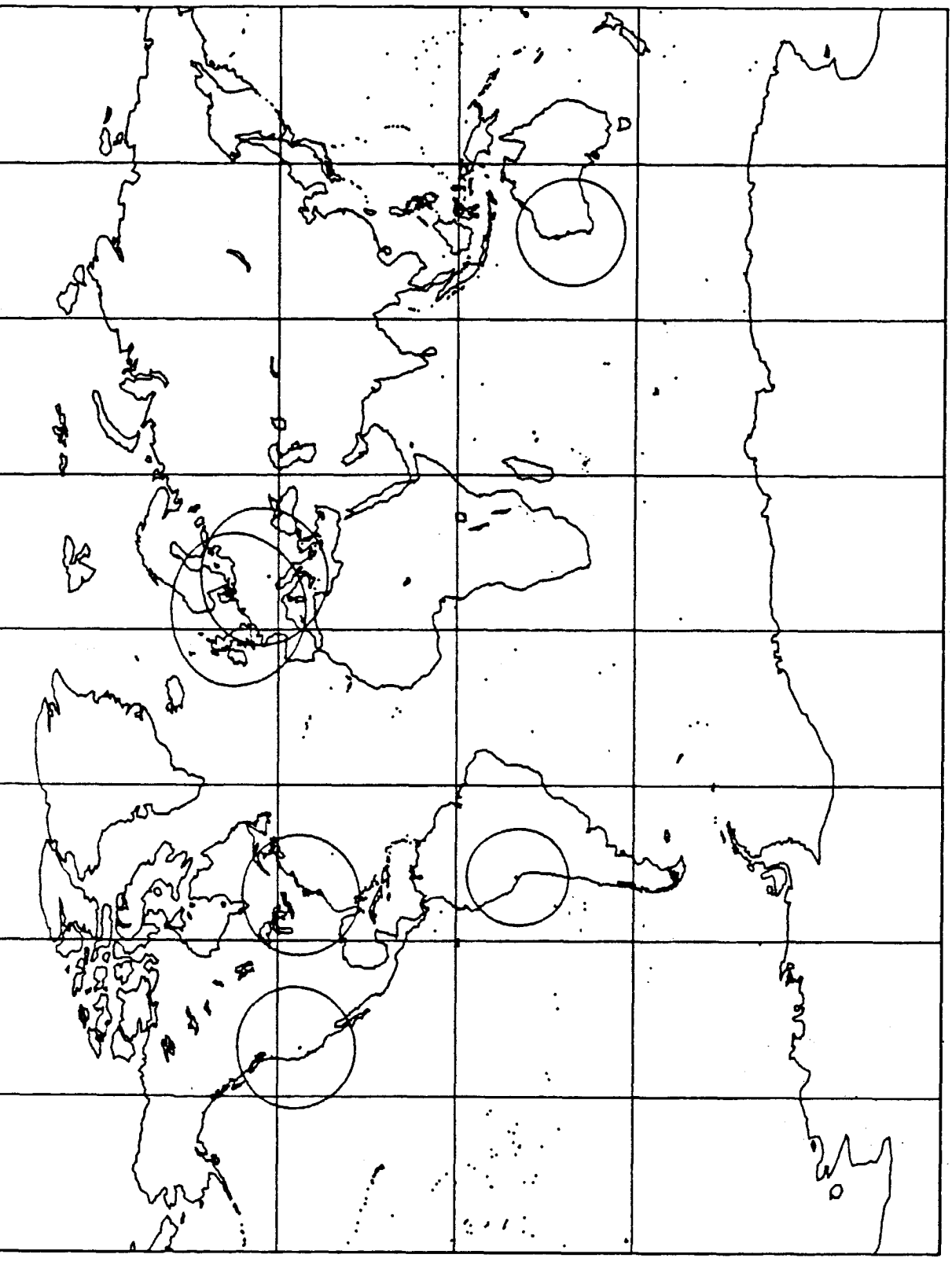
The network of 16 TRANET tracking stations and the visibility contours for a 20-deg cut-off elevation



The network of 5 TRANET tracking stations and the visibility contours for a 20-deg cut-off elevation.



The network of 14 laser tracking stations and the visibility



The network of 6 laser tracking stations and the visibility contours for a 20-deg cut-off elevation.

Summary of the tracking coverage by the full laser and TRANET networks for the 3-day arc.

	14 laser stations	45 TRANET stations
Total number of passes	117	451
Passes per station	6-10	6-28
Average	8.4	10.0
Maximum view period (min)	7	7
Average (min)	5.3	5.3
Percentage total tracking time	14.4	55.2
Maximum non-tracked period (min)	219.5	55.0
Average (min)	55.0	8.6
Periods with simult.tracking from 2 or more stations*)	20	62

*) only periods $\geq$ 3 min.

Summary of the tracking coverage by the various laser and TRANET networks for the 3-day arc.

