Comparative Test between Geodetic Y-code GPS Receivers (Part 1)

This paper has been extracted from a report on investigations carried out by the Netherlands Geodetic Commission (Working Group for Applied Space Geodesy). The Commission advises mainly Government Organisations and is an Institute of the Royal Netherlands Academy of Arts and Sciences. The Working Group took the initiative for this project to evaluate the performance of various Y-code receivers at the end of 1993 and carried out the data acquisition in 1994, shortly after the US Department of Defense implemented Anti-Spoofing.

The first part consists of a general introduction and of the results of surveying baselines. The second part describes the susceptibility to Radio Frequency Interference. Literature references and acknowledgements are given at the end of part II which will be published in the August issue of GIM.

Survey of Baselines

The performance of four civilian two-frequency receivers is compared, viz. the Ashtech Z-12, the Leica SR299, Allen Osborne Associates' SNR 8000 (the TurboRogue) and the Trimble 4000 SSE; all in their mid-1994 versions with associated postprocessing software. They are so-called Y-code 'busting' receivers, which means they overcome many of the restrictions that the Anti-Spoofing feature imposes on civilian users of GPS.

One and Two-frequency Systems

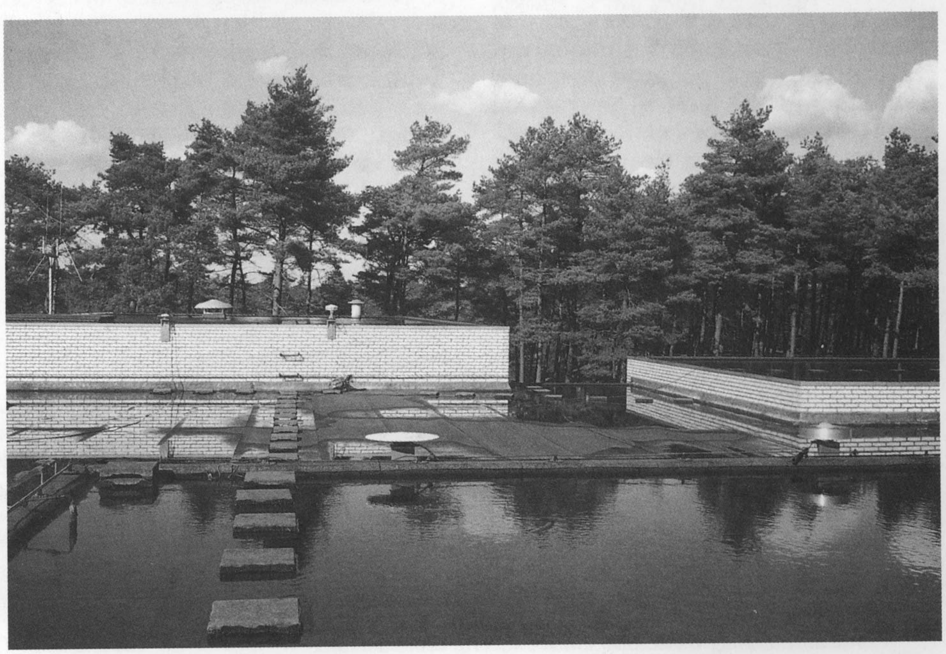
The first question a survey organisation has to answer when considering buying GPS receivers for centimetre accuracy work is: 'Do I buy a one-frequency or a two-frequency system'? The first is considerably cheaper but two-frequency systems are capable of taking more observations, which has the following advantages:

- Ionospheric effects can be compensated. In this way long baselines can be observed more accurately
- The cycle ambiguities can be resolved faster and more reliably by using the so-called wide-laning technique. This is of particular importance on short baselines for rapid static and kinematic (using moving receivers) survey work. This latter advantage is however being challenged by increasingly accurate C/A code observations

What represents a long or a short baseline depends on the variability of the atmosphere. The crossover point is in general in the region between 5 and 20 kilometres.

Cycle Ambiguity and Wide-laning

To achieve centimetre accuracy in the



Antenna locations at Kootwijk (Long and short baseline)

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observation of a baseline it is necessary to observe the phase of the carrier wave. This can be done with a precision of better than one millimetre. But it is difficult to determine the total number of whole wavelengths of about 20cm, also called cycles, in the distance difference from satellites to the two ends of the baseline. This problem is analogous to what hydrographic surveyors are familiar with when using a phase-comparison terrestrial radio-positioning system.
They solve this so-called lane identification problem by transmitting a second frequency. Subtracting the two phase measurements gives wider 'lanes', that are easier to resolve. The same can be done with GPS, though these 'wide' lanes are still only 86 centimetres.

