DELFT UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF AEROSPACE ENGINEERING

Report LR-295

A STUDY ON THE DETERMINATION OF THE KOOTWIJK-WETTZELL BASELINE FROM SATELLITE LASER RANGING AT THESE STATIONS

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Summary

This report presents the results of a preliminary study to determine the Kootwijk-Wettzell baseline and the Wettzell coordinates from satellite laser ranging. Five different estimates were obtained, based on 3 single-arc, 1 two-arc and 1 four-arc solutions. The arcs were formed from 32 passes of four satellites over only the Kootwijk and Wettzell ranging stations during the period July 11 to August 24, 1978. Special attention was paid to the effects of the orbit-station geometry, the number of passes and the distribution of the passes over a time-span.

Contents

1. Introduction

Since summer 1979 the Working Group for Satellite Geodesy (WSG), the Geodetic Computing and Analysis Center (LGR) and the Section Orbital Mechanics (SOM) of Delft University of Technology take part in the NASA project on "Data use investigations for the Laser Geodynamics Satellite (LAGEOS) mission". The aim of the combined investigations of the three groups is to evaluate the actual precision of the laser ranging data as related to the reliability of network structures, in particular to determine relative station positions. In that study, SOM is reponsible for all orbit computations and for the operational aspects of the GEODYN/ORAN parameter estimation computer programs, which were implemented in 1979 on the Delft University IBM 370/158 computer.

To get some experience with GEODYN, a preliminary study was done in which laser ranging data from a limited number of passes over Kootwijk (Netherlands, station 7833) and Wettzell (Fed. Rep. Germany, station 7834) were used to determine the Wettzell coordinates and in particular the Kootwijk-Wettzell baseline. The ranging data were taken from the Kootwijk databank. Within the period July 11 to August 24, 1978, 5 data-arcs were selected comprising about 2200 measurements to 4 different satellites: LAGEOS (7603901), STARLETTE (7501001), GEOS-1 (6508901) and GEOS-3 (7502701). Some characteristics of these satellites are listed in Table 1. Estimates

Table 1: Satellite data

	LAGEOS	STARLETTE	GEOS-1	GEOS-3
Satellite number	7603901	7501001	6508901	7502701
Launch date	May 4	Febr. 6	Nov. 6	April 9
Shape	sphere	sphere	truncated octagon with truncated pyramid	truncated octagon with truncated pyramid
Dimensions (cm)	60 Ø	24 Ø	132 wide 81 high	135 wide 81 high
Mass (kg)	409.0	47.0	172.5	345.9
Area*) (m^2)	0.2827	0.04522	1.230	1.437
Orbit**)				
a (km)	12271	7335	8073	7221
e	0.0044	0.0207	0.0717	0.0014
i (deg)	109.9	49.8	59.4	115.0
P (min)	225	104	120	102

*) The values for the cross-sectional area used in this study

**) Based on mean elements for July-August, 1978.

of the Wettzell coordinates and the baseline were obtained from 3 single-arc, 1 two-arc and 1 four-arc solutions. It was realized that these solutions could only have a limited accuracy, because they are based on passes over only two ground stations. However, the aim of the present study is not to get very accurate results, but merely to obtain physical insight in how the number of passes used in the solution, the station-orbit geometry and the distribution of these passes over a time-span, influence the computed results.

2. Study philosophy

In addition to the actual solution for the baseline and Wettzell coordinates and the computed standard deviations, GEODYN also generates a large amount of information which may be used to judge the overall solution. An important source of information are the range residuals, defined as the actual measurements minus the range values as computed from the orbit determined within the parameter estimation process. These residuals are a measure of how well the orbit fits the actual measurements. If, for a given pass, the majority of the residuals plotted as a function of time, do not lie within a band about zero, having a width in the order of the accuracy of the measurements, it is a clear indication that the parameter modelling is not optimal. On the other hand, if the residuals are nicely scattered about zero, this does not necessarily mean that a good solution was obtained. It only says that a combination of parameters was found that agrees with the observations, but the values of these parameters need not to be physically correct. So, in general, it is possible to find a wrong orbit and wrong station coordinates, although GEODYN computes small standard deviations for the estimated parameters. A suitable test to determine if a correct orbit has been found, is to compute the residuals for observations which were not used in the orbital solution. However, because so few observations were available, this technique was not applied in this study.

The main goal of the Netherlands investigations within the NASA project is to determine the reliability of the solutions of parameter estimation schemes. For this, advanced techniques developed at the LGR will be applied. However, as long as a GEODYN solution for a specified number of parameters is based on a relatively small amount of data, it can be expected that the reliability of the solution will be relatively poor. If these parameters are already accurately known from other investigations, an engineering indication of the reliability of the GEODYN solution can be obtained by simply comparing the solution with the external information. This approach was adopted in this study.

The problem, however, was that no external information was available about the Wettzell coordinates as determined within or from a recent global Goddard Earth Model (GEM) solution, while in this study a GEM-10B solution was chosen to model the earth's gravitational field (Section 5). For Kootwijk both GEM-9 and GEM-10B coordinates were available (Ref. 1). These coordinates differ mutually less than 0.25 m. On the other hand, for both stations laser coordinates derived from doppler antenna coordinates are known relative to the Naval Weapons Laboratory's NWL-9D coordinate system (Ref. 2). These coordinates were obtained from doppler multipoint solutions using the precise ephemeris. In the major part of this study, the Kootwijk coordinates were kept fixed at the GEM-9 X, Y, Z values while the Wettzell coordinates were solved for. For the baseline the value determined from the NWL-9D coordinates is taken as a reference to which the results of this study are compared. The computed Wettzell coordinates can be judged by comparing the differences between the coordinates and the NWL-9D Wettzell coordinates with the differences between the GEM-9 Kootwijk coordinates and the NWL-9D Kootwijk coordinates. In a final experiment, the Wettzell coordinates as well as the latitude and height of Kootwijk were solved for. The longitude was still kept fixed at the GEM-9 value. This experiment was primarily performed to investigate if even with this larger number of solved-for parameters a solution on basis of the limited number of passes could be obtained.

