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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Activities of the Institut Geographique National (I.G.N.) in the Field of Doppler Satellite Geodesy

C. Boucher

Phil. Trans. R. Soc. Lond. A 1980 **294**, 261-270
doi: 10.1098/rsta.1980.0032

Phil. Trans. R. Soc. Lond. A **294**, 261–270 (1979)
Printed in Great Britain

Activities of the Institut Géographique National (I.G.N.) in the field of Doppler satellite geodesy

By C. Boucher

Institut Géographique National, Service de Géodesie,
2 Avenue Pasteur, 94160 Saint-Mandé, France

The Institut Géographique National (I.G.N.), the French national geodetic and mapping agency, started in 1974 a research and development programme on Doppler satellite techniques, in order to determine their accuracy and capabilities, to investigate possible geodetic uses and to establish various operational positioning methods, according to a cost:precision ratio. A review is given to the current (1978) status and investigations planned for instrumentation and field facilities, modelling and data processing techniques, and geodetic applications. As a general result from several comparisons, the precision of position computed with the I.G.N. software (GDP) is 3 m for single point positioning (s.p.p.) with the use of broadcast ephemerides (option I), and 1 m with s.p.p. with DMA precise ephemerides (option II) and short arc positioning (option III). Present investigations seem to indicate that the precision of option II can be improved to a few decimetres, whereas option III in its present formulation has some limitations.

1. Activities of I.G.N. in the field of Doppler satellite geodesy: a general view

1.1. *Role of I.G.N.*

The Institut Géographique National (I.G.N.) is the French governmental agency in charge of the geodetic and cartographic survey of the National territory. In this field of activity, the I.G.N. devotes an important part of its potential to scientific research, technological developments and technical education. On the other hand, contracts with French or foreign organizations permit numerous operations in France or overseas countries.

1.2. *Development and uses of satellite geodetic techniques*

In the late 1960s and the early 1970s, considerable developments in the geodetic uses of satellite Doppler techniques stimulated initial investigations in France, in the framework of the Groupe de Recherches de Géodésie Spatiale (G.R.G.S.) to which the I.G.N. belongs.

The occurrence of portable receivers fulfilling geodetic accuracy standards, and the increasing necessity to develop operational positioning methods with better performance than astronomical stations or even satellite photographic methods, compelled the I.G.N. to be more directly involved. In late 1974, several geodetic Doppler receivers (JMR-1) were purchased.

At this time a research and development programme was scheduled on this topic. Two major actions were programmed:

(*a*) A series of test observations campaigns. Four were of particular interest: marginal participation (two stations) in the first European Doppler Observation Campaign (Edoc-1, May 1975), a test of six stations of the French control network (August 1975), a cooperative campaign of nine stations in France, Spain, Senegal and South America (Lesard, October 1976; Piuzzi & Charpentier 1977; Perret 1977; Piuzzi *et al.* 1978), and finally participation in the Edoc-2 campaign (April–May 1977; Wilson *et al.* 1978). A more detailed list of Doppler field operations executed by the I.G.N., including surveys under contract, can be found in Boucher (1977).

(*b*) Development of data processing capabilities. A first software (GDOP) was written in 1975–6. Its complete revision in late 1976 and 1977 led to the GDP package, allowing both point positioning and short arc options. At present a completely new software is under development. Details are given in § 3.

1.3. *Consequences*

The investigations quoted above have provided many results which are analysed below under three headings: instrumentation, modelling and data processing, and geodetic uses.

2. Status and developments in instrumentation

As mentioned in § 1, the I.G.N. is equipped with JMR instruments (12 JMR-1 receivers, several JMR-1-CR or CRR cassette readers, and a JMR-1-MP microprocessor). Globally, the reliability of JMR-1 receivers is satisfactory, considering this type of electronic instrument and can be roughly evaluated to 80–90%. Nevertheless, two weak points should be stressed:

(*a*) Some failures in the measurement recording device are often very difficult to detect in real time. This can lead to complementary field work and, incidentally, to a very costly operation The new microprocessor, which can operate in a field environment, seems to provide a satisfactory answer to this problem.

(*b*) The magnetic cassette is certainly a very suitable medium for data recording, regarding storage and handling problems. Nevertheless, the transcription of such cassettes onto a standard magnetic tape often gives rise to hardware failures. Up to now, the paper tape medium seems more satisfactory with respect to loss of information.

