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Variations of Doppler results with software and time

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The variations of station coordinates deduced from Doppler observations with the use of a single point positioning method based on a precise ephemeris are estimated according to different models and softwares.

An identical set of Doppler observations produces station coordinates whose coherence is generally better than 1 m. However, greater differences of 1.5 or 3 m can exceptionally be detected.

Apart from the incoherence caused by the differences of models and criteria of data rejection, the reproducibility of Doppler results depends also, through the ephemeris used, on the epoch of measurements. From consecutive periods of 10 days of observations performed on the same site and analysed with the precise ephemeris computed by D.M.A., a set of station coordinates with a scatter of less than 1 m results. To keep the results near their true value it is also necessary to apply the model to a set of data having as characteristics a good balance between N–S and S–N passes, an approximate knowledge of the true meteorological parameters and at least 40 passes.

1. Comparison of results produced by different single point positioning softwares

If Doppler observations are submitted to different analyses based on an identical ephemeris, how good will the agreement between the various resulting sets of station coordinates be? Before giving numerical comparisons, I shall define the performances of the software with reference to the observations: (*a*) remove perturbations such as atmospheric refraction, timing error and equipment delay, (*b*) reject doubtful measurements, and (*c*) fit observed against computed values according to some mathematical models.

(*a*) *Softwares applied after identical data validation*

Each of these three steps causes a differentiation of the results. To determine the contribution of the last, an identical process has been used to remove the perturbations and to validate the data. After this preprocessing, the fit is performed with four different single point positioning models generally used in Doppler analysis and combining several of the next possible unknowns: X, Y, Z, the station coordinates; ΔF_i, the frequency offset for the ith pass; ΔF_0, initial frequency offset at epoch t_0; $\Delta\dot{F}$, the frequency drift; L_i, R_i, the station displacement defined in the Guier reference system (along track, range).

Figure 1 shows how these unknowns define the models called ORB, ORB3, ORB4 and ORB5. In the two first models the frequency offset is definitively determined during the preprocessing using as unknowns ΔF_i, L_i, R_i: in ORB, the equations of observations in $(L_i R_i)$ are directly expressed in a geocentric system having as unknowns ΔF_i, X, Y and Z, and ΔF_i is removed from the normal equations (Usandivaras *et al.* 1976); in ORB3, the observation equations in X, Y, Z only are recomputed in a geocentric reference system.

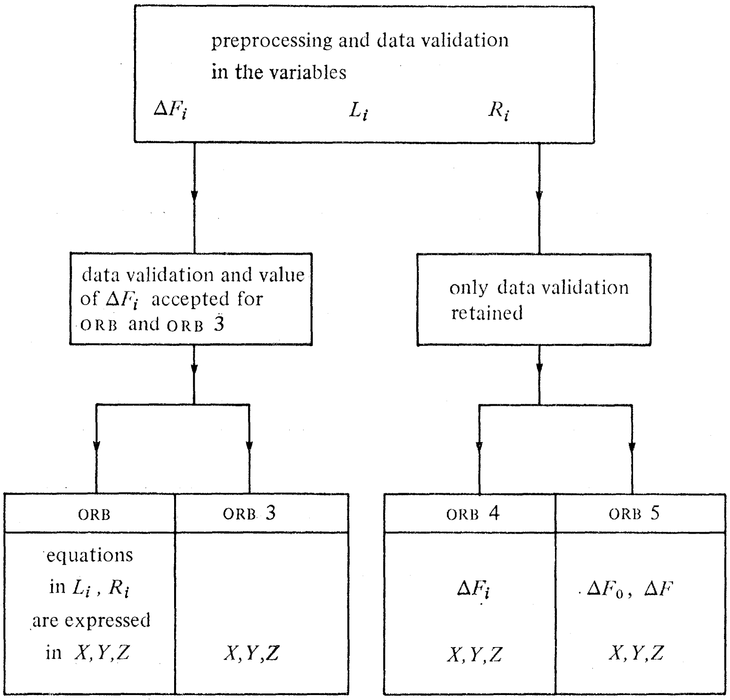

FIGURE 1. Processing procedures for ORB models.

The data acquired by five stations (EDOC-1) were submitted to these models; the differences between the resulting coordinates are given in table 1.