3. Arc selection

Since the Kootwijk databank at present contains only a small amount of Wettzell data, the possibilities to select suitable arcs were limited. One of the arc selection criteria was that each arc should contain data both from Kootwijk and Wettzell. It was also felt that at least five passes should be taken into each arc, but the arc length should not become too large. This resulted in the selection of 5 arcs: 2 for LAGEOS, 1 for STARLETTE, 1 for GEOS-1 and 1 for GEOS-3. It was also tried to include some overlapping passes where the satellite was tracked both from Kootwijk and from Wettzell. It was thought that a comparison between the Kootwijk and Wettzell range residuals for such passes could give some additional information on the accuracy of the solution. A summary of the arcs selected is presented in

Table 2: Summary of data-arcs used in the solutions

Arc	Satellite	First observation	Last observation	Passes	Observations
1	LAGEOS	780721, $21^h\ 29^m\ 14^s$	780724, $21^h\ 20^m\ 33^s$	K2; W3	K215; W268
2	LAGEOS	780728, $0^h\ 2^m\ 0^s$	780804, $20^h\ 22^m\ 52^s$	K5; W2	K139; W137
3	STARLETTE	780821, $1^h\ 17^m\ 59^s$	780824, $2^h\ 21^m\ 54^s$	K2; W3	K101; W101
4	GEOS-1	780711, $16^h\ 35^m\ 34^s$	780713, $23^h\ 11^m\ 11^s$	K8; W2	K611; W353
5	GEOS-3	780728, $19^h\ 49^m\ 29^s$	780730, $19^h\ 25^m\ 14^s$	K3; W2	K146; W139

Table 2. For each arc the following quantities are listed: the satellite involved, the time (UTC) of the first and last observation, the number of passes over Kootwijk (K) and Wettzell (W) and the number of observations from each station which were used in the solutions. These numbers do not include some wild Kootwijk data points which were removed from the original set of data (see Section 7). The distribution of the passes over each arc is shown in Fig. 1. The length of the bars indicates the number of observations for the pass; overlapping passes are given by two touching bars.

4. General considerations

It will be clear that an accurate orbit determination and Wettzell coordinate estimation will require that the passes over Wettzell and in particular the passes over Kootwijk are evenly distributed over the arc. It can be seen in Fig. 1 that arc 3 (STARLETTE) is very weak in this respect.

The sub-satellite point at the times of observation are plotted for all arcs in Figs. 2 to 6.*) These plots contain important qualitative information about the expected accuracy of the orbit determination. It can be seen that for LAGEOS, STARLETTE and especially for GEOS-3 the sub-satellite tracks are essentially near parallel. As the length of the arcs is only a few days, this means that the measurements taken during the different passes of an arc all refer to nearly the same part of the orbital path. From the orbit determination point of view, this is a bad situation because, in general, an accurate orbit determination requires observations distributed along the orbit. How well the orbit can be determined for these conditions depends on the accuracy of the perturbation models. For the PROP-6 (Ref. 3) orbit determination program, which was used extensively by SOM in the last

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*) Software is developed to improve the quality of this kind of maps.

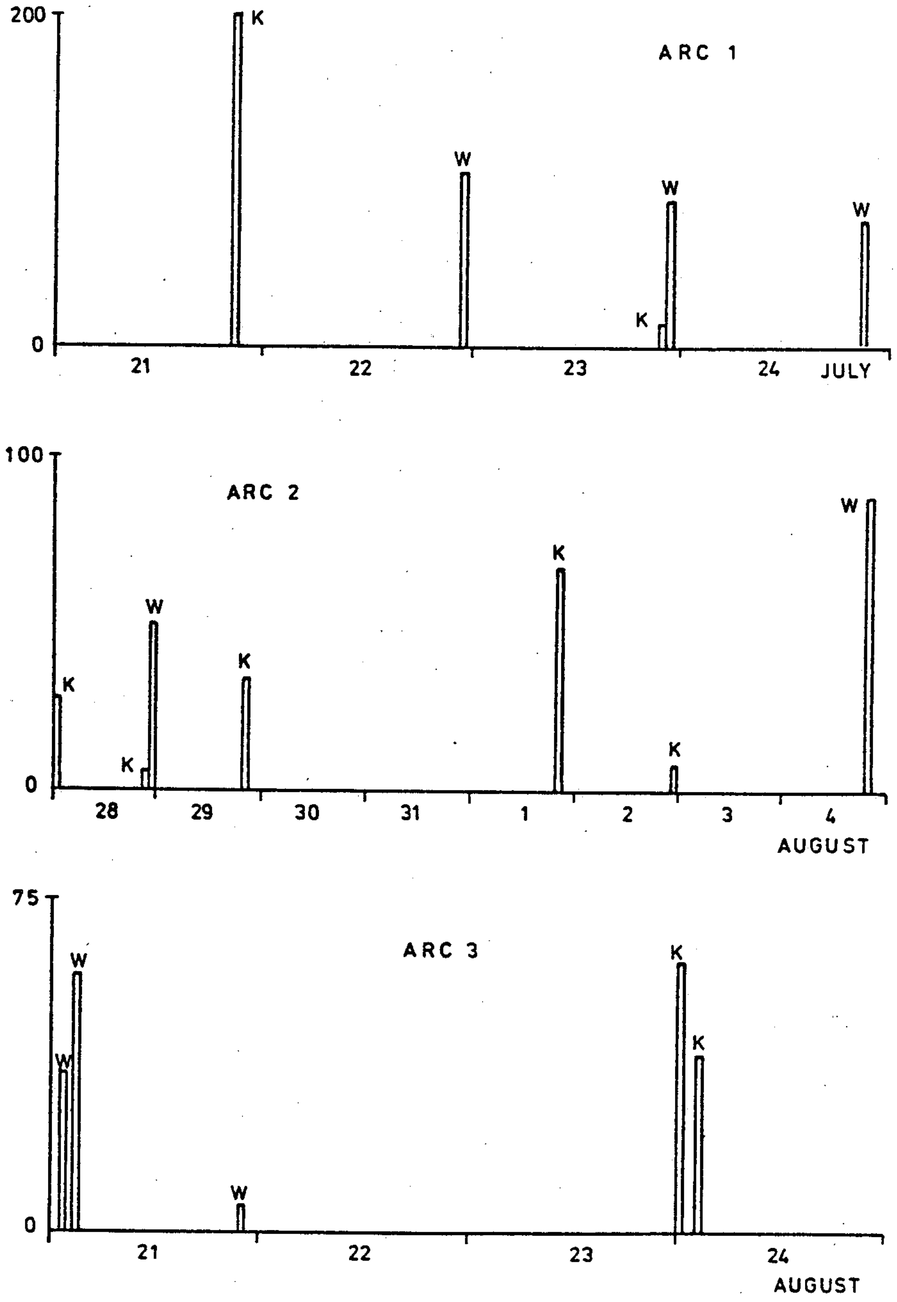


Fig. 1: The distribution of Kootwijk (K) and Wettzell (W) passes over an arc. The length of a bar indicates the number of observations.