	Laser network			TRANET network		
	full 14 stations	degraded 14 stations	degraded 6 stations	45 stations	16 stations	5 stations
Total number of passes	117	67	30	451	161	72
Percentage total tracking time	14	6.6	3.5	55	20	9.6
Non-tracked period (min)						
Maximum	220	378	1215	55	96	166
Average	55	82	139	9	24	52

Error parameters for the 3-day and 2-revolution arcs analyses

ESTIMATED PARAMETERS	• orbit state at epoch
UNADJUSTED MEASUREMENT ERRORS	• station coordinates - for lasers 10 cm in each local X,Y,Z; for TRANET 30 cm in each local X,Y,Z • pole position - 0.002 arcsec • tidal uplift - 10% of the effect • measurement noise - laser: 10 cm; TRANET: 1 mm/s • tropospheric refraction - laser: 0.5%; TRANET: 2% of the effect • ionospheric refraction - 2% of the effect at 400 MHz; ionospheric conditions of June 21-24, 1977
UNADJUSTED DYNAMIC ERRORS	• gravity field - 30% of the differences between GEM-10 and GEM-10B models, truncated at order and degree 30 • atmospheric drag - 5% of the effect; solar and geomagnetic activity level of June 21-24, 1977 • gravitational parameter - 0.005 ppm • direct solar radiation - 3% of the effect • albedo radiation - 10% of the effect • solid earth tides - 3% of the effect

Contribution of individual error sources to the radial , cross-track and along-track position errors for the 3-day arc of laser or doppler tracking. Listed are maximum/ rms values in centimeters.

Error source	14 laser stations Radial	Cross	Along	45 TRANET stations Radial	Cross	Along
Gravity field	174/56	198/56	694/208	179/56	202/55	666/205
Gravit. parameter	2/1	0/0	1/0	1/1	0/0	0/0
Atmospheric drag	7/3	2/1	251/107	5/2	10/7	265/107
Direct solar radiation	25/10	3/1	64/21	25/10	3/1	52/20
Albedo radiation	4/2	1/1	128/54	3/1	5/3	133/54
Solid earth tides						
force	0/0	15/6	3/1	0/0	16/6	4/1
uplift	0/0	0/0	1/1	0/0	0/0	0/0
Pole position	1/1	2/1	4/2	0/0	1/1	3/2
Tropospheric refract.	1/0	0/0	1/1	7/5	2/2	14/10
Ionospheric refract.	-	-	-	5/4	11/8	23/13
Measurement noise	0/0	1/1	2/1	0/0	1/1	0/0
Station coordinates	0/0	4/3	4/3	2/2	8/6	11/7
Overall (rss)	176/57	199/56	752/241	181/59	203/57	732/239

A comparison of the rms radial position errors in centimeters for the 3-day tracking period from various laser and TRANET tracking networks.

Error source	Laser network			TRANET network		
	14 stations	degraded 14 stations	degraded 6 stations	45 stations	16 stations	5 stations
Gravity field	56	57	57	56	55	59
Gravit. parameter	1	1	1	1	1	1
Atmospheric drag	3	3	10	2	2	3
Direct solar radiation	10	10	10	10	10	10
Albedo radiation	2	2	5	1	1	2
Solid earth tides						
force	0	0	0	0	0	0
uplift	0	0	0	0	0	0
Pole position	1	1	1	0	0	1
Tropospheric refract.	0	0	0	5	5	6
Ionospheric refract.	-	-	-	4	6	3
Measurement noise	0	1	1	0	0	0
Station coordinates	0	1	2	2	4	7
Overall (rss)	57	58	59	59	57	61

Contributions of different classes of error sources to the rms errors in the position components for the 3-day data arcs and various tracking networks. Listed are the rms errors in centimeters for the radial/cross-track/along-track position components.

Tracking network	Gravitational forces	Surface forces	Geometry	Signal propagation	Measurement noise
Global laser network					
14 stations	56/56/208	11/2/122	1/3/4	0/0/1	0/1/1
degraded 14 stations	57/55/211	11/3/123	1/4/5	0/0/1	1/1/1
degraded 6 stations	57/58/212	15/5/124	2/5/6	0/1/1	1/2/2
Global TRANET network					
45 stations	56/55/205	10/7/121	2/6/7	6/8/16	0/1/0
16 stations	55/53/205	10/11/121	4/8/10	8/10/21	0/1/1
5 stations	59/104/209	11/16/124	7/19/18	6/6/16	0/2/1

Comparison of the contributions of the individual error sources to the radial, cross-track and along-track position errors for the 3-day and 2-revolution arcs of doppler tracking from 45 TRANET stations. Listed are rms values in centimeters.

Error source	3-day arc			2-revolution arc		
	Radial	Cross	Along	Radial	Cross	Along
Gravity field	56	55	205	31	39	47
Gravit. parameter	1	0	0	1	0	0
Atmospheric drag	2	7	107	0	0	0
Direct solar radiation	10	1	20	1	0	1
Albedo radiation	1	3	54	0	0	0
Solid earth tides						
force	0	6	1	0	0	0
uplift	0	0	0	0	0	0
Pole position	0	1	2	0	5	7
Tropospheric refract.	5	2	10	6	3	12
Ionospheric refract.	4	8	13	2	57	11
Measurement noise	0	1	0	1	4	1
Station coordinates	2	6	7	6	20	15
Overall (rss)	59	57	239	32	72	52

Comparison of the contributions of different classes of error sources to the *rms* errors in the position components for the 3-day and the 2-revolution arcs and the full global laser and TRANET networks. Listed are the rms errors in centimeters for the radial/cross-track/along-track position components.

Tracking network	Gravitational forces	Surface forces	Geometry	Signal propagation	Measurement noise
14 laser stations					
3-day arc	56/56/208	11/2/122	1/3/4	0/0/1	0/1/1
2-revolution arc	67/51/141	1/1/3	10/12/26	4/3/11	4/5/11
45 TRANET stations					
3-day arc	56/55/205	10/7/121	2/6/7	6/8/16	0/1/0
2-revolution arc	31/39/47	1/0/1	6/21/17	6/57/16	1/4/1

The effects of solving simultaneously with the state-vector at epoch for 12 gravity coefficients on the contributions of individual error sources to ERS-1's radial, cross-track and along-track position errors. The results hold for the 3-day arc of doppler tracking from 45 TRANET stations. Listed are maximum/rms values in centimeters.