Anti-Spoofing and Y-code Receivers

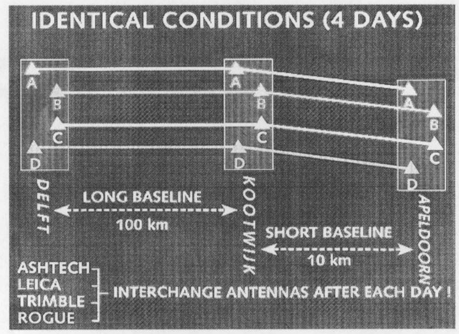
Anti-Spoofing (A-S) encrypts the publicly accessible P-code, changing it into the secret Y-code. It was introduced on 31st January 1994. Apart from its main purpose, which is to make it more difficult for potential enemies of the U.S.A. to interfere with the signals by 'jamming' transmissions, it also has an adverse effect on the capabilities of civilian users. Conventional receivers can no longer observe the L2 frequency, reducing them in fact to one-frequency receivers. Authorised users can obtain a special module to observe the Y-code.
For non-authorised users, the four manufacturers mentioned at the start of this article have developed different techniques, that partly overcome the restrictions of A-S. The details thereof are beyond the scope of this article but a fierce competitive struggle has been going on as to which technique is the best. The various claims to excellence led to the decision by our Working Group to carry out independent comparative tests.

Description of the Investigation

On theoretical grounds the Signal to Noise Ratio (SNR) of the receivers is different. It was however decided that the proof of the pudding is in the eating.
In other words, ignore all claimed theoretical advantages and look only at the results. So we observed and processed two baselines:

- A long (100km) baseline (Kootwijk-Delft), where compensation for differential ionospheric effects is important
- A short (10km) baseline (Kootwijk-Apeldoorn). This enables the testing of rapid static applications

In addition the susceptibility to Radio Frequency Interference (RFI) has been investigated; the results are given in the second part of this paper.
It is important to realise that our results represent only the performance at one point in time. Improved instruments have become available in 1995, such as Trimble's SSi and Leica's SR399. Also improved software has been introduced by various manufacturers since this test was done.



Schematic overview of baselines and off-set stations

GEODETIC Y-CODE RECEIVERS

	METHOD	WAVELENGTH
ASHTECH	Z-TRACKING	FULL
LEICA	CODE-AIDED SQUARING (P-Y2)	HALF
TRIMBLE	CROSS CORRELATION (Y1-Y2)	FULL
ROGUE	CROSS CORRELATION (Y1-Y2)	FULL

Characteristics of the four receivers

Data Acquisition and Processing

It is generally known that the performance is affected by reflections from nearby surfaces.
This 'multi-path' effect may differ considerably even if antennas are only a few metres apart. To ensure that no receiver had an unfair advantage, four eccentric sites (A to D) were selected at each baseline end.
All receivers observed simultaneously during a full day at each of these sites. In this way we obtained for each receiver nearly 24 hours of observations for each baseline A-A, B-B, C-C and D-D. The data was recorded every 30 seconds, except that for the first three hours of the short baselines observations a five-second recording interval was used. No significant difference in performance at the four sites was noticed.
For Ashtech the PRISM software was used to compute long baselines and PNAV for short ones, in both cases version 2.0.00. Leica data was processed with SKI, using version 1.08 for long and version 1.09 for short baselines. In the case of Trimble we used GPSurvey, WAVE version 1.19a, later repeated with version 2.0, which gave a better success ratio. TurboRogue data could not be processed with the manufacturer's software because AOA's Turbo Survey package was not available. Data of all four receivers was also processed with GEOTRACER (TOPAS) software; these results are NOT reported here.
For all these software packages the principle of 'hands-off' processing with optimum default parameters was adhered to. This means that we did not try to improve the result by operator intervention.
Much of the work has been done by inexperienced personnel after a brief study of the manual or a short instruction period. In addition all data was computed with the scientific Bernese software package. This cannot be done by inexperienced personnel. An extensive training course and consid-

	Manufacturer's software S.d. in 1-hour session			Bernese software S.d. in 3-hour session		
Receiver	σ_{nor}	σ_{eas}	σ_{hgt}	σ_{nor}	σ_{eas}	σ_{hgt}
ASHTECH	3.3	6.7	7.4	0.4	0.4	1.4
LEICA	3.4	7.6	5.9	0.4	0.4	2.0
TRIMBLE	3.5	4.7	6.2	0.3	0.3	1.3
T-ROGUE	n/a	n/a	n/a	0.2	0.2	0.9