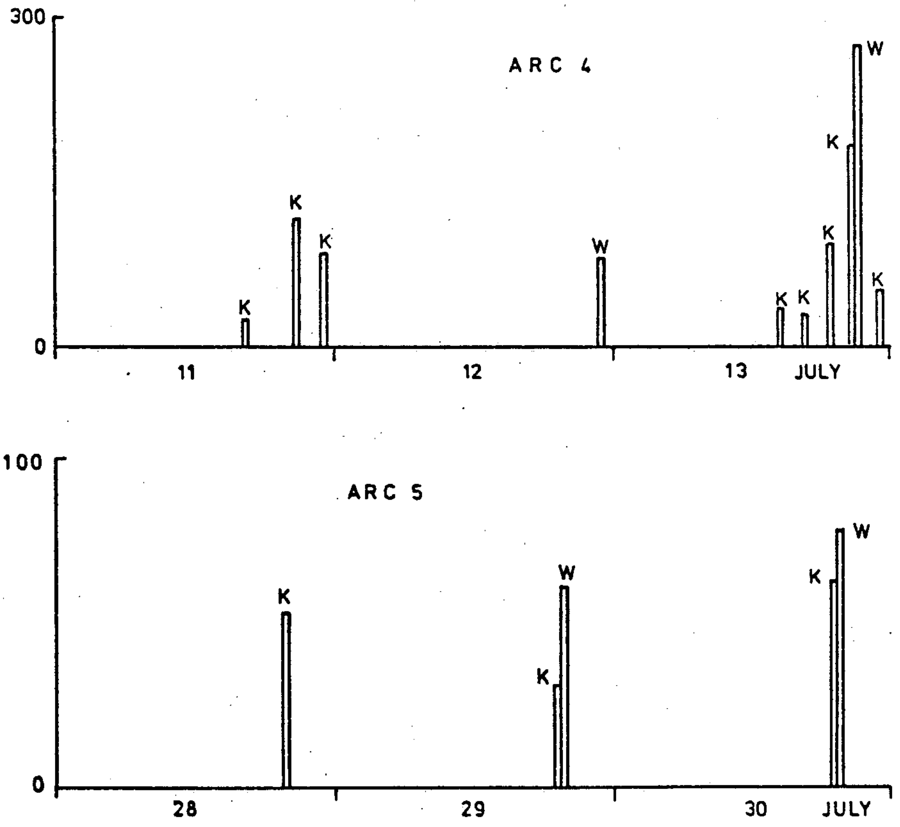


Fig. 1: (Cont.)

few years and which is based on analytical techniques for the determination of mean orbital elements, the effects of bad orbital coverage often lead to very unreliable orbit solutions from laser ranging measurements. For numerical schemes, like those applied in GEODYN, where the perturbations are modelled much more accurate, less problems may be expected. These effects are, of course, the largest for low orbits, where the total pass time is small in comparison to the orbital period. For LAGEOS, the mean time between the first and the last measurement of the passes is about 18 minutes or about 8% of the orbital period. For STARLETTE and GEOS-3 the corresponding value is about 4.5%. So, it may be expected that the orbit determination for STARLETTE and GEOS-3 will yield relatively poor results and that the more accurate orbits will be found for LAGEOS and in particular for GEOS-1.

Another point to be mentioned is that for the computation of the baseline it is attractive to have sub-satellite tracks nearly parallel to the interstation line. Comparing the tracks of STARLETTE and GEOS-3, it therefore

Fig. 2: The sub-satellite points at the observation times for all passes in arc 1 (LAGEOS). The satellite moves from south to north.

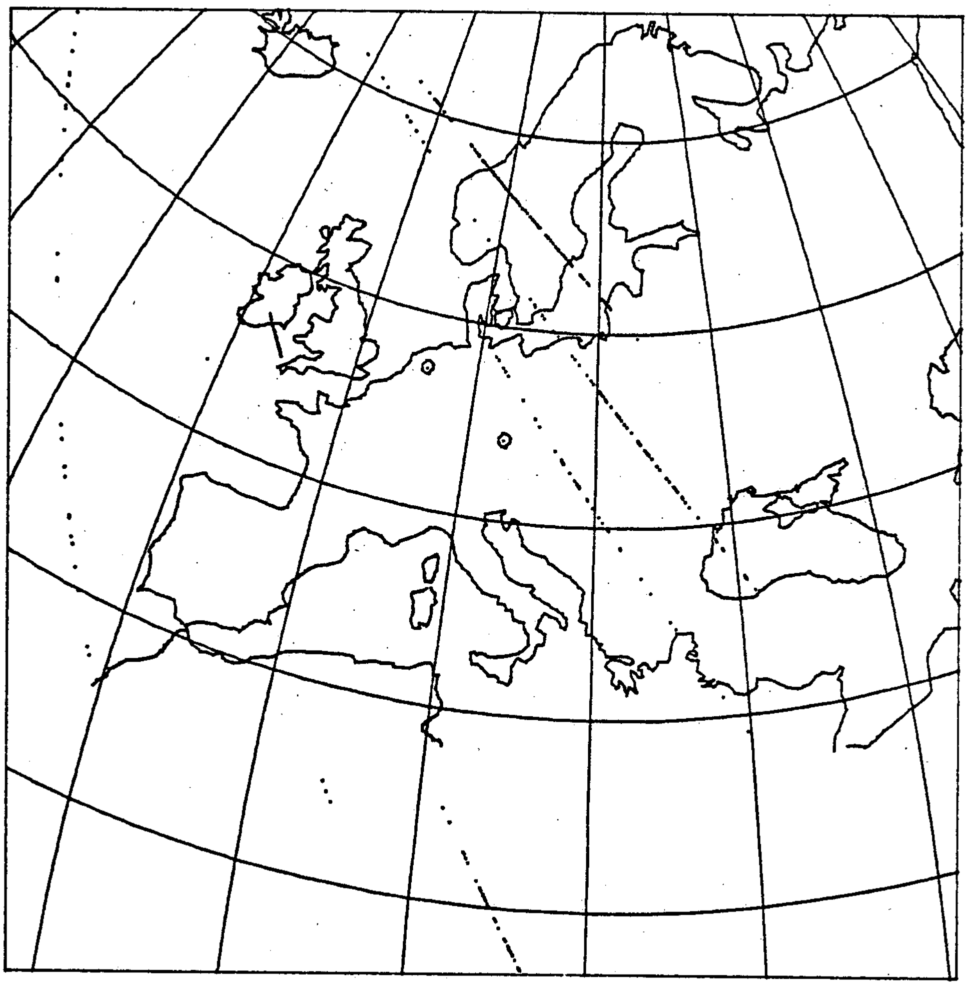


Fig. 3: The sub-satellite points at the observation times for all passes in arc 2 (LAGEOS). The satellite moves from south to north.

Fig. 4: The sub-satellite points at the observation times for all passes in arc 3 (STARLETTE). The satellite moves from west to east.

Fig. 5: The sub-satellite points at the observation times for all passes in arc 4 (GEOS 1). The general direction of the satellite motion is from west to east.

Fig. 6: The sub-satellite points at the observation times for all passes in arc 5 (GEOS-3). The satellite moves from south to north.

may be expected that GEOS-3 will give a more accurate value for this baseline, although the orbital solutions may be quite bad.