On the other hand, the analysis of results from data processing has shown some instabilities in the receiver frequency and some unexpected trends of the behaviour of the local clock during a satellite pass. Details are to be found in Boucher (1978*a*). Similar results have been produced by DMA investigations (Harris 1979). See also § 3.1 and figure 2.

Several tests in the laboratory have shown that the technical specifications in JMR documents (oscillator stability over 100 s averaging, 5×10^{-12}; oscillator ageing rate 5×10^{-11}/day) are generally fulfilled, but not always. In particular it is recommended to wait 2–3 days for oscillator stabilization (Tests of the Laboratoire Primaire de Temps et Fréquence, Paris).

In conclusion, and besides these remarks, the operational use of this type of receiver is very simple and well adapted to all-weather and all-country field work. A refined modelling can remove most of these biases, though hardware improvements would be more satisfactory in some cases.

3. Status and developments in data processing

Many investigations have been made on this topic. We plan to summarize results here, distinguishing problems related to the physical model of Doppler satellite measurement from characteristics of various adjustment options such as point positioning and short arc. For references to similar investigations, see Anderle (1976), Beuglass (1975); O'Toole (1976), Smith *et al.* (1976), Kouba & Boal (1975), Kouba & Wells (1976), Wells (1974), Nouel (1972), and Usandivaras *et al.* (1976).

3.1. *The Doppler satellite measurement modelling*

The establishment of an observation equation for Doppler count integrating receivers such as JMR, Magnovox or Canadian Marconi, is described in detail in Boucher, (1978*a*, *b*). We shall nevertheless summarize the major results here. The basic equation is

$$\phi = (f_R - f_S)(t'_2 - t'_1) + (f_S/c)(\rho_2 - \rho_1) + \Delta N_{tropo} + \Delta N_{iono} + \Delta N_{rel} - N = 0,$$

where:

f_R is the stable frequency of the receiver, usually expressed by a scale factor p from the nominal 400 MHz (for Transit satellites, or the higher frequency in other cases, if any) $f_{R,400}$: $f_R = pf_{R,400}$, or, nominally, $\bar{f}_R = p\bar{f}_{R,400} = p \times 400$ MHz.

f_S is the stable frequency of the satellite, usually expressed by an offset $\bar{\omega}$ from the nominal $\bar{f}_R$: $f_S = \bar{f}_R(1-\bar{\omega})$, and $\bar{\omega}$ is about 80×10^{-6} for Transit satellites. The scale factor is $p = 55/64$ for JMR-1 receivers.

t'_1 (t'_2) is the epoch of the beginning (end) of the Doppler count N.

c is the velocity of light in vacuum.

ρ_i is the distance in an inertial frame between the position of the centre of phase of the satellite antenna at the epoch t_i and the centre of phase of the receiver antenna at the epoch t'_i. Here, $t_i = t'_i - \Delta t_{prop,i}$ is the epoch of emission corresponding to t'_i, where $\Delta t_{prop,i}$ is the propagation delay.

ΔN_{tropo} is the tropospheric correction, ΔN_{iono} is the ionospheric correction and ΔN_{rel} is the relativistic correction.

From the numerical point of view, and considering the previous observation, ϕ, expressed in counts for $f_{R,400}$ frequency ($p = 1$), the noise level of the measurement itself is given for geodetic receivers from the time recovery of t'_1 and t'_2 on a local clock.

Basically, a standard deviation σ_t of 0.5 μs for t' gives for ϕ:

$$\sigma_\phi = (\bar{f}_R - \bar{f}_S)\,\sigma_t\sqrt{2} = \bar{f}_R\,\bar{\omega}\sigma_t\sqrt{2} = 0.023 \text{ count.}$$

We wish to point out here various items that influence the computation of ϕ, to the 0.001 count level. Several parameters can be introduced as unknown variables in the least-squares estimation technique as discussed in § 3.2, but the tendency to use too many parameters can influence the station coordinates, at least in absolute value. The basic observed quantities are N, t'_{R_1} and t'_{R_2} where t_R is the local time scale, related to uniform time scale by an equation generally assumed to be

$$t = A + Bt_R,$$

where B is close to 1 and A is the synchronization constant. B is the ratio of the nominal receiver frequency to the actual one. The knowledge of this last quantity (for instance given by pre-processing) is usually sufficient for the computation of B. For A, an estimation to 100 μs is generally available, but A is a possible calibration parameter to be introduced as an unknown. $\Delta f = f_R - f_S$ is classically introduced as an unknown parameter for each satellite pass. A more restrictive modelling, such as $\Delta f = \Delta f_0 + (\mathrm{d}/\mathrm{d}t)\Delta f(t-t_0)$ for a full Doppler data set, can only be used when the receiver oscillator is highly stable (caesium clock).

