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GEODETIC DUAL-FREQUENCY GPS RECEIVERS UNDER ANTI-SPOOFING

COMPARISON OF FOUR RECEIVERS FOR BASELINE ACCURACY

SUSCEPTIBILITY TO RADIO FREQUENCY INTERFERENCE

NOISE IN THE OBSERVABLES

P.G. SLUITER

A PROJECT OF THE WORKING GROUP FOR APPLIED SPACE GEODESY

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NEDERLANDSE COMMISSIE VOOR GEODESIE, THIJSSEWEG 11, 2629 JA DELFT, THE NETHERLANDS
TEL. (31)-(0)15-782819, FAX (31)-(0)15-782745

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Contents

Summary

On 31 January 1994, the Anti-Spoofing (AS) feature was activated by the GPS control segment. This restricts the capabilities of conventional two-frequency GPS receivers. Several manufacturers of geodetic receivers have developed methods to overcome most of the adverse effects of AS.

The Working Group for Applied Space Geodesy of the Netherlands Geodetic Commission, (an institute of the Royal Netherlands Academy of Arts and Sciences) decided to investigate and compare the performance of four of these receivers, i.e. the ASHTECH Z-12, the LEICA (or WILD) System 200, Allen Osborne Associates' TurboRogue-(SNR8000) and the TRIMBLE 4000SSE.

Major attention was given to the ability to accurately and quickly resolve two baselines; one of 10 km and one of 100 km length. Furthermore, the susceptibility to radio frequency interference (RFI) was investigated, mainly because in the past years this has on several occasions been a problem during surveys in Holland. And finally an effort has been made to determine the noise in the various observables that are output by the receivers.

We stress that this is not a comprehensive evaluation to be used to decide on which receiver to purchase. For that purpose many other aspects should be taken into account, such as performance under low signal levels (foliage), availability of software and peripheral modules to integrate GPS into normal survey operations, weight, transportability, kinematic operation, price and other aspects for specialized applications.

Some guidance to the reading of this report may be useful. Individual chapters of the report can mostly be read separately, though some aspects overlap. The most important results are always included in the text, often with short tables. More detailed tables or figures are -grouped per chapter- included in the appendices.

Chapter 1 is an introduction, mainly consisting of a short explanation on AS and how the various manufacturers try to overcome its restrictions. In it, the rationale is given why we choose to evaluate the aspects as described.

Chapter 2 describes the data acquisition for the evaluation of baselines and the noise in the various observables.

Chapter 3 gives the results of "hands-off" processing of baselines, using the standard software provided by the manufacturers and a commercially available receiver-independent package, i.e. TOPAS from TerraSat, recently renamed into GEOTRACER from the company Geotronics. The guiding principle in this chapter is that no efforts have been made to improve the results by means of data editing or any other method.

Chapter 4 gives the results of processing with the scientific "Bernese" software package. Here extensive efforts have been made to get the best out of the available data.

Chapter 5 describes the effects of both unintentional and intentional radio frequency interference (RFI) on the performance.

Chapter 6 explains efforts to analyse the noise in the various observables, using one single receiver per manufacturer. Results are given.

Chapter 7 contains the most important conclusions. More detailed conclusions are given at the end of chapters 3,4,5 and 6.

The report concludes with acknowledgements and a list of literature references.

1. Introduction

1.1. Anti-Spoofing

Anti-Spoofing (AS) encrypts the publicly available P-code into a secret Y-code. It is done by a modulo-2 addition of the 10.23 MHz P-code and a W-code of about 500 KHz. The encryption was introduced on 31 January 1994. The main purpose of AS is to make the (military) GPS system more immune to deliberate jamming by unfriendly forces. It has however the additional effect that conventional civilian GPS receivers can no longer use the L2 frequency for measurements. This has two major impacts:

1. The capability to measure a precise correction for the effect of the ionosphere is lost.
2. The number of observables is reduced.

The measurement of a code range -be it for C/A, P or Y code- requires that the incoming, code-modulated carrier wave is crosscorrelated with an internally generated, identical code. It results in a time off-set between the two, from which the distance is computed. So if the Y-code modulation is not known, the two code ranges (Y1 and Y2) can no longer be observed.

For geodetic surveys, also the phase of the incoming carrier wave needs to be measured. To do this, the modulation has to be removed and this also requires knowledge of that modulation. So if Y2 is not known, it is in principle also impossible to measure the L2 carrier phase. C/A code range and carrier wave phase of L1 continue to be available as normal.

1.2. Y-code busters

There are however several methods to (partly) overcome these restrictions. Receivers that do this are sometimes referred to as Y-code busters. In general they use the fact that the Y-code modulation is the same on L1 as on L2. This makes it possible to do a cross-correlation between Y1 and Y2, even though the actual modulation is not known. It will however not result in an observation of the travel time (and distance) from satellite to receiver, but in a difference in travel time of the two signals on two different frequencies. This is a measure for the ionospheric effect. By adding this difference to the observed C/A-code range on L1, an observed code range on L2 is obtained.

There is another method to obtain a range using the code on L2. This makes use of the fact that the Y-code is generated by a modulo-2 addition between a secret W-code and the publicly known P-code. So there is some similarity between the two. Cross-correlating the incoming signal with a copy of the P-code, also gives a range, but much less accurate than if the correct Y-code had been used. This may be done for the Y-code on both the L1 and L2 frequency.

In this way the restrictions to the measurement of code ranges are (partly) overcome. It is also possible to recover the phase of the L2 carrier. Because of the binary bi-phase modulation - it is only plus 1 or minus 1 - used in GPS, a multiplication of two identically modulated signals, will remove this. This process results in two unmodulated carrier waves, one has a frequency equal to the difference of the two carriers and the other has a frequency equal to the sum. Filtering out one of these leaves only one CW, the phase of which can be measured. This process can also be done in different ways.

One method is to multiply the L1 and L2 signals after aligning the code. Filtering out the sum frequency leaves only the beat frequency L1 minus L2, the phase of which can be measured. This is in fact what is often called the wide-lane (L5) frequency with wavelength 86.2 cm. Adding this phase to the one on L1 obtained from C/A code tracking gives the L2 phase. Another method is to multiply the L2 signal with itself, i.e. it is squared. The difference frequency is then zero (a DC term). Removing that one by filtering leaves only the sum frequency, which is twice the original one. This gives the so-called half-wavelength L2 phase.

1.3. Implementation

The receiver manufacturers considered here have applied different combinations of the described principles. They lead to slightly different observables and - on theoretical grounds - also to different Signal to Noise Ratios (SNR). See [Van Dierendonck, 1995]. The SNR depends mainly on the bandwidth of the tracked signal; the wider the band, the more noise can enter into the process. A fierce competitive battle is being waged as to which method is the most successful. This lead to the decision to carry out this comparison, with as a main objective to find out whether the different SNRs have a significant effect on the quality of the survey results.

In this report the four receivers that have been mentioned in the summary will be indicated by the names ASHTECH, LEICA, ROGUE and TRIMBLE. The actual versions and other relevant information for these instruments are detailed at the end of chapter 3. All four receivers obtain C/A-code range and L1 phase observation in the conventional way. The way in which information from the L2 frequency is obtained is briefly described hereafter.

ASHTECH has given their method the name Z-Tracking. They correlate both Y1 and Y2 with a locally generated P-code. After filtering, they cross-correlate and mix the aligned L1 and L2 signals. It results in two Y-code ranges and full wavelength carrier phase for L2 as described by [Ashajee et al., 1992].

LEICA only correlates the Y2 signal with a locally generated P- code. To remove the modulations, they multiply L2 with itself, so a squaring operation. This gives as observables a code range for Y2 and half-wavelength carrier phase for L2 [Hatch et al.,1992].

It is believed that both ROGUE and TRIMBLE cross-correlate Y1 and Y2, most likely with different detailed implementation. The difference between the Y-code ranges is added to the C/A range to provide a range for Y2. Mixing the two frequencies gives full wavelength carrier phase on L2.

1.4. Significance for geodetic surveys

For geodetic applications it is only the capability to do surveys that counts, so this has been the major subject of the investigations reported here. These surveys may be split into two main categories, viz. rapid static work over short distances and survey of long baselines. Hence the decision to acquire data over a short 10 km baseline and over one of 100 km length.

Most geodetic users will purchase the combination of hardware and software from the same manufacturer; therefore such full packages have been compared. To try and evaluate separately the performance of the hardware, the data output by the receivers has also been processed with receiver-independent packages. In routine surveys a minimum of operator intervention is desirable, which is called here "Hands-off"processing.
For non-routine surveys, additional processing efforts may be justified to obtain the highest possible accuracy. For that reason the data have also been processed with "Bernese" software. This also gives an extra possibility to evaluate the quality of both the hardware and software supplied by the various manufacturers.

The reason for investigating the susceptibility to frequency interference was two-fold. Firstly, operational users experienced on several occasions in the past considerable interference from near-by radio sources. Secondly, the different signal to noise ratios claimed by manufacturers suggest that this should be reflected in their survey performance in high noise areas. This has also been the reason why an effort was made to establish the noise in all observables of the four instruments.

2. Data acquisition

2.1. Locations

The vector Kootwijk - Delft was used for the long baseline and Kootwijk - Apeldoorn for the short one.

At Kootwijk points were selected on the roof of the Kootwijk Observatory for Satellite Geodesy, at Delft on the roof of the building of the Faculty of Geodetic Engineering of the Delft University of Technology and in Apeldoorn on the roof of offices of the National Cadastre and Triangulation Service.

2.2. Antenna sites

For a fair comparison between different receivers there are several complicating factors. Ideally the external circumstances should be identical for all instruments. This means observations are to be done simultaneously and all antennas should be on the same spot. Because we wanted each instrument to use its standard antenna, this is physically impossible. We designed therefore a good compromise between these conflicting conditions.

Four sites - called A, B, C and D - were selected at each of the three locations. The maximum distance between any of these four was 23 meter; their relative positions were accurately surveyed by conventional means. In the analysis these surveys are assumed to be without error. To ensure identical satellite geometry, observations at each station continued for 23 hours, followed by one hour of data downloading and antenna moves. This procedure was repeated the next three days, so that each instrument-type measured each of the four baselines (i.e. A-A, B-B, C-C, D-D) for nearly a full day. With a long and a short baseline, it involved eight days of data acquisition.

Appendices A.1 to A.4 gives all basic co-ordinate information for the baselines, the site sketches and photographs. All antenna sites had a clear view of the horizon above 10°, except for stations C and D in Apeldoorn, where a wall to the North obscured signals to about 25° elevation. However, at this latitude no satellites in that direction exceed 15° elevation. The wall might however contribute to an increased multipath effect.

It was realized that an incidental malfunction of an instrument could invalidate a comparison. Only the short baseline ROGUE observations suffered from loss of data for unknown reasons. The nature of the malfunction - and absence of it at other locations on subsequent days - does not exclude that some external source may be the cause. The instrument recorded data, but suffered repeated loss of all signals, as shown in app. A.5.

2.3. Recorded data

The observations were carried out during the eight days between 10.00 a.m. on March 3 and 08.00 a.m. on March 11, 1994.

To keep the amount of data within reasonable limits, the normal recording interval during the eight observation days, was set at 30 seconds. For better evaluation of the rapid static performance on the short baseline, this interval was reduced to five seconds during the first three-hour period of each day (from 12-15 hr).

These data have been used for the analyses described in chapters 3, 4 and 6; the data acquisition to investigate the effect of radio frequency interference is described in chapter 5.

Immediately after the acquisition of the raw data in receiver- dependent format, back-up copies were made for safe keeping. Thereafter everything was converted into RINEX-2 format, paying special attention to the fact that the correct antenna heights were included in the RINEX files.

3. "Hands-off" processing (commercial software)

3.1. General

This chapter is a slightly adapted version of [Sluiter et al., 1994].

In operational use, often a large number of points is surveyed and processed in a short time. The personnel to do this, is often specialized in the routine work, but not in detailed knowledge of GPS. For this reason the "hands-off" method was chosen, meaning that no operator intervention with the processing was allowed, other than assuring that data was available for the selected sessions. This is also in line with the often heard remark that it is easier and cheaper to repeat a survey, than to try and edit previously recorded data.

For the long baseline, it was decided to divide each day into 22 consecutive sessions of one hour each. For the short baseline, with five seconds recording interval, one ten-minute session was computed each half hour (six baselines) and for the 30 seconds recording interval, one ten-minute session was computed each hour (20 baselines). For reasons not related to instrument performance, sometimes less than the 22 long or 26 short baselines were computed. Furthermore each day the windows were advanced by four minutes, to have identical geometry per fix for successive days. We computed all baselines - using broadcast ephemeris - with the software that each manufacturer provides for his own receiver (there was no such software for the ROGUE available). In addition all computations have been repeated with GEOTRACER software (of Geotronics) also known by the name TOPAS-TURBO (of TerraSat); hereafter it is referred to as TOPAS.

Originally it was intended to do all processing from the RINEX files. For ASHTECH these files turned out to be too large so the raw data was used. The processing of the long baselines was done with the PRISM package; for the short baselines the PNAV package was used. It was deemed better to use the raw data files also for TRIMBLE in their package GPSurvey (WAVE). By that time the processing of LEICA data with the SKI package had already been completed, using the RINEX files. TOPAS is especially designed to work from the RINEX files.

Theoretically 88 long and 104 short baselines could be computed for each receiver. For all these, the station Kootwijk was held fixed at its "known" WGS84 co-ordinates. We did not use observed meteorological data. Basic co-ordinate information is given in appendix A.1.

3.2. Analysis of the results

The first step after computing the baselines, was to select the required parameters from the ASCII output of the software. The decision was made to limit the analysis of baseline results to the differences in the computed WGS84 Cartesian X, Y and Z co-ordinates vectors and their associated standard deviations; each solution being identified by a time tag. Hereafter standard deviation is abbreviated to s.d.

From this the following was prepared per receiver and per day:

- Time series graphs of results and their s.d.
- A weighted (using the s.d. computed by the software) average of the hourly results per day, which was then subtracted from the "known" (hereafter called "datum") co-ordinate-vectors given in app. A.1. Similarly an average over four days is compared with this datum, using the known position relation of the A, B, C and D points.
- The number of times the computation failed to give a result, or for which a predetermined (see later) accuracy criterion was not achieved. The spread in the hourly results per day has been used to estimate an "external" s.d. for a session of one hour.
- A multiplication factor required for the s.d. computed by the software to make it consistent with the external s.d. mentioned in the preceding item.
- Lists of correlation coefficients that can be computed between the various time series.

In addition a discussion of each receiver gives details about the rejections and other relevant information. All of these results are presented separately for the long and short baselines and discussed hereafter.

3.2.1. Acceptance criteria

It is of crucial importance to be clear on the criteria used for rejecting a result. If the software was unable to compute a fix or rejected the result, we rejected it also. In addition we rejected the solutions when the s.d. computed by the software exceeded the value described hereafter. The s.d. output by the software is often too optimistic, therefore we augmented this by a multiplication factor, as explained in section 3.4. We rejected, if this augmented value exceeded the external s.d. (computed from the daily spread in the results) by a factor 10. Furthermore the results of a short baseline were rejected, if the ambiguities on L1 were not fixed, and for TOPAS processing of LEICA data we found it was essential that they were fixed for both L1 and L2 phase observations. All rejected results had nearly without exception large errors.

3.2.2. Time series

Per day and per receiver the deviations from the weighted average have been plotted for each WGS84 Cartesian co-ordinate component. The displayed time-tags are for the start of the one hour period for the long baseline and for the end of the 10 minute period for the short baseline. Since the results per receiver and per day differ slightly, the zero-lines for the deviations do NOT refer to identical values for the co-ordinate differences. The augmented s.d. per solution has been graphed on either side of the zero-lines. When the computation was not successful or did not satisfy the earlier mentioned acceptance criteria, a small black rectangle is inserted. This has the advantage that the vertical scale could be made fairly large and the graphs remained legible. Appendix B.1 gives the results for the long baseline on four days, using the software of the manufacturer; therefore there are no ROGUE results. Appendix B.2 gives the results when using TOPAS software. Similarly the short baseline results - using manufacturer's software - are presented in appendix B.3 and using TOPAS software in appendix B.4. The short baseline results for the ROGUE are absent because of the earlier mentioned problems at one of the stations. The LEICA computation with TOPAS software, had so few acceptable results, that it was not worth making a graph.

3.2.3. Long baselines

On the basis of the success ratio, TOPAS performed better than TRIMBLE's GPSurvey and - to a lesser extent - also better than LEICA's SKI. However, recomputing with TRIMBLE's new version Wave 1.2 of GPSurvey, when it became available later in the year gave a 100% success ratio. The fact that TOPAS was not very successful with the ROGUE data, was later diagnosed to be due to malfunctioning of the receiver at the end of the last day. With ASHTECH data, both PRISM and TOPAS software gave a 100% success ratio.

It is interesting to note that on two occasions a complete day's work has been accidentally computed using co-ordinates for the fixed Kootwijk station that differed about 50 meter from the values given in app. A.1. The effect was that the fluctuations in the hourly results for those days increased by a factor of nearly four!

3.2.4. Short baselines

A comparison of the rejections by TOPAS and by manufacturer's software is of interest, because it gives an indication to which extent the results can be improved by software modifications. The most remarkable case is that the TRIMBLE short baselines had 13 rejections by TOPAS and 12 by GPSurvey; NONE of which were for identical observation periods! Indeed, when also these were recomputed with TRIMBLE's new version Wave 1.2., the success ratio improved to 100%.

ASHTECH's PNAV gave a good success ratio, but processing the same data with TOPAS was less successful. Yet two of the three baselines rejected by PNAV were accepted by TOPAS!

For the short baseline, the 5 sec. sampling interval was used from 12-15 hours; the rejection ratio for that period is only slightly better than for the 30 sec. sampling interval. The lower success of LEICA's SKI software can however be partly explained by the use of 30 sec. samples. The software always issued a warning that it considered the observation session too short. In operational work that information is available in real time and the operator would observe somewhat longer. To investigate the very disappointing performance of TOPAS, the LEICA data has been passed on to the supplier. He recomputed with a new version, called GEOTRACER GPS 2.0. and reports an 89% success ratio.

3.3. Results, failures and s.d.'s

For each instrument and each day of observation, the weighted average (using the s.d. output by the software for each baseline) has been computed. We also listed the number of fixes that did not pass the rejection criteria and we computed the s.d. of the accepted results. All these results are given in appendix B.5 for the long baseline and in appendix B.6 for the short one. The same has been done by taking all four observation days together; these results are summarized in tables 3.1 and 3.2 for the long and short baselines respectively. The s.d.'s in the accepted results show little difference, though for the short baseline, the TRIMBLE with its own software gives somewhat higher s.d.'s than ASHTECH and LEICA.

For the long baselines TOPAS gives slightly higher s.d.'s than the manufacturer's software; for the short baselines this is just the opposite. The new software versions for TRIMBLE and TOPAS came too late to be included in this evaluation.
Concerning the computed co-ordinates - averaged over four days -, the following remarks can be made:

- The long baseline vectors obtained with manufacturer's software are very similar, but differ about 4 cm. from the known datum co-ordinates (obtained from an EUREF campaign) in the direction of the line, indicating a scale difference of 0.4 ppm.

- The long baseline vector results from TOPAS, differ consistently from these results by 5 cm., mainly in X direction. [1)]
- The short baseline vector results from LEICA with SKI software differ more than 2 cm. with the others, mostly in X- and Y-direction. It suggests the presence of a scale difference.

		Diff. of average with datum coords (cm.)			S.d. in 1 hour obs. period, computed from spread in results (cm.)		
Manufact. software	Success ratio [2)]	dX	dY	dZ	sx	sy	sz
ASHTECH	100%	-2.0	+3.3	+0.3	5.5	6.6	5.7
LEICA	95%	-2.2	+3.9	+0.7	5.4	7.6	4.2
TRIMBLE	94%	-0.9	+4.7	+0.2	4.9	4.8	5.3
TOPAS software	Success ratio	dX	dY	dZ	sx	sy	sz
ASHTECH	100%	-6.9	+1.6	-0.1	6.7	8.1	5.8
LEICA	98%	-7.4	+1.6	0.0	6.7	8.8	4.8
TRIMBLE	100%	-6.8	+2.9	-0.3	5.5	7.3	5.0
ROGUE	90%	-5.4	+1.0	0.0	7.4	7.5	4.8

Table 3.1: *Long (100 km) baseline, using 88 observation periods of 1 hour each.*

		Diff. of average with datum coords (cm.)			S.d. in 10 min obs. period computed from spread in results (cm.)		
Manufact. software	Success ratio [2)]	dX	dY	dZ	sx	sy	sz
ASHTECH	97%	-0.4	+1.1	+0.4	1.2	0.7	1.1
LEICA	93%	+0.3	-0.9	-0.2	1.2	1.2	1.6
TRIMBLE	88%	-0.8	+1.6	+0.4	2.7	1.3	2.0
TOPAS software	Success ratio [2)]	dX	dY	dZ	sx	sy	sz
ASHTECH	82%	+0.2	+1.1	+0.3	0.9	0.5	1.1
LEICA	22%	+0.5	+1.1	+0.9	1.2	0.4	1.0
TRIMBLE	86%	+0.2	+1.3	+0.6	0.9	0.5	1.1

Table 3.2: *Short (10 km) baseline; using about 100 observation periods of 10 minutes each.*

[1)] The supplier of TOPAS attributes this to using an earlier value for the WGS84 earth rotation rate. He reports it has been corrected in their new version.

[2)] New 1994 software gives mostly much improved succes ratio's for both short and long baselines.

3.4. Multiplication factor for standard deviations (s.d.)

It is remarkable that the covariance matrices output by most software are far too optimistic. In an effort to convert these to more realistic values, factors have been computed per co-ordinate component, per day. These factors are the square root of the ratio between the a-posteriori and the a-priori variance. A-posteriori was computed from e^2/n, where e is the deviation of each result from the weighted daily average and n the number of valid observations. For a-priori we used the variance that is output by the software.

The results are given per receiver, per software, per day and per co-ordinate component in the last columns of appendices B.5 and B.6. These computed factors show a rather large spread and sometimes differ systematically for the X, Y and Z component. This is most evident in two cases, viz. the Y-component of the LEICA-SKI short baseline computation, being nearly five times larger than for Z and the TRIMBLE-GPSurvey long baseline factor for Y being more than twice as large as for Z.

Table 3.3 gives a summary of the results for each software package. It appears that only the Ashtech output has realistic values. In the time series graphs we used approximate values that sometimes differ slightly from this table.

	LONG BASELINE				SHORT BASELINE			
	fx	fy	fz	All	fx	fy	fz	All
ASHTECH	0.8	0.6	1.1	0.9	1.4	1.2	1.1	1.2
LEICA	7.6	7.4	9.2	8.1	12.1	24.1	5.3	13.8
TRIMBLE	25.4	43.4	20.4	29.7	5.9	6.9	6.3	6.4
TOPAS	7.2	6.6	8.7	7.5	4.8	4.1	5.3	4.7

Table 3.3.: *Multiplication factors for s.d. output by software*

3.5. Correlation coefficients

When studying the time series graphs closely, there appear to be varying degrees of similarity between days, between receivers, between stations and between software packages used. We expressed this agreement in a numerical value, by computing correlation coefficients (C_{12}). This has been done by subtracting corresponding results (e.g. 1 and 2) and applying the following formula, where σ_1, σ_2 and σ_{1-2} are the s.d.'s in the results 1, 2 and the difference 1 minus 2.

$$C_{12} = \left(\sigma_1^2 + \sigma_2^2 - \sigma_{1-2}^2\right) / \left(2 \bullet \sigma_1 \bullet \sigma_2\right)$$

The coefficients vary for the different combinations of days, of receivers and also for the co-ordinate components X, Y and Z. The details of these correlations are in appendices B.7 till B.10 for the long baseline and B.11 till B.13 for the short one.
In Table 3.4. the average values and their s.d.'s are given.

The only significant correlation occurs between TOPAS processing on the one hand and ASHTECH or LEICA processing of the same data on the other. Furthermore there is some correlation between the baseline results from different receivers observing on the same day, when using TOPAS. Most other correlations are rather insignificant.

Between	Software	Long Baseline Cor.Coef.	Long Baseline S.d.	Short Baseline Cor.Coef.	Short Baseline S.d.
Receivers (same day)	TOPAS	0.6	0.3	0.7	0.1
	MANUF	0.3	0.3	0.0	0.3
Days (same receiver)	TOPAS	0.1	0.3	0.3	0.2
	MANUF	0.1	0.3	0.5	0.3
Receivers (same stat)	TOPAS	0.1	0.3	0.4	0.1
	MANUF	0.1	0.2	-0.1	0.3
TOPAS and MANUF software	ASHTECH	0.9	0.1	0.7	0.1
	LEICA	0.8	0.1		
	TRIMBLE	0.4	0.3	0.4	0.2

Table 3.4. *Correlation coefficients and their s.d.*

3.6. Remarks per receiver/software

ASHTECH

The receivers were ASHTECH Z-XII-3, version 1C111C0, using the geodetic L1/L2 microstrip antenna. We used program ASHTORIN for the conversion to RINEX. The long baselines were processed with PRISM 2.0.00 (12/8/93), using the L1C (ionosphere free) option. For the short baselines we used PNAV 2.0.00; kinematic L1 + L2 in the static option. A tropospheric model was used (not known which); the parameters were 1010 mbar, 50% humidity and 5°C.

There were no rejections for the long baseline and three for the short one; all due to the s.d. exceeding the tolerance. The graphic output provided by PNAV showed that the computation failed to converge. These graphs also showed that normally convergence was achieved after two minutes when using 5 sec. data interval and after five minutes when this data interval was 30 sec.

Efforts to compute the long baseline with PNAV and the short one with PRISM gave less satisfactory results. This suggests that somewhere between 10 and 100 km, one should change from PNAV to PRISM. It is not known which parameters govern the choice of the best software.

LEICA

The receivers were SR299's, version 2.10, with internal antenna. RINEX conversion took place with OBSTORNX, version 1.08; The long baselines were computed using the ionosphere free observable in program SKI, version 1.08. For the short baseline this was version 1.09, using both L1 and L2. Tropospheric correction used the Saastamoinen model with standard parameters (1013.25 mbar, 50% humidity and 18° C). SKI failed to produce results for three long baselines (too many cycle slips); for a fourth one the s.d. was too large. Seven short baselines were rejected; all because no reliable integer ambiguities could be found. The reasons varied. They were:

a. Did not comply with measurement specifications (twice)
b. One satellite had just a few observations (three times)
c. No unique solution according to the FARA testing (twice).

Of these seven rejections, one occurred when the recording interval was 5 sec. and was for reason b. The software issued a warning for all periods with 30 sec. interval stating that the occupation time was shorter than recommended.

TRIMBLE

The receivers were 4000SSE's version 5.71, with the compact L1/L2 antenna. For the RINEX conversion we used TRRINEXO V2.2.4. and for all processing the optimum solution of GPSurvey; WAVE version 1.10.a. A standard troposphere and the Saastamoinen model were used to compute tropospheric corrections. Of the five rejected long baselines, three failed to produce a result for unclear reasons, (giving a cryptic error message). For two others the s.d. was too large. Ten short baselines also gave this same error message and two had a too large s.d. Originally there were more rejections, the use of an undocumented Beta release (said to be version 1.19a), reduced this number. As stated before, software version Wave 1.2. came too late to be included in this report.

ROGUE

The receivers were TurboRogue SNR-8000's (Allen Osborne Ass.), version 93.06.08/1.16 with Dorne Margolin choke-ring antenna. The RINEX conversion was done with RGRINEXO V2.1.0. Nine computed fixes of the long baseline were rejected because of large s.d.'s, caused by repeated loss of lock, particularly at the end of the last day. At one of the short baseline stations the receiver lost lock on all satellites every few minutes, (not simultaneously) during all four observation days. This made it impossible to compute any fixes at all. The reason for this failure is unknown. The software package TurboSurvey was not yet available.

TOPAS

This is a receiver independent software package. We used the version TOPAS TURBO 3.3.b to compute the long baselines and version GEOTRACER GPS 1.1.c for the short ones. The long baseline was processed using the ionosphere free observable. The short baseline was computed in the automatic mode fixing the ambiguities. We have no detailed information on the tropospheric model used. According to the supplier of this software, (who had been given our data), version GEOTRACER GPS 2.0 improved the results, as already mentioned before.

3.7. Conclusions

- The ROGUE analyses is incomplete due to lack of manufacturer's software and loss of data for unknown reasons.
- The data acquired by all four receivers appears to be of similar quality and is capable of producing baseline results of comparable precision.
- There is also very little difference in the performance of the manufacturers' software packages. For the long baseline one hour of data gave s.d.'s of about 5 cm. in all three Cartesian co-ordinate components. For the short one ten minutes of data resulted in s.d.'s between 1 and 2 cm., the higher values being obtained with TRIMBLE's software.
- The resulting co-ordinates are similar for all receivers, except that the short baseline computed with LEICA's SKI software indicates a scale difference of 2 ppm with all other software.
- The s.d.'s output by most software packages were too optimistic by varying degrees. Only ASHTECH's values were realistic.

- With new software that became available during 1994 for some packages, the success ratios for all of them approached 100%; in general the ratio is lowest for the LEICA. Most software packages suffer from insufficient information to interpret their output and do not explain their methods and algorithms.

4. Advanced processing ("Bernese software")

4.1. Introductory remarks

For specialized applications, it may be necessary and justified to spend considerable effort and time to obtain the best possible results. This chapter is a condensed and adapted version of a study into this subject, commissioned by the Dutch Ministry of Transport, Public Works and Water Management and described in [Springer,1994b].