Error source	Fixed gravity model			12 gravity coefficients adjusted		
	Radial	Cross	Along	Radial	Cross	Along
Gravity field	179/56	202/55	666/205	119/46	201/56	584/183
Gravit. parameter	1/1	0/0	0/0	1/1	0/0	0/0
Atmospheric drag	5/2	10/7	265/107	11/5	33/14	217/104
Direct solar radiation	25/10	3/1	52/20	23/6	3/1	45/12
Albedo radiation	3/1	5/3	133/54	6/3	17/7	110/52
Solid earth tides						
force	0/0	16/6	4/1	0/0	8/2	4/1
uplift	0/0	0/0	0/0	0/0	0/0	0/0
Pole position	0/0	1/1	3/2	3/1	3/1	7/2
Tropospheric refract.	7/5	2/2	14/10	8/5	3/2	15/10
Ionospheric refract.	5/4	11/8	23/13	11/4	45/19	34/14
Measurement noise	0/0	1/1	0/0	0/0	2/1	1/1
Station coordinates	2/2	8/6	11/7	14/5	14/7	30/10
Overall (rss)	181/59	203/57	723/239	123/47	210/62	636/218

Effects of lowering the orbit from the nominal 778 km mean altitude to a mean altitude of 670 km on the contribution of individual error sources to the radial, cross-track and along-track position errors. These results are for a 3-day arc of laser tracking from the full 14-stations network. Listed are rms errors in centimeters.

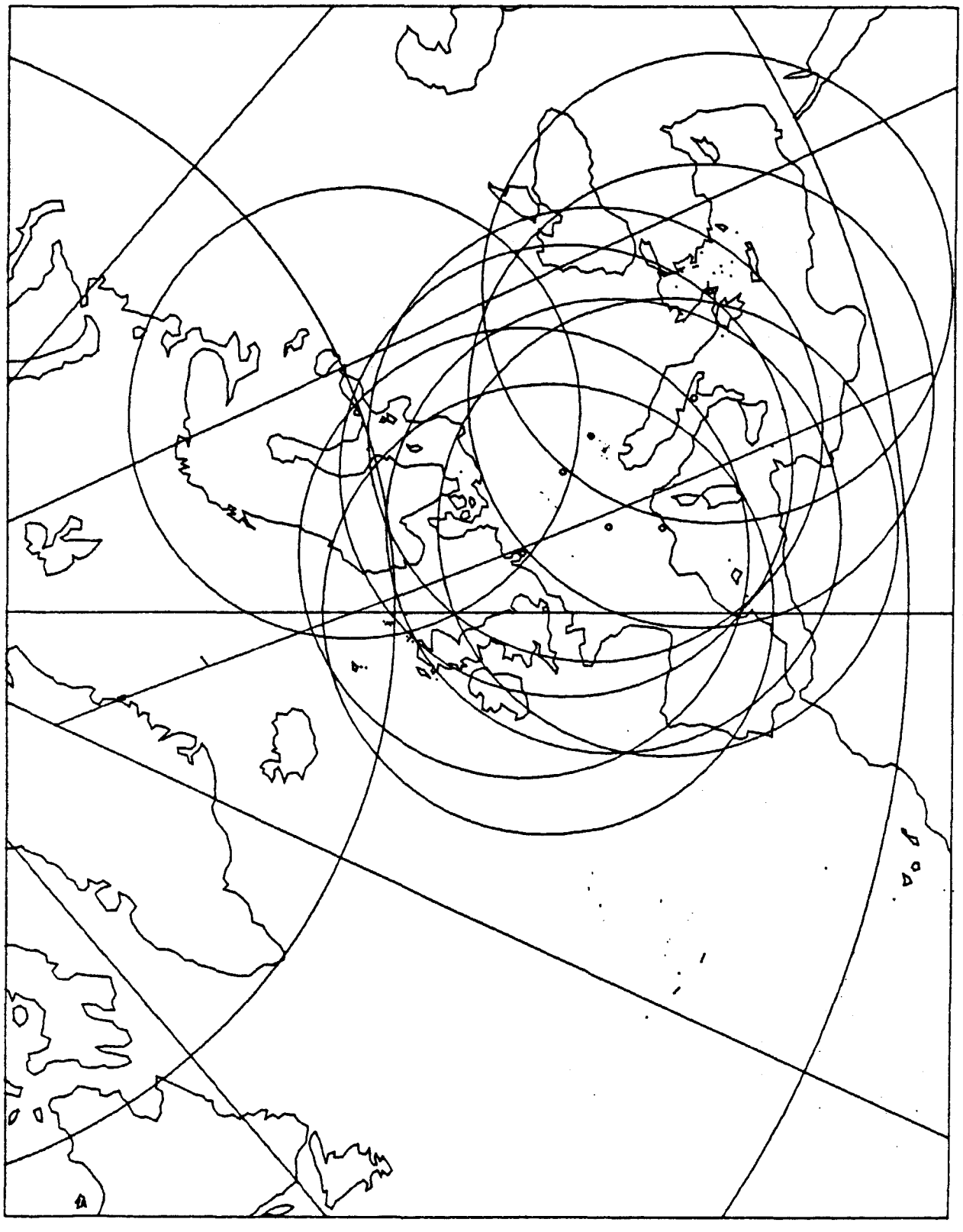
Error source	778 km; 14 1/3 rev/day			670 km; 14 2/3 rev/day		
	Radial	Cross	Along	Radial	Cross	Along
Gravity field	56	56	208	91	78	385
Gravit. parameter	1	0	0	1	0	0
Atmospheric drag	3	1	107	6	7	295
Direct solar radiation	10	1	21	10	1	20
Albedo radiation	2	1	54	1	1	53
Solid earth tides						
force	0	6	1	0	6	1
uplift	0	0	1	0	0	1
Pole position	1	1	2	1	1	2
Tropospheric refract.	0	0	1	1	0	1
Measurement noise	0	1	1	0	1	1
Station coordinates	0	3	3	0	3	3
Overall (rss)	57	56	241	92	79	488