TABLE 1. STATION COORDINATE VARIATIONS (METRES) RESULTING FROM A SAME-DATA VALIDATION AND DIFFERENT SOFTWARES

	ORB − ORB 3					
	ΔX	ΔY	ΔZ	total passes	total equations	total eliminated
Barton-Stacey	0.03	−0.24	−0.03	92	2112	248
Brussels	0.14	−0.32	−0.08	118	2817	274
Florence	−0.13	0.28	0.08	93	3969	522
Grasse	−0.17	−0.58	0.12	35	1251	385
Wettzell	−0.18	0.53	0.32	70	2022	109

	ORB − ORB 4			ORB − ORB 5		
	ΔX	ΔY	ΔZ	ΔX	ΔY	ΔZ
Barton-Stacey	0.00	−0.01	−0.04	−0.48	−0.78	0.26
Brussels	0.08	−0.52	−0.08	−0.15	−0.52	0.24
Florence	0.04	0.04	0.12	0.58	−0.48	−0.21
Grasse	0.15	−0.10	−0.32	−0.61	−1.53	0.68
Wettzell	−0.03	−0.03	0.03	0.19	−0.97	0.00

Table 1 shows that, even with the same data validation, the formulation of the fitting introduces appreciable differences, mainly for the model ORB5 compared with the others. These greater variations of ORB5 result from the frequency unknown which is expected to have a linear drift during the whole observation campaign. From figure 2 where daily values of the satellite frequency have been plotted, we conclude that such a hypothesis must only be used

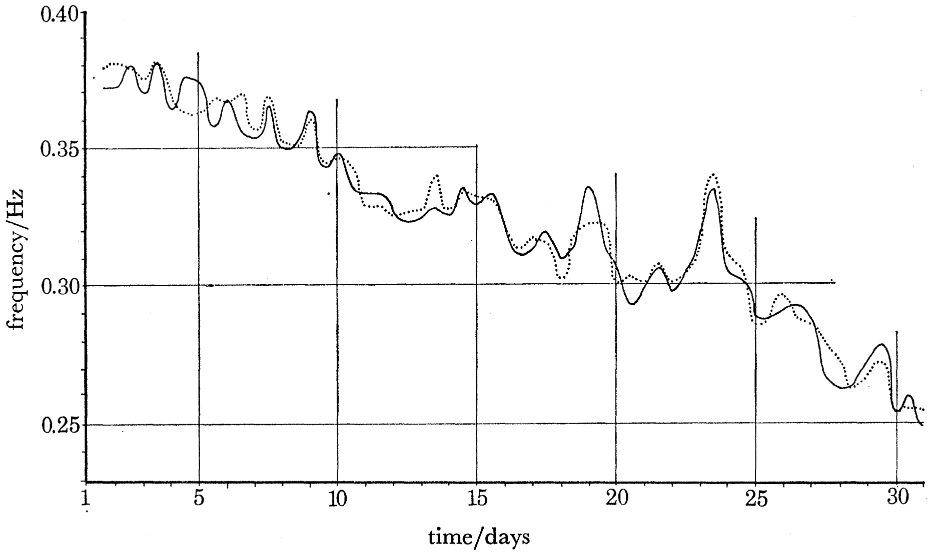

FIGURE 2. Transmission frequency of satellite 30190 (N–S and S–N passes). The daily mean initial frequency was 399987973 Hz. ——, ORB; ..., ORB4.

for a short time interval. For this reason we adopted a model with a pass-by-pass frequency determination. Disregarding some exceptional values in ORB5, we can accept a possible difference of 50 cm between coordinates resulting from these different models applied to exactly the same data.

(*b*) *Comparisons between three models IGN, IFAG, ORB*

The data acquired during the campaign EDOC-2 were submitted to three computing centres with the use of their own methods of data validation and different softwares for the determination of the station coordinates. Some details of these computations are given in Wilson *et al.* (1978), from which the values of table 2 are taken, remembering that the three models are IGN, IFAG (Geodop) and ORB. Between them the main difference is the evaluation of the tropospheric correction: IGN and ORB use Hopfield's tropospheric model as described in Hopfield (1972), while IFAG introduces a simplified model complemented by an unknown which represents the tropospheric bias.