The purposes of the study were to:

a. Determine the highest achievable accuracy for both long and short baseline. Because there was a particular interest in the height component, the analysis used the North, East and height component, rather than the ECEF Cartesian X, Y and Z in chapter 3.
b. Find the optimum parameter settings and the shortest possible observation period to obtain that result.
c. Determine the receiver giving the best result.

The study was later extended to also use these "Bernese" results for a further evaluation of the software of the instrument manufacturers and to obtain an impression of the precision that can be obtained from a full day's observation. These results are given in section 4.7.

The criterion to judge the quality was the standard deviation that can be computed from the spread in the results of a large number of sessions observed during one day. It is a measure for the repeatability. The same data was processed in many different ways, varying amongst others the length of the observation period, the elevation cut-off, the tropospheric parameters to be estimated, the ambiguity search method etc. This was done using a pre-release of the Bernese software version 3.5; it uses the double differencing approach. [Rothacher et al.,1993] gives details of the software version 3.4. It has numerous options; an insight into the ones actually used is given in [Springer,1994b].

The precise ephemeris of the International GPS Service for Geodynamics (IGS), described by [Beutler et al.,1994] has been used. This service also gives accurate clock information for the satellites at 15 minutes interval. The position for Kootwijk has for all computations been held fixed at the epoch (1-MAR-1994) position as given by the ITRF'92. These co-ordinates differ about 15 cm. from the ones used in chapter 3.

The sessions used for the 3 hour, 1 hour and 10 minutes runs are shown in App. C.1. Times are not changed to match the 4 minutes by which the same geometry comes earlier every day and sessions are therefore not identical to the ones used in chapter 3.

4.2. Determination of receiver-clocks biases

Prior to forming double differences, the biases of the receiver clocks with respect to GPS time have to be determined. This can be done by computing single point positions for all epochs, using the clock data in the broadcast ephemeris. We chose to use in stead the accurate clock information that IGS provides at 15 minutes epoch intervals. In addition to clock biases, the computation gives also an RMS for the fit of the observed (pseudo-) ranges to the computed precise IGS ranges. Doing this for all epochs in an entire day gives an interesting insight into the behaviour of the satellite clocks, as affected by the SA clock dither. It turned out to also identify a malfunction of the ROGUE receiver on one day.

To achieve this we used two different comparisons, viz.:

a. Only at every 15-minute epoch. In that case the SA effect is not present, since IGS has eliminated it.
b. At all observed 30-second epochs, by fitting a third degree polynomial through the IGS clock data. This does not remove the high frequency SA dither at the interpolated epochs.

Table 4.1 shows the RMS of both comparisons, for all four receivers at both ends of the long baseline, during all four observation days. The SA-clock dithering with an RMS of about 23 meters is very apparent. The 4 meter found for non-SA is higher than the value of 1 meter that is normally found using C/A code data. This is probably due to the fact that the data used here is from March 1994, about one month after implementation of AS. At that time the IGS clock solutions may still have suffered from trying to cope with AS. The high value on the last day for the ROGUE is an indication of problems with that receiver. Although it would have been possible to process part of the day it was decided not to do so.

Stat. /day	ASHTECH		LEICA		ROGUE		TRIMBLE	
K/62	4.27	22.33	3.86	23.30	4.67	22.19	4.00	23.28
D/62	4.29	22.36	4.54	23.44	4.55	22.11	3.93	23.41
K/63	3.10	22.25	2.88	23.11	3.43	22.36	2.70	23.13
D/63	3.24	22.34	3.37	23.24	3.56	22.39	2.91	23.25
K/64	3.68	22.87	3.09	23.79	4.00	22.97	3.15	23.75
D/64	3.80	22.81	3.57	23.72	3.98	22.88	3.22	23.77
K/65	3.89	23.28	3.45	24.34	4.08	23.37	3.56	24.31
D/65	3.88	23.26	3.57	24.33	22.59	34.19	3.68	24.31

Table 4.1: *RMS of C/A code ranges, using precise IGS clock data every 15 minutes (left receiver column) and using data every 30 sec. after a polynomial interpolation (right column). The first two lines are for day 62 at Kootwijk and at Delft. Subsequent lines are similar for days 63, 64 and 65. Units are meters.*

4.3. Ambiguity solution

The so-called "sigma" method has been used. First ambiguities are resolved for the "wide-lane" (L5) observations. These are then used for processing the "ionosphere-free" (L3) observations. If only one integer ambiguity value falls within 3 times a specified sigma value (here 0.15 m.), it is fixed. The computation then re-iterates with those fixed integers till all are fixed or till no more integers satisfy the specified sigma value. An evaluation showed that it appears advisable to follow this procedure for both the short and the long baseline.

The ambiguity solution is rather demanding on CPU time. For reasons of efficiency an initial run was therefore made using all data for a full day, to compute all integer ambiguities. These were then kept fixed in the many other runs, using different parameter settings. Of course, after the optimum settings and observation times had been determined, it still has been verified that indeed all integer ambiguities could be resolved for those cases.

4.4. Long baseline results

4.4.1. Presentation of the test runs

Of the many processing runs, the results of ten of them are presented in table 4.2. The most important parameters are explained hereafter. Normally - if not stated otherwise - a tropospheric parameter was estimated for both ends of the baseline and a cut-off elevation of 20° was used. The ten runs are:

a. Four runs using 1, 2, 3 and 4 hour long data sets, to determine the optimum observation period.
b. For the 3 hour data set, one extra run was made without estimating tropospheric parameters and another estimating only one differential parameter instead of two absolute parameters. (2 runs, named NO_T and 1_T)
c. One run used the 3 hour data set without ambiguity fixing to show the (large) influence of fixing the ambiguities in (relatively) short sessions. (Run named Free 3HR).
d. Furthermore the 1 hour and 3 hour data sets were processed using a 15° cut-off elevation instead of 20°.
e. The 15°, 1 hour run was repeated to try and resolve the ambiguities using only 1 hour of data (Run 15° 1HRF).

What is shown in table 4.2 is the rms of the scatter in the North, East and Up co-ordinate solutions around the mean solution for each day. So for the 1 hour data set, they represent estimates of the standard deviation of one observation session of one hour, computed from a set of 23 daily solutions. And for a 3 hour data set the standard deviation has been estimated using only eight such individual solutions per day. This co-ordinate repeatability is a good measure of the precision of the results. To compute the daily means, the covariance matrix of the individual solutions has not been used, in other words: they are NOT weighted means.

A graphic representation of the results of the 3-hour data sets is given in app. C.11 till C.14 as time series plots.

4.4.2. Interpretation of the results

From inspecting table 4.2. it is concluded that the 3 hour data gives the best precision. Longer observation times do not show a significant increase in precision. Sometimes precision even decreases when going from 3 to 4 hours. One reason for this may be that the program estimates one tropospheric parameter per station for a complete session. Actual variations during 4 hours may be too large to be accommodated in one parameter.

Furthermore it can be seen that the s.d.s for the ROGUE are clearly better than for the three others. It is not certain whether this is due to the receiver or due to the fact that it was the only one using a choke-ring antenna. This was also the only calibrated antenna for which the height of the phase center for both L1 and L2 was known. For L2 it is 18

		15 1HRF	15 1HR	1HR	2HR	3HR	15 3HR	NO_T 3HR	1_T 3HR	4HR	FREE 3HR
ASHTECH											
DELF 21 A	N	18	8	9	5	5	5	5	6	5	8
DAY 062	E	62	10	10	6	6	7	6	7	7	38
	U	45	37	48	25	23	14	25	24	22	47
DELF 20 B	N	20	5	5	3	3	3	2	3	2	12
DAY 063	E	59	6	6	4	3	3	2	1	2	15
	U	68	24	34	17	14	10	18	12	11	31
DELF 15 C	N	15	5	5	4	4	3	4	4	4	11
DAY 064	E	53	9	9	6	6	3	4	4	2	31
	U	92	37	38	35	21	11	60	13	23	33
DELF 18 D	N	8	5	5	2	2	3	1	1	2	6
DAY 065	E	12	7	8	6	5	5	3	3	6	11
	U	46	34	46	36	10	20	10	10	18	23
LEICA											
DELF 21 A	N	20	6	6	4	2	3	2	2	3	10
DAY 065	E	45	4	5	6	5	2	2	2	3	33
	U	42	21	30	20	23	13	6	21	11	30
DELF 20 B	N	50	9	9	6	5	5	3	3	3	12
DAY 062	E	63	9	14	9	7	6	3	3	4	37
	U	135	61	74	33	30	30	20	31	20	43
DELF 15 C	N	31	7	6	5	4	4	3	3	3	12
DAY 063	E	75	9	9	7	3	4	3	2	3	47
	U	60	35	41	27	20	22	15	19	22	44
DELF 18 D	N	20	6	4	3	3	3	3	3	5	11
DAY 064	E	70	7	11	5	4	4	4	4	5	26
	U	65	33	78	21	19	17	54	19	27	32
ROGUE											
DELF 21 A	N	17	4	3	3	2	3	2	2	2	18
DAY 064	E	110	8	5	3	3	3	3	3	3	29
	U	53	27	22	24	10	6	54	7	21	48
DELF 20 B	DAY 065 not available				-	-	-	-	-	-	-
DELF 15 C	N	15	3	3	2	2	2	2	2	2	5
DAY 062	E	28	5	4	4	3	2	3	3	2	14
	U	32	23	28	14	9	13	19	10	10	25
DELF 18 D	N	20	3	4	3	2	2	2	2	2	5
DAY 063	E	33	3	4	2	2	2	2	2	2	9
	U	16	16	23	13	9	7	16	11	9	11
TRIMBLE											
DELF 21 A	N	13	4	4	2	2	3	3	3	2	5
DAY 063	E	54	5	6	4	5	3	3	3	3	17
	U	42	28	45	24	21	12	18	20	12	25
DELF 20 B	N	5	4	4	4	3	2	3	3	3	10
DAY 064	E	35	5	6	5	3	3	3	3	5	23
	U	59	27	30	31	23	15	55	24	36	25
DELF 15 C	N	15	4	4	3	4	2	4	3	3	6
DAY 065	E	53	4	5	4	3	2	2	2	3	16
	U	57	27	43	27	10	14	10	12	11	13
DELF 18 D	N	17	6	8	4	3	3	3	3	3	11
DAY 062	E	55	7	10	4	5	3	4	4	4	13
	U	56	33	60	19	22	12	18	25	25	28

Table 4.2: *Repeatability of the long base line test runs. The headings above the 10 columns are explained in the text. The values given are standard deviations in the N(orth), E(ast) and U(p) directions for a single run as computed from the spread in the results of all runs for that day. All values are millimeters.*

mm. higher than for L1 and that information has been used in processing. The ASHTECH and TRIMBLE show about equal precision, followed by the LEICA.

For the ROGUE, the column with heading 3HR indicates a precision of mostly better than 10 mm. in the height and 3 mm. in the horizontal co-ordinates. For the other 3 receivers they are mostly better than 25 mm. in height and 6 mm. horizontally; more than twice the ROGUE values.

The results for the test with only one differential tropospheric parameter are very similar to the normal run with two (absolute) tropospheric parameters. A very interesting effect is visible in the results of the test without troposphere parameter estimation. All receivers show a large RMS (about 55 mm. in the height component) on day 064. This must be caused by large differences in the tropospheric conditions at both stations on that day. Also App. B.5. of the previous chapter showed mostly large s.d.'s for day 064. This very well illustrates the necessity to estimate tropospheric parameters on long base lines. No time has been spent to try and recompute all baselines using actual meteo data or to obtain weather maps for the days concerned. This would be worth pursuing.

The column without ambiguity fixing (FREE 3HR) clearly gives inferior results, with s.d.'s as bad as 48 mm. In fact the 3 hour free solution is (except for height) mostly worse than the 1 hour solution using the correctly fixed ambiguities. It is also interesting to compare the 1 hour results of Bernese software with the ones in App. B.5., using commercial software. This is admittedly somewhat difficult because the first is expressed in North, East and Up, and the other in Cartesian X, Y and Z. The Bernese results in the column 1HR have smaller s.d.'s, but these used ambiguities that had already been fixed to integers from a longer run. Column 1HRF 15° tried to fix the ambiguities from only one hour data. The Bernese s.d.'s are than higher than for the commercial software but this is due to not rejecting fixes.

For the 1 hour data sets, the results using 15° cut-off elevation are better than when using the 20° elevation cut-off. For the 3 hour data sets an improvement can still be seen but not for all tests. This is due to the fact that there is more data available, with better geometry. But that advantage is partly off-set by the fact that the data is of lower quality (irregular influence of the troposphere at low elevations and more multipath). For the 1 hour data sets there is about 15% increase in the number of observations and that appears to have a larger influence than the increase in the RMS, which - as explained in the section 4.6. - is about 20%. For the larger 3 hour data sets the increase of data points has less effect and therefore not all results improve.

4.4.3. Rejections and ambiguity fixing

Efforts to resolve the ambiguities for the ROGUE on the last day of the long baseline observations indicated a problem, which had already become apparent during the run to determine the receiver clock biases. All data for that day has been discarded.

After the test runs, it had to be ensured that the integer ambiguities used to prepare table 4.2. (which had been obtained for reasons of efficiency using all data of one day) could indeed be fixed using only 3 hours (or 1 hour) of data. The same approach as for the 24 hour data set was followed, i.e. the sigma strategy, fixing first the L5 frequency (wide-lane), followed by using L3 observations.

Using a 3 hour observation period, all ambiguities were indeed successfully resolved for the ROGUE and TRIMBLE receivers. For the ASHTECH one ambiguity in one of the 3 hour data sets was not fixed and for the LEICA one ambiguity in two 3 hour data sets was not fixed. This would have a negative influence on the results as can be expected by looking at results in the column "FREE 3HR", though it should be borne in mind that in that last run no effort was done to fix any ambiguities at all.

The results obtained when trying to fix integer ambiguities using only 1 hour data sets, were rather poor; quite a number could not be fixed. Also for this procedure the options for the sigma ambiguity resolution strategy had to be set differently. Both the maximum and minimum sigma were set to 0.08 meters instead of 0.15 meters. The results of this test are given in Table 4.2. in the column "15° 1HRF".

The percentages of 1 hour solutions for which all ambiguities could be fixed are:

ASHTECH: 54%
LEICA : 30%
ROGUE : 70%
TRIMBLE : 49%

4.4.4. Additional remark

It is worth mentioning that good results may still be obtained - even for the one hour data sets - if during ambiguity fixing, the co-ordinates of the unkown end of the baseline can be restrained to an a-priori known value, with an accuracy of some 5 cm. This may for example be the case if a subsidence or settlement survey is repeated at regular intervals. Runs testing this option showed that in one hour all ambiguities could be fixed for the ROGUE, all but one for TRIMBLE and ASHTECH and only in three data sets for LEICA did one ambiguity remain unresolved. Since in each of the 92 sessions per instrument there are at least five ambiguities to be determined, it represents a success ratio of about 99.7% ! The difference of the resulting co-ordinates with those using 24 hours of data were negligible, even for the five runs where not all fixing was successful.

4.5. Short baseline results

4.5.1. Presentation of the test runs

As already explained in chapter 2. there are only results from three of the four receivers, due to a malfunction of the ROGUE. To find the optimum parameters, less runs had to be done than for the long baseline. Experiments in the past had indicated that on short baselines, 45 minutes of observations are sufficient to get the highest precision [Springer,1994a]. It was decided to use data sets of 1 hour; these were done in three different ways, viz. using observations of L1, of L2 and of the "ionosphere-free" combination L3. For a comparison with the "hands-off" processing in chapter 3, a fourth run is presented using data sets of ten minutes duration. This did not use L3, but L1 AND L2.

The results appear in Table 4.3 in a similar way as for the long baseline, i.e. as estimates for the standard deviations in the East, North and Up co-ordinates of one observation session of one hour (or ten minutes) length, computed from about 23 results per day. Elevation cut-off was 20°; tropospheric parameters were not estimated.

App. C.15, C.16 and C.17 give time series plots of the L3 results from the 1-hour data sets.

4.5.2. Interpretation of the results

Inspection of table 4.3 shows that on 3 of the 4 days the L1 results have smaller s.d. than the L3 results. This is caused by the fact that noise for the L3 observable is three times higher than for L1, due to the combination of observables. On day 66 however the

		L3 1HR	L1 1HR	L2 1HR	10 min.
		ASHTECH			
APEL 21 A	N	4	8	13	9
DAY 066	E	3	4	10	5
	U	11	16	21	15
APEL 20 B	N	6	4	5	11
DAY 067	E	4	3	5	6
	U	11	8	10	18
APEL 15 C	N	4	4	6	8
DAY 068	E	5	2	3	5
	U	7	6	9	19
APEL 18 D	N	4	3	5	6
DAY 069	E	3	2	5	6
	U	7	6	10	16
		LEICA			
APEL 21 A	N	6	3	5	12
DAY 069	E	3	2	4	5
	U	11	6	8	17
APEL 20 B	N	5	10	17	10
DAY 066	E	4	5	7	7
	U	7	18	28	22
APEL 15 C	N	6	4	6	10
DAY 067	E	4	4	5	9
	U	9	8	10	20
APEL 18 D	N	5	3	5	21
DAY 068	E	5	2	3	11
	U	12	6	10	34
		TRIMBLE			
APEL 21 A	N	4	3	5	9
DAY 067	E	3	4	5	6
	U	9	8	9	18
APEL 20 B	N	4	3	5	11
DAY 068	E	2	2	3	4
	U	8	6	9	13
APEL 15 C	N	4	3	6	9
DAY 069	E	2	2	5	5
	U	6	6	12	16
APEL 18 D	N	5	10	16	8
DAY 066	E	3	5	8	5
	U	7	19	28	13

Table 4.3: *Repeatability of the short baseline for 4 test runs using the L1, L2 and L3 observations for data sets of 1 hour and one test using 10 min. All ambiguities were fixed for this test using the full 24 hour data set. Values are in millimeters.*

results on L1 are clearly much worse by a factor of about 2. This must be due to large ionospheric variations on that day, introducing noise on L1, while it is eliminated in L3. This illustrates nicely the advantage of using the L3 measurement even on this short baseline of 10 km. It is a "safety net" against unexpected ionospheric disturbances. The L2 results are worse than the L1 results. This is caused by the fact that the ionospheric influence on L2 is a factor 1.6 larger than on L1. The lower s.d. for L1 than for L3 does not mean that the resulting co-ordinates are more accurate. Not correcting for ionospheric effects may introduce a bias in the L1 results.

Comparing the results for the 1 hour data sets on L3 shows no significant differences between the three receivers although the TRIMBLE might be said to perform slightly better than the others.

It may be concluded that one hour of observations is sufficient to achieve an accuracy of about 10 mm. in the height component and 5 mm. in both horizontal co-ordinates. It is of interest to note that horizontal precision is similar to the 3-hour result for the 100 km. base line; height is more than a factor 2 better. The 10 minute data sets (using one 10 minute interval each hour, e.g. 23 intervals in one day) show for TRIMBLE and ASHTECH a 15-20 mm. height precision and some 10 mm. in the horizontal co-ordinates. For LEICA the results are slightly worse.

The noise values for the results using the L1 and L2 frequencies in table 4.3. can also be used to study the relative data noises for the receivers on these frequencies. The three receivers use different methods to recover the phase of the L2 signal. As mentioned in chapter 1 this results on theoretical grounds in different SNR values and it was expected that this would be reflected in the relation between the noise in the observables on L1 and L2. This does not appear to be the case. The average ratio is the same for ASHTECH and TRIMBLE (1.66) and slightly better (1.54) for LEICA. What we see in table 4.3 is the 1.6 times higher ionosphere noise on L2, rather than differences in receiver noise.

4.5.3. Rejections and ambiguity fixing

From the data sets of one hour, a few solutions had to be rejected due to the computed RMS in the single difference between receivers (output by Bernese software) being much larger than normal. If the value was higher than 10 mm. it was rejected; normal values are about 2 to 5 mm. This was the case for three LEICA runs (sessions 7,12 and 13 on day 69) and for four TRIMBLE runs (sessions 12, 13, 14 on day 68 and session 13 on day 69). All ASHTECH sessions could be used. The test whether all ambiguities could indeed be determined using ONLY the one hour data set was successful for all remaining cases.

There were more rejections for the 10-minute sessions, viz.:

2 for ASHTECH:	session 7 on days 066 and 067.
5 for LEICA :	session 7 on days 067, 068 and 069, and session 12 and 13 on day 069.
6 for TRIMBLE :	session 7 on days 067, 068 and 069, and session 12, 13 and 14 on day 068.

For all accepted 10 minutes and 1 hour sessions it was tested if ambiguities could be resolved using these short periods. This was the case in all but one 10 minute session, for each of the 3 receivers. In this case the "search" algorithm had to be used, rather than the "sigma" algorithm. The search option compares the RMS of the float and fixed solutions and the best fixed with the second best; setting limits to both ratios. This is similar to the FARA method described in [Frei et al.,1992].

4.6. Additional remark on phase noise

The Bernese software outputs the RMS of the L1 single differences already mentioned in the preceding section. This enables an additional study of the phase noise. One should keep in mind that this RMS is scaled to represent a fictive L1 single difference RMS. So effectively the L3 RMS is down-scaled by a factor of 3, and L1 and L2 are assumed to have the same RMS. In this way we can compare runs using different frequencies. Table 4.4. lists these values for 3 long and 3 short baseline runs on a specific day.

One interesting aspect is that the 20% noise increase when going from 20° to 15° cut-off elevation, which was mentioned earlier, becomes apparent when comparing columns 2 and 3 of the long baseline in table 4.4. Yet, in table 4.2 it was seen that the results were often better for the 15° elevation. This must be related to the increase of the number of observations which is about 15%. Another important factor is that when using lower elevations the estimated tropospheric parameters are better decorrelated from the estimated station height thanks to the better geometry of the observations at lower elevation angles. But since the gain in precision is rather small it might be better to use the "safe" 20° cut-off elevation. This will avoid problems caused by troposphere mis-modelling.

	Long baseline			Short baseline (1 hour)		
Receiver	3 hours	1 hour	1 hour 15°	L3	L1	L2
ASHTECH	3.21	2.77	3.26	3.13	4.92	6.89
LEICA	3.54	3.26	3.75	3.66	5.10	7.74
ROGUE	1.95	1.67	2.18			
TRIMBLE	2.54	2.25	2.67	2.48	4.60	6.61

Table 4.4: *Mean RMS of single differences in millimeters. (Note: Noise for L3 has been down-scaled by a factor 3!)*

The table also clearly shows the excellent data quality of the ROGUE receiver. The RMS is a factor 1.3 lower than for the TRIMBLE, a factor 1.65 lower than for ASHTECH and 1.8 lower than for LEICA. The co-ordinate repeatabilities for the long baseline have also already indicated that. The difference in RMS between the TRIMBLE and ASHTECH receiver does not show up in the co-ordinate repeatabilities. Nevertheless it may be concluded that the TRIMBLE is a good second in this test but very closely followed by the ASHTECH receiver. The LEICA clearly has the least accurate results, probably due to the half-wavelength L2 of this squaring receiver.

From the short baseline runs using different frequencies it can be seen that the assumption that L3 observation noise is a factor three higher than the noise of the L1 observations is not confirmed. Based on the results presented here it seems to be only a factor two. This could well be because the values computed for L1 and L2 are affected by an ionospheric bias, which is corrected for in L3. The 1.6 times more influence of the ionosphere on the L2 measurements seems to be accurate.

4.7. Precision per day and comparing software

4.7.1. Method

So far only the repeatability of observing numerous sessions of various duration on one day (and for one baseline) have been investigated for receivers of all manufacturers. Very useful information can also be obtained by averaging the resulting co-ordinates over one day and comparing these between different stations, receivers and days. At most there are only results for four different days etc. This is too low for a reliable statistical analysis, but for want of a better quantification, we computed the biased standard deviations. In this way we obtain an impression of the improvement that averaging over one day gives.

To achieve this it is essential that we assume the relative positions of the four off-set stations at each baseline-end to be known without error. We compared all daily averages with the a-priori baseline vectors, given in app. A.1 as "datum" values. These datum values are not considered to be better than the results from our observations, but serve only as reference values. We evaluated local North, East and Up co-ordinates, rather than the ECEF Cartesian X, Y an Z values.

The described procedure was done for Bernese and manufacturer's software, because it makes following evaluations possible:

a. Manufacturer software shows the combined effect of instrument and software performance.
b. Bernese software shows relative instrument performance.
c. Bernese minus manufacturer's shows the performance of each manufacturer's software relative to Bernese.

The daily averages resulting from Bernese software compared with "datum" are given in app. C.2. and those from manufacturer's software are in C.3., which is now for N, E and Up, rather than for Cartesian X, Y and Z as in chapter 3. In addition the difference between the two is in app. C.4. These values have been grouped in three ways, viz.:

a. Per station
b. Per receiver
c. Per day.

The results are in app. C.5, C.6 and C.7 for the long baseline and in C.8, C.9 and C.10 for the short one. For clarity, the averages per receiver are also given in tables 4.5 and 4.6 of the following two sections.

4.7.2. Long baseline

A. Bernese software

There is some doubt about the validity of the height resulting from the LEICA on day 63 at station off-set C. (see App. C.2). It differs about 4 cm. with most other results, but that difference is not evident from the processing with SKI or TOPAS software. There is however not enough evidence to justify a rejection.

From the top part of table 4.5. we conclude:

a. In comparison with the results for the 3 hour sessions in table 4.2., the s.d.'s in height improved by a factor 2, for ASHTECH, LEICA (without day 63) and TRIMBLE; all going from about 2 cm. to 1 cm. There is also a small improvement in N. and E.; they are now all under 5 mm. The ROGUE hardly improved, but was already under 1 cm. in height and under 4 mm. horizontally in table 4.2.

b. The s.d.'s are nearly the same for all four instruments (if LEICA day 63 is rejected!).
c. The co-ordinates resulting from different instruments differ most in the height component (up to 30 mm.), followed by East (12 mm.) and North (6 mm.). N.B. All have a fairly similar bias relative to "datum".

Inspection of app. C.5. shows that there is very little bias between days or between stations; mostly well under 10 mm. per co-ordinate. Standard deviations in height are lowest for day 65 and for stations D. Station C and day 63 are affected by the already mentioned anomalous height results for LEICA.

B. Manufacturer's software
There was no software by the manufacturer of the ROGUE.

Inspection of the mid section of table 4.5. shows:

a. For all instruments s.d.'s improve by a factor of more than 5 in relation to results from 1 hour sessions (see table 3.1.; which is for X,Y,Z not N,E,U!!). All s.d.'s are under 15 mm. in height and 10 mm. horizontally.
b. It is remarkable that LEICA has the lowest s.d. in height and highest horizontally, but in general precision of the three software packages is similar.
c. The difference in the biases in height are at most 6 mm., horizontally the maximum is 16 mm.

	Diff. of 4-day average with datum co-ords (mm.)			S.d. in one day average, comp. from 4 days (3 Rogue) in mm.		
	North	East	Up	North	East	Up
Bernese software						
ASH	1	31	22	3	4	8
LEI	5	26	14! 5	2	3	8! 16
ROG	4	24	35	2	2	7
TRI	7	36	19	3	2	9
Avg.ALL 15:	4	30	22! 19	S.d.ALL 15: 3	5	8! 15
Manuf. software						
ASH	19	36	0	5	3	13
LEI	21	41	-4	7	9	5
TRI	11	52	2	5	8	13
Avg.ALL 12:	18	43	-1	S.d.ALL 12: 7	10	11
Manuf.minus Bern soft.						
ASH	-18	-5	23	3	2	19
LEI	-16	-15	10	6	7	15
TRI	-5	-17	16	4	6	18
Avg.ALL 12:	-13	-12	16	S.d.ALL 12: 7	7	18

Table 4.5: *Long baseline; Comparing co-ordinates resulting from Bernese and manufacturer's software and datum values, per receiver. The line "ALL" averages all receivers over all days, and gives the s.d. for one day observation. 14! etc. are the Up values when excluding height for LEICA, day 63.*

The comparisons between days and stations are in app. C.6. All s.d.'s and biases have similar magnitudes, only the height bias varies up to 24 mm. between days, which may be due to the fact that in manufacturers' software the differential troposphere has been neglected.

C. Bernese minus manufacturer's software
The most remarkable fact in the lower part of table 4.5. is the fairly consistent biases of about 15 mm. in all co-ordinates. A possible explanation is the fact that Bernese software estimates the troposphere at both ends. This could be a confirmation of the following two statements regarding tropospheric parameters:

a. A differential error results in a height error.
b. A common error results in a scale error. Within our precision limits the biases can be interpreted as a scale error.

The s.d.'s in the differences for the three manufacturers are largest for the height, but still just under 20 mm. Horizontally they are well under 10 mm. No software package appears to perform significantly better relative to Bernese than the others. In general, the s.d.'s from Bernese are better than manufacturer's software by a factor of about 1.5.

Appendix C.7. shows no anomalies, except that for days 62 and 65 the s.d. in the height is smallest, but the height biases on those days differ much. No explanation is ventured!

4.7.3. Short baseline

All comparisons are for only 3 receivers due to malfunctioning of the ROGUE.

A. Bernese software
From the top section of tables 4.6 we may conclude:

a. In comparison with table 4.3 (column L3 1hr) all s.d.'s are nearly a factor 2 better. They are now about 5 mm. in height and somewhat better horizontally.
b. The biases for ASHTECH and LEICA are similar. TRIMBLE differs from these two by some 10 mm. in horizontal position.

App. C.8. shows that the s.d.'s do not differ significantly between days or stations. The bias in height for stations A and B is about 8 mm. more than for C and D. It was suspected to be due to inaccuracies in the trigonometrical height transfer between these two pairs; A and B are located on a superstructure on the roof and are about 5 meter higher than C and D. A subsequent resurvey showed indeed an average error of 5.5 mm.