The previous considerations fulfil the computation of $\phi_1 = (f_R - f_S)(t'_2 - t'_1)$ in the expression for ϕ. For the second term, $\phi_2 = (f_S/c)(\rho_2 - \rho_1)$, the following statements have to be made.

A relative estimation of f_S of 3×10^{-8} gives better than 0.001 count for ϕ_2. As $\Delta f_S/f_S \approx \Delta\varpi$, we see that ϖ has to be known to 0.3 part/10^6. For Transit satellites, the use of the nominal value of ϖ, 80 parts/10^6, can introduce an error of 0.1 part/10^6, i.e. 0.003 count. The use of the broadcast estimation of ϖ, or other estimates (see, for example, *U.S.N.O. Bulletin*) can guarantee 0.005 part/10^6, which is quite satisfactory.

For c, the change from the IUGG 1957 value

$$c = 299\,792\,500 \text{ m s}^{-1}$$

to the new IUGG 1975 value

$$c = 299\,792\,458 \text{ m s}^{-1}$$

gives

$$\Delta c/c = 1.4 \times 10^{-7}$$

and the same relative error in the ϕ_2 term (up to 0.004 count). In this case, as in the previous one, this creates a small but systematic error in ϕ_2 which can be regarded as a scale factor, and thence an influence on the height of the computed position of the station.

The computation of ρ_i requires the position of the centres of phase of the antennae of the satellite and the receiver, and must take into account an aberration effect (Jenkins & Childress 1978; Boucher 1978*a*). In the last reference, it is shown that neglect of this effect leads to a shift in longitude of 0.2 m in the station computed position (confirmed by J. Kouba & P. Pâquet, private communications).

For the position of the centre of phase of the emitting antenna, ephemerides of the centre of mass of the satellite are used. The shift between those two points has to be taken into account, otherwise it again produces a scale bias. Two major kinds of ephemerides are currently available: broadcast ephemerides (b.e.), computed by the Navy Astronautical Group (error up to 20 m); precise ephemerides (p.e.), computed now by DMATC (error up to 3 m). The ephemeris error is certainly the major one in the error budget, especially for b.e. In short or long arc techniques (cf. § 3.2), parametrization removes these errors. In the point positioning (translocation) technique, a suitable data set tries to remove those biases by balancing (to create the same bias on each station position).

For the position of the centre of phase of the receiver antenna, a stationary position is chosen introducing fixed unknown coordinates in an average terrestrial system. In fact, two kinds of perturbing motions are to be taken into account: geodynamical ones such as Earth tides, and variations of the electrical centres (150 and 400 MHz). The first can be modelled (I.C.E.T. 1978; Boucher 1978*a*); the second could be more satisfactorily removed by instrumental improvements.

We finally review the last corrections.

(*a*) The tropospheric correction. This is computed by using a range correction formula. The basic problems are the choice of a formula (two major studies have been made by H. S. Hopfield and J. Saastamoinen), the use of standard or local meteorological data and the introduction of a parameter. Many investigations have been made and published. We think that no fully satisfactory answer has been given up to now.

(*b*) The ionospheric correction. As the range correction due to the ionosphere is dependent upon carrier frequency, and can be expanded into powers of f_S^{-1}, it can be classically shown that the first order correction can be removed by hardware or software with the use of two frequencies. In this case, ΔN_{iono} is of second order. Nevertheless, it has been emphasized that second and third order terms are not negligible with respect to our requirements. Investigations have been

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made (see, for example, Tucker *et al.* 1976), and are currently continued to provide a correction model for those remaining terms.

(*c*) The relativistic correction. General Relativity or any other current general theory of gravitation requires a correction term to the classical Newtonian model (see, for example, Jenkins 1969; Harkins 1973; Boucher 1978*c*). This term is almost constant as expressed in terms of frequency ($\phi/(t_2'-t_1')$), and consequently can be almost considered as a relativistic bias on Δf. Nevertheless, to the 0.001 count level, it is more satisfactory to compute it explicitly (Boucher 1978*a*).