Orbit, satellite and tracking parameters for the short arc over Europe.

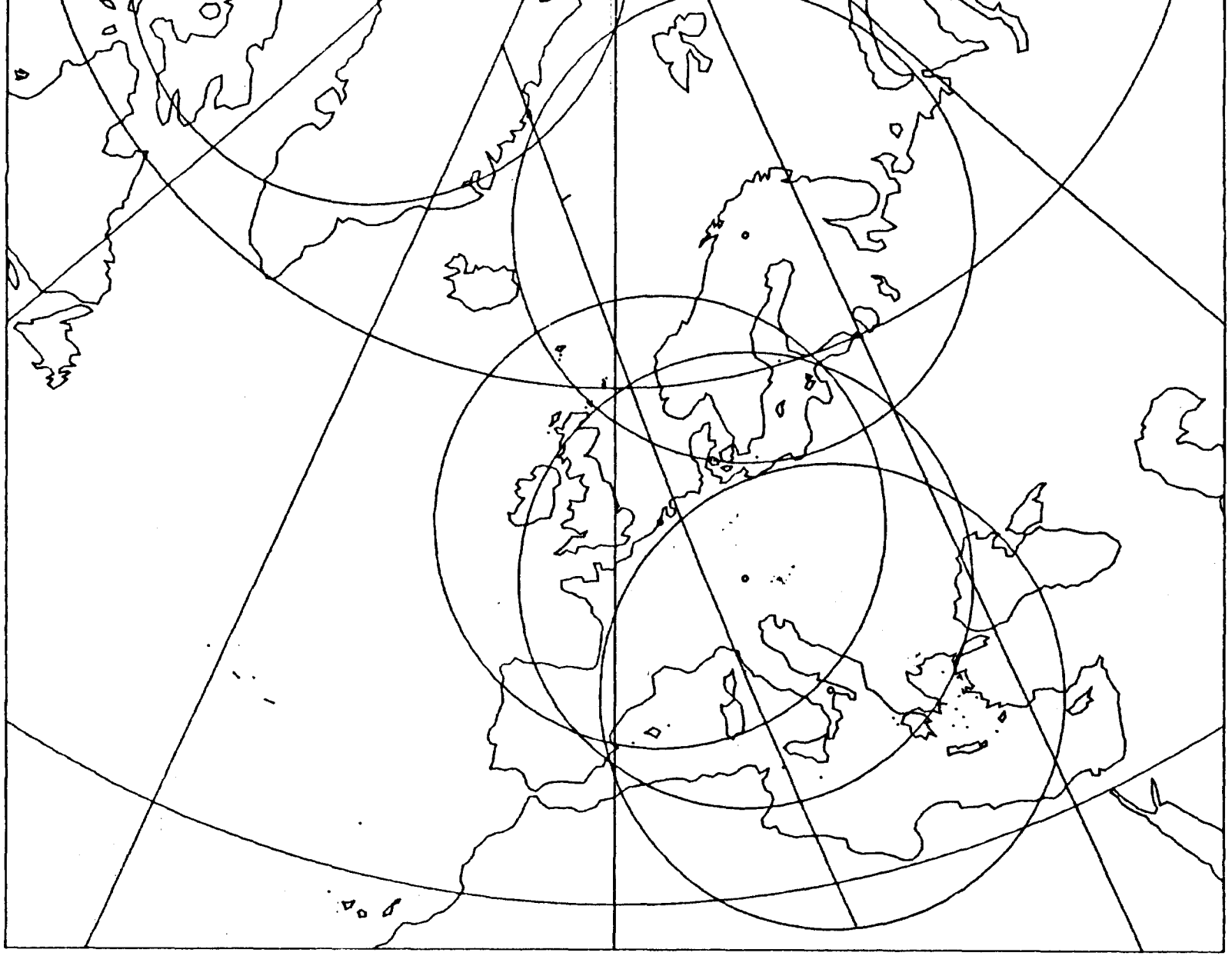
ORBIT	Epoch : 88/6/22 , 21^h12^m UT		
	Elements: a = 7158.2 km ; e = 0.001319 ; i = 98.518 deg;		
	Ω = 248.428 deg; ω = 98.698 deg; M = 289.348 deg		
SATELLITE	Area/mass ratio = 0.01 m^2/kg		
	Drag coefficient = 2.2		
	Solar reflectivity = 1.5		
LASER NETWORK	Kootwijk	Wettzell	Grasse
	Graz	Metsahovi	Zimmerwald
	Dionysos	Herstmonceux	Matera
PRARE NETWORK	Thule	Kiruna	Delft
	Munich	Matera	
OBSERVATIONS	Type : laser range and/or PRARE range		
	Arc length : laser 11 and 15 min; PRARE 15 min		
	Repetition rate : 1 measurement per 5 s		
	Cut-off elevation: 20 deg		

The locations of the laser and PRARE tracking stations.