Table 1, *Long (100km) baseline. Standard deviations in centimetres*

	Manufacturer's software Average from 4 days			Bernese software Average from 4 days		
Receiver	dNor	dEas	dHgt	dNor	dEas	dHgt
ASHTECH	+1.5	+0.2	-2.2	-0.4	+0.1	0
LEICA	+1.7	+0.7	-2.6	-0.1	-0.3	-0.5
TRIMBLE	+0.7	+1.8	-1.9	+0.2	+0.6	-0.3
T-ROGUE	n/a	n/a	n/a	+0.1	-0.4	+0.8

Table 2, *Long (100km) baseline coordinate results. Deviations (in centimetres) from most likely values* erable expertise are required to obtain the best results.

Criteria to Judge Performance

In general the results cannot be compared with some ultimate 'ground truth'; it is nearly impossible to obtain results that are better than GPS. Therefore, the following two criteria were used:

- The repeatability per instrument by selecting many observation windows from the available data. This is expressed in a standard deviation (s.d.), meaning that 67% of the results per coordinate component will fall within that s.d.
- A comparison of the overall average result per receiver with the most likely coordinate vector derived from the Bernese software

To obtain a sufficient number of results for our analysis, we processed for the long baseline 88 consecutive windows of one hour per receiver; i.e. 22 sessions for each of the lines A-A, B-B, C-C and D-D (or for each day). For the short one, each hour a 10-minute session was computed, giving similarly 88 results per receiver.

Originally we found for some software a fairly large number of results that did not pass our acceptance criteria. Newer software versions that came available later in 1994 improved this and by also slightly relaxing the 'hands-off' principle, the success ratio was no longer considered to be a significant performance indicator. The analysis was done for the three coordinate components defined by local North, East and Height.

Results of the Long Baseline

For each receiver with its own software, the fluctuations around the four-day average position were evaluated. From this the standard deviation in the result from a one-hour observation session was computed. The same was done for the results with the Bernese software but in this case three-hour observation sessions were used because that was found to be the optimum duration to achieve the best results. It resulted in the standard deviations shown in Table 1.

It may be concluded that all receivers give about the same accuracy. The differences in s.d. are not significant; they can easily be due to different rejections (for these Tables we used software of early 1994, which occasionally gave unacceptable results). The s.d.'s are highest in the height, as was expected. With the software of the manufacturers they are also fairly high in East direction.

This is probably due to differential tropospheric conditions at the end points and because the line-direction is nearly East-West (azimuth 258º).

The TurboRogue was the only receiver using a choke-ring antenna. This suppresses multipath and may have contributed to the excellent results with the Bernese software (no manufacturer's software available).

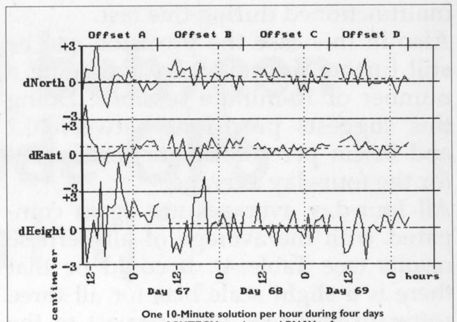
Several different processing parameters are given hereafter, which are possible reasons why the results with Bernese software are so much better (parameters for Bernese mentioned last):

- Session duration (1-hour and 3-hour)
- Ephemeris (broadcast and precise)
- Elevation cut-off (15º and 20º)
- Operator attention (none for manufacturers)
- Estimation of tropospheric parameters (not done for manufacturers). This is believed to be a very important reason

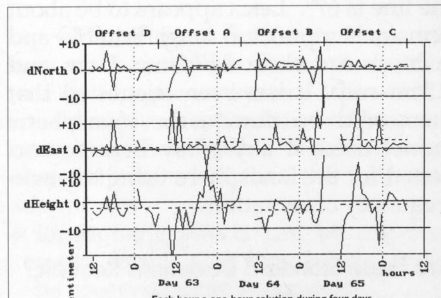
When taking the average of several one-hour sessions the precision of the results with manufacturer's software improve greatly. This has been done by grouping the results into 28 sessions of 3 hours; 16 sessions of 6 hours, 8 sessions of 11 hours and 4 sessions of 22 hours (one day). It showed that the s.d.'s decreased by slightly less than $\sqrt{N}$, with N the number of hours averaged. In this way the s.d. in the overall average of the four days is expected to be between 0.5 and 1.5 cm for the three coordinate components.