B. Manufacturer software
From the mid section of table 4.6 we conclude:

a. All s.d.'s are better by a factor of about 3 than the ones obtained when computing sessions of only 10 minutes, as shown in table 3.2 (Note again they are for X,Y,Z not N,E,U). The maximum s.d.'s are 8 mm. in height and 6 mm. horizontally.
b. It is remarkable that scale corrections of +1.3 ppm to ASHTECH, -1.1 ppm to LEICA and +2 ppm to TRIMBLE would reduce all horizontal differences to near zero! Such scale differences could possibly be caused by the use of different ionospheric models, or by using no model at all.

The s.d.'s are about the same for all days and stations (see app. C.9.). They are highest for East, due to the possible scale differences between softwares. The height bias between station pairs A, B and C, D is less clear than with Bernese software, but still apparent.

C. Bernese minus manufacturer's software
According to table 4.6. the ASHTECH and TRIMBLE software differ little from Bernese, as witnessed by small s.d.'s and biases. The bias in North and East for LEICA indicates again a scale bias, as mentioned above and in chapter 3. This bias is somehow not apparent for TRIMBLE and ASHTECH.

App.C.10. indicates no significant differences between days or stations.

	Diff. of 4-day average with datum co-ords (mm.) North	East	Up	S.d. in one day average, computed from 4 days (mm.) North	East	Up
Bernese software						
ASH	1	8	5	2	1	5
LEI	4	8	4	5	3	6
TRI	8	18	4	4	1	4
Avg.ALL 12:	4	11	4	S.d.ALL 12:5	5	5
Manuf. software						
ASH	3	12	4	2	2	5
LEI	-3	-10	-1	1	6	8
TRI	7	18	1	4	2	7
Avg.ALL 12:	2	6	1	S.d.ALL 12:5	12	7
Manuf.minus Berne soft.						
ASH	-2	-4	1	2	1	3
LEI	7	19	5	5	6	5
TRI	1	0	2	2	2	4
Avg.ALL 12:	2	5	3	S.d.ALL 12:5	11	5

Table 4.6: *Short baseline; Comparing co-ordinates resulting from Bernese and manufacturer's software and datum values, per receiver. The line "ALL" averages all receivers over all days, and gives the s.d. for one day observation.*

4.8. Conclusions

Bernese software; long (100 km.) baseline:

- The optimum session length is three hours, resulting in standard deviations of from 6 to 30 mm. in height and mostly less than 5 mm. in the horizontal co-ordinates.
- The s.d.'s in the co-ordinates were similar for ASHTECH, LEICA and TRIMBLE; for ROGUE (with choke-ring antenna) they were about a factor 2 better!
- The s.d.'s in the carrier phase single differences between stations were also the best for ROGUE, followed by TRIMBLE, ASHTECH and LEICA in that order.
- Averaging eight 3-hour sessions in a day improved all s.d.'s to under 10 mm. in height and about 3 mm. in North and East.
- It is important to let the software estimate a tropospheric parameter at the two baseline ends.

- No significant biases were found between the co-ordinates computed from the data of the four receivers.
- Of the four receivers, the LEICA was least successful in fixing ambiguities for one hour sessions. This was expected since it has half the wavelength when using L5 (widelane) and L2 observations.
- For short observation times it can be advantageous to use a 15° cut-off elevation instead of 20°, but care has to be taken with data from lower elevation because the increased effects of the troposphere and of multipath.

Bernese software; short (10 km.) baseline.

- For a session length of one hour, the s.d. in height was about 10 mm. In North and East it was mostly less than 5 mm. for all three receivers ASHTECH, LEICA and TRIMBLE. The ROGUE malfunctioned.
- Contrary to the above, there was a difference in the s.d. of the single differenced carrier phases. It was lowest for TRIMBLE, followed by ASHTECH and LEICA in that order.
- Averaging 23 one-hour sessions in a day improves all s.d.'s to about 5 mm. in height and about 3 mm. in North and East.
- As a safeguard against local ionospheric disturbance, it is advisable to use the ionosphere-free L3 observable, but with a quiet ionosphere, the use of L1 AND L2 gives lower s.d.'s.
- There is an indication of a bias of 10 mm. in East direction for the TRIMBLE results, relative to the other two.

Comparing Bernese and manufacturer's software:

- The precision in the daily averages from Bernese is about a factor 1.5 better than from manufacturer's software. This was not unexpected, because Bernese had following advantages:
  - using precise rather than broadcast ephemeris
  - estimating tropospheric parameter at both baseline endpoints
  - more operator attention rather than "hands-off" processing
  - Bernese averaged three-hour sessions for the long baseline and one-hour sessions for the short one, rather than the one-hour and 10 minute sessions used with manufacturer software.
- There is a bias in the resulting co-ordinates, that can be interpreted as a difference of 0.15 ppm in scale and 1.5 cm. in height for the long baseline. Probable causes are that Bernese estimated tropospheric parameters and used a precise ephemeris.
- All three manufacturer's software are about equal in precision, but there are indications of scale biases between them of more than 2 ppm for the short baseline.

General:

- Comparing the height transfer for the long baseline with those from EUREF results in a difference of about 20 mm. for Bernese and about 0 mm. for the average from manufacturers' software.
- For the short baseline the height differences with datum values were about 0 mm. (Bernese) and 3 mm. (manufacturers). These differences include more than 10 km. levelling, trigonometric transfers to the roof of buildings, a geoidal height model and errors in the GPS survey. They are after correcting errors in the trigonometric height transfer between off-set stations at Apeldoorn. These errors were diagnosed from our GPS results and have not been incorporated in the tables and appendices.

5. Susceptibility to radio frequency interference

5.1. General

During operational use of GPS, it has been noticed that nearby radio transmitters may cause severe interference in geodetic receivers [Haagmans,1994]. We decided to study this aspect for the four receivers. It was soon found that any investigation is hampered by the fact that interference occurs only intermittently; that one has no control over the transmissions and that even its source is often unknown. However near the entrance to Rotterdam harbour at Hoek van Holland, Radio Frequency Interference (RFI) is nearly always present. Many transmitters are operating in that area, but the most likely "culprit" is a directional data link transmitter, operating at 1240 MHz. Hereafter all interfering radio transmissions - either intentional or unintentional - are called "jammers".

Three different experiments were carried out for our study, viz:

a. Uncontrolled jamming at the Hoek van Holland site.
b. Controlled jamming by purposely generating unmodulated CW RFI signals. The power levels were stepped up till a pre-selected maximum, or till all receivers lost lock. This was done in two ways:
    b.1. By jamming on exactly the L1 and L2 frequency, radiating into the GPS antennas from 0° elevation i.e. horizontally.
    b.2. Because the first test was inconclusive, we repeated it by jamming at many different frequencies between 1100 and 1725 MHz., this time radiating from 23° elevation.

5.2. Uncontrolled jamming

The four receivers were set up on March 2, 1994 at three sites at the following distances from the data link transmitter at Hoek van Holland.

SITE A. Within 200 meter.
SITE B. At 1 km. distance.
SITE C. At 2 km. distance.

Site A
During the 10 minutes that the site was occupied, only the ASHTECH tracked all 10 satellites that were available above 10° elevation. We neglected however to save the data. None of the other three was able to lock on to any satellite.

Site B
The elevation mask was lowered to 0°. During the period from 14.32 - 14.47 hour, a total of 11 SV's were above the horizon. ASHTECH tracked all 11, LEICA and ROGUE tracked five each and TRIMBLE none. The tracking ability was clearly a function of satellite elevation, the highest being tracked. The noise in the L1 CW phase observable has been computed in the manner described in Chapter 6, that is we assumed that noise

for L2 (expressed in mm.) is 1.3 times higher than for L1. The values include multipath and ionospheric noise and are given in Table 5.1.

Site C
During the period that this site was occupied from 15.15 - 15.25 hour, there were 8 SV's above the horizon. ASHTECH tracked all, LEICA six, ROGUE seven and TRIMBLE tracked only intermittently four, but gave no useful data. The L1 CW phase noise for the 7 SV's above 10° is given in table 5.1. in an identical way as for site B.

It may be observed that noise increases for low satellites and is nearly always higher when closer to the jammer. All interference problems cease to exist when the direct ray-path from the jammer is obstructed by a house.

Elev. (deg)	ASH	LEI	ROG	TRI	Elev. (deg)	ASH	LEI	ROG	TRI
79	1.4	1.7	1.3	-	80	0.8	2.0	0.7	-
68	1.8	4.1	2.1	-	56	0.6	2.9	0.6	-
60	2.9	3.0	1.4	-	52	0.7	-	0.6	-
35	3.6	5.0	-	-	44	1.7	2.9	1.1	-
35	3.2	3.9	1.3	-	40	0.6	2.2	-	-
15	13.8	-	7.0	-	24	0.7	6.6	6.7	-
12	11.0	-	-	-	21	2.9	4.1	3.8	-
Site B.		1 km. from jammer.				Site C.	2 km. from jammer.		

Table 5.1.: *Noise (+ multipath + ionospheric noise) in the L1 phase observable, as a function of satellite elevation. Values are in millimeters; a dash (-) means an available SV was not tracked.*

5.3. Controlled jamming

5.3.1. General

Two tests were performed by intentionally transmitting interfering signals (unmodulated carrier waves). In both cases all four GPS antennas were set up at the same distance from the jamming transmitter. A spectrum analyzer near the antennas was read and these readings were corrected for different polarization (Right Handed Circular vs Vertical), pre-amplifier gain, position difference between spectrum analyzer antenna and GPS antennas, cable losses and effective antenna area. This resulted for all transmissions in values for the local power density of the jamming signal, expressed in dBmW/m². Typical power densities for the satellite signals are -101.6 dBmW/m² for L1 C/A code and -109.8 for L2 P code [Czopek et al.,1993]

5.3.2. In-band jamming at L1 and L2

This test was done on March 11, 1994 using the facilities of the Netherlands National Aerospace Laboratory (NLR). The four receiver antennas and spectrum analyzer were set up at about 100 meter from the jammer and at the same height (see app. D.7), so the jamming signal radiated into the antennas from 0° elevation.

First the jamming signals were transmitted on the L2 frequency (1227.6 MHz); each 15 minutes the power was stepped up causing loss of lock on satellites. During each period, the noise in the L1 phase observable (in millimeters) was computed, using the formula

1.546 * (L1 – L2) in the manner described in chapter 6. The results are given in app. D.1. Power density was not stepped up higher than -54 dBmW/m², even though some receivers had not yet lost all satellites. Subsequently the procedure was repeated for L1 (1575.42 MHz), this time stepping up the power every 5 minutes.

Comparing the performance of the four receivers was made difficult, because during the first 90 minutes the ROGUE tracked only 4 SV's for reasons not related to jamming. Such behaviour of the ROGUE was not unusual during previous operational work. For a fair comparison it was decided to record the power density for the following three events that were clearly related to RFI:

a. When the first SV was lost.
b. When lock was lost on 3 SV's.
c. When loosing all SV's.

These power densities are listed in table 5.2. It shows the ROGUE to be most resistant to jamming on the exact GPS frequencies, followed by the TRIMBLE. The LEICA and ASHTECH show about the same susceptibility. There were reasons not to increase the power density on L2 above -54 dBmW/m²; all the receivers had by then lost survey capability anyhow.

Nr of Sv's lost	ASHTECH	LEICA	ROGUE	TRIMBLE
		L1 jamming/L1 lost		
1	-75	-69	-63	-63
3	-63	-63	-57	-57
all	-57	-63	-45	-45
		L2 jamming/L2 lost		
1	-69	-69	-60	-69
3	-66	-66	>> -54	-60
all	-54	-54	>> -54	>> -54

Table 5.2: *Power density in dBmW/m² of the L1 and L2 jamming signal at the GPS receiver antennas, at which lock is lost on 1, 3 and all satellites. >> signifies that lock was not lost, but power was not stepped up higher.*

These results do not explain the difference in performance that was seen in the uncontrolled test. Two reasons may be given for this. In the first place is the gain of the GPS antennas for low elevations -as was the case for the jamming signal- much lower than for high elevations, especially for the choke-ring antenna used by the ROGUE. Secondly there are no authorized transmissions exactly on the L1 and L2 frequencies, so RFI is normally caused by transmissions on other frequencies. Therefore we did the additional test described in the following section.

5.3.3. Jamming at many different frequencies

This test was executed in Delft on August 10, 1994. The four receivers were set up close together at equal distances of about 80 meter from the "jammer", which was located on the roof of a building and radiated into the GPS antennas from an elevation angle of 23°. This building was North of the GPS antennas and obscured therefore no satellites that were higher than 15°. The jamming signals were generated at discrete frequencies in the range from 1100 to 1725 Mhz. The spacing between them was a function of their relation to the GPS frequencies, making a distinction between in-band (10 MHz either side); near-band (10 - 50 MHz either side) and out-of-band. In total 49 different frequencies have been transmitted. The power density of the jamming signal was stepped up with 3, 5 or 10 dBmW/m² till all receivers lost lock or till a predetermined maximum was reached. This brought the total number of measurements to nearly 300. To be able to complete the test in one day, each power level was sustained for only one minute. Appendix D.2. lists the jamming transmissions.

The power density near the GPS antennas - as derived from the readings of the spectrum analyzer - ranged from -78 dBmW/m² at the low end, up to -25 dBmW/m². This is much higher than the incoming GPS signals, in fact the corresponding Jammer-to-Signal ratios are of the order of 25 to 75 dB for the L1 signal.

To be independent of the number of channels available for tracking we again determined the power density of the jamming signal for three events, being the moments when tracking was lost on one, three or all satellites, both for L1 and L2. These events were the times when carrier phase cycle slips started occurring in the data recorded in the RINEX file, or when data was no longer being recorded. Loosing three satellites does normally not leave enough SV's for survey. Most often low satellites are lost between 5 and 10 dB earlier than high ones. The results are plotted for each receiver in figures 5.1. to 5.4. and discussed hereafter.

In addition the operators read in real time from the screen, which satellites were lost and when. This information is given in app. D.3 to D.6, grouped in three ranges of satellite elevations. There are some differences with figures 5.1. to 5.4. due to subjective interpretations. Cycle slips - using the RINEX files - were identified as discontinuities in the difference of phase ranges (L1 – L2) on the two frequencies, followed by an analysis whether it occurred in L1 or L2. For ROGUE data this was complicated by the fact that these discontinuities were often small (between 3 and 20 cm.) and sometimes difficult to distinguish from ionospheric noise.

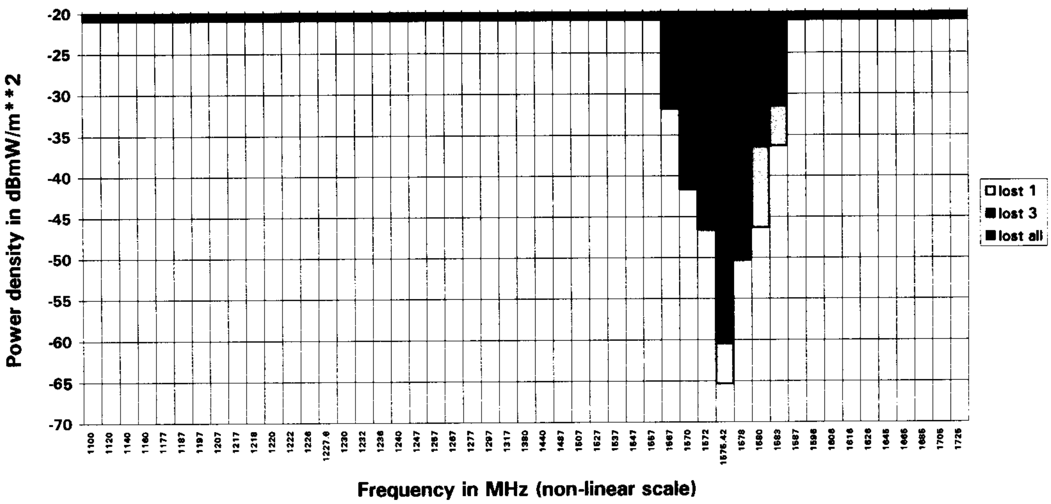
Ideally L1 should only be lost when jamming in the L1 frequency band, so the plot for L1 should show only one dip. L2 should be lost when jamming in the L2 band, but also when L1 is no longer tracked, because tracking the L1 signal is always required. Therefore one would expect the L2 plot to show two dips. All other losses of lock indicate to what extent near-band and out-of-band interference affects the performance.

Inspection of the figures shows that only the ASHTECH receiver approximates the ideal situation just described. The other three suffer to varying degrees from interference by near-band and out-of-band jammers. Particularly the loss of lock on L1 due to jamming near the L2 frequency is remarkable.

The ROGUE showed in general the highest resistance to in-band interference, except for the lower satellites (effect of choke-ring antenna?). It was also the only receiver affected by strong jammers on out-of-band frequencies. The uncontrolled test suggests that such strong interference may occur in operational situations. It can also be seen from the figures that all differences in performance at sites A, B and C in the uncontrolled jamming test may well be due to the presence of a jammer at 1240 MHz.

A list of the frequencies of jammers that caused loss of lock for L1 or L2 is:

ASHTECH	L1:	10 MHz either side L1.
	L2:	10 MHz either side L2 plus loss of L1.



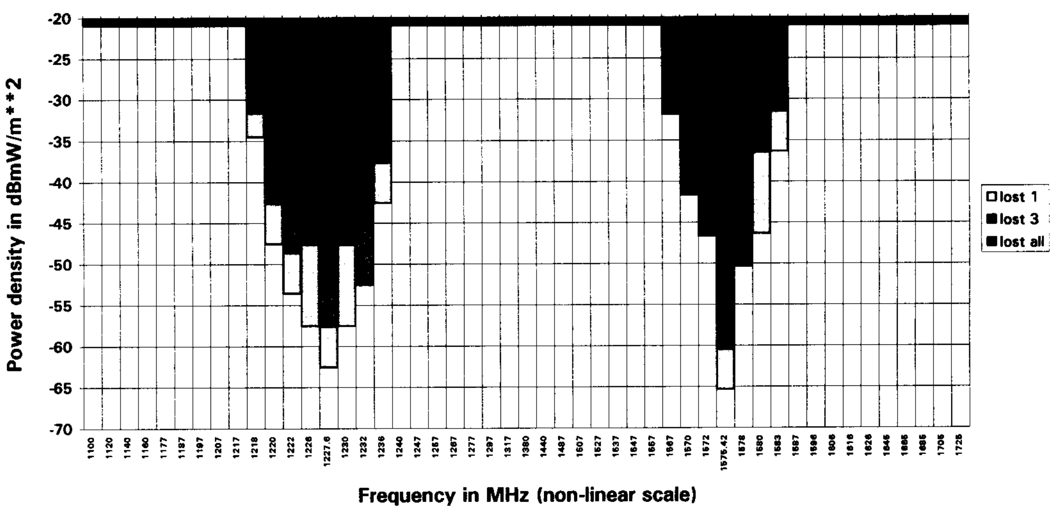
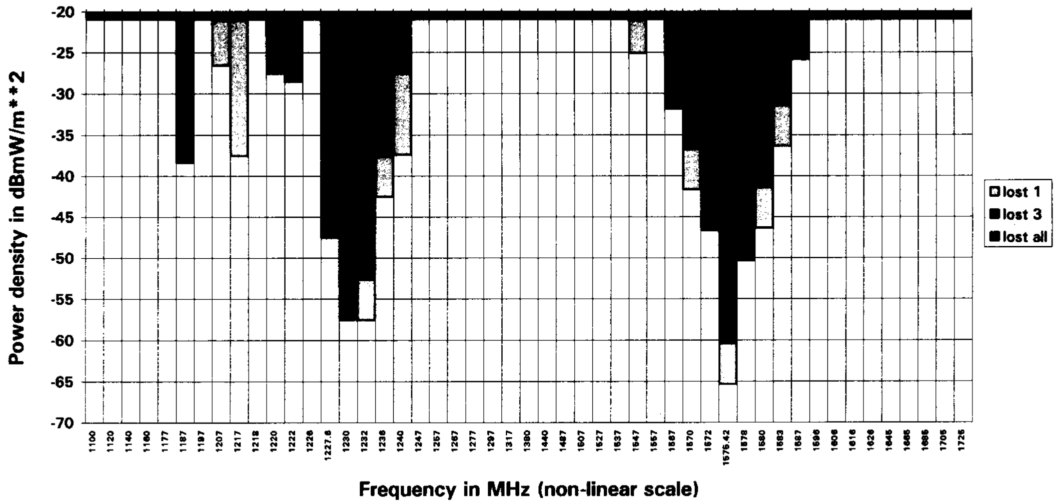


Figure 5.1: *Susceptibility ASHTECH for L1 (top) and L2 (bottom).*



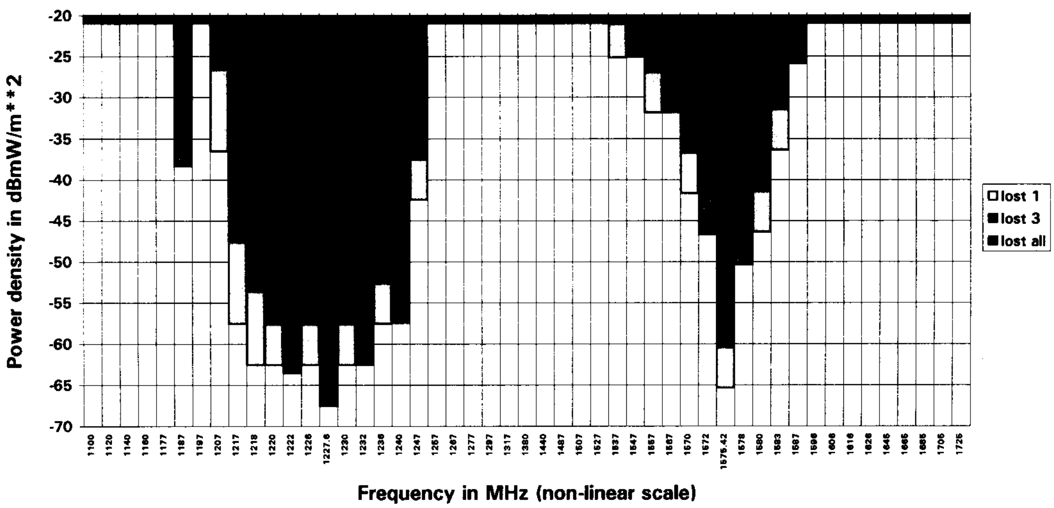
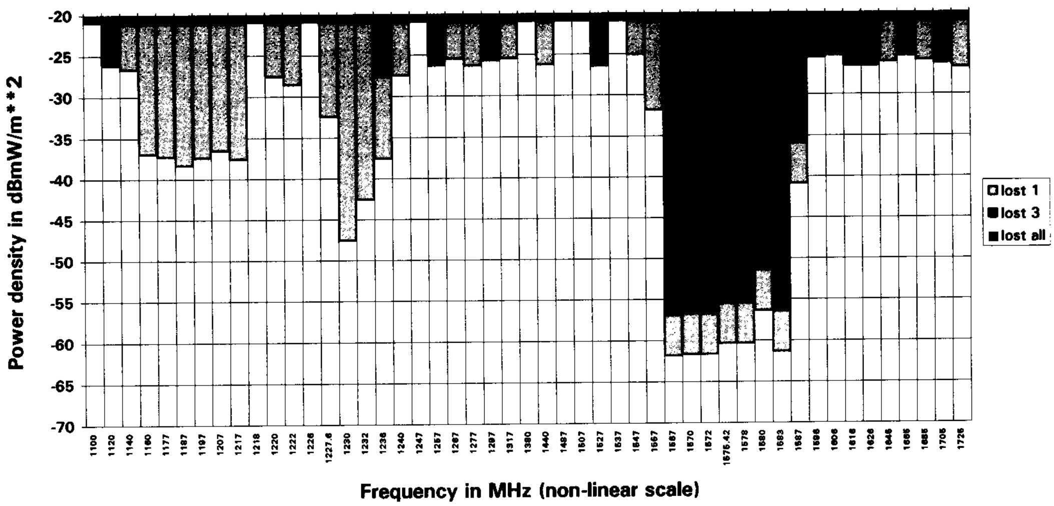


Figure 5.2: *Susceptibility LEICA for L1 (top) and L2 (bottom).*



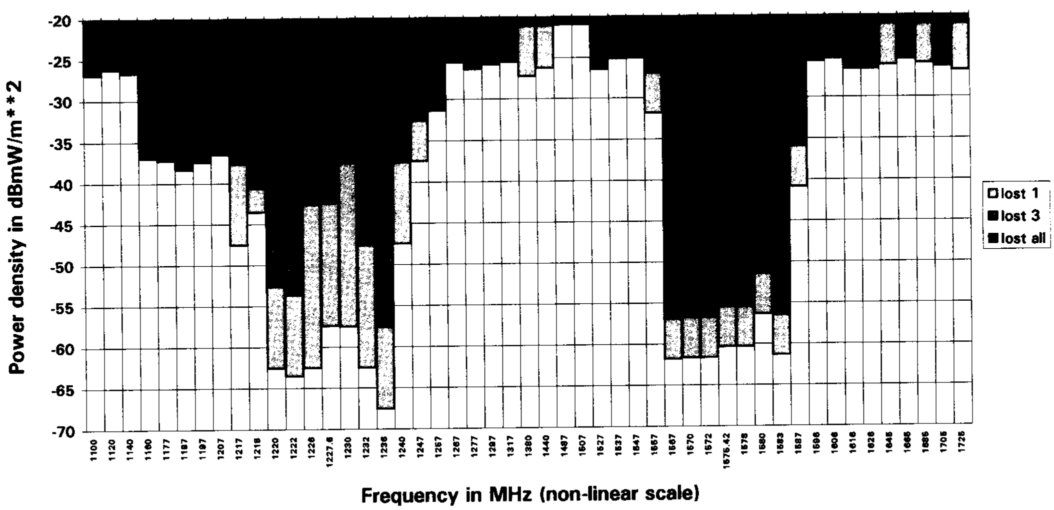


FIGURE 5.3: *Susceptibility ROGUE for L1 (top) and L2 (bottom).*

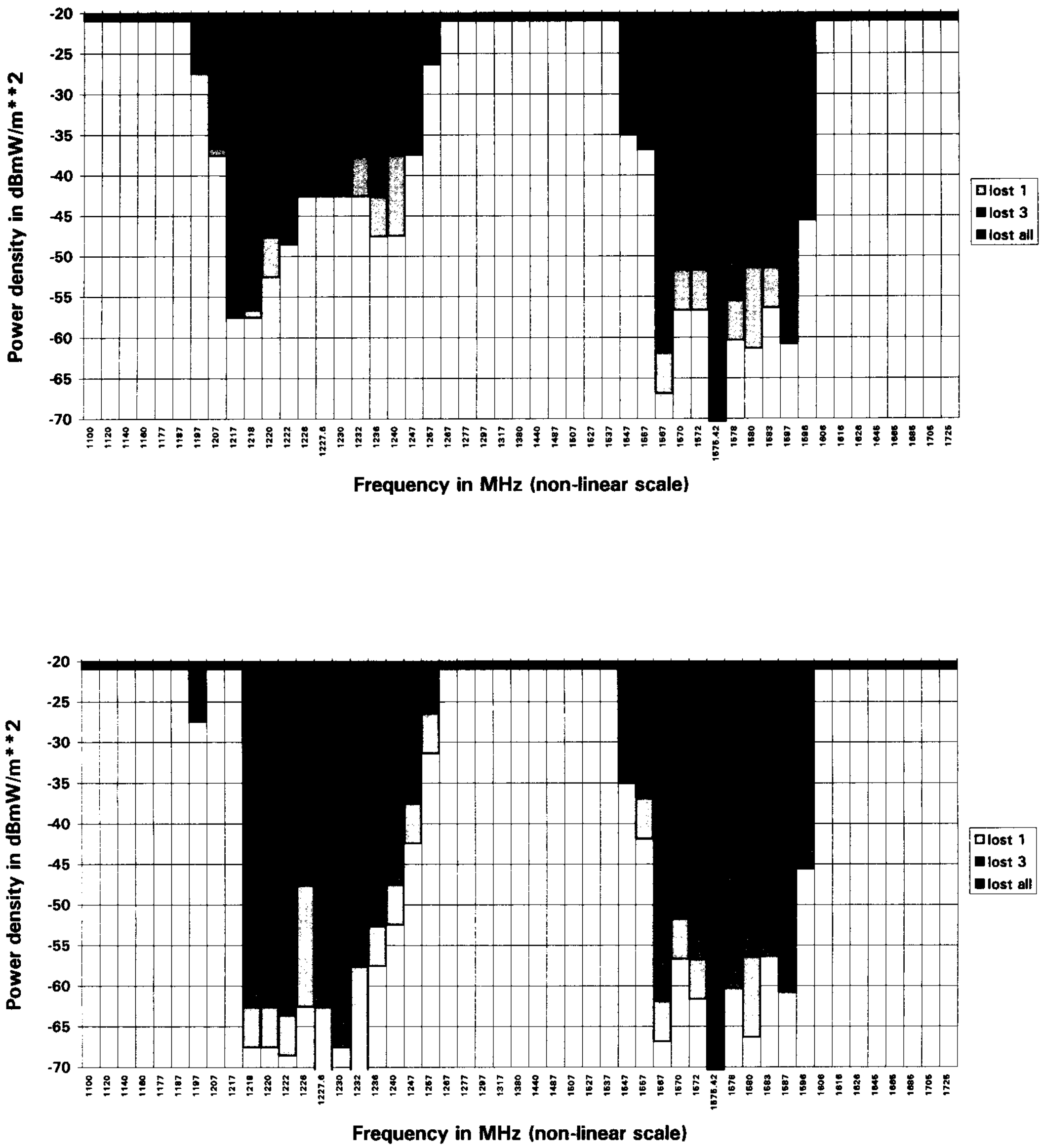


Figure 5.4: *Susceptibility TRIMBLE for L1 (top) and L2 (bottom).*

LEICA	L1:	12 MHz either side L1 and -40 MHz to +15 MHz from L2.
	L2:	Same as L1, but at lower power levels.
TRIMBLE	L1:	20 MHz either side L1 and 30 MHz either side L2.
	L2:	Same as L1, but at lower power levels.
ROGUE	L1:	15 MHz either side L1 and to some extent all the frequencies in the tested band from 1100 to 1725 MHz but only for strong interference.
	L2:	Is lost simultaneously with L1, but also in a wide range of frequencies of about 100 Mhz on either side of L2.