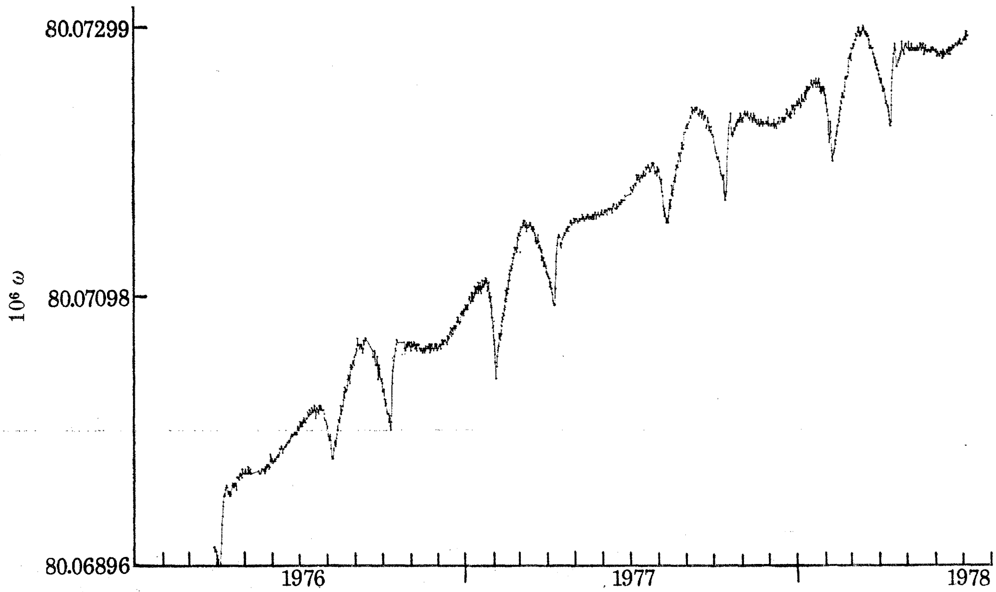

FIGURE 1. Satellite 30190 (Transit): variations in time of the offset parameter, $\overline{\omega}$. Source: *U.S.N.O. Bulletin.*

Considering now the measurement perturbations, we can treat them under two headings.

(i) Emission of the satellite: usually, no failure occurs and a high stability is guaranteed. Nevertheless, some problems may appear to the user. For instance, figure 1 shows the variation of $\overline{\omega}$ for the Transit satellite 30190 over several years.

(ii) Reception at the receiver: two kinds of perturbations may exist, environmental and instrumental. In the first category come radioelectric interference, secondary reflexions and poor visibility in elevation. They can be removed by a suitable choice of site. Instrumental perturbations include radio carriers recovery by the antenna and unsatisfactory phase locking. For instance, in figure 2, the delay between the theoretical mark decoding epoch (time of emission + propagation + standard electronic delay) and the recorded one is shown for JMR-1 SN 76189 during the EDOC-2 campaign (1977). These problems should be solved by hardware improvements.

3.2. *Adjustment techniques*

Following the recommendations of Kouba (1976), we distinguish the three adjustment methods: point positioning (p.p.), short arc (s.a.) and long arc (l.a.). We shall not consider translocation which seems rather ambiguous in the literature, and in fact not different from either p.p. or s.a., depending on the authors.