Table 2 compares all four-day averages with the most likely values, derived from Bernese software using all receivers. The differences between the three instruments and their software are mostly under 1cm, which proves the absence of any bias between them.

There is however an average bias with the Bernese results of about 1.5 centimetres in all three coordinates. This is probably due to the use of a precise ephemeris and to estimating tropospheric delay parameters by the Bernese software.



One 10-Minute solution per hour during four days
ASHTECH receiver and PNAV software
Short (10 km) baseline



Each hour a one-hour solution during four days
TRIMBLE receiver and GPSurvey software
Long (100 km) baseline

Examples of results over four days, with daily (= per station) averages

Results of the Short Baseline

The results for the short baseline have been evaluated in an identical way as for the long one.

The only difference is that the standard deviations apply to a ten-minute observation session using manufacturer's software and a one-hour session using the Bernese. They are given in Table 3. The better precision with Bernese software is in this case mainly due to the duration of the session. Unfortunately the TurboRogue

	Manufacturer's software S.d.in 10-minute session			Bernese software S.d. in 1-hour session		
Receiver	σ_{nor}	σ_{eas}	σ_{hgt}	σ_{nor}	σ_{eas}	σ_{hgt}
ASHTECH	0.8	0.7	1.5	0.4	0.4	0.9
LEICA	0.8	1.0	1.8	0.6	0.4	1.0
TRIMBLE	1.8	1.2	2.9	0.4	0.2	0.8
T-ROGUE	n/a	n/a	n/a	n/a	n/a	n/a

Table 3, *Short (10km) baseline. Standard deviations in centimetres*

	Manufacturer's software Avg. 88*10-min in 4 days			Bernese software Avg. 88*1-hour in 4 days		
Receiver	dNor	dEas	dHgt	dNor	dEas	dHgt
ASHTECH	+0.3	+0.6	+0.4	-0.3	-0.3	+0.1
LEICA	-0.3	-1.3	+0.1	-0.1	-0.3	0
TRIMBLE	+0.5	+1.3	+0.1	+0.3	+0.6	0
T-ROGUE	n/a	n/a	n/a	n/a	n/a	n/a

Table 4, *Short (10km) baseline coordinate results. Deviations (in centimetres) from most likely values*

malfunctioned during this test.
Also in this case the precision can be still further improved by averaging a number of 10-minute sessions. Doing this suggests precisions between 0.2 and 0.5cm per coordinate component for the four-day average.
All four-day averages are again compared with the average of all Bernese results (see Table 4). It could be that there is a slight scale bias for all three software packages with respect to the Bernese results, since the azimuth of the line is 67°. Leica appears to be about 1cm (or 1 ppm) too long, Trimble and Ashtech are short by some 1 cm and 0.5cm resp. It has been suggested that this could be due to the ionospheric model used, if any. Only Bernese corrected for the ionosphere using the two-frequency observations.

Are These Standard Deviations Realistic?

The answer is yes. The position and height transfer over the 10 and 100km baseline can be checked against the local survey between the stations A to D, which are some ten metres apart. The maximum difference of the four-day averages was never more than 1.6cm for the long baseline. The GPS height transfer over the 10km baseline indicated stations A and B in Apeldoorn to be some 8mm too high. The two stations are located on a superstructure on the roof and about 5 metres higher than stations C and D. A check survey did indeed reveal a 6mm error in the initial local survey, which has since been corrected.

Conclusions

There are no significant differences in the performance of the four receivers and their software.
Routine processing produced results with a s.d. of about 7cm observing the long baseline during one hour. With ten minutes data for the short line this value was about 2cm. By increasing the observation period to a full day and/or using specialised software, these values are further reduced to about 2cm and better than 1cm respectively.◆

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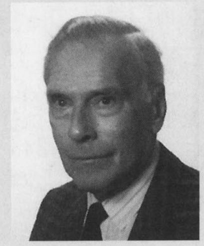
Biography of the Author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Mr P G Sluiter graduated in 1949 from the Faculty of Geodetic Engineering of Delft University of Technology in The Netherlands.
For 33 years he was employed in the international on and off-shore operations of Shell International Petroleum Company, for which he lived and/or worked in all continents.
He has been involved in the practical applications of satellite positioning since 1968, when he took delivery of one of the first commercial Doppler Transit satellite receivers for use at sea in Shell's oil exploration.
Since 1983 he has worked as a consultant in Geodesy and Hydrography. In his capacity of Chairman of the Working Group for Applied Space Geodesy of The Netherlands Geodetic Commission he took the initiative for, organised and actively participated in the project here described.