Some additional remarks:

a. On several occasions the LEICA and ROGUE lost lock in the minute after the jamming had stopped. This may be due to a long averaging time as mentioned in chapter 6.
b. Normal re-acquisition time is within two minutes after jamming has stopped. When jamming near the L1 frequency the receivers re-acquire nearly simultaneously, except in two cases where the ROGUE once needed 4 minutes and once required a complete "re-boot". When jamming near L2 the ASHTECH recovers nearly one minute earlier than the others.
c. When jamming the ASHTECH in-band the L2 frequency, the loss of lock indicator for the L2 phase in the RINEX file is often set even if no cycle slip is apparent and recording continues as normal. This occurs at jamming levels that are some 5 to 15 dB lower than required for actual loss of lock.
d. The ROGUE behaved in general differently than the others as described hereafter:
   - The fact that the discontinuities in (L1 – L2) are often only 4 cm. or a multiple thereof, could mean that phase tracking of the two frequencies is heavily slaved.
   - Low satellites (under 20°) are lost quickly, possible due to the choke-ring antenna.
   - Sometimes, but luckily not during the test in Delft, only 3 or 4 satellites were being tracked, when in fact there were 7 or more available. Prior to the tests, receivers had to be replaced because of this, but the problem has also been seen to disappear for no apparent reason.
   - Jammers that are far from the GPS frequencies may interfere. Unfortunately this was only tested for strong jammers, so the lower power density where this occurs is not known.

5.3.4. Comparing results from the two tests

Jamming on the exact L1 and L2 frequencies was done twice. Once during the test on March 11 at NLR and once on August 10 at Delft. Generating, measuring and computing the jamming power was done independently by different staff, using different equipment. Also other GPS receivers were used. For quality control it is interesting to see if the results confirm each other.

The power levels at which the stated number of satellites are lost in Delft, do not have to be the same as stated in table 5.2. for the first test, because they depend on the actual elevation of the satellites. In general it was found that the ASHTECH and LEICA in Delft were more resistant to RFI than at NLR by about 5 dB, while the reverse was expected, because the jamming signal in Delft came from 23° elevation. For the TRIMBLE it was the other way around and for the ROGUE it became clear that at NLR we had not transmitted a powerful enough jammer on L2, and that the L1 results were about the same.

5.4. Conclusions

- In an area notorious for RFI to GPS reception (probably due to a directional datalink transmission on 1240 MHz) the ASHTECH was not affected at all. The LEICA and ROGUE had problems that decreased with distance and finally disappeared at about two kilometer from the visible radio transmitters. The TRIMBLE was still not able to maintain lock at any satellite at a distance of two kilometers. Intentional jamming over a wide frequency range, with Jammer-to-Signal ratios up to 80 dB confirmed that such differences exist for jammers on many frequencies.
- The ASHTECH is only affected by in-band interference, i.e. 10 MHz on either side of the L1 and L2 frequency.
- The LEICA and TRIMBLE suffer from both in-band and near-band interference in a rather similar way. For LEICA the width of the band that causes interference, is about 25 MHz near L1 and 55 MHz near L2. For the TRIMBLE these bandwidths are 40 MHz near L1 and 60 MHz near L2.
- The ROGUE is the most resistant of all to in-band interference; especially for L2, except for low satellites. However strong jammers anywhere in the band from 1100 - 1700 MHz may cause loss of lock. The interfering bandwidth near L1 is about 30 MHz.
- It is very remarkable that all receivers - except the ASHTECH - often also lose lock on L1, when lock is lost on L2. And because of the essential role of C/A tracking, no receiver can track L2 when it does not track L1.

6. Noise in the basic GPS observables

6.1. Introduction

In chapters 3 and 4 we reported on an investigation into the noise in the phase observables by analysing single and double differences and the results of baseline computations. It is however also possible to determine noise using only one single receiver, i.e. without measuring a baseline. This is done by differencing observations of the same satellite, taken at the same epoch. Hereafter the observations of C/A, P or Y code ranges on the two frequencies are called C1, P1, P2, Y1 and Y2 resp. and the phases of the carrier wave on both frequencies are L1 and L2. The frequencies will be indicated by f1 and f2. In some literature Y2 is called C2 if it has been obtained by adding an observed range difference Y2 − Y1 to a C1 range.

Since only one satellite and one receiver are involved, we do not need ephemeris data and nearly all errors due to the space segment, the receiver and the signal propagation through the atmosphere are the same for all observables and are eliminated in differencing. The fact that the ionosphere advances the phase as much as it delays the code can be accounted for. An analysis of a time series will therefore show the measurement noise in the observables plus multipath effects (which are different for the various observables).

Such an analysis has been carried out, using satellites that were tracked by all four receivers during the same time period on one day. There is of course the possibility that the four antennas experienced different multipath effects, but the baseline analyses described in previous chapters did not indicate that this was a problem. The Faculty of Geodesy of Delft University kindly provided their program "Quick-Look" for this analysis. The principle of the method is generally known, for clarity it is described in section 6.2, extracted from [vander Marel,1992].

6.2. Method

The basic principle is that the effect of the ionosphere on signal propagation (a delay for the code) can be determined in several ways by making linear combinations of observables. Since the change in this effect with time should be the same, no matter which method is used, subtracting two of such time series should give a constant value, except for the noise.

The first method to measure the ionosphere is by using the property that the code is delayed inversely proportional to the square of the frequency. So, with delays d1 and d2 on f1 and f2 (expressed in meters):

$d/(1/f1^2) = d2/(1/f2^2)$ or $d1/f2^2 = d2/f1^2 = (d1 - d)/(f2^2 - f1^2)$

and since $d1 - d2 = P1 - P2 = C1 - P2 = Y1 - Y2$ it follows that:

$$d1 = (P1 - P2) * (f2^2/(f2^2 - f1^2)) = 1.546 * (P2 - P1) \qquad (1)$$

$$d2 = (P1 - P2) * (f1^2/(f2^2 - f1^2)) = 2.546 * (P2 - P1) \tag{2}$$

with similar formulae when using Y1, Y2 and C1.

The ratio between the two delays is: $d2/d1 = f1^2/ f2^2 = 1.647$

The second method is using the property that the ionosphere advances the phase as much as it delays the code, so:

$$d1 = 0.5\,(C1 - L1) \tag{3}$$
$$d1 = 0.5\,(P1 - L1) \tag{4}$$
$$d2 = 0.5\,(P2 - L2) = 1.647 * d1 \tag{5}$$

and by replacing P2 by -L2 and P1 by $-$L1 in (1) en (2):

$$d1 = 1.546 * (L1 - L2) \tag{6}$$
$$d2 = 2.546 * (L1 - L2) \tag{7}$$

Formulae (3) till (7) have a bias due to the unknown number of integer cycles in the phase observables, but as long as no cycle slips occur, these will be constant in time. This means that differencing (3) and (6); or (4) and (6); or (5) and (7) all give a value that remains constant in time (except for some - usually small - drift in the code). The fluctuations around these straight lines are a measure for the noise (plus multipath !!) in the various observables. So, with all observables in meters:

(3) $-$ (6) (times 2): $Mc = C1 - 4.092 * L1 + 3.092 * L2$
(4) $-$ (6) (times 2): $M1 = P1 - 4.092 * L1 + 3.092 * L2$
(5) $-$ (7) (times 2): $M2 = P2 - 5.092 * L1 + 4.092 * L2$

The noise in the phase observables L1 and L2 is likely to be more than a factor 50 smaller than in the codes (as evident from table 6.1). So the noise in C1, P1 and P2 (or Y1 and Y2) deviates nearly never more than 1% from the noise in the linear combinations Mc, M1 and M2. These latter values can be easily computed from a time series of say 15 or 30 minutes duration.

It is also possible to obtain an estimate for the noise in L1 and L2 from the time series of the linear combination in formula (6). A complication is that this time series does not represent a straight line, but shows the change in time, of the ionospheric effect d1. This effect changes mainly with the satellite's elevation and can be approximated by a quadratic curve. Fluctuations around such a best fitting curve, are due to the noise in the phase observable, but it is contaminated by the noise in the ionosphere over the evaluated period. In addition it is necessary to make an assumption for the relation between the noises in L1 and L2. We assumed these to be proportional to the wavelength, so noise (in millimeter) on L2 is a factor 1.3 larger than on L1. However, if L2 is obtained from the sum of L1 and the phase of the beat frequency f2 $-$ f1, the factor may be much larger.

6.3. Data acquisition and results

Data acquired for the long baseline at Kootwijk between 11:30 on day 63 and 07:50 on day 64 has been used for the analysis. The recording interval was 30 sec. To eliminate drift from the code data and the ionospheric effect from the phase data, a straight line was fitted if the linear combination involved a code range and a quadratic curve if only phase ranges were used. All data was extracted from the RINEX files. According to [Gourevitch,1994], the ranges recorded by ASHTECH have been smoothed; no information is available whether the same is true for the other receivers. Unsmoothed data for ASHTECH has been taken from their raw data file.

Three elevation ranges have been analysed, i.e. from 60°- 80°, 35°- 50° and 10°- 25°. For each range five satellites were selected that were tracked by all receivers simultaneously during 30 minutes. In this way anomalies due to large multipath effects are likely to be detected.

The results are presented in app. E.1 for phase (L1), E.2 for C/A code and E.3. for Y2. Average values for each elevation range are summarized in table 6.1. The phase noise is nearly the same for all receivers. The most remarkable fact for C/A code noise is that the smoothed values for ASHTECH are lowest and the unsmoothed value highest. This is also the case for Y2, except for the low LEICA values and the rapid increase for TRIMBLE and ROGUE with decreasing elevation. The ASHTECH also tracks Y1. The noise therein is not tabulated, but was found to be for the high elevations about 10 % lower than for Y2 and for the low ones some 35 % lower. This may be due to the fact that the L1 signal is 3dB stronger than for L2. Consequently the noise in Y1 is lower than in C/A, probably because the sharper Y-code pulse is less affected by multipath.

NOISE IN THE PHASE OBSERVABLE L1 (in millimeter)

AVG. ELEV.	ASH	TRI	LEI	ROG
70°	1.3	1.3	1.3	1.0
43°	4.2	4.2	4.5	4.2
17°	4.5	5.1	4.6	4.2

NOISE IN THE C/A CODE OBSERVABLE (in centimeter)

AVG. ELEV.	ASHTECH smooth	ASHTECH not smooth	TRI	LEI	ROG
70°	10.8	41.9	24.6	14.8	18.5
43°	23.3	60.8	32.5	22.2	25.9
17°	41.9	105.6	60.7	47.8	58.3

NOISE IN THE Y2 CODE OBSERVABLE (in centimeter)

AVG. ELEV.	ASHTECH smooth	ASHTECH not smooth	TRI	LEI	ROG
70°	9.0	24.3	25.1	10.0	13.5
43°	20.3	41.1	36.0	14.5	30.3
17°	52.1	93.7	102.9	33.8	117.4

Table 6.1: *Noise in L1, C1 and Y2 observables for four receivers in three satellite elevation ranges.*

Drawing a useful conclusion from these tables presents a problem, especially for someone with a geodetic background, who has no experience with receiver design - as is the case for the author. It is however likely that the noise is very closely related to the bandwidth of the tracking loops and that receiver designers are facing the hereafter described dilemma. If it is not possible to satisfy both, a compromise solution is required. Accurately tracking weak signals (e.g. through foliage or at low elevations) requires a narrow bandwidth. However, tracking the dynamics of a moving receiver - such as during kinematic survey - requires a wider band. This applies to tracking the C/A code and the associated L1 carrier phase. To track the other observables, the dynamic changes as already observed can be used. In other words, the C/A carrier loop "guides" the other loops, and these can therefore use much narrower bands. But they should still be wide enough to accommodate any rapid changes in the difference between L1 and L2, which may occur during ionospheric disturbances or due to sudden interference.

An important advantage of dual-frequency receivers over the cheaper one-frequency instruments is that they can quickly resolve the ambiguities for rapid static survey and resolve them "on-the-fly" for kinematic survey. This is made possible by the wide laning technique, which needs two frequencies and even that advantage is being challenged by increasingly accurate C/A code observations. So it should not be a foregone conclusion that lower noise in the output observables is better; it may be off-set by better dynamic tracking. The next section on tracking loops is an effort to understand this better.

6.4. Tracking loops

Cross correlation between an incoming code and for example a locally generated code requires a certain integration time (T), which can also be indicated by a bandwidth (1/T). The basic integration time can be anywhere between 1 and 20 millisecond; since it has to stay within the phase changes of the 50 Hz data modulation (though other designs are now being used). Such a short integration time gives a rather noisy range; therefore the tracking loop sums (or rather averages) many of these measurements. The result is used as a feedback signal for more accurate tracking of the range. For example 50 measurements of 20 msec. may be integrated giving a bandwidth of 1 Hz for the tracking loop and a new range for output every second. See [Thomas, 1992]. Modern receivers have special techniques to remove the 50 Hz data modulation and can therefore use longer integration times. It is believed that most geodetic receivers use a C/A carrier tracking bandwidth of between 10 and 30 Hz (corresponding to integration times between 33 and 100 milliseconds), and much narrower bandwidths for the other observables.

It is also possible to further average the code-range output from the tracking loops without using the result as a feedback signal to the loop. This may be done by fitting a polynomial, but is normally implemented by phase-aiding the code. Such a process can be referred to as "post-correlation" or "outside-the-tracking loop" smoothing. Averaging may extend over several hundred seconds for stationary receivers, but that period is limited by the requirement to accurately track the receiver's position at all instants, if that receiver is also used for kinematic survey operations. It is understood that this post-correlation smoothing is applied by ASHTECH and output to the RINEX file, while the unsmoothed ranges are the direct output from the tracking loops. The binary ASHTECH file gives both smoothed and unsmoothed ranges. Inspecting these appears to indicate that for the recording rates we used, smoothing is done over 100 seconds, using 400 samples spaced 0.25 sec.

We furthermore subtracted the ASHTECH smoothed ranges from the unsmoothed ones, and averaged this difference over periods of 30 minutes for several satellites. It then became apparent that on the L1 frequency (C/A and Y1 code), the unsmoothed ranges are about 3 cm. longer than the smoothed ones, when the satellite elevation is about

70°. This difference increases to 8 cm. at 43° and to 13 cm. at 17°. For the Y2 code ranges these differences are 5 cm., 14 cm. and 22 cm. respectively. This is a factor 1.6 higher, which seems to indicate that the difference is due to the different effect of the ionosphere on the phase and the code.

If the recording interval is shorter than the smoothing interval (or correlation time), the output is over-sampled. Consecutive output ranges will then have used partly the same observations and will be mathematically correlated, with as a result a lower noise, but not a better dynamic tracking performance. It would be interesting to have detailed information on the tracking loop bandwidths and smoothing procedures of all four receivers.

6.5. Conclusions

- The analysis of phase noise hardly shows differences between the four receivers.
- There are fairly large differences in the noise for the C/A and Y code ranges as recorded in the RINEX files, but the importance of this is not readily evident. Insufficient information is available on the integration times and on the amount of smoothing applied, if any.
- It is hoped that publishing the result of this noise analysis stimulates further investigation into this aspect.

7. Conclusions

The major conclusion is that all four receivers are capable of providing the data required for highly accurate survey results of similar quality. Also the software packages provided with the receivers (at the time of this test no such software was available for the ROGUE), give results of nearly the same precision.

For the 10 kilometer baseline the ROGUE malfunctioned. The other three all achieved a standard deviation of about 10 to 30 mm. in the three Cartesian co-ordinate components, using only 10 minutes of observations and the software provided by the manufacturer. Averaging 24 such periods in a day further improved the precision to about 7 mm. in height and 5 mm. in North and East. There are however indications of scale differences of about 2 ppm between various software packages. This could be due to the way in which ionospheric effects are treated.

For the 100 kilometer baseline, one hour of observations gave precisions (s.d.'s) up to 100 mm. in the three Cartesian co-ordinate components using manufacturers' software. Averaging 22 of these hourly sessions, the s.d.'s decreased to under 15 mm. in height and nearly 10 mm. in North and East.

With Bernese software the precisions were nearly 1.5 times better. For the short baseline the s.d. was under 13 mm. in height and under 7 mm. in North and East, using 1 hour observations. Averaging 22 such sessions in a day improves this further by about a factor two. For the long baseline 3 hours of observations is the optimum duration, providing 9 to 30 mm. in height and less than 7 mm. in North and East; the better values applying to the ROGUE. It is not known whether this is due to the receiver or the choke-ring antenna. Averaging eight such sessions from one day, brings the precision for all instruments under 10 mm. in height and 5 mm. horizontally.

There is a bias between Bernese and manufacturer's software for the long baseline of about 0.15 ppm (about 15 mm.) in scale and about 15 mm. in height. This may be because Bernese software used a precise ephemeris and estimated tropospheric parameters at the baseline ends. It may also be the reason why the precision with the Bernese software is about a factor 1.5 better.

The standard deviation in the single differences (between stations) of the carrier phase - as determined with Bernese software - was lowest for the ROGUE, followed by TRIMBLE, ASHTECH and LEICA in that order. However further noise analysis in the observables per single receiver - using the Quick Look program - gave no further evidence that there was a significant difference in noise for these phase observables.

All software packages, except ASHTECH's, gave far too optimistic estimates for the precision achieved from processing an observation session.

Susceptibility to Radio Frequency Interference (jamming tests), showed very large differences between receivers. The ASHTECH was only susceptible to in-band jamming and did not experience any interference from other transmissions. The other three all suffered from interference from near-band transmissions and frequently lost lock on L1 when L2 was no longer tracking. The ROGUE had the greatest resistance to in-band interference of all four, especially for L2. It was however the only receiver that was affected by strong out-of-band interference from many frequencies between 1100 and 1725 MHz.

Detailed conclusions appear at the end of chapters 3, 4, 5 and 6.

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Major staff participants were G.J. Husti (DUT) and J.F. Zomerdijk and M.E.E. Haagmans (RWS).

Many other persons were involved, either in the execution of the work or by participation in discussions and giving support in varying degrees. More in detail, the more tangible contributions were:

From the Faculty of Geodesy of Delft University of Technology; G.J. Husti, Data acquisition and processing; C.D. de Jong and D. van Loon, data acquisition; H. v.d. Marel, Quick-Look software.

From the Survey Department of the Dutch Ministry of Transport, Public Works and Water Management:
J.F. Zomerdijk, data acquisition and processing; M.E.E. Haagmans, data analysis, M. Aussems and M. Kollard, data acquisition.

From the Netherlands National Aerospace Laboratory:
F. Klinker and M. Schaap; Organizing the jamming tests at NLR.

From the Faculty of Electrical Engineering of Delft University of Technology (under paid contract):
D.J. Moelker and C.M. v.d. Knaap; Organizing the jamming test at Delft. Moelker also significantly contributed to improving the knowledge of the author in the subject of GPS receiver designs.

T.A. Springer of the Faculty Aerospace Engineering of Delft University of Technology carried out (under contract to RWS) all processing with Bernese software and wrote a detailed report of this work that has been extremely valuable for our study.

J. van Buren of the National Dutch Triangulation Service assisted in the operations at Apeldoorn.

Staff of the Office of the Netherlands Geodetic Commission arranged the final preparation for printing this report.

The continuous support of all persons involved was a major factor in bringing the project to a successful end.

The author, in his capacity of chairman of the Working Group for Applied Space Geodesy, initiated and organized the project, took part in all data acquisition and processing and analysed the results.

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Appendices chapter 2

APPENDIX A.1: BASIC INFORMATION ON CO-ORDINATES

The co-ordinates of the stations at KOOTWIJK have been held fixed at the following WGS84 values:

Baseline	Ref.Stat.	Latitude	Longitude	Ht.(ell.)
A	KA28	52 10 42.6996 N	5 48 36.4906 E	89.389 m.
B	KB33	52 10 42.2737 N	5 48 36.6475 E	88.761 m.
C	KC32	52 10 42.2738 N	5 48 36.4896 E	88.758 m.
D	KD31	52 10 42.6992 N	5 48 36.3327 E	89.380 m.

Approximate position of the "unknown" ends of baselines:

LONG BASELINE at DELFT	:	51 59 10 N	4 23 15 E	74 m.
SHORT BASELINE at APELDOORN	:	52 12 44 N	5 56 25 E	112 m.

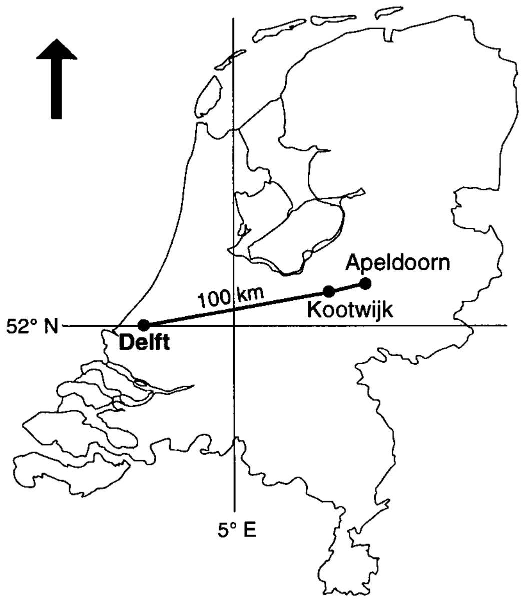
Approximate baseline parameters:

Baseline		Distance	Azimuth	Height diff.
KOOTWIJK - DELFT	:	99850 m.	258.17 deg.	-15 m.
KOOTWIJK - APELDOORN	:	9634 m.	67.15 deg.	+23 m.

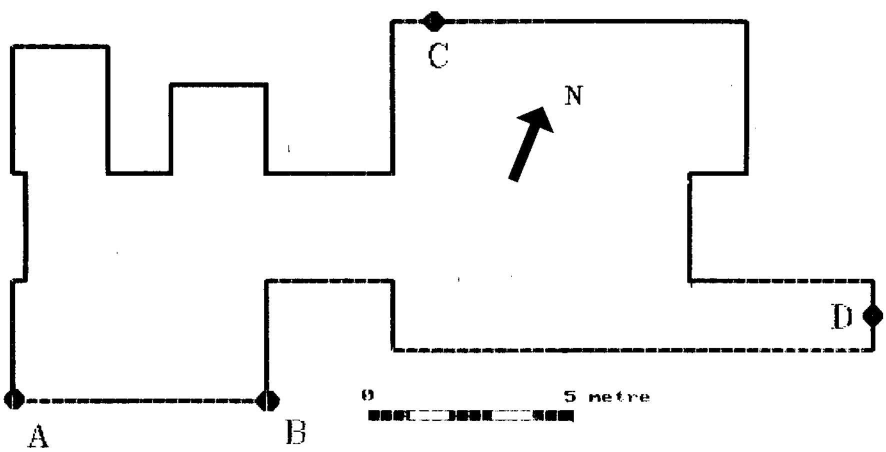
The line KOOTWIJK - DELFT has been accurately determined in an EUREF campaign. The stations at APELDOORN are related to a minor control point, corrected for a known anomaly with GPS of about 13 centimeter in Northerly direction. The height was not corrected. From this we computed the "datum vectors" that were used in our evaluation. They are:

	LONG BASELINE			SHORT BASELINE		
	dX	dY	dZ	dX	dY	dZ
A	+25491.434	-95638.395	-13177.652	-3829.416	+8533.575	+2307.295
B	+25479.259	-95636.230	-13167.494	-3837.712	+8524.868	+2315.268
C	+25470.275	-95634.053	-13160.538	-3836.886	+8533.006	+2307.382
D	+25480.718	-95615.764	-13170.688	-3821.296	+8518.361	+2294.967

APPENDIX A.2: SITUATION OF BASELINES AND DELFT OFF-SETS

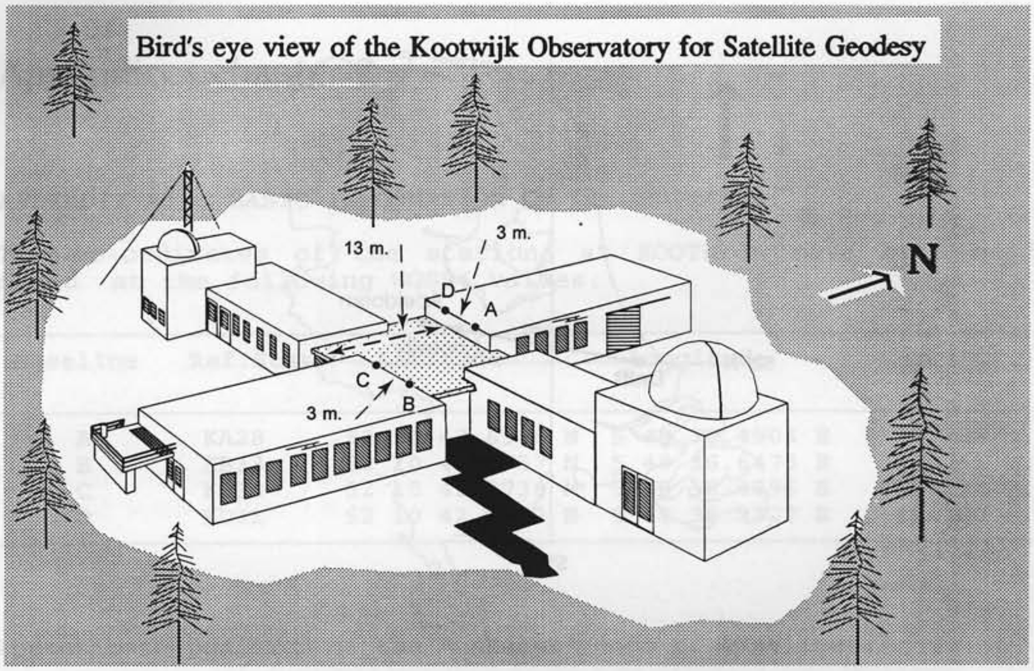


Long and short baseline.

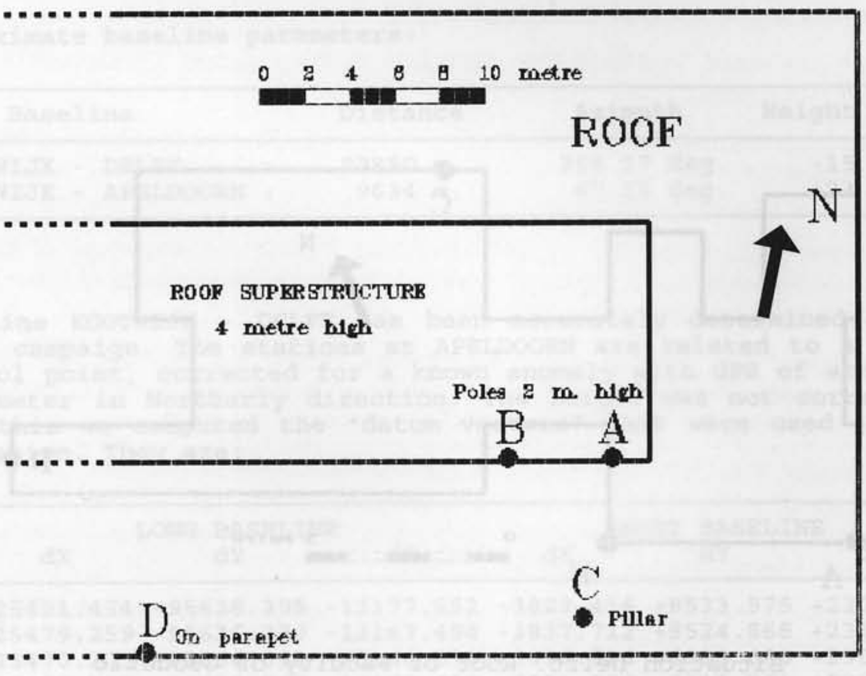


Situation Delft. Roof of Faculty of Geodetic Engineering, TU Delft.

APPENDIX A.3: SITUATION OF KOOTWIJK AND APELDOORN OFF-SETS

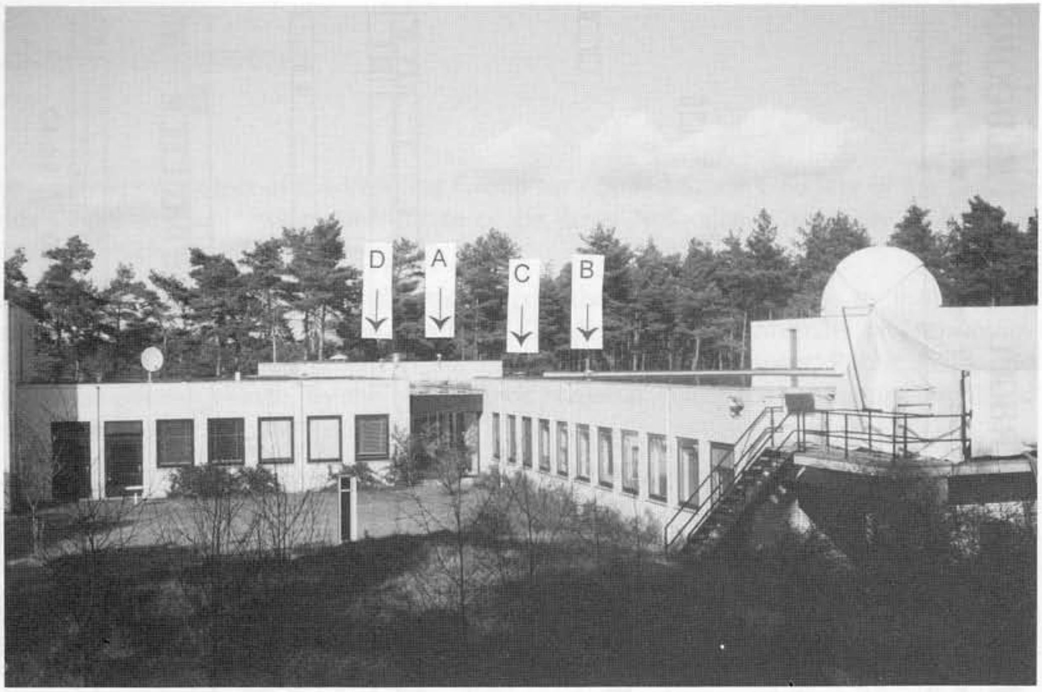


Situation Kootwijk, Observatory for Satellite Geodesy.