5. Computation model

For the numerical integration of the equations of motion and the variational equations, a fixed-stepsize 11th-order Cowell predictor-corrector method was used. The stepsize was 138.5 s for LAGEOS; for the other satellites it was 100 s. The Kootwijk and Wettzell coordinates are given in Table 3. For Wettzell the NWL-9D laser coordinates are taken as reference values in this

Table 3: Station coordinates

Kootwijk laser NWL-9D coordinates	
x	3899228.49 m
y	396727.59 m
z	5015072.25 m
λ	5°48'34.582"
φ	52°10'42.149"
h	85.94 m

Kootwijk laser GEM-9 coordinates	
x	3899225.15 m
y	396738.37 m
z	5015072.85 m
λ	5°48'35.055"
φ	52°10'42.215"
h	74.997 m

Wettzell laser NWL-9D coordinates	
x	4075536.30 m
y	931766.05 m
z	4801616.90 m
λ	12°52'40.341"
φ	49°8'41.692"
h	654.07 m

Reference baseline from NWL-9D: 602423.26 m study. The reference baseline, based on the NWL-9D coordinates for both stations, is 602423.26m.For the earth's gravitational field the GEM-10B model (Ref. 4) was used. This field was truncated for LAGEOS at order and degree 13; for the other satellites all coefficients up to order and degree 36 were included. Solar and lunar attraction, solar radiation pressure and solid earth tides were also taken into account. For all satellites, except for LAGEOS, atmospheric drag perturbations were computed; the air density was modelled according to the Jacchia 1971 reference atmosphere (Ref. 5). Values for the satellite's mass and cross-sectional area, used in computing solar radiation and atmospheric drag perturbations, are given in Table 1. Preprocessing corrections were applied to all data as requested by the data-records, except for laser-reflector offset corrections, which were only applied for GEOS-3. The reason for this was that for GEOS-3 the correction was known to be considerably larger than for the other satellites, although precise values for GEOS-1 were not available.

6. Solved-for parameters

In the GEODYN computation process, solved-for parameters can be divided into arc-dependent parameters and common parameters. In this study the arc-dependent parameters are the satellite's state-vector at a specified epoch and its (constant) drag coefficient. The epoch was selected at $0^m\ 0^s$ UTC of the hour corresponding to the first measurement of an arc. The drag coefficient was chosen to be a solved-for parameter because it can absorp unmodelled along-track perturbations and its computed value may give some indication of this. The common parameters to be solved for were the Wettzell station's rectangular coordinates. In a final experiment only the longitude of Kootwijk was kept fixed at the GEM-9 value and the latitude and height of Kootwijk were also solved for.

7. Initial results

The first computations were based on a combined solution of arc 1 and arc 2. Initially, all Kootwijk measurements for that time-span were used. These data included 54 observations which had been identified by a Kootwijk screening technique as probable outliers. The computation process failed completely due to divergence in the iteration process for the orbital parameters. Therefore, the bad data points were removed, leaving 759 observations distributed over 12 passes. Now the solution converged, yielding a value

Table 4: Initial results for the baseline

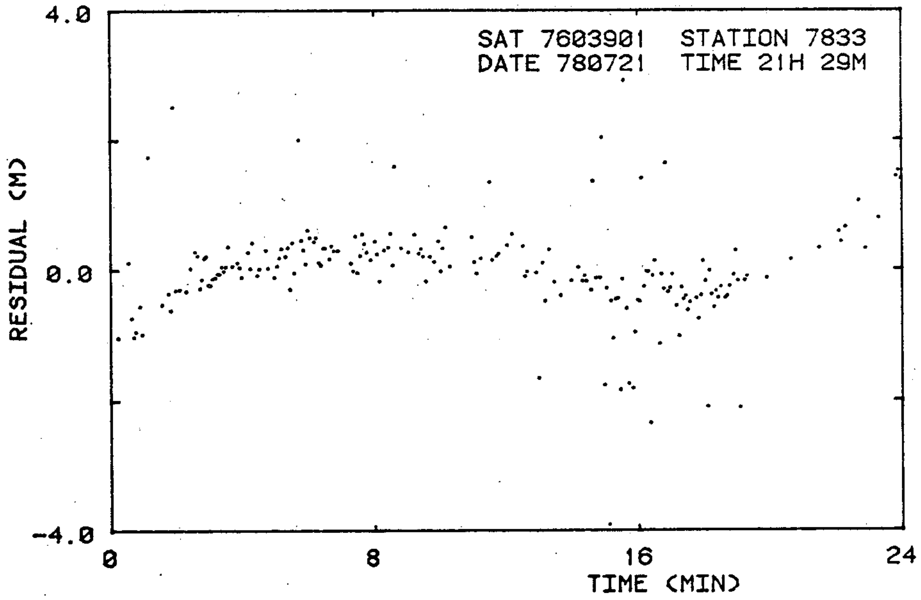
	Baseline (m)	1 σ (m)
Arc 1 + 2	602358.741	0.115
Arc 3	602419.777	0.781
Arc 4	602462.979	0.034

for the baseline of 602358.741 m, with a standard deviation of 0.115 m (Table 4). This value differs about 65 m from the value taken as a reference in this study. The mean values and the root-mean-squares (rms) of the range residuals are given in Table 5 for both arcs. These values refer to the observations which remained in the solution after the automatic editing during the iteration process. As a representative example, Fig. 7 shows the range residuals for one pass over Kootwijk and one over Wettzell. In each graph the satellite and station number, the date of the pass and the time that corresponds to the zero-point of the time-scale for that pass are indicated. The rms's listed in Table 5 are quite high and the residuals for all passes show very pronounced signatures. Figure 7 shows that for both passes this signature is in the 2 m level. As discussed in Section 2, this indicates that there is something wrong in the parameter modelling. At first it was thought that this strange behavior of the residuals might be the result of insufficient data. Therefore, a simulation with ORAN was performed, which clearly demonstrated that for the given amount of data and realistic values of perturbation model and station coordinate errors, better residuals and a more-accurate baseline could be expected. As a test, a GEODYN run was made in which also (constant) timing- and range-biases for each station were taken as solved-for parameters. However, this did not

Table 5: Initial results for the range residuals from the individual arc solutions)*

	Kootwijk		Wettzell	
	mean (m)	rms (m)	mean (m)	rms (m)
Arc 1	0.006	1.068	-0.074	0.828
Arc 2	-0.163	1.666	0.069	0.597
Arc 3	-0.438	1.412	0.008	1.557
Arc 4	-0.042	0.675	0.068	0.877

*) The values for arc 1 and 2 were obtained from a combined arc 1 and 2 solution.