TABLE 2. STATION COORDINATE VARIATIONS (METRES) BETWEEN THE SOFTWARES IGN, IFAG AND ORB

IGN (B) – ORB				IFAG (B) – ORB			
station	ΔX	ΔY	ΔZ	station	ΔX	ΔY	ΔZ
220	−0.15	−0.03	−0.01	400	−0.76	−0.92	−0.32
221	−0.10	0.42	0.11	405	−0.57	−0.50	0.28
222	0.15	0.31	0.20	410	−0.44	−0.29	−0.09
223	−0.01	0.09	−0.12	415	−0.85	−0.70	0.01
224	−1.01	0.83	−0.45	420	−0.53	−0.18	0.30
225	−0.27	0.19	−0.22	425	0.30	0.07	0.50
223	−0.10	−0.06	0.47	430	−3.44	−0.13	−0.62
234	−0.17	0.20	0.03	435	−0.39	−0.01	−0.57
				445	−0.26	−0.18	0.40
				643	0.31	−0.35	0.48

Although the scatter is greater between IFAG and ORB than between IGN and ORB, the agreement is generally good; however, there is a very important difference in the X component of station 430. The reason for this difference is not well known but is mainly due to the data validation which was unusual for this particular station: because of site difficulties about 59 % of the passes are eliminated.

A last example of software divergences is given in table 3 in which the last digits of the coordinates of the Doppler station at Brussels are given. For this station two separate solutions of the coordinates are computed with the precise ephemeris; one solution, called DARCUS, is given by Anderle (NSWC/DMATC) and the other results from the ORB model. These two models compute station coordinates for each period of 5 days. The first part of table 3 gives the annual means while the second part gives the differences DARCUS – ORB and the number of passes and equations for each year. Taking into account the high number of passes the differences between these solutions are mainly induced by the models. For example, Anderle's model introduces a refraction bias parameter which could change the station's height by 1 m. In 1976, along the Y and Z components we notice also a variation of the systematic differences observed in 1973, 1974 and 1975.

TABLE 3. COORDINATES OF BRUSSELS AS ANNUAL MEANS

	ORB			DARCUS		
year	X	Y	Z	X	Y	Z
1973	6.43	10.58	3.92	7.13	10.42	5.00
1974	6.55	10.53	4.10	6.96	10.29	5.08
1975	6.58	10.24	4.05	7.22	10.00	5.20
1976	6.65	10.00	4.35	7.42	9.57	5.91
1977	6.53	10.00	4.52	7.45	9.72	5.92

	DARCUS – ORB				
year	ΔX	ΔY	ΔZ	number of passes	number of equations
1973	0.70	–0.16	1.08	1190	27179
1974	0.41	–0.24	0.98	1362	31385
1975	0.64	–0.24	1.15	1280	29091
1976	0.77	–0.43	1.56	1133	25930
1977	0.92	–0.28	1.40	1079	24031

Thus, except for some special cases, such as station 430 (table 2) and the Z component between DARCUS and ORB models (table 3), the agreement between the softwares is generally better than 1 m even if the data validation is not performed on an identical basis.

2. VARIATIONS OF THE DOPPLER RESULTS WITH TIME AND SATELLITE

Because the Doppler measurements are influenced by meteorological parameters, and as the single point positioning solutions are based on a satellite ephemeris, station coordinates depend upon the epoch of the measurements even if the precise ephemeris of DMATC is used. A clear example is given in figure 3, where the deviations from the mean of the Brussels coordinates are computed for a continuous observation period of 10 days for one satellite (30190) for which a precise ephemeris is delivered. In the X, Y and Z components the errors of one determination are respectively 0.45, 0.43 and 0.49 m. It is interesting to notice the deviations of the X and Z

components during the years 1976 and 1977. Spectral analyses of such measurements were performed by Schulter (1978) and he came to the conclusion of the possible existence of terms having periods near 1 year and 128 days.