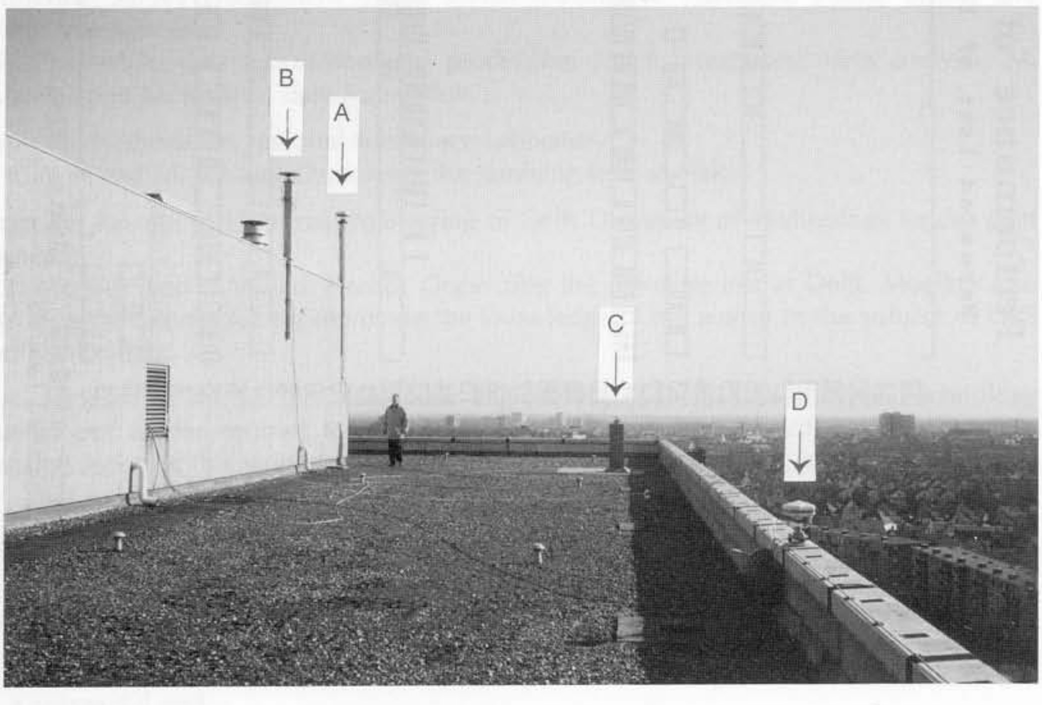


Situation Apeldoorn. Roof of Cadastre Office.

APPENDIX A.4: PHOTOGRAPHS OF KOOTWIJK AND APELDOORN

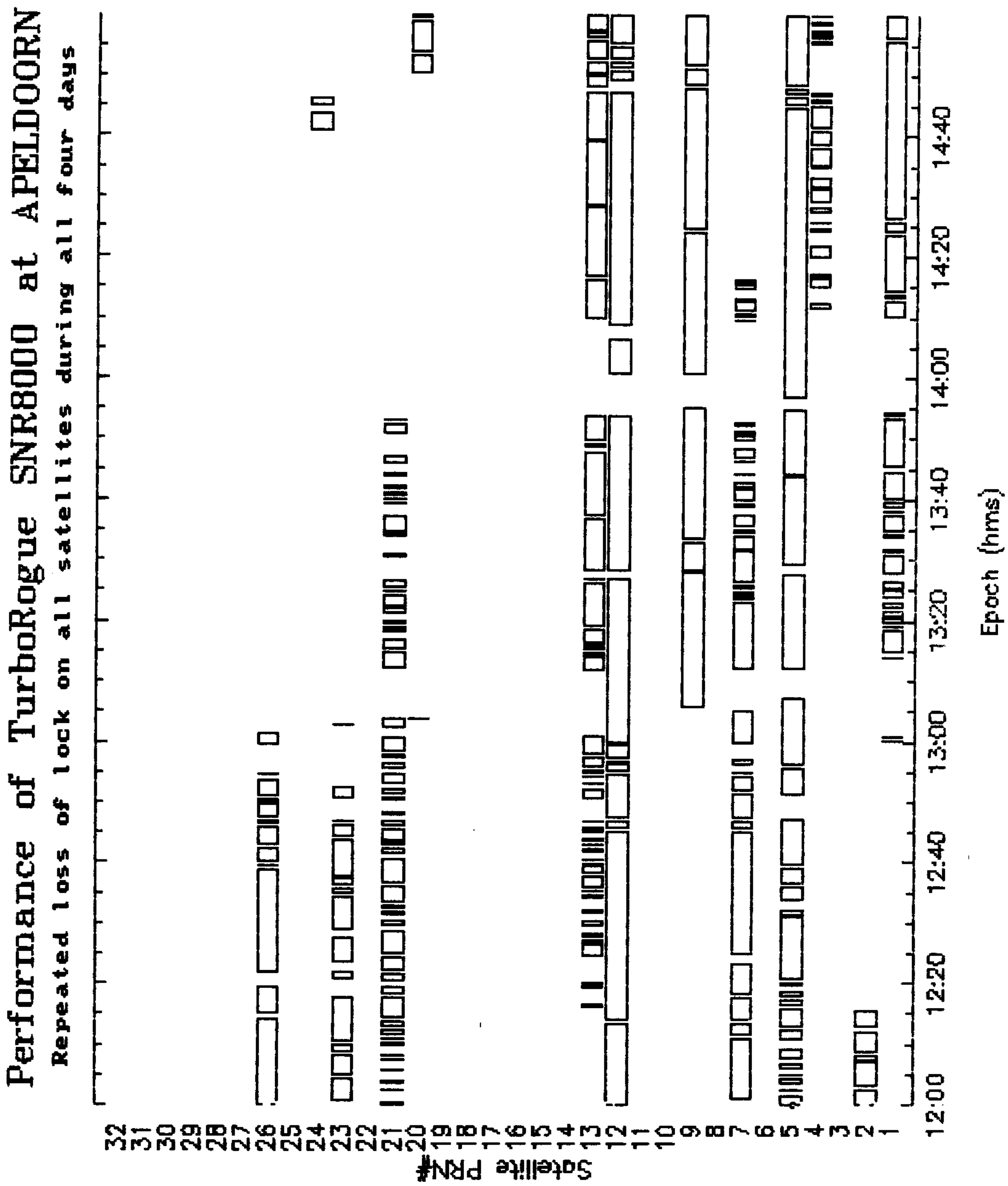


Kootwijk stations.



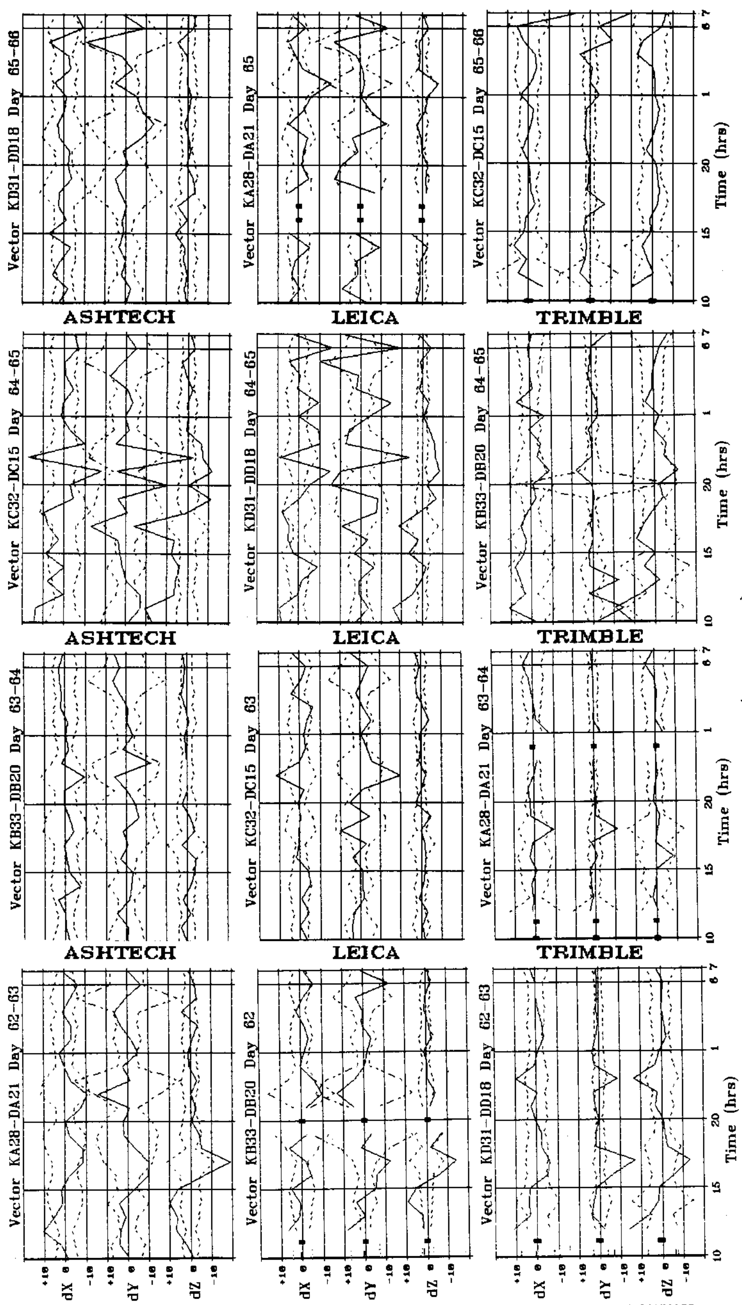
Apeldoorn stations.

APPENDIX A.5: SIGNAL LOSSES OF ROGUE AT APELDOORN



Appendices chapter 3

APPENDIX B.1: LONG BASELINE (TIME SERIES); MANUFACTURER'S SOFTWARE



LONG (100 KM) BASELINE

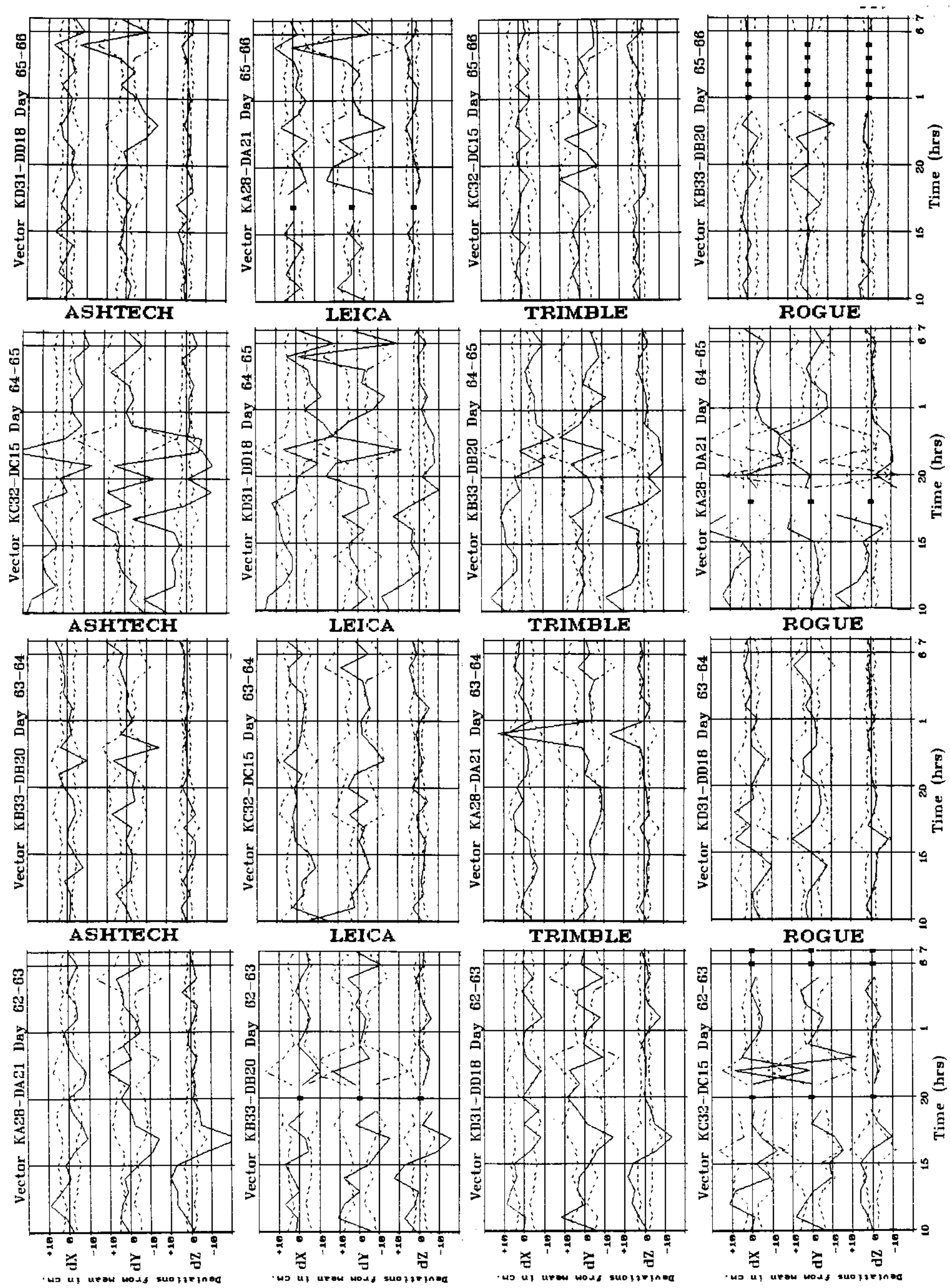
MANUFACTURER'S SOFTWARE (for ROGUE not available)

Fluctuations of one-hour solution around daily mean; and their s.d.

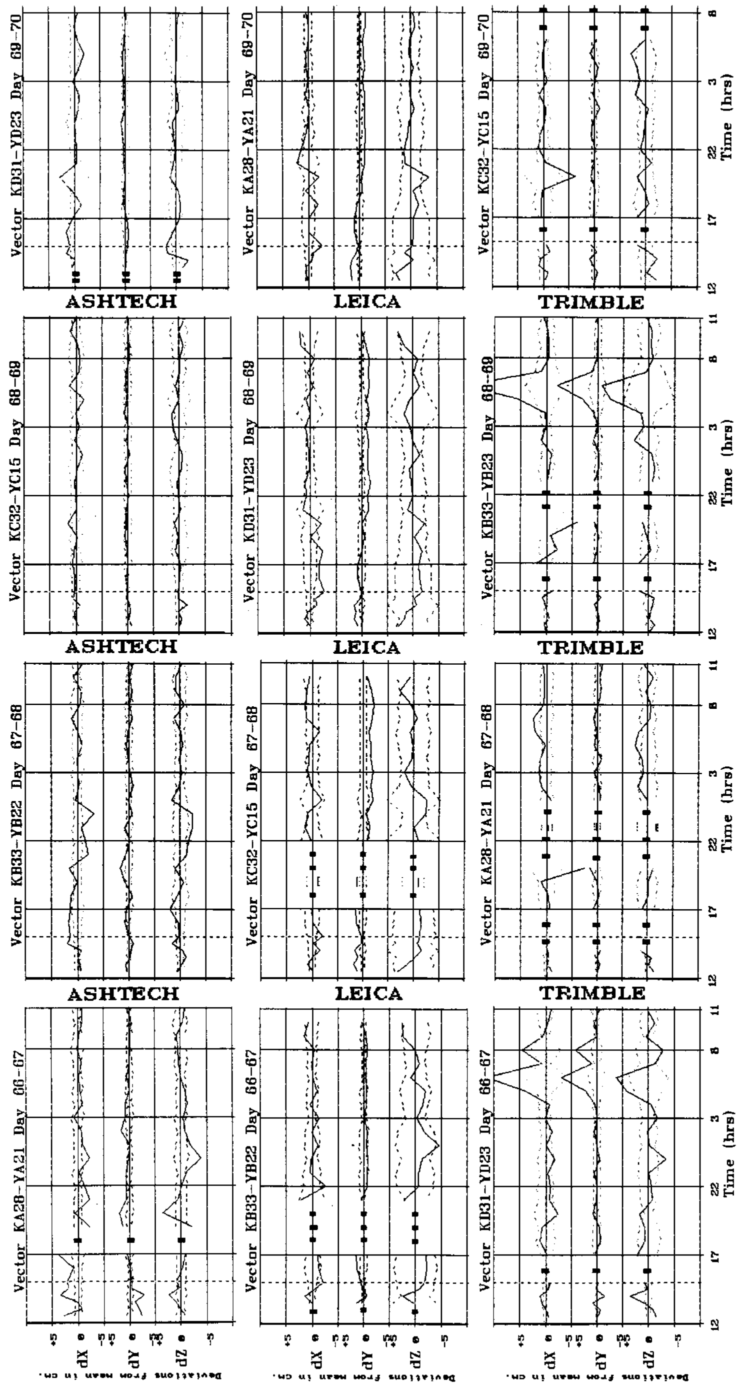
Cartesian WGS-84 coordinates. 30 sec. data recording interval

—— Solution; - - - - Standard deviation; ■ No accepted solution;

APPENDIX B.2: LONG BASELINE (TIME SERIES); TOPAS SOFTWARE



LONG (100 KM) BASELINE -TOPAS SOFTWARE; Legend see app. 2



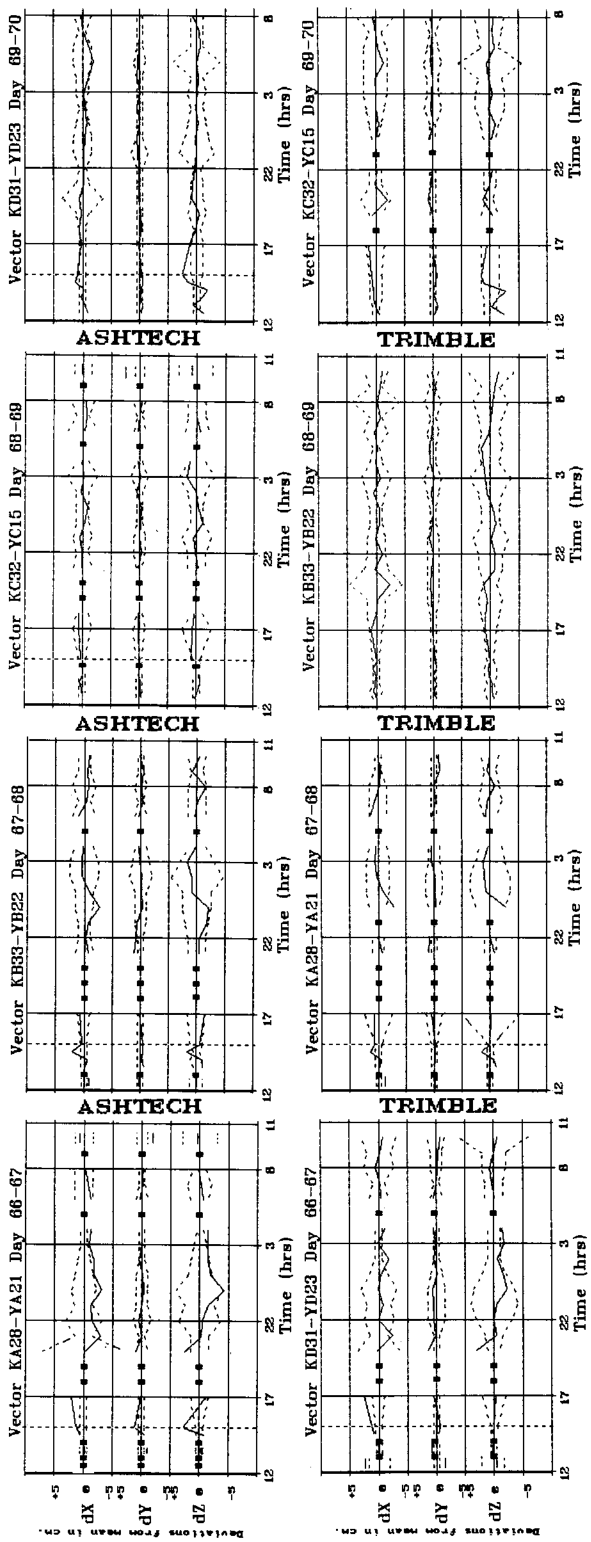
SHORT (10 KM) BASELINE

MANUFACTURER'S SOFTWARE (no ROGUE data available)

Fluctuations of ten-min. solution around daily mean; and their s.d.

Cartesian WGS-84 coordinates. 30 (partly 5) sec. data recording interval

—— Solution; ---- Standard deviation; ■ No accepted solution;



SHORT (10 KM) BASELINE

TOPAS SOFTWARE (no ROGUE data and not enough LEICA results)

Fluctuations of ten-min. solution around daily mean; and their s.d.

Cartesian WGS-84 coordinates. 30 (partly 5) sec. data recording interval

—— Solution; ---- Standard deviation; ■ No accepted solution;

APPENDIX B.5: RESULTS OF LONG BASELINE; COMMERCIAL SOFTWARE

			S.d. in 1 hr. period from spread in results (cm)			Diff. of average with datum co-ords (cm)			Multiplication factor for s.d. from software			
Day Baseline	Tot. obs.	Fail	σx	σy	σz	dX	dY	dZ	fx	fy	fz	(x, y, z)
ASHTECH with PRISM												
62 A	22	0	4.8	5.2	5.8	-0.1	3.2	2.3	1.0	0.7	1.3	
63 B	22	0	3.1	4.3	2.1	-2.5	3.2	0.2	0.4	0.5	0.6	
64 C	22	0	8.2	9.5	9.1	-2.1	3.7	2.1	1.2	0.8	1.9	
65 D	22	0	4.0	6.3	2.5	-2.5	3.7	-0.0	0.7	0.6	0.7	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 0.9
Total	88	0	5.5	6.6	5.7	-2.0	3.3	0.3	0.8	0.6	1.1	S.d. 0.4
LEICA with SKI												
62 B	22	2	4.0	6.0	4.7	-1.8	3.7	1.6	5.7	7.9	8.9	
63 C	22	0	3.8	5.7	2.1	-2.6	4.6	0.7	5.8	5.3	6.0	
64 D	22	0	7.5	10.2	5.9	-3.2	4.7	1.3	12.5	9.6	15.2	
65 A	22	2	5.1	7.0	2.8	-1.4	2.7	0.3	6.3	6.8	6.9	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 8.1
Total	88	4	5.4	7.6	4.2	-2.2	3.9	0.7	7.6	7.4	9.2	S.d. 2.9
TRIMBLE with GPSurvey												
62 D	22	1	4.2	5.0	6.1	-0.5	5.9	2.3	24.9	56.3	26.8	
63 A	22	3	4.0	2.9	2.4	-1.0	3.9	-0.2	23.2	25.8	12.4	
64 B	22	0	4.7	4.7	6.7	-0.5	5.0	1.5	26.7	37.7	26.1	
65 C	22	1	6.2	5.6	3.9	-2.6	5.8	-0.0	26.7	53.6	16.3	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 29.7
Total	88	5	4.9	4.8	5.3	-0.9	4.7	0.2	25.4	43.4	20.4	S.d. 12.7
ASHTECH with TOPAS												
62 A	22	0	4.2	5.5	6.6	-6.5	1.2	2.0	7.3	6.0	10.6	
63 B	22	0	3.8	5.2	2.1	-10.6	1.3	-0.3	4.5	4.4	5.0	
64 C	22	0	10.5	12.2	8.8	-7.4	2.0	0.5	12.1	7.0	14.5	
65 D	22	0	3.6	7.5	2.2	-3.7	3.0	-0.1	5.4	5.0	5.3	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 7.2
Total	88	0	6.7	8.1	5.8	-6.9	1.6	-0.1	7.3	5.6	8.8	S.d. 3.2
LEICA with TOPAS												
62 B	22	1	4.3	7.1	5.8	-8.9	1.1	1.0	4.3	5.3	7.8	
63 C	22	0	4.7	7.2	2.7	-9.8	1.0	-0.0	4.4	9.8	4.8	
64 D	22	0	9.7	10.9	7.1	-7.5	1.9	0.6	10.3	6.3	10.7	
65 A	22	1	4.4	9.4	2.2	-3.6	3.1	-0.1	4.7	4.7	4.1	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 6.4
Total	88	2	6.7	8.8	4.9	-7.4	1.6	0.0	5.9	6.5	6.8	S.d. 2.4
TRIMBLE with TOPAS												
62 D	22	0	4.6	6.1	4.8	-8.7	4.2	0.4	7.5	6.3	9.5	
63 A	22	0	3.8	10.1	4.0	-9.3	-1.6	-0.8	5.7	16.1	6.5	
64 B	22	0	8.0	5.4	7.4	-6.8	2.0	-0.4	13.5	5.4	14.2	
65 C	22	0	2.7	5.0	2.2	-4.8	3.8	-0.4	3.8	4.7	5.7	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 8.2
Total	88	0	5.5	7.3	5.0	-6.8	2.9	-0.3	7.6	8.1	9.0	S.d. 3.9
ROGUE with TOPAS												
62 C	22	3	8.1	11.9	3.7	-8.8	1.8	1.0	8.7	8.3	9.2	
63 D	22	0	4.2	4.1	2.3	-10.8	0.5	-0.9	5.6	4.3	5.3	
64 A	22	1	9.7	6.4	8.0	-6.3	-1.3	-0.1	13.4	7.9	18.3	
65 B	22	5	2.2	4.3	2.1	-3.2	2.8	0.7	3.4	3.8	7.0	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 7.9
Total	88	9	7.4	7.5	4.8	-5.4	1.0	0.0	7.8	6.1	10.0	S.d. 4.1

Note: Using newer software versions greatly reduces the number of failures.

APPENDIX B.6: RESULTS OF SHORT BASELINE; COMMERCIAL SOFTWARE

			S.d. in 1 hr. period from spread in results (cm)			Diff. of average with datum co-ords (cm)			Multiplication factor for s.d. from software			
Day Baseline	Tot. obs.	Fail	σx	σy	σz	dX	dY	dZ	fx	fy	fz	(x, y, z)
ASHTECH with PNAV												
66 A	26	1	1.6	1.1	1.4	0.4	1.5	1.0	2.0	2.1	1.4	
67 B	26	0	1.2	0.6	1.1	-0.1	1.1	0.9	1.6	1.3	1.1	
68 C	26	0	0.7	0.3	0.7	-0.6	1.0	0.1	0.9	0.7	0.7	
69 D	22	2	1.0	0.3	0.9	-0.4	1.1	0.3	1.0	0.6	1.2	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 1.2
Total	100	3	1.2	0.7	1.1	-0.4	1.1	0.4	1.4	1.2	1.1	S.d. 0.5
LEICA with SKI												
66 B	24	4	1.2	0.7	1.8	-0.2	-0.3	-0.6	13.1	14.9	6.3	
67 C	25	3	1.0	1.3	1.5	-0.1	-1.8	-0.9	10.0	24.0	4.5	
68 D	25	0	1.3	1.0	1.4	0.4	-1.3	-0.4	13.7	28.5	5.0	
69 A	23	0	1.1	1.0	1.3	1.0	-0.7	-0.7	11.7	28.9	5.4	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 13.8
Total	97	7	1.2	1.2	1.6	0.3	-0.9	-0.2	12.1	24.1	5.3	S.d. 8.5
TRIMBLE with GPSurvey												
66 D	26	1	2.7	1.6	2.1	-0.4	1.8	0.4	6.3	8.7	7.7	
67 A	26	5	1.9	0.6	1.1	0.0	1.8	0.5	6.1	5.6	5.8	
68 B	26	3	3.7	1.7	2.6	-0.5	2.0	1.3	7.2	8.4	6.7	
69 C	23	3	1.5	0.5	1.4	-1.6	1.4	-0.1	3.9	5.0	5.2	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 6.4
Total	101	12	2.7	1.3	2.0	-0.8	1.6	0.4	5.9	6.9	6.3	S.d. 1.4
ASHTECH with TOPAS												
66 A	24	7	1.3	0.7	1.6	-0.0	1.2	0.6	8.3	5.1	8.8	
67 B	24	5	1.0	0.5	1.1	0.2	1.3	0.8	6.1	4.4	5.5	
68 C	24	5	0.4	0.3	0.7	0.1	1.0	0.2	2.1	2.2	3.2	
69 D	22	0	0.7	0.3	0.9	0.2	1.2	0.2	4.8	3.1	7.4	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 5.1
Total	94	17	0.9	0.5	1.1	0.2	1.1	0.3	5.3	3.7	6.2	S.d. 2.2
LEICA with TOPAS												
66 B	23	17	1.1	0.3	1.3	-0.9	1.6	0.1				
67 C	24	22	0.5	0.1	0.5	-0.8	0.9	-0.2				
68 D	24	20	0.6	0.3	0.6	-0.0	0.8	0.3	insufficient results			
69 A	22	14	0.5	0.2	0.4	1.2	1.2	1.2				
	----	----	----	----	----	----	----	----				
Total	93	73	1.2	0.4	1.0	0.5	1.1	0.9				
TRIMBLE with TOPAS												
66 D	24	5	1.2	0.7	1.1	-0.3	1.4	0.0	7.0	6.3	4.6	
67 A	24	6	1.0	0.51	0.9	0.4	1.7	0.8	5.2	4.7	5.0	
68 B	24	0	0.7	0.3	0.7	0.4	1.3	1.0	2.5	2.9	2.7	
69 C	22	2	0.7	0.4	1.0	-0.2	1.3	-0.1	2.6	3.7	4.9	
	----	----	----	----	----	----	----	----	----	----	----	Avg. 4.3
Total	94	13	0.9	0.5	1.1	0.2	1.3	0.6	4.3	4.4	4.3	S.d. 1.4

Note: Using newer software versions greatly reduces the number of failures.