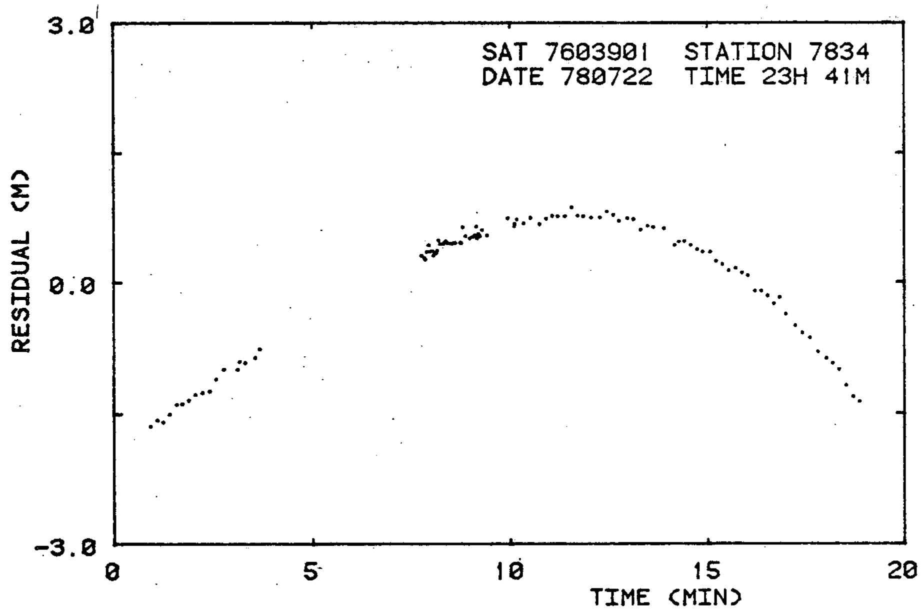


Fig. 7: The initial range residuals of an arc 1 (LAGEOS) pass over Kootwijk (top) and a pass over Wettzell (bottom).

improve the results.

Next,for the satellites STARLETTE, GEOS-1 and GEOS-3 single-arc solutions were derived. Again, probably outliers had been removed from the data. As the altitudes of these satellites were much lower than for LAGEOS, the drag coefficient was also solved for. In the solution for GEOS-3 problems arose during the so-called inner-iterations: due to high correlations the normal matrix was ill-conditioned, causing difficulties during its inversion. This indicated that GEODYN was not able to determine a reliable orbit. It was a clear illustration of the fact discussed in Section 4 that a good orbit determination requires observations distributed well along the orbit. The values for the baseline from arc 3 and 4 are given in Table 4. It can be seen that they differ about 3 m and 40 m from the reference value. The mean values and the rms's of the range residuals are listed in Table 5. In Fig. 8, the residuals are plotted for a representative pass of GEOS-1 over Kootwijk and one over Wettzell. These are overlapping passes during which measurements were taken both from Kootwijk and from Wettzell. For Wettzell, again the residuals show a strong signature. Such signatures were also found for STARLETTE. An attempt to combine all arcs in one solution failed completely; the residuals for all satellites soared up to tens of meters, much larger than for the individual solutions.

At that stage the question was raised if there could be something wrong with the Wettzell data. The arguments for this were the following. If it was assumed that the GEOS-1 solution for the Wettzell coordinates was the most accurate one, and this was quite realistic because of the good orbital coverage in arc 4, than the combined arc 1 and 2 solution yielded station coordinates which were in error (relative to the arc 4 solution) by about 88 m in latitude and -64 m in longitude. So the station had shifted about 110 m to the north-west. Since this was just in the direction of the LAGEOS ground-tracks, it suggested the possibility of a timing error in the Wettzell data. It seemed most likely that transit-time corrections had already been applied to the Wettzell data, although the data-record indicated that the specified times were ground-transmit times. Taking a mean distance of 6500 km between Wettzell and LAGEOS, the mean one-way signal travel time is about 22 ms, corresponding to an along-track position change for LAGEOS of about 125 m to the north-west. This was just about the value of the station shift. Therefore, it was hypothesized that the times of the Wettzell measurements

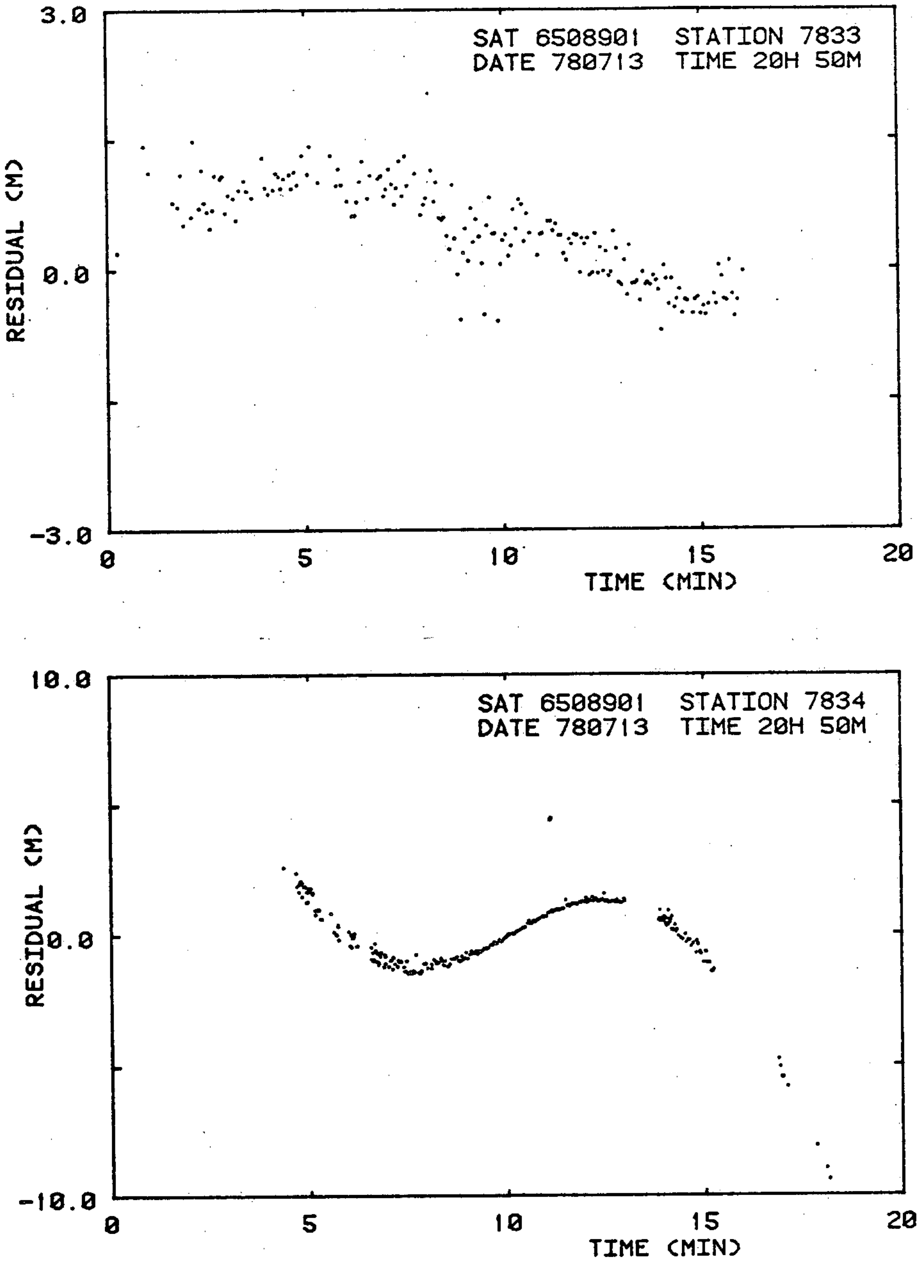


Fig. 8: The initial range residuals of a simultaneous arc 4 (GEOS-1) pass over Kootwijk (top) and Wettzell (bottom).

actually refer to the instant of time that the satellite was hit by the laser pulse. To test this assumption, all computations were repeated without transit-time corrections for the Wettzell data.