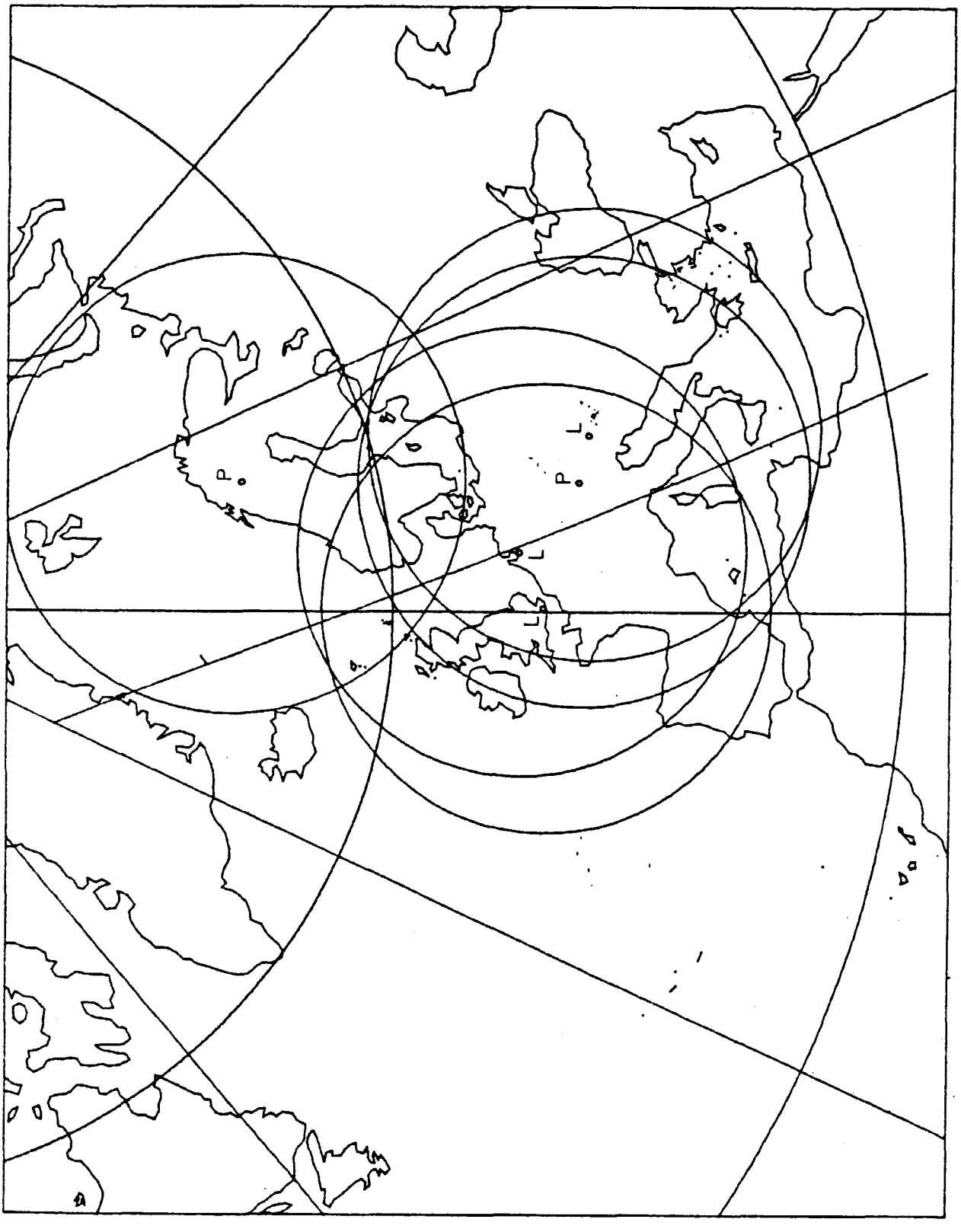
	Tracking station	Latitude (deg)	Longitude (deg)
Laser	Kootwijk	52.2	5.8
	Wettzell	49.1	12.9
	Grasse	43.8	6.9
	Graz	47.1	15.5
	Metsahovi	60.2	24.4
	Zimmerwald	46.9	7.5
	Dionysos	38.1	23.9
	Herstmonceux	50.9	0.3
	Matera	40.7	16.6
PRARE	Thule	76.5	291.2
	Kiruna	67.9	20.2
	Delft	52.0	4.4
	Munich	48.1	11.6
	Matera	40.7	16.6