APPENDIX B.7: CORRELATION COEFFICIENTS 100 KM BASELINE

CORRELATION BETWEEN RECEIVERS PER DAY (Topas software)

Day 62				Day 63				Day 64				Day 65			
CORR	cx	cy	cz	CORR	cx	cy	cz	CORR	cx	cy	cz	CORR	cx	cy	cz
as-le-62	0.6	0.8	0.9	as-le-63	0.1	0.1	0.6	as-le-64	0.8	0.1	0.9	as-le-65	0.6	0.7	0.7
as-ro-62	0.6	0.7	0.9	as-ro-63	0.4	0.3	0.6	as-ro-64	0.4	-0.3	0.9	as-ro-65	0.1	0.4	0.4
as-tr-62	0.8	0.6	0.9	as-tr-63	0.3	0.1	0.3	as-tr-64	0.7	0.1	0.9	as-tr-65	0.5	0.0	0.8
le-ro-62	0.6	0.7	0.7	le-ro-63	0.4	0.2	0.6	le-ro-64	0.7	0.2	0.9	le-ro-65	0.6	0.8	0.6
le-tr-62	0.7	0.6	0.9	le-tr-63	0.5	0.1	0.4	le-tr-64	0.9	0.4	1.0	le-tr-65	0.7	0.2	0.7
ro-tr-62	0.6	0.7	0.9	ro-tr-63	0.6	0.0	0.4	ro-tr-64	0.8	0.5	1.0	ro-tr-65	0.6	0.8	0.7
Avg.	0.6	0.7	0.9	Avg.	0.4	0.1	0.5	Avg.	0.7	0.2	0.9	Avg.	0.5	0.5	0.6
S.d.	0.1	0.1	0.1	S.d.	0.1	0.1	0.1	S.d.	0.1	0.3	0.0	S.d.	0.2	0.3	0.1
Overall	(x,y,z)	avg	0.7	Overall	(x,y,z)	avg	0.3	Overall	(x,y,z)	avg	0.5	Overall	(x,y,z)	avg	0.5
Overall	(x,y,z)	s.d	0.1	Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.4	Overall	(x,y,z)	s.d	0.2

CORRELATION BETWEEN RECEIVERS PER DAY (Manufacturer's software)

Day 62				Day 63				Day 64				Day 65			
CORR	cx	cy	cz	CORR	cx	cy	cz	CORR	cx	cy	cz	CORR	cx	cy	cz
as-le-62	0.6	0.8	0.9	as-le-63	-0.3	0.0	0.5	as-le-64	0.8	0.4	0.9	as-le-65	0.3	0.6	0.5
as-tr-62	0.6	0.5	0.6	as-tr-63	0.3	0.0	0.5	as-tr-64	0.5	0.1	0.8	as-tr-65	0.3	-0.2	0.4
le-tr-62	0.3	0.4	0.5	le-tr-63	0.1	-0.4	0.3	le-tr-64	0.2	0.1	0.8	le-tr-65	-0.2	-0.2	0.3
Avg.	0.5	0.6	0.7	Avg.	0.0	-0.1	0.4	Avg.	0.5	0.2	0.8	Avg.	0.1	0.1	0.4
S.d.	0.1	0.2	0.2	S.d.	0.2	0.2	0.1	S.d.	0.2	0.1	0.1	S.d.	0.2	0.4	0.1
Overall	(x,y,z)	avg	0.6	Overall	(x,y,z)	avg	0.1	Overall	(x,y,z)	avg	0.5	Overall	(x,y,z)	avg	0.2
Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.3	Overall	(x,y,z)	s.d	0.3	Overall	(x,y,z)	s.d	0.3

APPENDIX B.8: CORRELATION COEFFICIENTS 100 KM BASELINE (CONT.)

CORRELATION BETWEEN DAYS PER RECEIVER (Topas software)

ASHTECH				LEICA				TRIMBLE				ROGUE			
Corrcoef	dx	dy	dz	Corrcoef	dx	dy	dz	Corrcoef	dx	dy	dz	Corrcoef	dx	dy	dz
ash62T63	0.1	0.2	-0.0	lei62T63	-0.4	-0.0	0.1	tri62T63	-0.2	-0.1	0.0	rog62T63	0.2	0.2	-0.3
ash63T64	-0.7	0.1	0.1	lei63T64	-0.0	0.4	0.2	tri63T64	-0.1	0.2	0.0	rog63T64	0.3	0.2	0.3
ash64T62	-0.1	-0.5	-0.3	lei64T62	0.4	0.0	0.2	tri64T62	0.2	-0.2	-0.1	rog64T62	0.2	-0.1	0.0
ash63T65	-0.2	0.3	0.0	lei63T65	-0.2	0.1	0.3	tri63T65	-0.0	-0.0	-0.1	rog63t65	0.5	0.0	-0.2
ash65T62	0.1	0.1	-0.1	lei65T62	0.4	0.3	0.4	tri65T62	0.4	0.3	0.0	rog65T62	0.4	0.6	0.5
ash64T65	0.3	0.5	0.7	lei64T65	0.2	0.3	0.4	tri64T65	0.2	-0.3	0.5	rog64T65	0.5	-0.3	0.2
Avg.	-0.1	0.1	0.1	Avg.	0.1	0.2	0.3	Avg.	0.1	-0.0	0.1	Avg.	0.3	0.1	0.1
S.d.	0.3	0.3	0.3	S.d.	0.3	0.2	0.1	S.d.	0.2	0.2	0.2	S.d.	0.1	0.3	0.3
Overall	(x,y,z)	avg	0.1	Overall	(x,y,z)	avg	0.2	Overall	(x,y,z)	avg	0.1	Overall	(x,y,z)	avg	0.2
Overall	(x,y,z)	s.d	0.3	Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.3

CORRELATION BETWEEN DAYS PER RECEIVER (Manufacturer's software)

ASHTECH-PRISM				LEICA-SKI				TRIMBLE-GPSurvey			
Corrcoef	dx	dy	dz	Corrcoef	dx	dy	dz	Corrcoef	dx	dy	dz
ash62-63	0.3	0.1	-0.1	lei62-63	-0.5	-0.2	0.3	tri62-63	0.1	-0.1	0.2
ash63-64	-0.5	-0.2	0.2	lei63-64	0.4	0.4	-0.1	tri63-64	0.2	0.0	-0.3
ash64-62	0.0	-0.6	-0.2	lei64-62	0.2	0.0	-0.0	tri64-62	-0.1	-0.2	-0.3
ash63-65	-0.1	0.4	0.0	lei63-65	0.1	0.0	0.1	tri63-65	0.0	-0.0	-0.2
ash65-62	0.1	-0.0	-0.0	lei65-62	0.5	0.2	0.3	tri65-62	0.1	0.1	0.1
ash64-65	0.4	0.2	0.6	lei64-65	0.4	0.3	0.4	tri64-65	-0.0	0.3	0.5
Avg.	0.0	-0.0	0.1	Avg.	0.2	0.1	0.2	Avg.	0.1	0.0	-0.0
S.d.	0.3	0.3	0.2	S.d.	0.3	0.2	0.2	S.d.	0.1	0.1	0.3
Overall	(x,y,z)	avg	0.0	Overall	(x,y,z)	avg	0.2	Overall	(x,y,z)	avg	0.1
Overall	(x,y,z)	s.d	0.3	Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.2

APPENDIX B.9: CORRELATION COEFFICIENTS 100 KM BASELINE (CONT.)

CORRELATION BETWEEN RECEIVERS PER STATION (Topas software)

	Station A				Station B				Station C				Station D		
CORR	cx	cy	cz	CORR	cx	cy	cz	CORR	cx	cy	cz	CORR	cx	cy	cz
as-le-AT	0.2	0.4	0.2	as-le-BT	-0.1	0.4	-0.0	as-le-CT	-0.1	0.2	0.1	as-le-DT	0.3	0.5	0.4
as-ro-AT	0.4	-0.1	-0.1	as-ro-BT	0.6	0.4	0.1	as-ro-CT	-0.4	-0.3	-0.1	as-ro-DT	0.0	0.3	0.0
as-tr-AT	-0.2	0.2	-0.1	as-tr-BT	-0.4	-0.6	0.2	as-tr-CT	-0.0	0.1	0.5	as-tr-DT	0.0	-0.2	0.0
ro-le-AT	0.1	-0.2	0.4	ro-le-BT	0.1	0.4	0.5	ro-le-CT	-0.3	-0.2	-0.1	ro-le-DT	-0.0	0.0	0.1
le-tr-AT	0.1	-0.1	0.1	le-tr-BT	0.5	-0.3	0.1	le-tr-CT	-0.2	-0.2	0.2	le-tr-DT	0.1	-0.3	-0.0
ro-tr-AT	-0.1	0.0	0.0	ro-tr-BT	0.1	-0.7	0.2	ro-tr-CT	0.5	0.5	0.0	ro-tr-DT	-0.2	-0.3	-0.1
Avg.	0.1	0.0	0.1	Avg.	0.1	-0.0	0.2	Avg.	-0.1	0.0	0.1	Avg.	0.0	-0.0	0.1
S.d.	0.2	0.2	0.2	S.d.	0.3	0.5	0.2	S.d.	0.3	0.3	0.2	S.d.	0.2	0.3	0.2
Overall	(x,y,z)	avg	0.1	Overall	(x,y,z)	avg	0.0	Overall	(x,y,z)	avg	-0.0	Overall	(x,y,z)	avg	0.0
Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.4	Overall	(x,y,z)	s.d	0.3	Overall	(x,y,z)	s.d	0.2

CORRELATION BETWEEN RECEIVERS PER STATION (Manufacturer's software)

	Station A				Station B				Station C				Station D		
CORR	cx	cy	cz	CORR	cx	cy	cz	CORR	cx	cy	cz	CORR	cx	cy	cz
as-le-A	0.2	0.4	0.2	as-le-B	0.1	0.1	-0.1	as-le-C	0.3	0.4	-0.1	as-le-D	0.4	0.3	0.4
as-tr-A	0.0	0.2	0.2	as-tr-B	-0.1	0.0	-0.1	as-tr-C	-0.0	-0.2	0.3	as-tr-D	0.2	0.1	-0.1
le-tr-A	-0.2	0.1	0.0	le-tr-B	0.3	0.1	0.0	le-tr-C	-0.3	-0.1	0.0	le-tr-D	-0.3	-0.3	-0.4
Avg.	0.0	0.2	0.1	Avg.	0.1	0.1	-0.0	Avg.	-0.0	0.0	0.1	Avg.	0.1	0.1	-0.0
S.d.	0.2	0.1	0.1	S.d.	0.2	0.0	0.1	S.d.	0.3	0.2	0.2	S.d.	0.3	0.3	0.3
Overall	(x,y,z)	avg	0.1	Overall	(x,y,z)	avg	0.1	Overall	(x,y,z)	avg	0.0	Overall	(x,y,z)	avg	0.0
Overall	(x,y,z)	s.d	0.1	Overall	(x,y,z)	s.d	0.1	Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.3

APPENDIX B.10: CORRELATION COEFFICIENTS 100 KM BASELINE (CONT.)

CORRELATION BETWEEN MANUFACTURER'S AND TOPAS software per day.

	ASHTECH				LEICA				TRIMBLE		
CORR	cx	cy	cz	CORR	cx	cy	cz	CORR	cx	cy	cz
as-as62T	1.0	0.9	1.0	le-le62T	1.0	0.9	1.0	tr-tr62T	0.7	0.7	0.7
as-as63T	0.9	0.9	1.0	le-le63T	0.7	0.6	0.8	tr-tr63T	0.1	0.4	0.2
as-as64T	0.9	0.7	1.0	le-le64T	0.9	0.9	1.0	tr-tr64T	0.6	0.1	0.8
as-as65T	1.0	1.0	1.0	le-le65T	0.7	0.9	0.8	tr-tr65T	0.1	0.5	0.7
Avg.	0.9	0.8	1.0	Avg.	0.8	0.8	0.9	Avg.	0.3	0.3	0.6
S.d.	0.0	0.1	0.0	S.d.	0.1	0.1	0.1	S.d.	0.2	0.2	0.3
Overall	(x,y,z)	avg	0.9	Overall	(x,y,z)	avg	0.8	Overall	(x,y,z)	avg	0.4
Overall	(x,y,z)	s.d	0.1	Overall	(x,y,z)	s.d	0.1	Overall	(x,y,z)	s.d	0.3

APPENDIX B.11: CORRELATION COEFFICIENTS 10 KM BASELINE

CORRELATION BETWEEN RECEIVERS PER DAY (Manufacturer's software)

	Day 66				Day 67				Day 68				Day 69		
Corrcoef	cx	cy	cz	Corrcoef	cx	cy	cz	Corrcoef	cx	cy	cz	Corrcoef	cx	cy	cz
as-le-66	-0.2	-0.1	0.5	as-le-67	-0.3	0.3	0.1	as-le-68	-0.3	-0.4	-0.1	as-le-69	-0.5	-0.6	0.0
le-tr-66	-0.0	-0.2	0.1	le-tr-67	0.1	-0.0	-0.2	le-tr-68	0.1	-0.3	-0.2	le-tr-69	0.5	0.0	-0.4
tr-as-66	0.0	0.2	0.4	tr-as-67	-0.3	0.6	0.1	tr-as-68	0.0	0.3	0.3	tr-as-69	-0.7	-0.0	0.4
Avg.	-0.1	-0.0	0.3	Avg.	-0.2	0.3	0.0	Avg.	-0.0	-0.2	-0.0	Avg.	-0.2	-0.2	0.0
S.d.	0.1	0.2	0.2	S.d.	0.2	0.2	0.1	S.d.	0.2	0.3	0.2	S.d.	0.5	0.3	0.3
Overall	(x,y,z)	avg	0.1	Overall	(x,y,z)	avg	0.0	Overall	(x,y,z)	avg	-0.1	Overall	(x,y,z)	avg	-0.2
Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.3	Overall	(x,y,z)	s.d	0.3	Overall	(x,y,z)	s.d	0.4

CORRELATION BETWEEN DAYS PER RECEIVER (Topas software)

ASHTECH-TOPAS				TRIMBLE-TOPAS			
Corrcoef	cx	cy	cz	Corrcoef	cx	cy	cz
ash66t67	0.5	0.2	0.0	tri66t67	0.1	0.3	0.2
ash67t68	0.4	-0.0	0.4	tri67t68	0.3	0.2	0.5
ash68t66	0.3	0.4	0.2	tri68t66	0.1	0.7	0.2
ash67t69	0.4	0.3	0.0	tri67t69	0.3	0.2	0.2
ash69t66	0.7	0.2	0.5	tri69t66	0.2	0.7	0.4
ash68t69	0.4	0.4	0.3	TRI68t69	0.7	0.7	0.4
Avg.	0.5	0.3	0.3	Avg.	0.3	0.5	0.3
S.d.	0.1	0.2	0.2	S.d.	0.2	0.2	0.1
Overall	(x,y,z)	avg	0.3	Overall	(x,y,z)	avg	0.4
Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.2

APPENDIX B.12: CORRELATION COEFFICIENTS 10 KM BASELINE (CONT.)

CORRELATION BETWEEN DAYS PER RECEIVER (Manufacturer's software)

ASHTECH-PNAV				TRIMBLE-GPSurvey				LEICA-SKI			
Corrcoef	cx	cy	cz	Corrcoef	cx	cy	cz	Corrcoef	cx	cy	cz
ash66-67	0.5	0.2	0.3	tri66-67	0.4	0.2	0.6	lei66-67	0.3	0.7	0.5
ash67-68	0.4	0.2	0.0	tri67-68	0.5	0.2	0.7	lei67-68	0.6	0.9	0.6
ash68-66	0.1	0.7	-0.0	tri68-66	0.8	0.8	0.7	lei68-66	0.5	0.7	0.5
ash67-69	0.5	0.0	0.0	tri67-69	0.8	0.4	0.5	lei67-69	0.5	0.9	0.5
ash69-66	0.4	0.5	-0.0	tri69-66	0.2	-0.1	0.1	lei69-66	0.4	0.7	0.4
ash68-69	0.6	0.6	0.4	tri68-69	0.3	0.1	0.6	lei68-69	0.8	1.0	0.8
Avg.	0.4	0.4	0.1	Avg.	0.5	0.3	0.5	Avg.	0.5	0.8	0.5
S.d.	0.2	0.2	0.2	S.d.	0.2	0.3	0.2	S.d.	0.2	0.1	0.1
Overall	(x,y,z)	avg	0.3	Overall	(x,y,z)	avg	0.4	Overall	(x,y,z)	avg	0.6
Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.3	Overall	(x,y,z)	s.d	0.2

CORRELATION BETWEEN RECEIVERS PER STATION (Manufacturer's software)

Station A				Station B				Station C				Station D			
Corrcoef	cx	cy	cz	Corrcoef	cx	cy	cz	Corrcoef	cx	cy	cz	Corrcoef	cx	cy	cz
as-le-A	-0.5	-0.7	-0.3	as-le-B	-0.4	0.4	-0.2	as-le-C	-0.0	-0.3	0.3	as-le-D	-0.4	-0.6	-0.1
le-tr-A	0.4	-0.1	-0.0	le-tr-B	-0.1	-0.2	-0.1	le-tr-C	0.1	0.1	0.0	le-tr-D	-0.0	-0.4	-0.4
tr-as-A	-0.3	0.3	-0.1	tr-as-B	-0.2	0.1	0.0	tr-as-C	-0.5	0.1	0.5	tr-as-D	-0.4	-0.1	-0.2
Avg.	-0.1	-0.2	-0.1	Avg.	-0.2	0.1	-0.1	Avg.	-0.1	-0.0	0.3	Avg.	-0.3	-0.4	-0.2
S.d.	0.4	0.4	0.1	S.d.	0.1	0.2	0.1	S.d.	0.3	0.2	0.2	S.d.	0.2	0.2	-0.1
Overall	(x,y,z)	avg	-0.1	Overall	(x,y,z)	avg	-0.1	Overall	(x,y,z)	avg	0.0	Overall	(x,y,z)	avg	-0.3
Overall	(x,y,z)	s.d	0.4	Overall	(x,y,z)	s.d	0.2	Overall	(x,y,z)	s.d	0.3	Overall	(x,y,z)	s.d	0.2

APPENDIX B.13: CORRELATION COEFFICIENTS 10 KM BASELINE (CONT.)

CORRELATION BETWEEN RECEIVERS PER DAY (Topas)

ASHTECH-TRIMBLE (all days)			
CORR	cx	cy	cz
as-tr-66	0.8	0.6	0.8
as-tr-67	0.9	0.8	0.9
as-tr-68	0.6	0.6	0.6
as-tr-69	0.5	0.8	0.9
Avg.	0.7	0.7	0.8
S.d.	0.2	0.1	0.1
Overall	(x,y,z)	avg	0.7
Overall	(x,y,z)	s.d	0.1

CORRELATION BETWEEN RECEIVERS PER STATION (Topas)

ASHTECH-TRIMBLE (all stations)			
CORR	cx	cy	cz
as-tr-AT	0.6	0.4	0.2
as-tr-BT	0.5	0.5	0.3
as-tr-CT	0.6	0.3	0.4
as-tr-DT	0.4	0.7	0.3
Avg.	0.5	0.5	0.3
S.d.	0.1	0.2	0.0
Overall	(x,y,z)	avg	0.4
Overall	(x,y,z)	s.d	0.1

CORRELATION BETWEEN MANUFACTURER'S and TOPAS software

ASHTECH				TRIMBLE			
CORR	cx	cy	cz	CORR	cx	cy	cz
ash-ast66	0.9	0.6	0.9	tri-trt66	-0.0	0.2	0.4
ash-ast67	0.7	0.7	0.6	tri-trt67	0.7	0.4	0.5
ash-ast68	0.5	0.7	0.6	tri-trt68	0.4	0.3	0.5
ash-ast69	0.7	0.6	0.8	tri-trt69	0.6	0.3	0.7
Avg.	0.7	0.6	0.7	Avg.	0.4	0.3	0.5
S.d.	0.1	0.0	0.1	S.d.	0.3	0.1	0.1
Overall	(x,y,z)	avg	0.7	Overall	(x,y,z)	avg	0.4
Overall	(x,y,z)	s.d	0.1	Overall	(x,y,z)	s.d	0.2

Appendices chapter 4

APPENDIX C.1: SESSIONS USED DURING BERNESE PROCESSING

Session	long baseline 1 hour	long baseline 3 hour	short baseline 10 min	short baseline 1 hour
1	08:50-10:00	08:50-12:00	12:20-12:30	11:50-13:00
2	10:00-11:00	12:00-15:00	13:20-13:30	13:00-14:00
3	11:00-12:00	15:00-18:00	14:20-14:30	14:00-15:00
4	12:00-13:00	18:00-21:00	15:50-16:00	15:00-16:00
5	13:00-14:00	21:00-24:00	16:50-17:00	16:00-17:00
6	14:00-15:00	00:00-03:00	17:50-18:00	17:00-18:00
7	15:00-16:00	03:00-06:00	18:50-19:00	18:00-19:00
8	16:00-17:00	06:00-08:00	19:50-20:00	19:00-20:00
9	17:00-18:00		20:50-21:00	20:00-21:00
.	.		.	.
.	.		.	.
.	.		.	.
20	04:00-05:00		07:50-08:00	07:00-08:00
21	05:00-06:00		08:50-09:00	08:00-09:00
22	06:00-07:00		09:50-10:00	09:00-10:00
23	07:00-08:00		10:50-11:00	10:00-11:40

APPENDIX C.2: DIFFERENCES BERNESE RESULTS WITH DATUM VECTORS

LONG BASELINE DATUM-BERNESE co-ords. Average of 8 three hour sessions				SHORT BASELINE DATUM-BERNESE co-ords. Average of 22 one hour sessions			
Stat/Rx/Day	dn	de	du	Stat/Rx/Day	dn	de	du
A-ASH-62	-3	25	11	A-ASH-66	0	9	9
A-LEI-65	1	25	17	A-LEI-69	-4	8	12
A-ROG-64	6	21	30				
A-TRI-63	3	32	31	A-TRI-67	5	20	8
B-ASH-63	4	32	21	B-ASH-67	5	8	10
B-LEI-62	6	22	5	B-LEI-66	5	11	7
B-ROG-65							
B-TRI-64	9	35	7	B-TRI-68	13	18	5
C-ASH-64	4	32	30	C-ASH-68	1	6	3
C-LEI-63	7	28	!!-20	C-LEI-67	7	11	-2
C-ROG-62	4	24	45				
C-TRI-65	10	37	19	C-TRI-69	11	18	-2
D-ASH-65	-2	35	27	D-ASH-69	-1	8	-3
D-LEI-64	5	30	20	D-LEI-68	8	4	-1
D-ROG-63	1	27	29				
D-TRI-62	4	39	18	D-TRI-66	3	17	3
AVG.ALL	4	30	19	AVG.ALL	4	11	4
S.D.ALL	3	5	15	S.D.ALL	5	5	5

Differences between the daily average co-ordinate vectors obtained from the Bernese software and the datum vectors. Results are expressed in millimeters, in the local North, East and Up system for the unknown ends of the long and the short baselines.

The height component for the LEICA results at station C on day 63 differs nearly 5 cm from most others and is suspect.

The datum vectors expressed in Cartesian ECEF components are given in app. A.1.

APPENDIX C.3: DIFFERENCES MANUFACTURER'S WITH DATUM VECTORS

LONG BASELINE DATUM-MANUFAC. co-ords. Average of 22 one hour sessions				SHORT BASELINE DATUM-MANUFAC. co-ords. Average of 25 ten min. sessions			
Stat/Rx/Day	dn	de	du	Stat/Rx/Day	dn	de	du
A-ASH-62	13	32	19	YA-ASH-66	0	15	11
A-LEI-65	11	28	-5	YA-LEI-69	-3	-8	11
A-TRI-63	4	40	-6	YA-TRI-67	2	18	5
B-ASH-63	19	34	-12	YB-ASH-67	5	11	7
B-LEI-62	22	38	3	YB-LEI-66	-2	-3	-6
B-TRI-64	10	50	11	YB-TRI-68	10	20	8
C-ASH-64	27	38	5	YC-ASH-68	5	11	-2
C-LEI-63	22	48	-8	YC-LEI-67	-3	-18	-9
C-TRI-65	17	60	-13	YC-TRI-69	11	16	-10
D-ASH-65	17	39	-14	YD-ASH-69	4	11	1
D-LEI-64	30	49	-7	YD-LEI-68	-5	-13	-2
D-TRI-62	15	59	18	YD-TRI-66	4	18	2
AVG.ALL	18	43	-1	AVG.ALL	2	6	1
STD.ALL	7	10	11	STD.ALL	5	12	7

Differences between the daily average co-ordinate vectors obtained from the Manufacturer's software and the datum vectors. Results are expressed in millimeters, in the local North, East and Up system for the unknown ends of the long and the short baselines.

N.B. The height anomaly for LEICA on day 63, as obtained from the Bernese processing, is absent!

The datum vectors expressed in Cartesian ECEF components are given in app. A.1.

APPENDIX C.4: DIFFERENCES BERNESE WITH MANUFACTURER'S

LONG BASELINE MANUFAC.-BERNESE co-ords. Averages as in app. C.2 and C.3				SHORT BASELINE MANUFAC.-BERNESE co-ords. Averages as in app. C.2 and C.3			
Stat/Rx/Day	dn	de	du	Stat/Rx/Day	dn	de	du
A-ASH-62	-16	-7	-8	A-ASH-66	0	-6	-2
A-LEI-65	-10	-3	22	A-LEI-69	-1	16	1
A-TRI-63	-1	-7	37	A-TRI-67	3	2	3
B-ASH-63	-15	-2	34	B-ASH-67	-0	-3	3
B-LEI-62	-16	-16	1	B-LEI-66	6	14	13
B-TRI-64	-1	-15	-4	B-TRI-68	2	-2	-3
C-ASH-64	-23	-6	25	C-ASH-68	-3	-4	5
C-LEI-63	-15	-20	-12	C-LEI-67	10	29	7
C-TRI-65	-7	-23	33	C-TRI-69	1	2	8
D-ASH-65	-19	-4	41	D-ASH-69	-6	-4	-3
D-LEI-64	-25	-19	27	D-LEI-68	13	18	0
D-TRI-62	-10	-21	1	D-TRI-66	-2	-2	1
AVG.ALL	-13	-12	16	AVG.ALL	2	5	3
S.D.ALL	7	7	18	STD.ALL	5	11	5

Differences between the daily average co-ordinate vectors obtained from the Bernese software and Manufacturer's software. Results are expressed in millimeters, in the local North, East and Up system for the unknown ends of the long and the short baselines.

N.B. The height anomaly for LEICA on day 63, as obtained from the Bernese processing, is not so pronounced as in app. C.2!

The datum vectors expressed in Cartesian ECEF components are given in app. A.1.

APPENDIX C.5: AVERAGE DIFFERENCES DATUM - BERNESE; LONG BASELINE

LONG BASELINE: DATUM - BERNESE coords. (daily avg. of 8 obs. of 3 hr)

	DATUM - BERN per station (mm) North	East	Up		S.d. in 1 day per stat. (mm) North	East	Up
Stat.A	2	26	22	Stat.A	3	4	9
Stat.B	6	30	11	Stat.B	2	5	7
Stat.C	6	30	19	Stat.C	3	5	24
Stat.D	2	33	23	Stat.D	3	5	4
	DATUM - BERN per receiver (mm) North	East	Up		**S.d. 1 day per receiver (mm)** North	East	Up
ASH	1	31	22	ASH	3	4	8
LEI	5	26	5	LEI	2	3	16
ROG	4	24	35	ROG	2	2	7
TRI	7	36	19	TRI	3	2	9
	DATUM - BERN per day (mm) North	East	Up		**S.d. in 1 day per day (mm)** North	East	Up
Day-62	3	27	20	Day-62	3	7	15
Day-63	4	30	15	Day-63	2	2	21
Day-64	6	30	22	Day-64	2	5	10
Day-65	3	32	21	Day-65	5	5	4
	DATUM - BERN all 15 obs. (mm) North	East	Up		**S.d. 1 day (from 15 obs;mm)** North	East	Up
Avg.ALL	4	30	19	S.D.ALL	3	5	15

Results of app. C.2 averaged per station, per receiver and per day.
N.B. Station C, LEICA and day 63 are all affected by ONE anomalous "UP" result in the BERNESE processing!