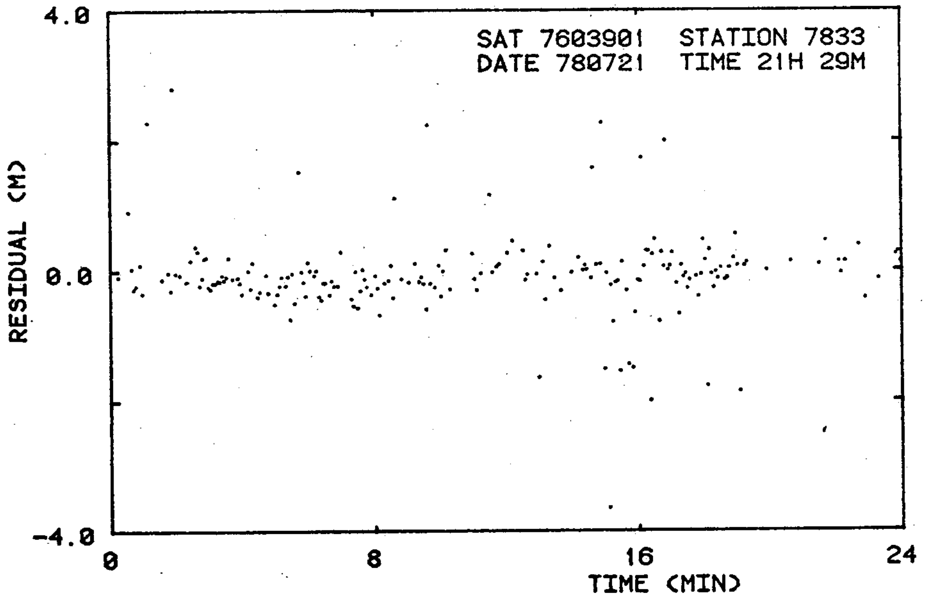
8. Final results

The improvements due to this change were impressive for all solutions. The signatures of the residuals became much smaller, in particular for the Wettzell passes. As an example, Figs. 9 and 10 show the residuals for the same passes as in Figs. 7 and 8. For the LAGEOS passes, the signature has disappeared almost completely; for the GEOS-1 pass over Kootwijk some imperfection is still visible. A particular pattern can be recognized in the residuals of the GEOS-1 pass over Wettzell. The narrowing of the band towards the middle might be due to the geometry of the laser reflector panels relative to the laser on the ground. Because of the gravity-gradient stabilization, the bottom of the satellite, where the panels are mounted, is oblique with respect to the incoming laser pulse when the satellite is near the horizon. Depending on which corner cube was hit by the photons received on earth, the measured range may vary by several tens of centimeters. The mean values and the rms's of the residuals are listed in Table 6 for all arcs, including arc 5, which still suffered from the matrix inversion problem. This might have affected the accuracy of the solution. Comparing the values of Table 5 and Table 6, the improvements are evident. Just as expected, the least-accurate orbit determination is found for arc 3, giving the largest rms's. The results for the baseline are shown in Table 7. The values for arc 1 and 2, and arc 4, which were expected to yield the best results, differ less than 0.12 m from the reference value. For arc 5 this is about 0.7 m. The arc 3 solution for the baseline is about 19 m less than the solutions for the other arcs.

Table 6: Final results for the range residuals from the individual arc solutions)*

	Kootwijk		Wettzell	
	mean (m)	rms (m)	mean (m)	rms (m)
Arc 1	-0.068	0.385	0.037	0.164
Arc 2	-0.124	0.812	-0.024	0.118
Arc 3	0.047	1.063	0.010	0.387
Arc 4	0.039	0.614	-0.003	0.182
Arc 5	0.026	0.570	-0.003	0.105

*) The values for arc 1 and 2 were obtained from a combined arc 1 and 2 solution.



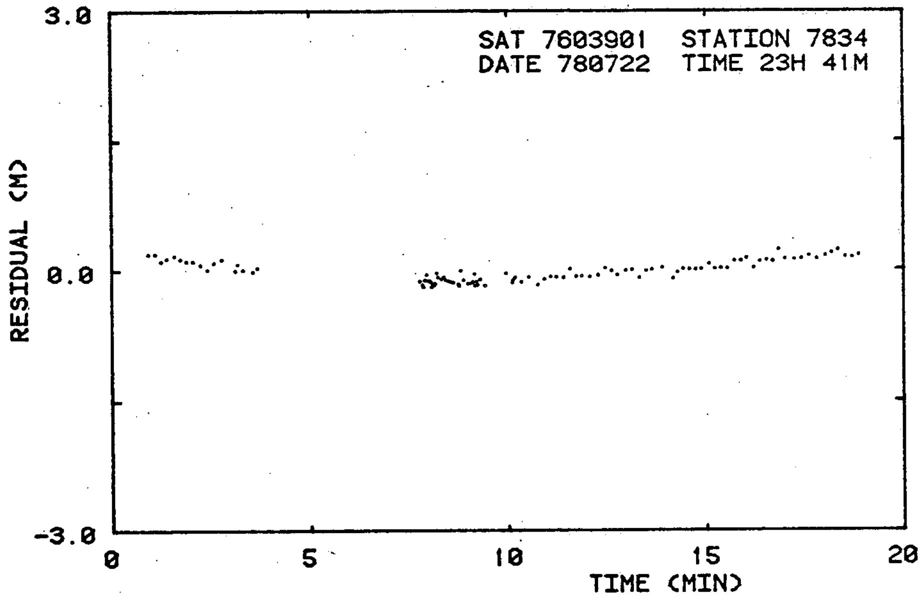
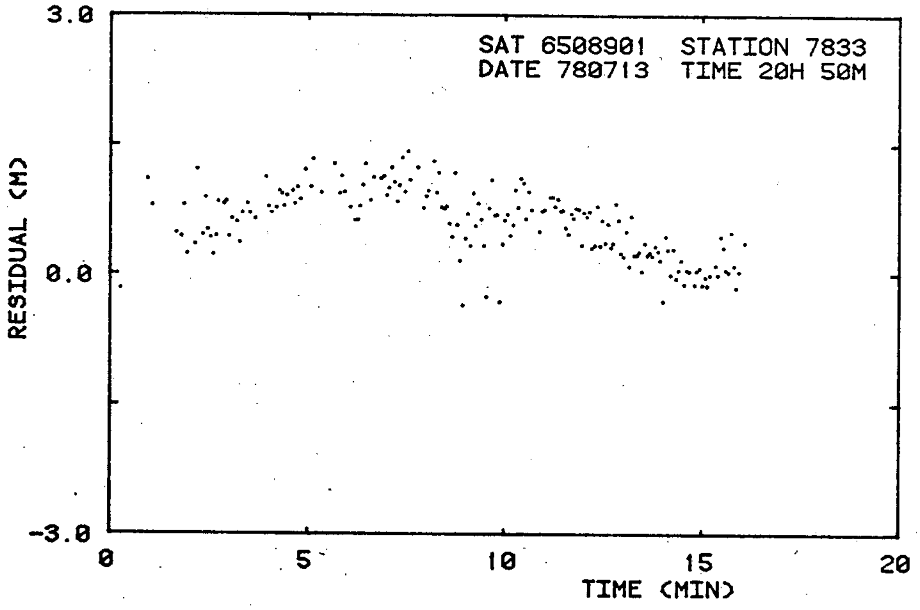