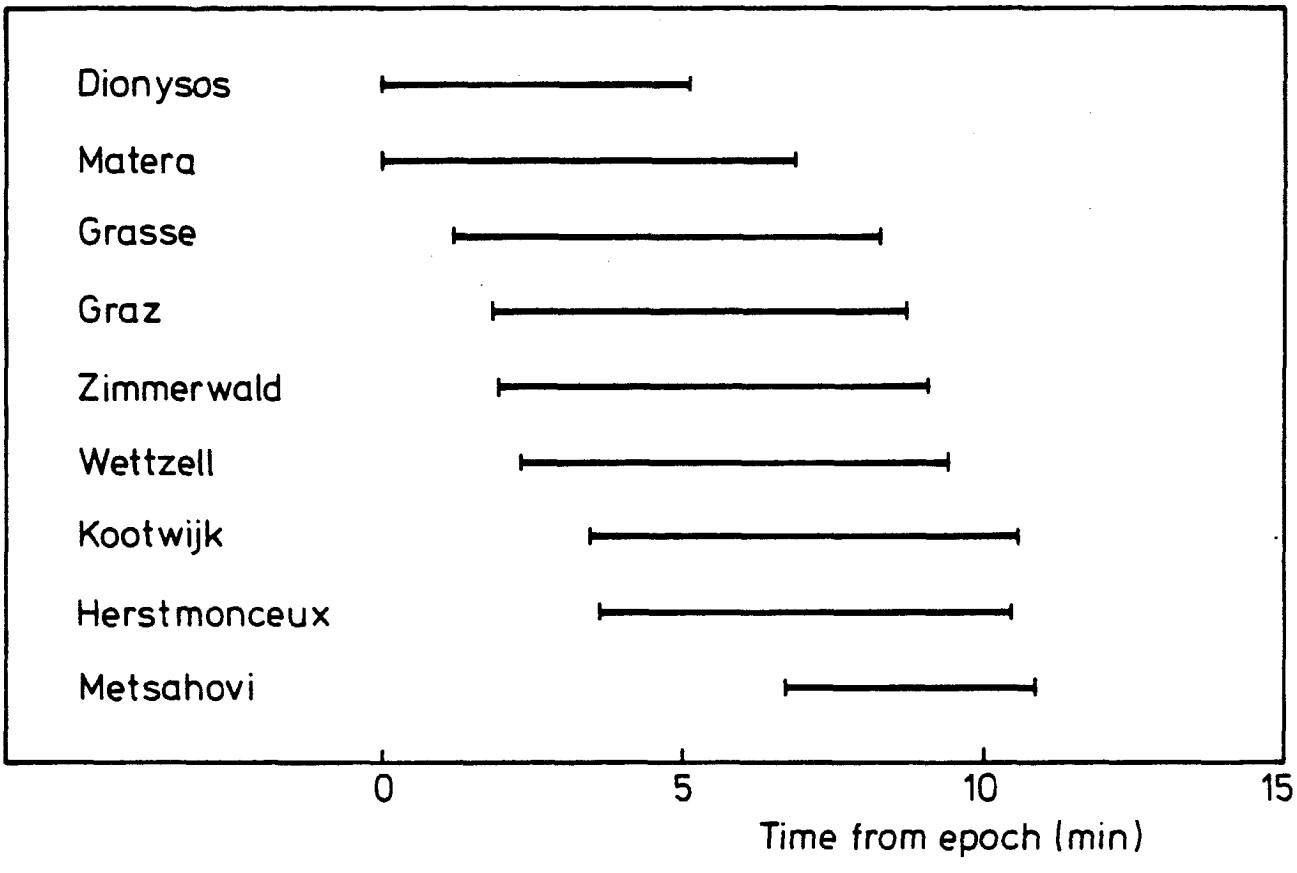
ERS-1's ground trace during the 15-min arc and the locations of the 9 laser tracking stations with the visibility contours for a 20-deg cut-off elevation



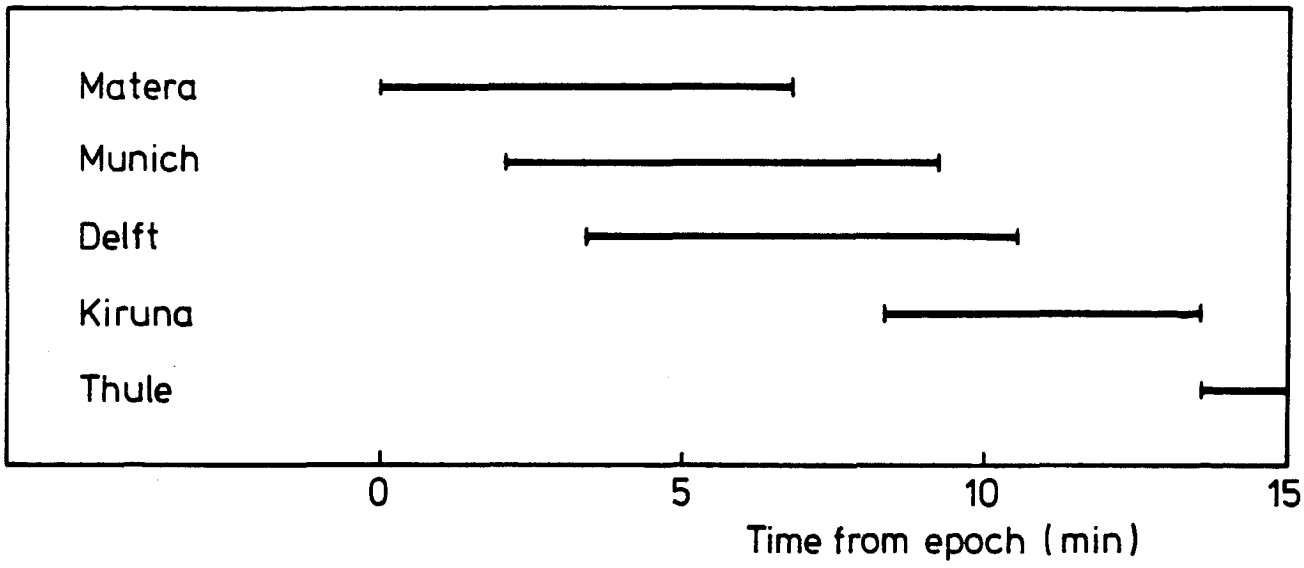
ERS-1's ground trace during the 15-min arc and the locations of the 5 PRARE tracking stations with the visibility contours for a 20-deg cut-off elevation.