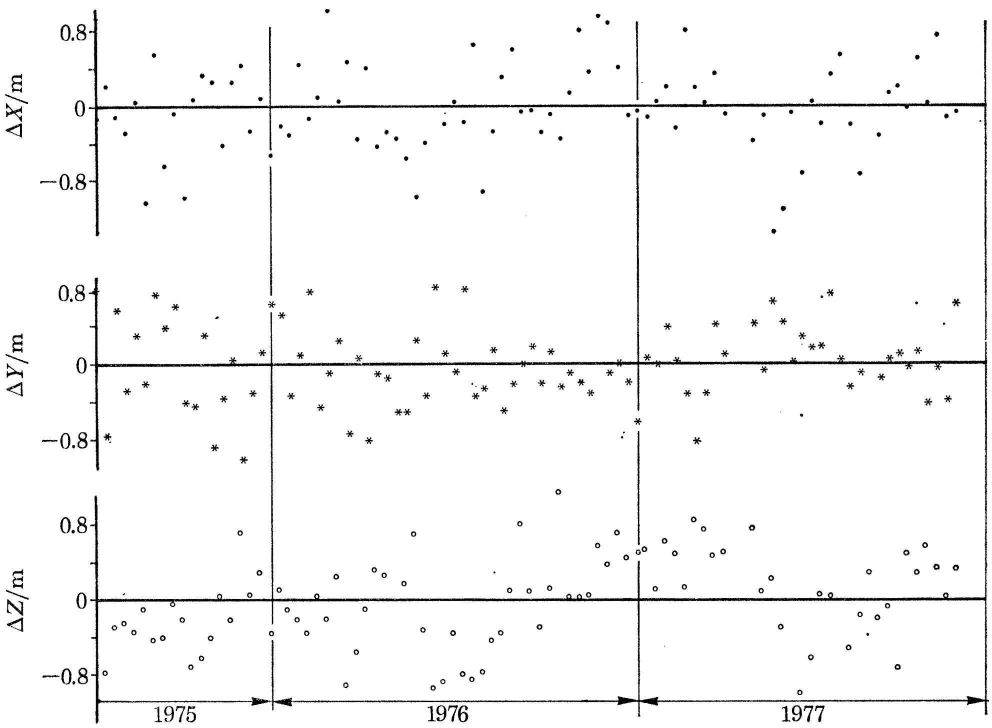

FIGURE 3. Variation in Brussels coordinates; satellite 30190.

The ephemeris variations are also well reflected through the coordinates of three stations which successfully participated in the EDOC campaigns. For EDOC-1 the precise ephemeris has been provided for one satellite (30190), while EDOC-2 was supported with the precise ephemeris of two satellites (30190, 30200); in table 4 the variations of the station coordinates deduced from these campaigns are given. Compared with the EDOC-1 results, a good agreement exists in X and Y. However, the independent solutions obtained with the ephemeris of 30190 and 30200 show important deviations, especially solution B for Florence. From figure 3 such differences may be considered exceptional.

From table 4 it is also interesting to notice how the relative coordinates are modified from one period to the other (table 5).

3. INFLUENCE OF THE STATION PARAMETERS ON THE COORDINATES

(a) *Equipment delay*

The clock of modern instruments being readjusted by the first satellite beep word, equipment delay is a potential source of large deviation. It is a constant time error which, along an axis positively orientated towards the satellite motion, systematically shifts the true satellite position. The along-track component of the Guier elements is a very sensitive detector of such time constant error (Usandivaras *et al.* 1976). Fortunately, if the equilibrium between north–south

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TABLE 4. VARIATIONS OF STATION COORDINATES (METRES): EDOC-1 – EDOC-2

(Three sets of station coordinates were deduced from EDOC-2: A, data of satellite 30190 only; B, data of satellite 30200 only; C, data of both satellites.)

station	ΔX	ΔY	ΔZ	EDOC-2 solution
Barton Stacey (BS)	0.24	−0.17	−0.87	A
	−0.19	0.49	−1.55	B
	0.01	0.12	−1.21	C
Florence (F)	0.19	0.14	−0.93	A
	0.29	0.74	−2.33	B
	0.26	0.40	−1.57	C
Wettzell (W)	−0.04	−0.28	−1.48	A
	−0.40	0.14	−1.83	B
	−0.06	−0.10	−1.63	C

TABLE 5. RELATIVE VARIATIONS OF COORDINATES (METRES): EDOC-1 – EDOC-2

differences	ΔX	ΔY	ΔZ	solution
BS – F	0.05	−0.31	0.06	A
BS – W	0.28	0.11	0.61	A
F – W	−0.33	0.42	0.55	A
BS – F	−0.48	−0.26	0.78	B
BS – W	0.21	0.35	0.28	B
F – W	0.69	0.61	−0.50	B

(N–S) and south–north (S–N) passes is realized, the effect of the delay error is, within limits, negligible for the determination of station coordinates. Table 6 gives coordinate displacements resulting from the application of different delays to a set of Doppler data satisfying a good N–S and S–N pass distribution.