Fig. 9: The final range residuals for the same passes as in Fig. 7.



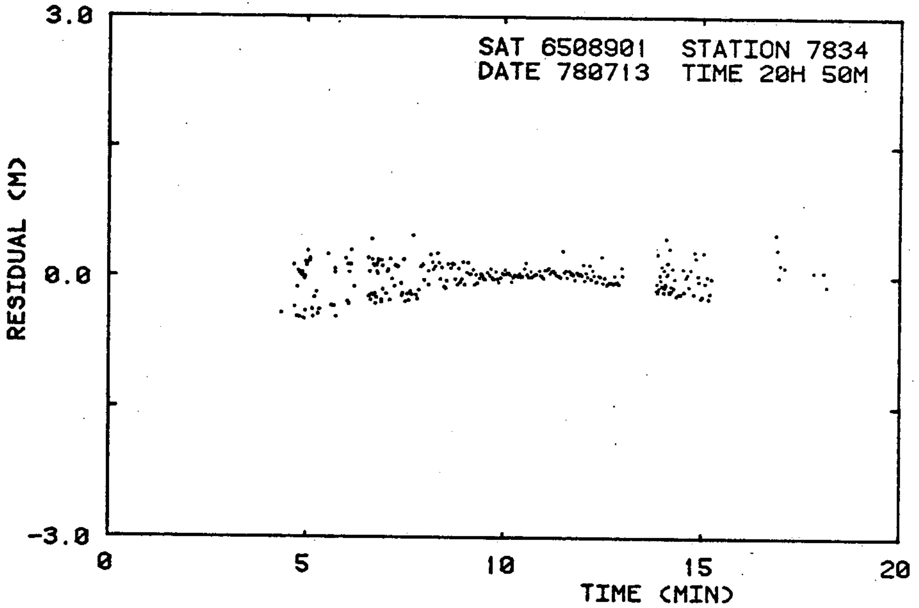


Fig. 10: The final range residuals for the same passes as in Fig. 8.

Table 7: Final values for the baseline

	Baseline (m)	1 σ (m)
Arc 1 + 2	602423.280	0.123
Arc 3	602404.199	0.824
Arc 4	602423.388	0.033
Arc 5	602422.584	0.075
Arc 1+2+3+4	602423.589	0.031

Also a four-arc solution was derived, based on arc 1, 2, 3 and 4. The results of this solution are given in Tables 7 and 8. It should be kept in mind that this solution includes arc 3, which had the largest residual rms's. Still the data from this arc do not seem to have had a large effect on the solution since the baseline is close to the values from the arc 1 and 2, arc 4 and arc 5 individual solutions. The values for the residuals show that the rms's have increased for each arc. Arc 3 again gives the largest mean and rms values. Because the residuals of some passes still showed a small signature, it was checked if the Wettzell data had also already been corrected for tropospheric refraction by short-cutting this correction in GEODYN. The results became worse than before.

The solutions for the Wettzell coordinates are presented in Table 9. The differences between the computed coordinates and the NWL-9D coordinates as well as the differences between the Kootwijk GEM-9 coordinates and the NWL-9D coordinates are given in Table 10. From this Table it can be argued that the real accuracy of the Wettzell coordinates from the arc 1 and 2, arc 4 and the combined solution is better than 1 m. The absolute accuracy of the arc 3 and arc 5 solutions is in the order of 15 m and 6 m, respectively. So, as expected from the sub-satellite track geometry the arc 5 solution yields a much more accurate value for the baseline than for the station

Table 8: Final results for the range residuals from the 4-arc solution

	Kootwijk		Wettzell	
	mean (m)	rms (m)	mean (m)	rms (m)
Arc 1	-0.045	0.665	0.002	0.120
Arc 2	0.095	1.314	-0.082	0.223
Arc 3	0.216	1.960	-0.253	0.754
Arc 4	-0.126	0.659	0.114	0.230

Table 9: Various solutions for the Wettzell coordinates

	Wettzell coordinates			Standard deviations		
	X(m)	Y(m)	Z(m)	X(m)	Y(m)	Z(m)
Arc 1+2	4075532.17	931777.18	4801617.57	0.08	0.14	0.07
Arc 3	4075536.33	931759.63	4801630.87	0.20	0.82	0.40
Arc 4	4075532.53	931776.52	4801615.90	0.04	0.04	0.04
Arc 5	4075540.98	931771.55	4801612.71	0.46	0.22	0.30
Arc 1+2+3+4	4075533.19	931776.58	4801616.04	0.04	0.03	0.03

coordinates. The differences between the computed coordinates and the NWL-9D values are plotted in Fig. 11 in terms of shifts in longitude, latitude and height above the standard ellipsoïd. The values refer to the GEM-10B ellipsoïd. As expected, for the LAGEOS, GEOS-1, GEOS-3 and combined arc solutions, the computed positions lie in the $\Delta\phi$ - $\Delta\lambda$ plane very close to a line normal to the baseline. The solution for STARLETTE is quite far from this line.