APPENDIX C.6: AVERAGE DIFFERENCES DATUM - MANUFAC; LONG BASELINE

LONG BASELINE: DATUM - MANUF. coords. (daily avg. of 22 obs. of 1 hr)

	DATUM - MANU per station (mm) North	East	Up		S.d. in 1 day per stat. (mm) North	East	Up
Stat.A	10	33	3	Stat.A	4	5	12
Stat.B	17	41	1	Stat.B	5	7	10
Stat.C	22	49	-5	Stat.C	4	9	8
Stat.D	21	49	-1	Stat.D	7	8	14
	DATUM - MANU per receiver (mm) North	East	Up		**S.d. 1 day per receiver (mm)** North	East	Up
ASH	19	36	-0	ASH	5	3	13
LEI	21	41	-4	LEI	7	9	5
TRI	11	52	2	TRI	5	8	13
	DATUM - MANU per day (mm) North	East	Up		**S.d. in 1 day per day (mm)** North	East	Up
Day-62	16	43	13	Day-62	4	12	7
Day-63	15	40	-9	Day-63	8	6	3
Day-64	23	46	3	Day-64	9	5	8
Day-65	15	42	-11	Day-65	3	13	4
	DATUM - MANU all 12 obs. (mm) North	East	Up		**S.d. 1 day (from 12 obs;mm)** North	East	Up
Avg.ALL	18	43	-1	S.d.ALL	7	10	11

Results of app. C.3 averaged per station, per receiver and per day. The results for LEICA at station C on day 63 were not anomalous.

APPENDIX C.7: AVERAGE DIFFERENCES MANUFAC - BERN; LONG BASELINE

LONG BASELINE: MANUF. - BERNESE coords.

	MANU - BERN per station (mm) North	East	Up		S.d. in 1 day per stat.(mm) North	East	Up
Stat.A	-9	-6	17	Stat.A	6	2	19
Stat.B	-11	-11	10	Stat.B	7	6	17
Stat.C	-15	-16	15	Stat.C	7	7	19
Stat.D	-18	-15	23	Stat.D	6	7	17

	MANU - BERN per receiver (mm) North	East	Up		S.d. 1 day per receiver (mm) North	East	Up
ASH	-18	-5	23	ASH	3	2	19
LEI	-16	-15	10	LEI	6	7	15
TRI	-5	-17	16	TRI	4	6	18

	MANU - BERN per day (mm) North	East	Up		S.d. in 1 day per day (mm) North	East	Up
Day-62	-14	-15	-2	Day-62	3	5	4
Day-63	-10	-10	20	Day-63	7	8	22
Day-64	-16	-13	16	Day-64	11	5	14
Day-65	-12	-10	32	Day-65	5	9	8

	MANU - BERN all 12 obs. (mm) North	East	Up		S.d. 1 day (from 12 obs;mm) North	East	Up
Avg.ALL	-13	-12	16	S.d.ALL	7	7	18

Results of app. C.4 averaged per station, per receiver and per day. Notes:
1. The anomaly in the height for LEICA from BERNESE software is hardly evident in this table.
2. The values of the coordinate biases are not equal to the differences of app. C.5 and C.6 because ROGUE results are used in C.5, but not in C.6 and C.7

APPENDIX C.8: AVERAGE DIFFERENCES DATUM - BERNESE; SHORT BASELINE

SHORT BASELINE DATUM - BERNESE coords. (daily avg. of 23 obs. of 1 hr)

	DATUM - BERN per station (mm) North	East	Up		S.d. in 1 day per stat.(mm) North	East	Up
Stat.A	0	12	10	Stat.A	3	6	2
Stat.B	7	13	7	Stat.B	4	4	2
Stat.C	7	12	-0	Stat.C	4	5	2
Stat.D	3	9	-0	Stat.D	4	5	2

	DATUM - BERN per receiver (mm) North	East	Up		S.d. 1 day per receiver (mm) North	East	Up
ASH	1	8	5	ASH	2	1	5
LEI	4	8	4	LEI	5	3	6
TRI	8	18	4	TRI	4	1	4

	DATUM - BERN per day (mm) North	East	Up		S.d. in 1 day avg. (mm) North	East	Up
Day-66	2	12	6	Day-66	2	3	3
Day-67	6	13	5	Day-67	1	5	5
Day-68	7	10	2	Day-68	5	6	3
Day-69	2	11	3	Day-69	7	5	7

	DATUM - BERN all 12 obs. (mm) North	East	Up		S.d. in 1 day (12 obs;mm) North	East	Up
Avg.ALL	4	11	4	S.d.ALL	5	5	5

Results of app. C.2 averaged per station, per receiver and per day.
Note: There is evidence of a height anomaly between station pairs A, B and C, D of about 8.5 mm. A check of the local survey revealed that the datum vectors for stations A and B need indeed a correction, but only 5.5 mm.

APPENDIX C.9: AVERAGE DIFFERENCES DATUM - MANUFAC; SHORT BASELINE

SHORT BASELINE DATUM-MANUF. coords. (daily avg. of abt. 25 obs. of 10 min.)

	DATUM - MANU per station (mm) North	East	Up		S.d. in 1 day per stat.(mm) North	East	Up
Stat.A	-0	8	9	Stat.A	2	11	3
Stat.B	5	10	3	Stat.B	5	10	7
Stat.C	4	3	-7	Stat.C	6	15	3
Stat.D	1	5	0	Stat.D	4	14	1
	DATUM - MANU per receiver (mm) North	**East**	**Up**		**S.d. 1 day per receiver (mm) North**	**East**	**Up**
ASH	3	12	4	ASH	2	2	5
LEI	-3	-10	-1	LEI	1	6	8
TRI	7	18	1	TRI	4	2	7
	DATUM - MANU per day (mm) North	**East**	**Up**		**S.d. in 1 day avg. (mm) North**	**East**	**Up**
Day-66	1	10	2	Day-66	2	9	7
Day-67	1	4	1	Day-67	4	15	7
Day-68	3	6	2	Day-68	6	14	5
Day-69	4	6	1	Day-69	6	10	9
	DATUM - MANU all 12 obs. (mm) North	**East**	**Up**		**S.d. in 1 day (12 obs;mm) North**	**East**	**Up**
Avg.ALL	2	6	1	S.d.ALL	5	12	7

Results of app. C.3 averaged per station, per receiver and per day. The evidence for a height anomaly between station pairs A, B and C, D is less pronounced than in app. C.8.

APPENDIX C.10: AVERAGE DIFFERENCES MANUFAC - BERN; SHORT BASELINE

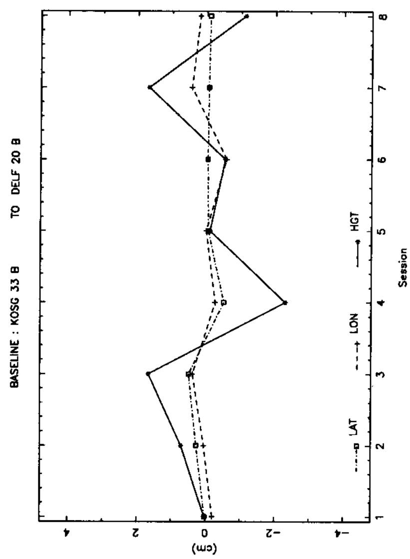
SHORT BASELINE: BERNESE - MANUF. coords.

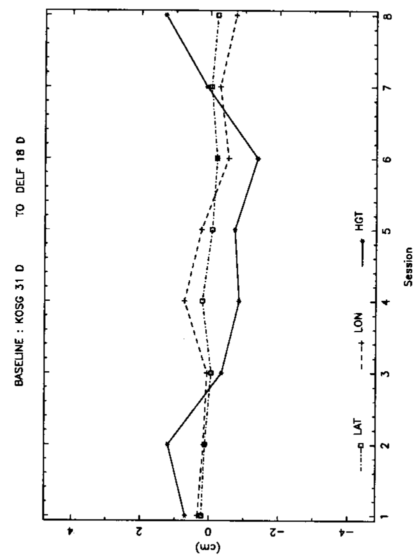
	BERN - MANU per station (mm) North	East	Up		S.d. in 1 day per stat.(mm) North	East	Up
Stat.A	1	4	1	Stat.A	2	9	2
Stat.B	3	3	4	Stat.B	3	8	7
Stat.C	3	9	7	Stat.C	6	14	1
Stat.D	2	4	-1	Stat.D	8	10	2
	BERN - MANU per receiver (mm) North	**East**	**Up**		**S.d. 1 day per receiver (mm) North**	**East**	**Up**
ASH	-2	-4	1	ASH	2	1	3
LEI	7	19	5	LEI	5	6	5
TRI	1	0	2	TRI	2	2	4
	BERN - MANU per day (mm) North	**East**	**Up**		**S.d. in 1 day avg. (mm) North**	**East**	**Up**
Day-66	2	2	4	Day-66	3	8	7
Day-67	4	9	4	Day-67	4	14	2
Day-68	4	4	1	Day-68	7	10	3
Day-69	-2	5	2	Day-69	3	8	5
	BERN - MANU all 12 obs. (mm) North	**East**	**Up**		**S.d. in 1 day (12 obs;mm) North**	**East**	**Up**
Avg.ALL	2	5	3	S.d.ALL	5	11	5

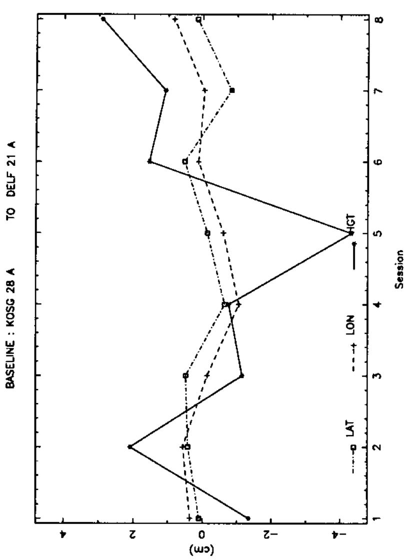
Result of app. C.4 averaged per station, per receiver and per day.

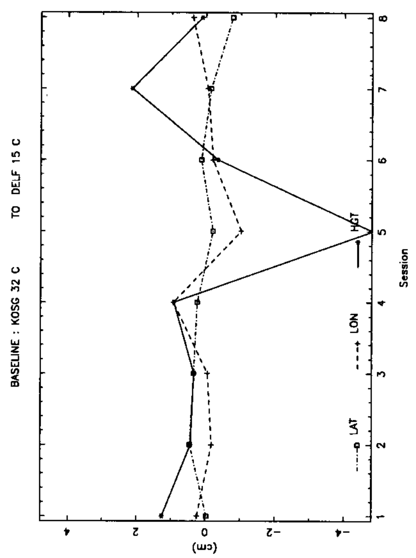
APPENDIX C.11: LONG BASELINES (TIME SERIES); BERNESE; ASHTECH

Residuals of the individual 3 hour data arc solutions with respect to the mean solution, based on all eight 3 hour solutions, for the long baseline (100 km). Therefore in every figure the y=0 value represents a (slightly) different mean value. Shown the results from the ASHTECH for days 062 (bottom left), 063 (top left), 064 (bottom right) and 065 (top right).



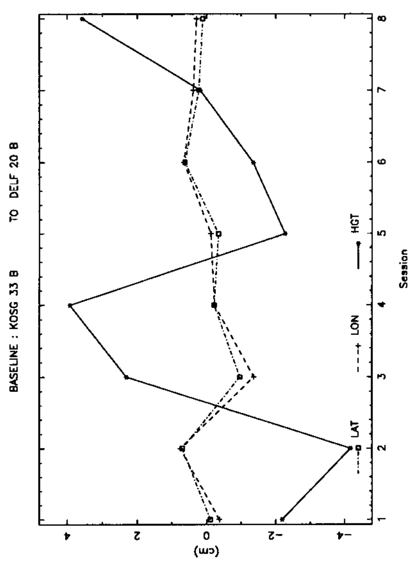


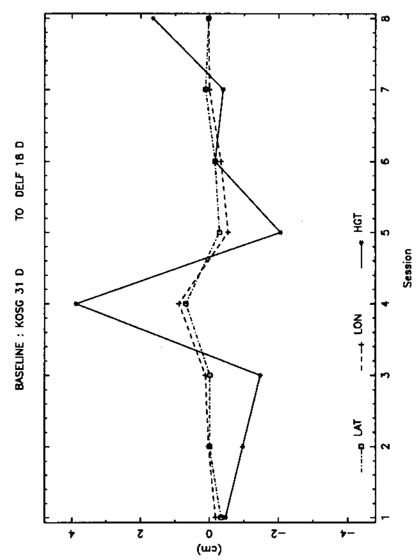


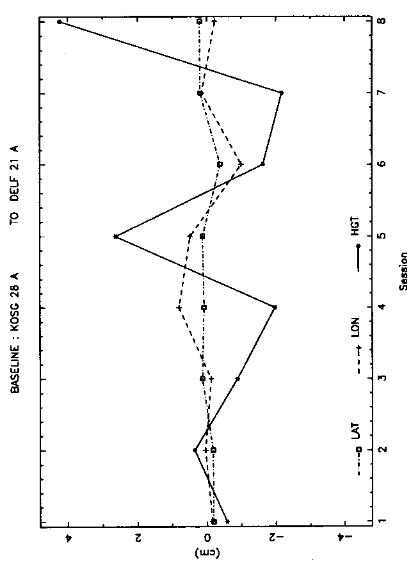


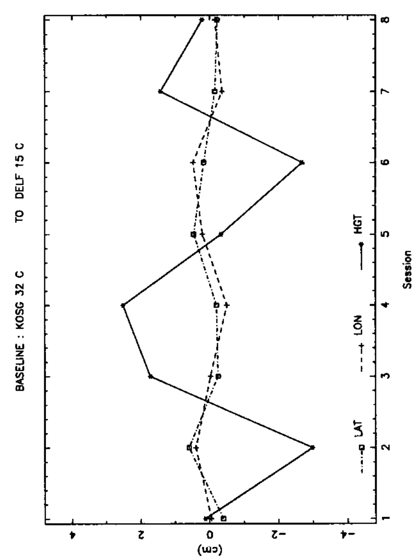
APPENDIX C.12: LONG BASELINES (TIME SERIES); BERNESE; LEICA

Residuals of the individual 3 hour data arc solutions with respect to the mean solution, based on all eight 3 hour solutions, for the long baseline (100 km). Therefore in every figure the y=0 value represents a (slightly) different mean value. Shown the results from the LEICA for days 065 (bottom left), 062 (top left), 063 (bottom right) and 064 (top right).



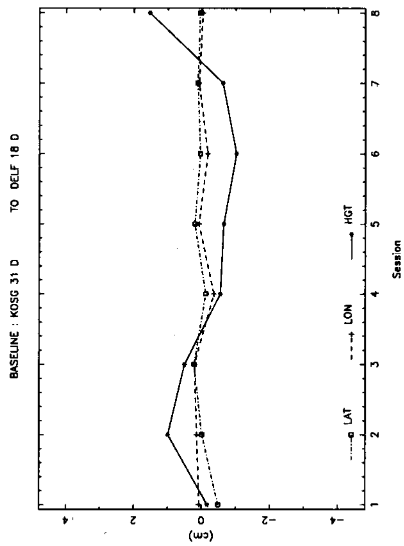


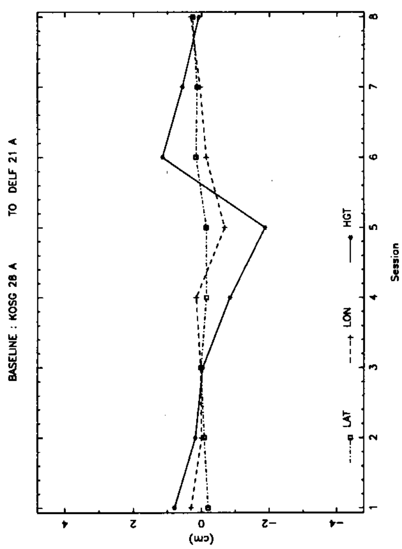


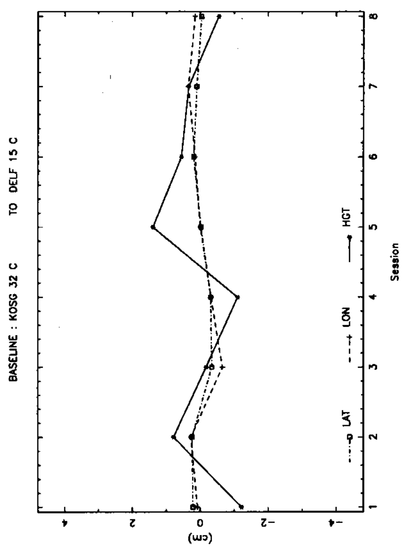


APPENDIX C.13: LONG BASELINES (TIME SERIES); BERNESE; ROGUE

Residuals of the individual 3 hour data arc solutions with respect to the mean solution, based on all eight 3 hour solutions, for the long baseline (100 km). Therefore in every figure the y=0 value represents a (slightly) different mean value. Shown the results from the ROGUE for days 064 (bottom left), 062 (bottom right) and 063 (top right).

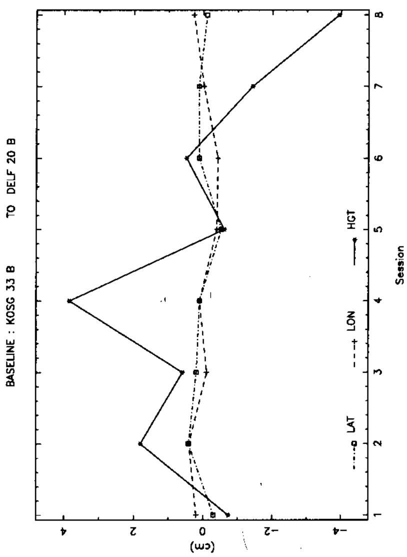


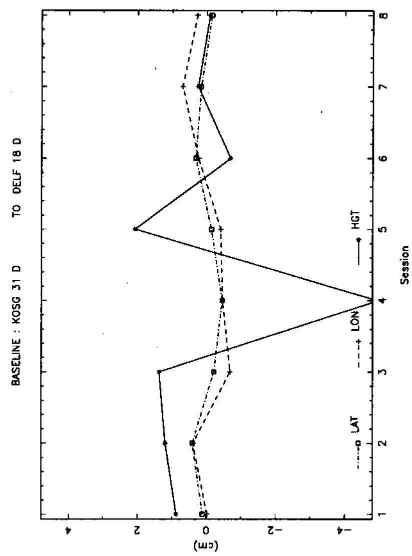


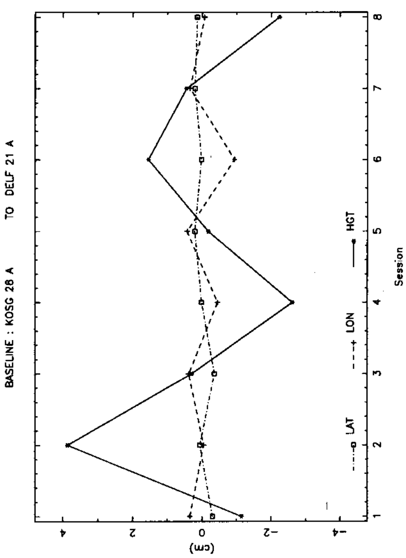


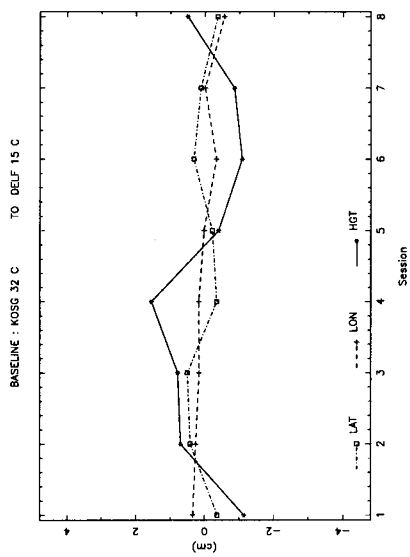
APPENDIX C.14: LONG BASELINES (TIME SERIES); BERNESE; TRIMBLE

Residuals of the individual 3 hour data arc solutions with respect to the mean solution, based on all eight 3 hour solutions, for the long baseline (100 km). Therefore in every figure the y=0 value represents a (slightly) different mean value. Shown the results from the TRIMBLE for days 063 (bottom left), 064 (top left), 065 (bottom right) and 062 (top right).



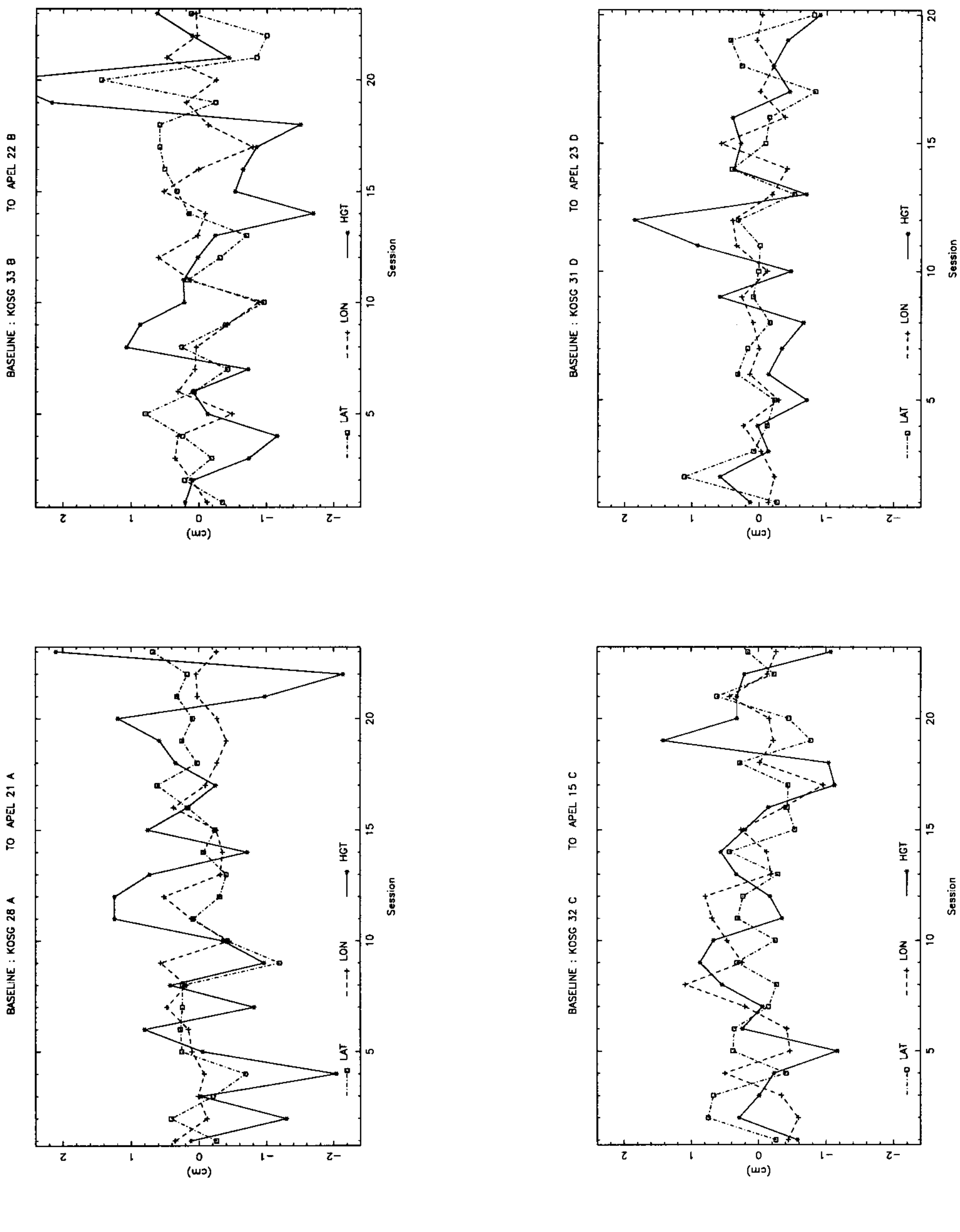






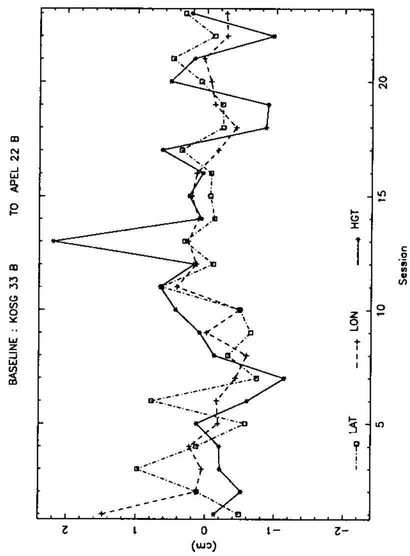
APPENDIX C.15: SHORT BASELINES (TIME SERIES); BERNESE; ASHTECH

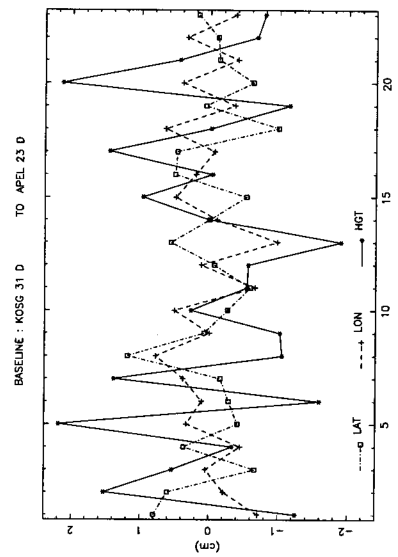
Residuals of the individual 1 hour L3 data arc solutions with respect to the mean solution, based on all 23 1 hour solutions, for the short baseline (10 km). Therefore in every figure the y=0 value represents a (slightly) different mean value. Shown are the results from the ASHTECH for days 066 (bottom left), 067 (top left), 068 (bottom right) and 069 (top right).

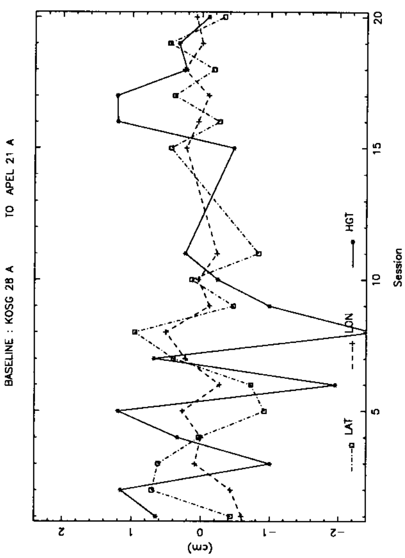


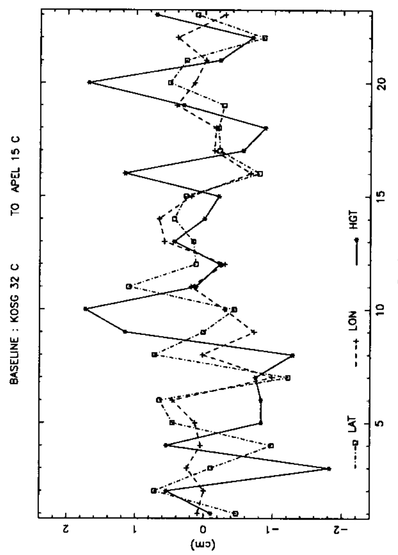
APPENDIX C.16: SHORT BASELINES (TIME SERIES); BERNESE; LEICA

Residuals of the individual 1 hour L3 data arc solutions with respect to the mean solution, based on all 23 1 hour solutions, for the short baseline (10 km). Therefore in every figure the y=0 value represents a (slightly) different mean value. Shown are the results from the LEICA for days 069 (bottom left), 066 (top left), 067 (bottom right) and 068 (top right).



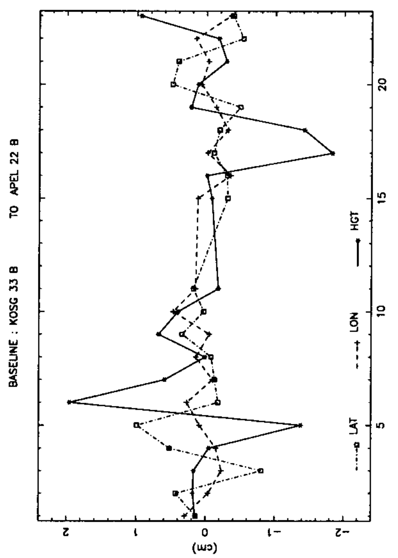


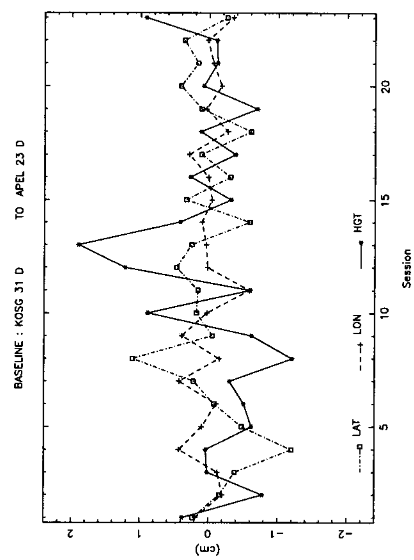


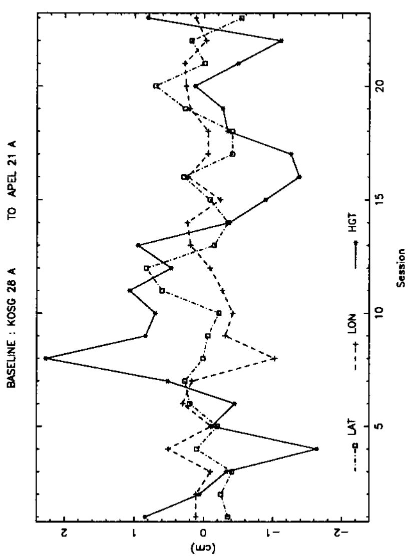


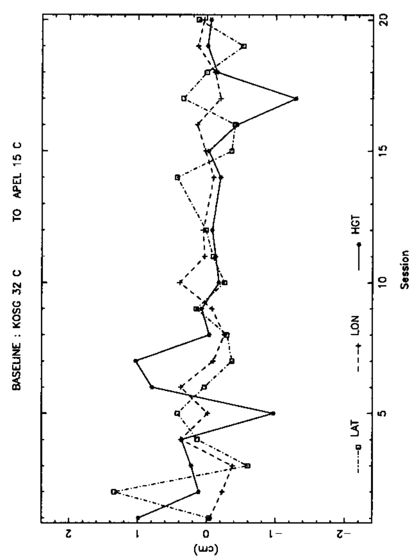
APPENDIX C.17: SHORT BASELINES (TIME SERIES); BERNESE; TRIMBLE

Residuals of the individual 1 hour L3 data arc solutions with respect to the mean solution, based on all 23 1 hour solutions, for the short baseline (10 km). Therefore in every figure the y=0 value represents a (slightly) different mean value. Shown are the results from the TRIMBLE for days 067 (bottom left), 068 (top left), 069 (bottom right) and 066 (top right).