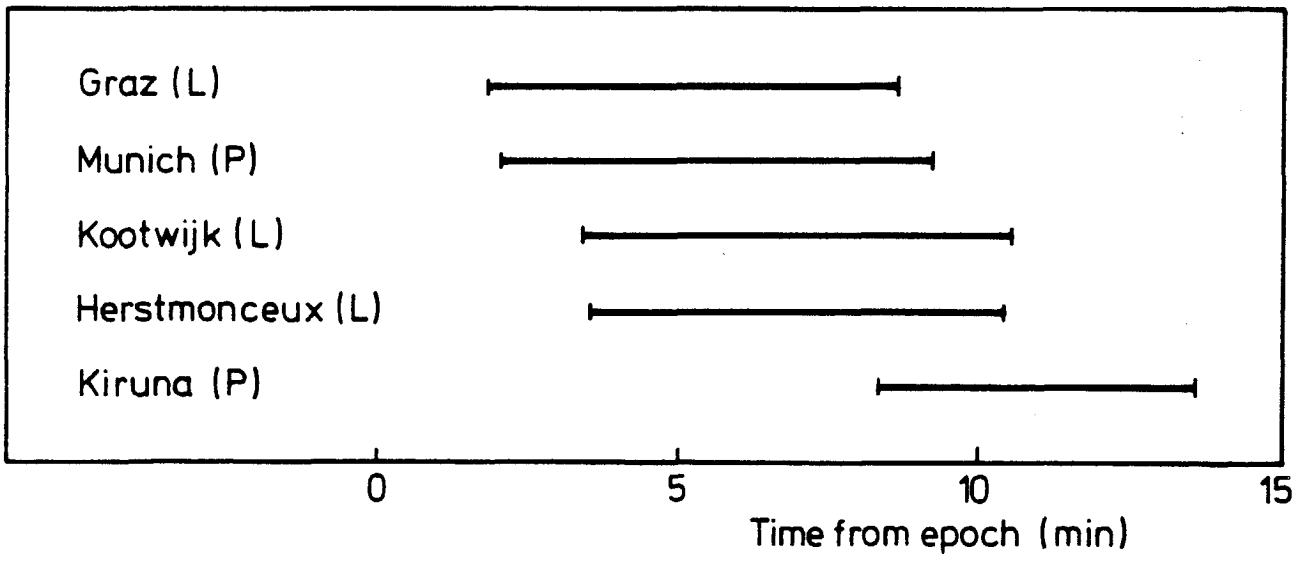
ERS-1's ground trace during the 15-min arc and the network of 3 laser and 2 PRARE tracking stations with the visibility contours for a 20-deg cut-off elevation



The distribution of the tracking periods from the full 9-station European laser network.



The distribution of the tracking periods from the full 5-station European PRARE network.



The distribution of the tracking periods from a European network consisting of 3 laser (L) and 2 PRARE (P) stations.

Error parameters for the short arcs over Europe.

ESTIMATED PARAMETERS	• orbit state at epoch
UNADJUSTED MEASUREMENT ERRORS	• station coordinates - for laser 10 cm in each local X,Y,Z; for PRARE 30 cm in each local X,Y,Z • pole position - 0.002 arcsec • tidal uplift - 10% of the effect • measurement noise - laser: 10 cm; PRARE: 5 cm • tropospheric refraction - laser: 0.5%; PRARE 2% of the effect • ionospheric refraction - 2% of the effect at 8 GHz; ionospheric conditions of June 22, 1977
UNADJUSTED DYNAMIC ERRORS	• gravity field - 30% of the differences between GEM-10 and GEM-10B models, truncated at order and degree 30 • atmospheric drag - 5% of the effect; solar and geomagnetic activity level of June 22, 1977 • gravitational parameter - 0.005 ppm • direct solar radiation - 3% of the effect • albedo radiation - 10% of the effect • solid earth tides - 3% of the effect

Contribution of the individual error sources to the radial, cross-track and along-track position errors for the 15-min arc of laser or PRARE tracking. Listed are maximum/rms values in centimeters.