Table 11 lists the values of the satellite's drag coefficients as determined for the various solutions. All values are not unrealistic, although the results for arc 4, and in the combined solution also for arc 3, seem to

Table 10: Station coordinate differences

Kootwijk GEM-9 minus NWL-9D		
X(m)	Y(m)	Z(m)
-3.34	10.78	0.60

Wettzell computed minus NWL-9D			
	X(m)	Y(m)	Z(m)
Arc 1 + 2	-4.13	11.13	0.67
Arc 3	0.03	-6.42	13.97
Arc 4	-3.77	10.47	-1.00
Arc 5	4.68	5.50	-4.19
Arc 1+2+3+4	-3.11	10.53	-0.86

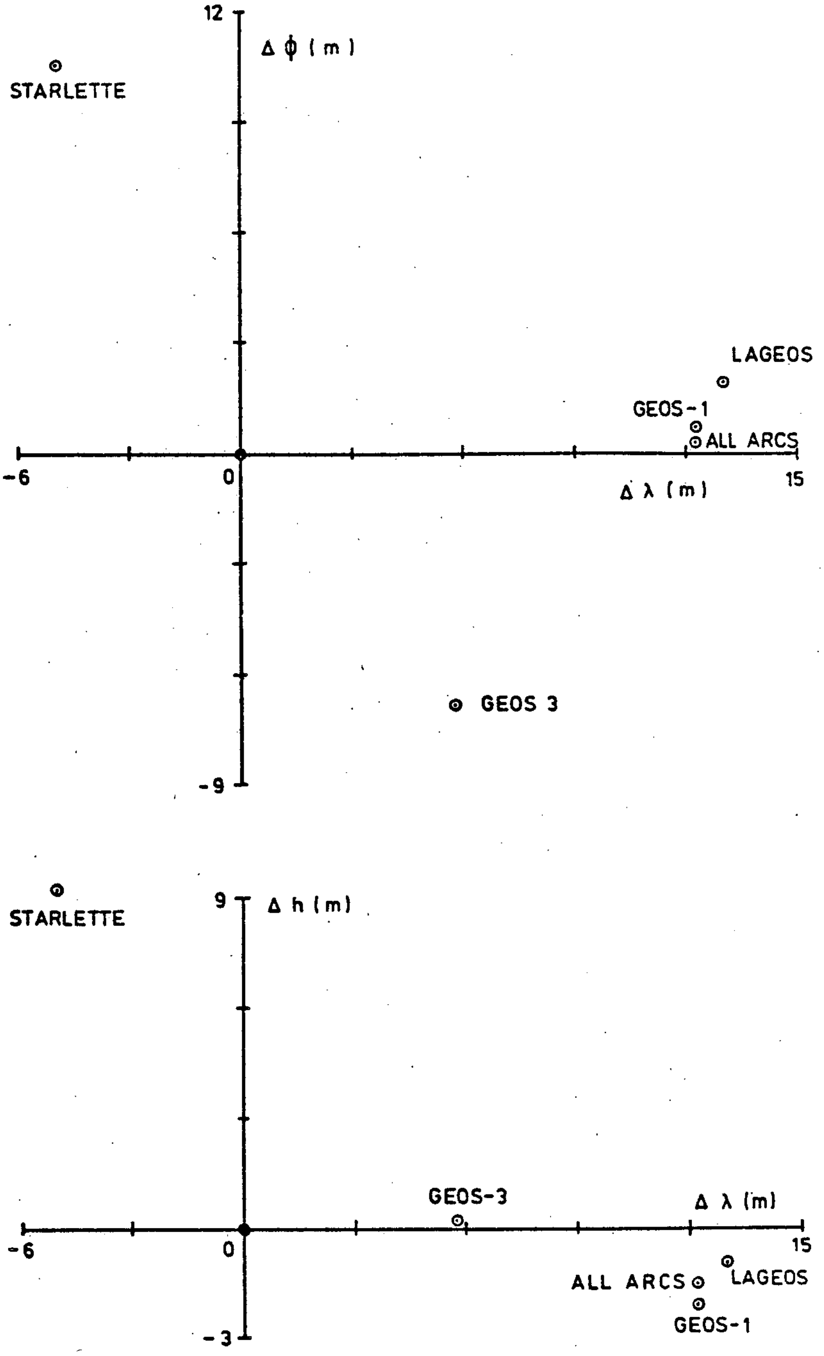


Fig. 11: Shift in computed latitude, longitude and height of Wettzell relative to reference values.

Table 11: Drag coefficient as determined from final solutions

		Value	1 σ
Arc 3	single-arc	4.45	0.16
Arc 4		1.00	0.04
Arc 5		5.61	0.01
Arc 3	4-arc	8.10	0.16
Arc 4		0.40	0.04

indicate that some unmodelled along-track errors were absorbed.

As a final experiment, the longitude of Kootwijk was kept fixed at the GEM-9 value and the latitude and height were also solved for. This computation was only performed for arc 4 and for the combined arcs 1, 2, 3 and 4, because for these arcs the best results were obtained in the previous solutions. Data on the range residuals are given in Table 12. Comparing these values with the values given in Tables 6 and 8, it is clear that the main result of the free adjustment of the latitude and height of Kootwijk is that the residuals for the Kootwijk passes have decreased. A comparison between the new values of the Wettzell and Kootwijk coordinates showed shifts in latitude, longitude (only Wettzell) and height of less than 1.5 m. The values for the baseline changed less than 0.15 m. So, even in this severe test, considering the limited amount of observations, GEODYN is able to produce accurate results. The main importance of this test, however, is that it again gives strong confidence in the reliability of the solutions for the Wettzell coordinates and the Kootwijk-Wettzell baseline.

Table 12: The range residuals when the latitude and height of Kootwijk were also adjusted.

	Kootwijk		Wettzell	
	mean(m)	rms(m)	mean(m)	rms(m)
Arc 1	-0.013	0.385	0.001	0.117
Arc 2	0.014	0.949	-0.071	0.204
Arc 3	0.197	1.884	-0.238	0.694
Arc 4	-0.108	0.700	0.113	0.225
Arc 4 (single)	0.010	0.601	-0.004	0.188

9. Conclusions

- It was demonstrated that transit-time corrections had already been applied to the Wettzell ranging data within the Kootwijk databank, although the data-record indicates that this is not the case.*)
- GEODYN is capable of determining accurate orbits from a limited amount of passes over only two groundstations, provided that the orbital coverage is not too bad. A coverage of 10% of the orbit can be used as a conservative lower-bound.
- The quality of the solution for the orbits and the station coordinates was found to be strongly correlated with the distribution of the passes within the arc-length and with the orbital coverage of the measurements.
- The noise on the Wettzell data is so small that spacecraft attitude variations may have been detected in the residuals pattern of GEOS-1.
- The values for the Kootwijk-Wettzell baseline obtained from the 3 single-arc solutions that yield the most accurate orbits range from 602422.58 m to 602423.39 m. One solution that also had a weakly-determined orbit gave a value of 602404.20 m. The combined four-arc solution yielded a value of 602423.59 m.
- The 3 solutions mentioned differ less than 0.7 m from the reference value computed from the station coordinates taken as a reference in this study.
- The small signatures in the residuals and the values obtained for C_D seem to indicate that some errors in the mathematical model still exist.
- Two solutions in which the latitude and height of Kootwijk were also adjusted contributed to the confidence in the reliability of the results.
- It is felt that the real accuracy of the best solutions for the baseline and Wettzell coordinates is better than 0.5 m for the baseline and better than 1 m for the coordinates.

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*) This error was later confirmed by IFAG (Ref. 6).

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