APPENDIX D.1: CARRIER PHASE NOISE WHEN JAMMING L2 FREQUENCY

Time >>	12:15-12:30				13:15-13:30				12:30-12:45				13:30-13:45				12:45-13:00				13:00-13:05			
Power >>	-72 dBmW/m²				-69				-66				-63 dBmW/m²				-60				-54			
Elev.	A	L	R	T	A	L	R	T	A	L	R	T	A	L	R	T	A	L	R	T	A	L	R	T
80					0.6	1.1	0.3	0.4	0.4	1.6	0.3	0.7	0.4	1.0	0.3	-	0.5	4.7	0.6	1.5	-	-	1.0	-
	0.5	0.8	0.4	0.7	0.5	0.5	0.2	0.5					0.5	3.0	0.5	1.3	0.4	1.2	-	-	-	-	0.3	0.8
60	0.9	0.9	-	1.2	1.0	1.6	0.9	0.8	0.4	0.7	-	0.7	0.4	3.5	0.5	1.0	-	-	-	3.0	-	-	1.4	5.4
	0.6	1.6	0.7	0.9					1.1	3.9	-	1.6	-	-	-	-	-	-	3.5	4.4	-	-	9.0	-
40	1.2	2.0	1.3	1.1	-	5.2	1.3	2.4	-	5.1	1.0	1.3												
	2.6	2.4	-	1.8	3.1	5.0	-	3.7	-	-	1.5	1.6	-	-	-	-	-	-	-	-	-	-	-	-
25	-	2.4	1.1	1.4	-	5.8	2.8	5.1	-	-	3.3	4.6	-	-	3.7	-	-	-	2.7	-	-	-	23.0	-
	1.5	3.6	-	2.0	1.9	-	-	-	1.4	-	-	5.3	-	-	6.2	-	3.0	-	-	-	-	-	-	-
15	5.5	4.3	-	3.1	2.6	-	4.7	-	2.9	-	-	-	-	-	-	-	-	-	4.7	-	2.9	-	-	-

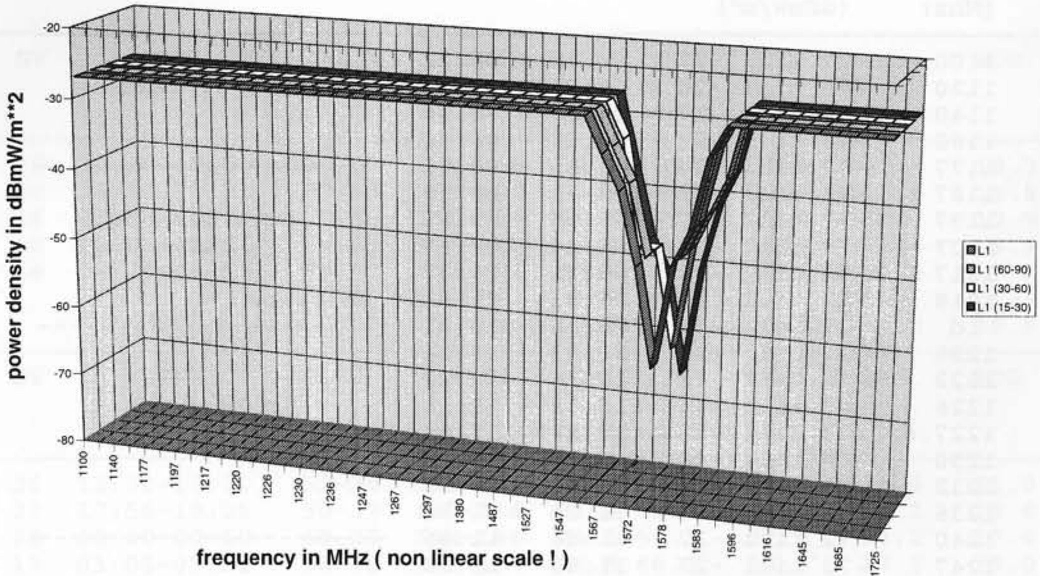
Jamming on L2 frequency. The values give the noise in the L1 phase observable in millimeter, computed from 1.546*(L1-L2) and assuming that noise on L2 is 1.3 higher than on L1. For each power density of the jammer, values are given for A(shtech), L(eica), T(rimble) and R(ogue). If lock on L2 is lost, no value is given.

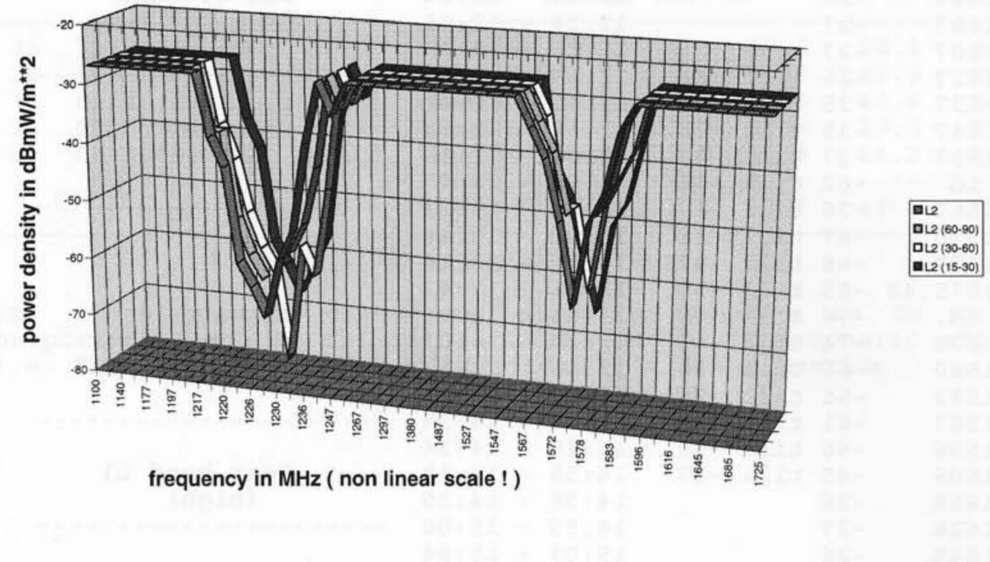
APPENDIX D.2: LIST OF JAMMING FREQUENCIES AND POWER DENSITIES

Freq. (Mhz)	Power density ($dBmW/m^2$)	Time	Remark
1100	-77 till -27	08:16 - 08:22	
1120	-76 till -26	08:23 - 08:29	Out of band
1140	-77 till -27	08:30 - 08:36	
1160	-77 till -27	08:36 - 08:42	
1177	-77 till -27	08:45 - 08:51	----------------------
1187	-78 till -28	08:53 - 08:59	
1197	-77 till -27	09:05 - 09:11	Near band L2
1207	-77 till -27	09:24 - 09:30	(low)
1217	-78 till -28	09:31 - 09:37	
1218	-57 till -29	09:41 - 09:51	3 dB steps
id	-78 till -58	09:56 - 10:01	----------------------
1220	-77 till -28	10:03 - 10:14	
1222	-78 till -29	10:16 - 10:27	
1226	-68 till -43	15:12 - 15:18	In band L2
1227.6	-73 till -28	10:33 - 10:43	
1230	-68 till -28	15:18 - 15:27	
1232	-73 till -28	10:48 - 10:58	
1236	-73 till -28	11:24 - 11:34	
1240	-72 till -27	11:36 - 11:46	----------------------
1247	-72 till -27	11:49 - 11:59	
1257	-46 till -26	12:02 - 12:07	Near band L2
1267	-40 till -25	12:10 - 12:14	(high)
1277	-41 till -26	12:15 - 12:19	
1297	-26	12:26 - 12:27	----------------------
1317	-26	12:29 - 12:30	
1380	-27	12:30 - 12:31	
1440	-26	12:33 - 12:34	Out of band
1487	-27	12:34 - 12:35	
1507	-27	12:36 - 12:37	
1527	-26	12:37 - 12:38	----------------------
1537	-35 till -25	12:45 - 12:48	
1547	-35 till -25	12:50 - 12:53	Near band L1
1557	-37 till -27	12:55 - 12:58	(low)
id	-62 till -42	13:02 - 13:07	
1567	-76 till -27	13:12 - 13:23	----------------------
1570	-67 till -32	15:30 - 15:44	
1572	-66 till -42	13:30 - 13:36	
1575.42	-65 till -50	13:38 - 13:42	
id.	-74 till -70	13:44 - 13:46	In band L1
1578	-74 till -41	13:47 - 14:01	
1580	-66 till -36	15:46 - 15:53	
1583	-66 till -26	14:06 - 14:17	
1587	-61 till -26	14:30 - 14:38	----------------------
1596	-66 till -26	14:49 - 14:54	
1606	-45 till -25	14:55 - 14:58	Near band L1
1616	-26	14:58 - 14:59	(high)
1626	-27	14:59 - 15:00	----------------------
1645	-26	15:03 - 15:04	
1665	-25	15:04 - 15:05	
1685	-26	15:05 - 15:06	Out of band
1705	-26	15:06 - 15:07	
1725	-27	15:07 - 15:08	

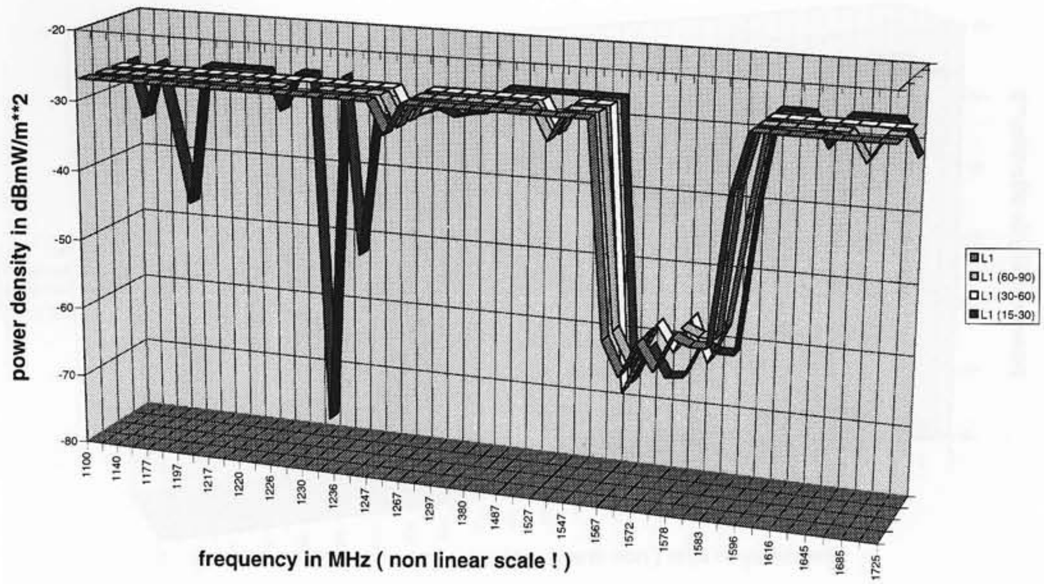
Power was increased 5 dB each minute for frequencies between 1218 and 1590 MHz unless stated otherwise. All other steps were 10 dB. -25 to -75 $dBmW/m^2$ is about 80 to 30 dB jam-to-signal ratio.

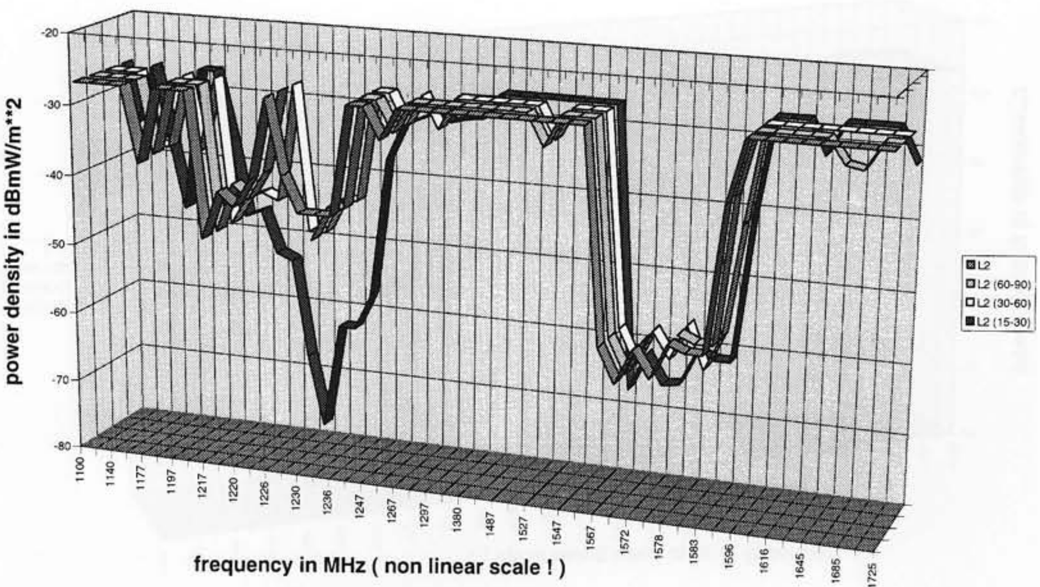
APPENDIX D.3: SIGNAL LOSS DURING JAMMING: ASHTECH L1/L2



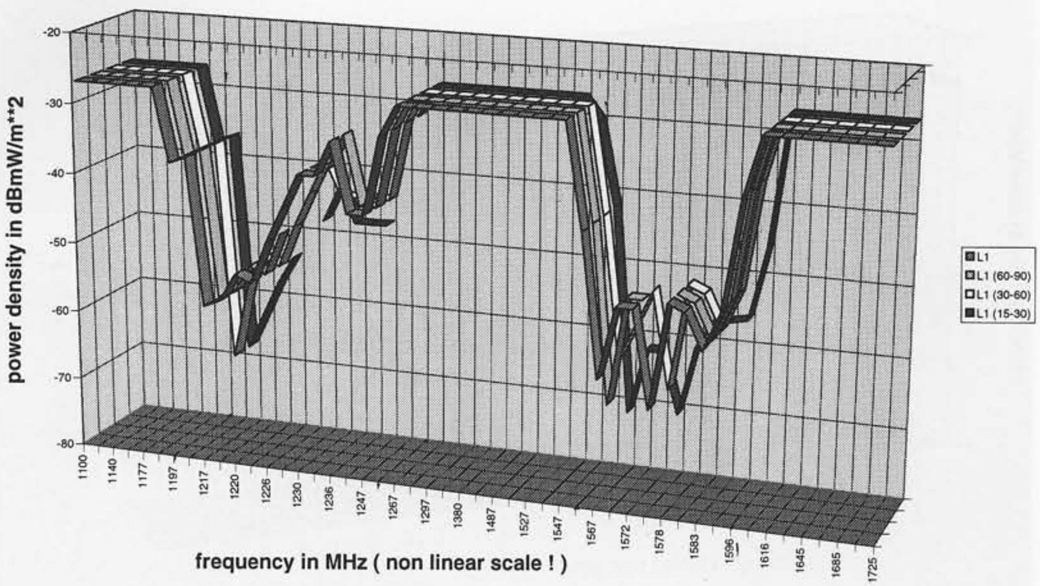


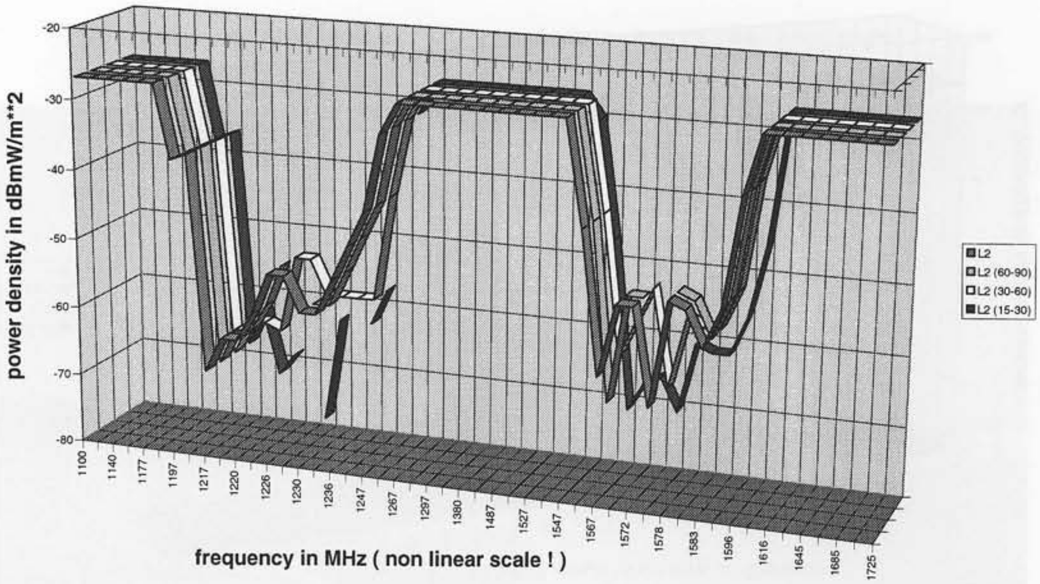
APPENDIX D.4: SIGNAL LOSS DURING JAMMING: ROGUE L1/L2



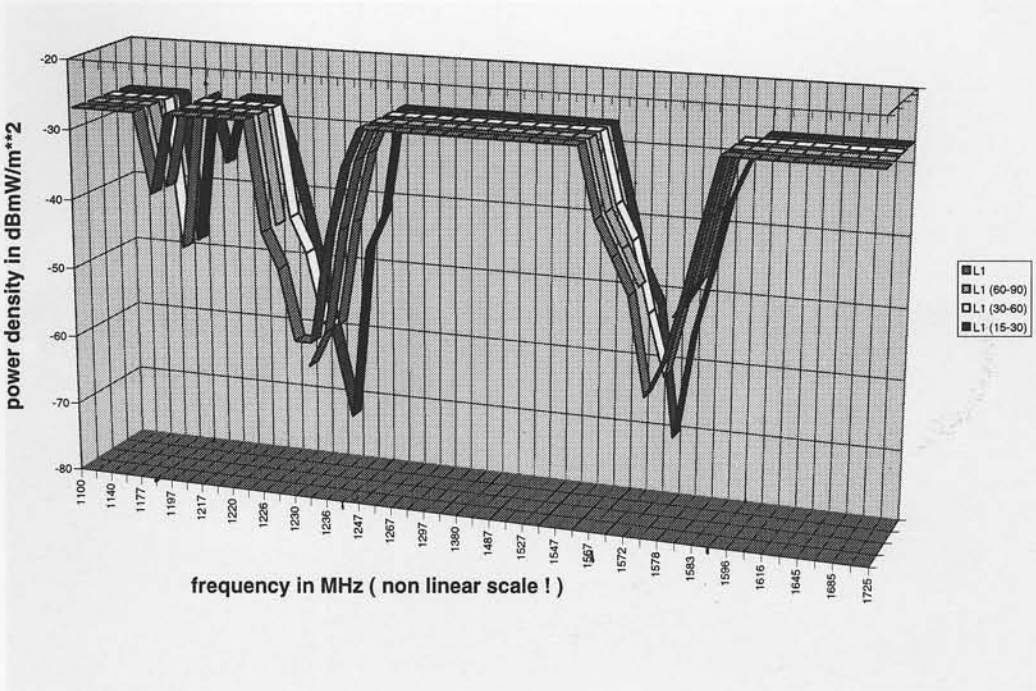


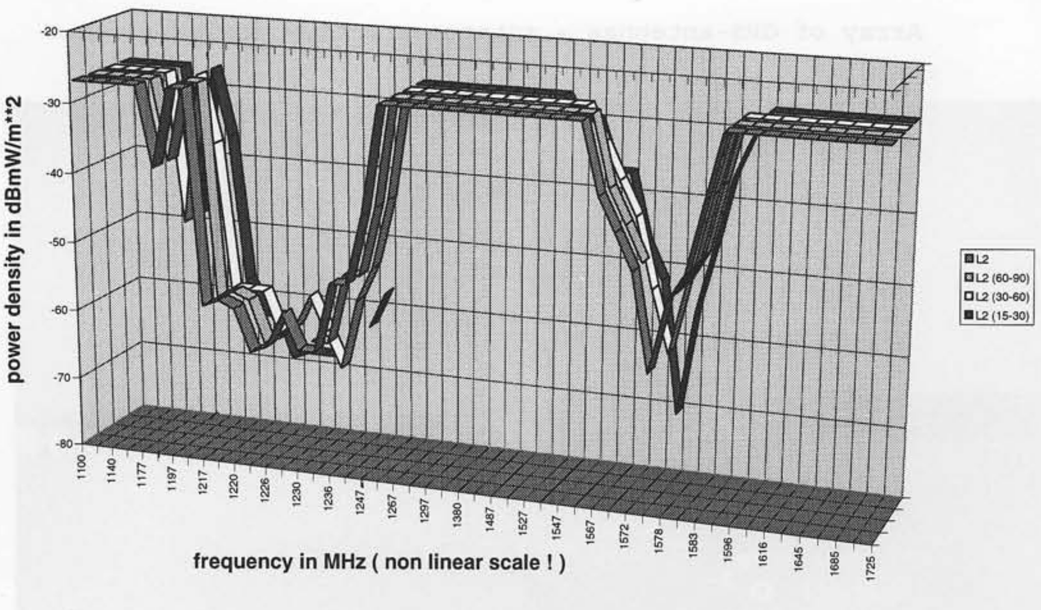
APPENDIX D.5: SIGNAL LOSS DURING JAMMING: TRIMBLE L1/L2





APPENDIX D.6: SIGNAL LOSS DURING JAMMING: LEICA L1/L2





APPENDIX D.7: PHOTOGRAPHS OF JAMMING TEST AT NLR

Array of GPS-antennas + antenna spectrum analyser.

Signal generator. Jamming test at NLR (11 March).

Appendices chapter 6

APPENDIX E.1: NOISE IN PHASE OBSERVABLE 1.546*(L1-L2)

Day 63-64 at Kootwijk: phase noise in mm

SV	TIME	ELEV.	AZIM.	ASH	TRI	LEI	ROG
26	11:30-12:00	80-67	192-166	3.3	3.4	3.0	1.9
20	16:55-17:25	77-63	83-100	4.1	4.2	4.6	3.8
28	22:40-23:20	77-63	130-136	2.7	2.3	2.5	1.9
15	02:05-02:35	79-65	106-118	3.2	3.0	3.6	2.3
18	06:20-06:50	76-62	72- 73	3.1	2.6	2.9	1.8
				---	---	---	---
		Avg. 70°		3.3	3.2	3.3	2.3
		Derived noise L1		1.3	1.3	1.3	1.0
		Derived noise L2		1.7	1.7	1.7	1.2
SV	TIME	ELEV.	AZIM.	ASH	TRI	LEI	ROG
26	12:30-13:00	52-38	162-164	6.5	5.4	8.2	5.7
20	17:55-18:25	50-37	110-116	12.4	12.0	11.6	11.4
28	23:40-00:10	48-35	142-146	7.1	8.7	6.3	8.5
15	03:05-03:35	50-36	126-134	12.2	12.3	13.6	13.2
18	07:20-07:50	48-36	76- 84	14.8	13.7	16.5	13.4
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		Avg. 43°		10.6	10.4	11.2	10.4
		Derived noise L1		4.2	4.2	4.5	4.2
		Derived noise L2		5.5	5.4	5.8	5.4
SV	TIME	ELEV.	AZIM.	ASH	TRI	LEI	ROG
26	13:30-14:00	24-11	164-166	16.0	19.2	16.4	18.4
20	19:35-20:05	23-11	126-130	10.8	12.0	10.0	8.3
31	01:45-02:15	23-10	168-168	7.2	12.0	12.0	9.3
15	02:05-02:35	23-10	140-143	12.5	12.1	8.2	11.1
29	06:55-07:25	24-12	79- 80	10.2	8.2	11.2	6.1
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		Avg. 17°		11.3	12.7	11.6	10.6
		Derived noise L1		4.5	5.1	4.6	4.2
		Derived noise L2		5.9	6.6	6.0	5.5

It is remarkable that there is rather a large difference between the noise at 70° and 43°, and very little between 43° and 17° !

APPENDIX E.2: NOISE IN C/A CODE OBSERVABLE

Day 63-64 at Kootwijk: code noise in centimeter

SV	TIME	ELEV.	AZIM.	ASHTECH smooth	ASHTECH not smooth	TRI	LEI	ROG
26	11:30-12:00	80-67	192-166	12.1	42.9	30.1	13.4	18.3
20	16:55-17:25	77-63	83-100	11.6	44.2	23.9	13.6	18.5
28	22:40-23:20	77-63	130-136	15.0	44.6	28.8	18.2	19.9
15	02:05-02:35	79-65	106-118	7.7	38.6	18.3	17.4	18.9
18	06:20-06:50	76-62	72- 73	10.8	39.1	21.9	11.5	17.1
		Avg. 70°		10.8	41.9	24.6	14.8	18.5
SV	**TIME**	**ELEV.**	**AZIM.**	**ASHTECH smooth**	**ASHTECH not smooth**	**TRI**	**LEI**	**ROG**
26	12:30-13:00	52-38	162-164	25.8	57.3	33.5	21.4	21.0
20	17:55-18:25	50-37	110-116	21.6	63.1	24.4	24.2	29.6
28	23:40-00:10	48-35	142-146	24.5	64.3	37.8	24.2	27.4
15	03:05-03:35	50-36	126-134	26.8	66.1	34.2	17.5	23.0
18	07:20-07:50	48-36	76- 84	17.6	53.3	32.8	23.8	28.3
		Avg. 43°		23.3	60.8	32.5	22.2	25.9
SV	**TIME**	**ELEV.**	**AZIM.**	**ASHTECH smooth**	**ASHTECH not smooth**	**TRI**	**LEI**	**ROG**
26	13:30-14:00	24-11	164-166	28.4	76.5	67.0	38.1	62.2
20	19:35-20:05	23-11	126-130	66.7	164.4	54.7	66.9	67.2
31	01:45-02:15	23-10	168-168	31.5	85.0	72.2	40.4	58.7
15	02:05-02:35	23-10	140-143	40.8	101.4	54.0	29.3	53.0
29	06:55-07:25	24-12	79- 80	41.9	100.6	55.8	64.2	50.6
		Avg. 17°		41.9	105.6	60.7	47.8	58.3

The increase with decreasing elevation appears to be nearly proportional to the obliguity factor for the tropospheric effect, i.e. from 1 to 3 when going from zenith to 15° elevation.

APPENDIX E.3: NOISE IN Y2 CODE OBSERVABLE

Day 63-64 at Kootwijk: code noise in centimeter

SV	TIME	ELEV.	AZIM.	ASHTECH smooth	ASHTECH not smooth	TRI	LEI	ROG
26	11:30-12:00	80-67	192-166	9.9	19.0	29.1	9.2	12.8
20	16:55-17:25	77-63	83-100	6.7	20.6	21.9	8.6	14.5
28	22:40-23:20	77-63	130-136	11.6	29.7	29.8	8.0	18.8
15	02:05-02:35	79-65	106-118	7.6	23.9	23.2	7.9	15.4
18	06:20-06:50	76-62	72- 73	9.4	28.1	21.5	16.2	15.8
		Avg. 70°		9.0	24.3	25.1	10.0	13.5

SV	TIME	ELEV.	AZIM.	ASHTECH smooth	ASHTECH not smooth	TRI	LEI	ROG
26	12:30-13:00	52-38	162-164	23.0	40.0	34.1	14.2	26.0
20	17:55-18:25	50-37	110-116	22.1	40.9	30.8	13.1	27.3
28	23:40-00:10	48-35	142-146	30.9	48.7	44.9	19.4	34.4
15	03:05-03:35	50-36	126-134	24.6	45.1	31.9	11.6	28.6
18	07:20-07:50	48-36	76- 84	12.1	30.6	38.3	14.8	35.4
		Avg. 43°		20.3	41.1	36.0	14.5	30.3

SV	TIME	ELEV.	AZIM.	ASHTECH smooth	ASHTECH not smooth	TRI	LEI	ROG
26	13:30-14:00	24-11	164-166	27.9	66.0	104.0	17.0	128.3
20	19:35-20:05	23-11	126-130	32.4	90.5	110.0	29.3	144.6
31	01:45-02:15	23-10	168-168	48.9	77.2	106.7	61.4	124.7
15	02:05-02:35	23-10	140-143	66.6	122.7	110.9	14.6	113.2
29	06:55-07:25	24-12	79- 80	84.5	112.3	83.1	46.5	76.4
		Avg. 17°		52.1	93.7	102.9	33.8	117.4

In addition the ASHTECH receiver has also a Y1 observable. The noise therein is for the high elevations about 10% lower than on L2 and for the elevations between 24° and 10° about 35% lower.

The increase of noise with decreasing elevation angle appears to be receiver dependent.