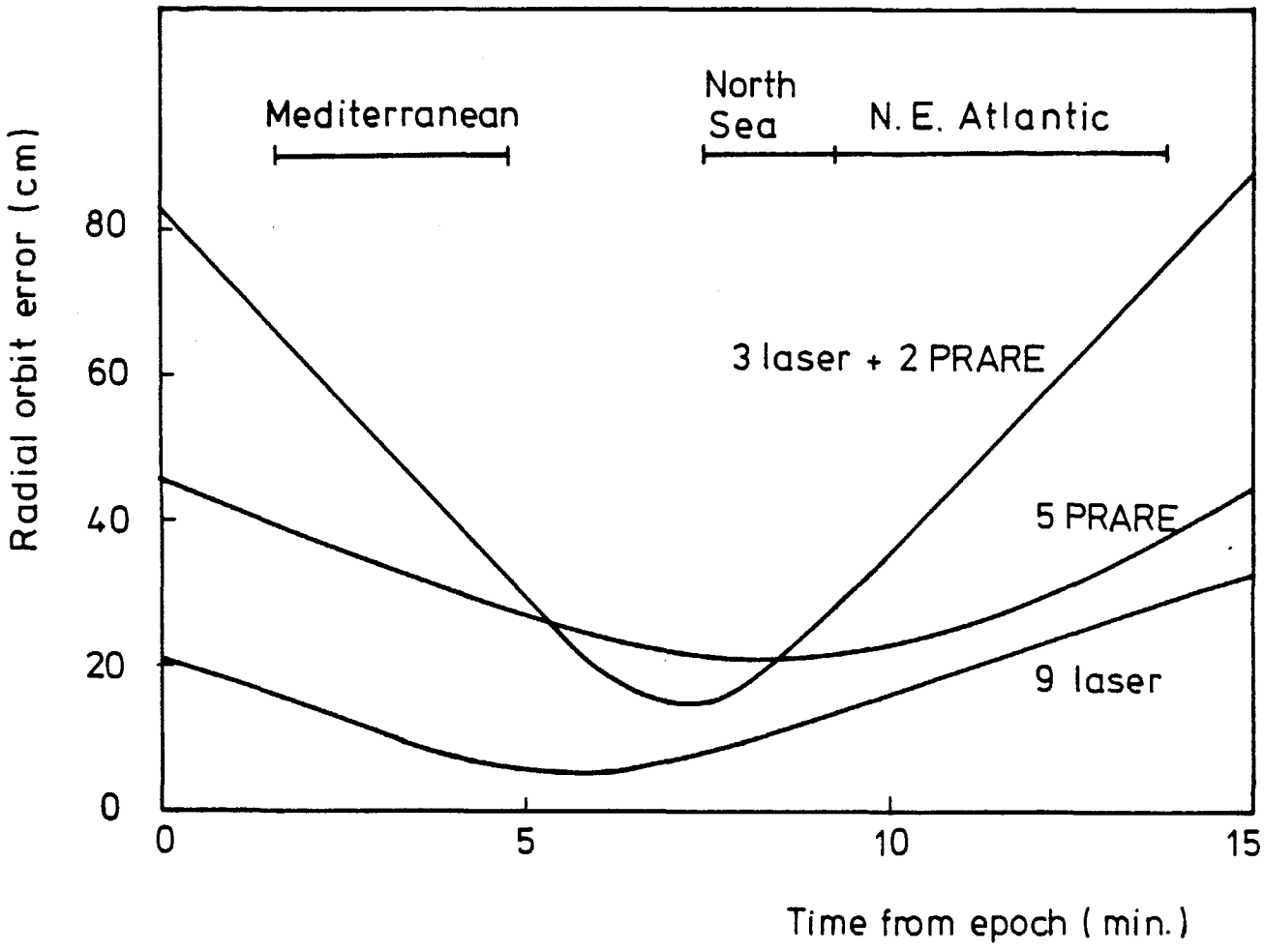
Error source	9 laser stations			5 PRARE stations		
	Radial	Cross	Along	Radial	Cross	Along
Gravity field	6/3	1/1	5/2	4/1	3/1	3/1
Gravit. parameter	0/0	0/0	0/0	0/0	0/0	0/0
Atmospheric drag	0/0	0/0	0/0	0/0	0/0	0/0
Direct solar radiation	0/0	0/0	0/0	0/0	0/0	0/0
Albedo radiation	0/0	0/0	0/0	0/0	0/0	0/0
Solid earth tides						
force	0/0	0/0	0/0	0/0	0/0	0/0
uplift	2/1	1/1	1/1	2/1	0/0	1/1
Pole position	0/0	7/5	7/7	0/0	7/5	7/7
Tropospheric refract.	6/3	2/1	3/2	23/12	5/3	9/4
Ionospheric refract.	-	-	-	0/0	0/0	0/0
Measurement noise	5/3	4/2	4/2	1/1	2/1	1/1
Station coordinates	31/16	25/14	26/13	52/28	99/55	45/25
Overall (rss)	33/17	26/15	28/15	57/30	99/55	46/26

Contributions of different classes of error sources to the rms errors in the position components for the 15-min data arcs and various tracking networks. Listed are the rms errors in centimeters for the radial/cross-track/along-track position components.

Tracking network	Gravitational forces	Surface forces	Geometry	Signal propagation	Measurement noise
9 laser stations	3/1/2	0/0/0	16/15/15	3/1/2	3/2/2
5 PRARE stations	1/1/1	0/0/0	28/55/26	12/3/4	1/1/1
2 PRARE stations	2/2/1	0/0/0	68/174/45	22/88/25	15/23/9
3 laser + 2 PRARE stations	2/1/2	0/0/0	8/11/11	8/8/4	3/3/2

Effects of shortening the 15-min arc to an 11-min arc, in which ERS-1 is continuously tracked from the 9-stations laser network, on the radial, cross-track and along-track orbit errors. Listed are rms values in centimeters.

Error source	15-minute arc			11-minute arc		
	Radial	Cross	Along	Radial	Cross	Along
Gravity field	3	1	2	2	1	2
Gravit. parameter	0	0	0	0	0	0
Atmospheric drag	0	0	0	0	0	0
Direct solar radiation	0	0	0	0	0	0
Albedo radiation	0	0	0	0	0	0
Solid earth tides						
force	0	0	0	0	0	0
uplift	1	1	1	1	1	1
Pole position	0	5	7	0	5	7
Tropospheric refract.	3	1	2	2	1	1
Measurement noise	3	2	2	2	2	2
Station coordinates	16	14	13	12	11	9
Overall (rss)	17	15	15	13	12	12



The overall radial orbit error during the 15-minute arc for 3 different tracking networks.