TABLE 6. COORDINATE SHIFTS (METRES) ACCORDING TO THE ADOPTION OF DIFFERENT EQUIPMENT DELAYS

delay/μs	$\Delta\lambda$	$\Delta\phi$	ΔH
600	0.18	−0.03	−0.09
420	0.08	−0.07	−0.02
350	0.03	−0.08	0.01
280	−0.02	−0.09	0.04
140	−0.11	−0.12	0.10
0	−0.20	−0.14	0.15

(*b*) *Meteorological parameters*

For the lower part of the atmosphere, perturbations are removed by a knowledge of the local meteorological parameters introduced in an appropriate atmospheric model, for example Hopfield's model (1972). The deviations of these parameters from the mean model of the atmosphere is a source of error along the station vertical that must be considered mainly for those sites that have important diurnal variations.

Table 7 demonstrates this effect by giving the variations of the station height for different sets of meteorological parameters, two of them being considered as constant during the period analysed: 15 days, 58 passes, 1426 observations. These variations, in metres, are expressed with respect to a conventional meteorological model: P = 101.3 kPa, T = 10 °C, relative humidity (h) = 60%.

Because of the important variations of the station height related to the meteorological parameters, we prefer to use the true values rather than a mean model.

Table 7. Variation of the station height (metres) according to the deviations of one meteorological parameter from a mean model defined by: P = 101.3 kPa, T = 10 °C, h = 60%

P_i/kPa	ΔH	T_i/°C	ΔH	h_i (%)	ΔH
80.0	3.26	−10	0.49	10	0.57
86.7	2.24	−5	0.43	30	0.33
93.3	1.21	0	0.29	40	0.21
96.0	0.84	5	0.16	50	0.09
98.7	0.55	10	0.00	60	0.00
100.0	0.20	15	−0.22	70	−0.09
101.3	0.00	20	−0.61	80	−0.20
102.7	−0.20	30	−1.31	90	−0.34
104.0	−0.42	40	−2.39	100	−0.55

(c) *Number of passes and coordinate variations*

The number of passes considered in the solution also changes the station coordinates. Table 8 gives two examples of the evolution of station coordinates as well as the convergence of the associated errors. By using the precise ephemeris as reference, it results that, if about 40 passes are taken into account, the station coordinate variations lie generally within the limits of twice the internal coherence. However, this is not a general rule because example (b) of the same table shows a non-negligible variation (53 cm) of the X component when the number of passes increases from 68 to 82.

Table 8. Evolution of station coordinates

(Column 1 shows coordinate variations (metres) with respect to the final adopted values; column 2 shows errors in coordinates in metres; column 3 shows the total number of passes with sub-totals of N–S and S–N passes; column 4 shows the total number of equations entered in the solution and the number eliminated.)

(a) data from station 230 CBR

1			2			3			4	
0.10	−0.08	0.85	0.18	0.30	0.17	12	5	7	344	53
0.10	0.08	0.66	0.13	0.20	0.12	22	9	13	622	95
−0.20	−0.19	0.44	0.11	0.17	0.10	33	15	18	925	158
−0.14	−0.12	0.17	0.09	0.14	0.09	44	21	23	1237	211
−0.08	−0.19	0.16	0.08	0.12	0.08	56	27	29	1568	268
−0.04	−0.12	0.05	0.07	0.12	0.07	67	32	35	1876	330
0.0	0.0	0.0	0.07	0.10	0.06	88	42	46	2457	432

(b) data from station 643 WTZ

1			2			3			4	
0.12	−0.76	0.37	0.16	0.24	0.14	13	4	9	343	38
−0.12	−0.20	0.49	0.12	0.18	0.11	24	9	15	621	63
−0.22	−0.40	0.35	0.09	0.13	0.08	38	17	21	1000	98
−0.03	−0.32	0.05	0.08	0.12	0.07	52	23	29	1379	134
−0.04	−0.12	0.17	0.07	0.10	0.06	68	30	38	1793	171
0.49	−0.22	0.07	0.06	0.09	0.05	82	37	45	2173	210
0.0	0.0	0.0	0.06	0.09	0.05	103	47	56	2728	271

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