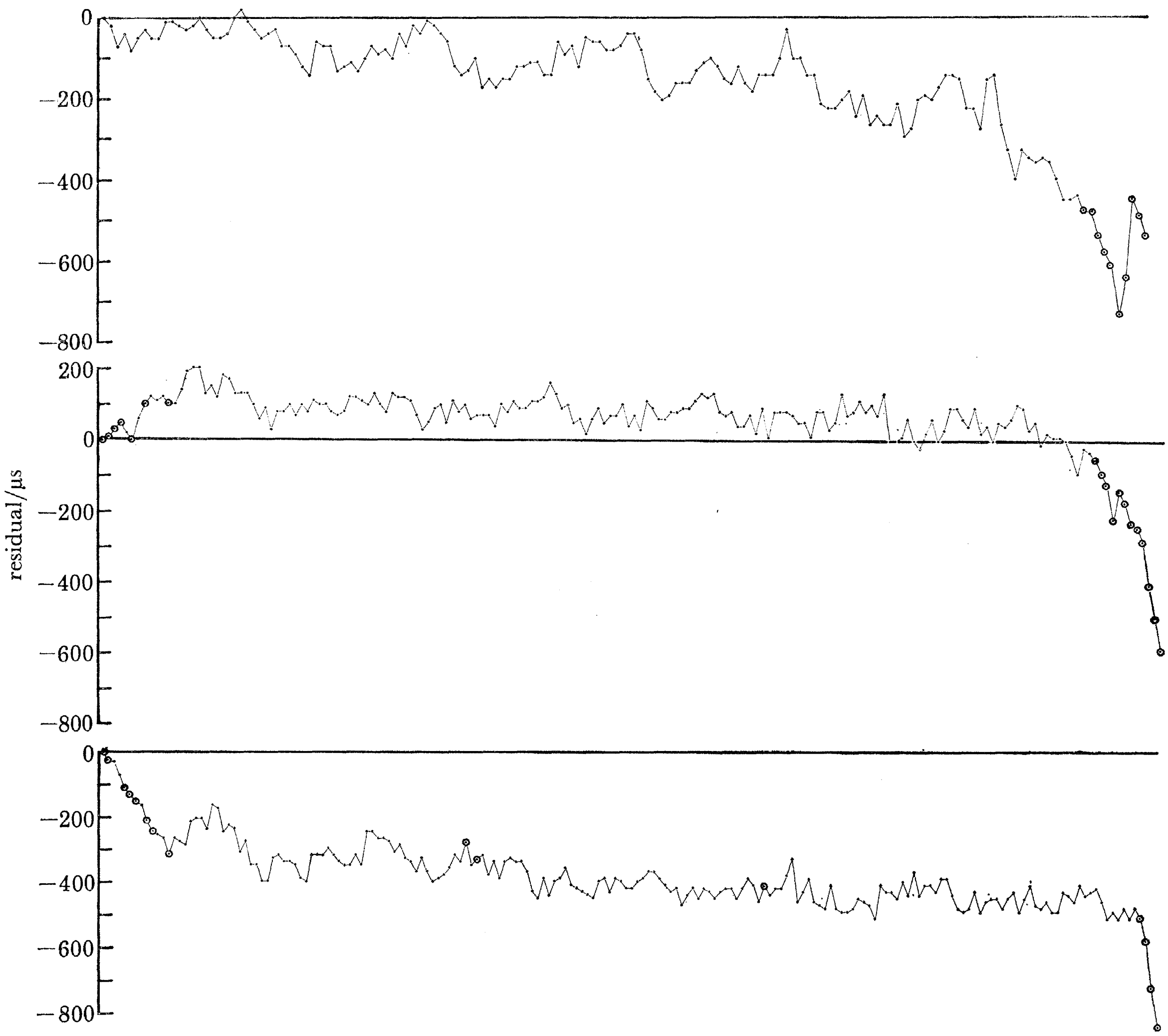

FIGURE 2. Three examples of residuals on the decoding time of successive 4.6 s words (JMR-1; satellite 76189). ⊙, Weak signal.

As mentioned in § 1.2, the present operational software established at the I.G.N. is GDP, allowing both p.p. and s.a. We give here the current options used.

(*a*) *Point positioning*

Relation ϕ used; parameters X, Y, Z (station coordinates) and Δf for each pass; f_S computed with ϖ from broadcast data; $c = 299\,729\,458$ m s^{-1}; aberration effect; satellite antenna shift neglected; Earth tide correction and motion of the centre of phase of the receiver neglected; ephemerides interpolation on six points (1 min interval) by barycentric formula, i.e. if $T \leqslant t < T+1$, we use $T-2$, $T-1$, T, $T+1$, $T+2$ and $T+3$; tropospheric correction, with Hopfield or Saastamoinen model, with the use of local meteorological data, and a cut-off angle introduced as input (usually 7.5 or 10°) (no bias parameter is used in routine); ionospheric correction, only first order is taken into account; relativistic correction computed.

Both sequential adjustment and filtering are done simultaneously. Raw Doppler data are used without compression, with an *a priori* standard deviation fixed for each receiver. No correlation is introduced.

Rejection criteria are:

(i) For individual data, rejection occurs if the residual, v is

$$|v| > f \sup(\sigma_0, \sigma_p),$$

where $f = 2.5$, σ_0 is the *a priori* standard deviation, and σ_p the computed standard deviation up to the pass being processed.

(*b*) A pass is rejected if its maximum elevation is under 15°, or if $N_b + N_a < N_m$, or if $N_a/(N_a + N_b)$ is not between 25 and 75%. Here $N_a(N_b)$ is the number of good data after (before) the time of closest approach. N_m is the minimum number of data allowed per pass (50 for 4.6 s data).

(*b*) *Short arc*

The currently used short arc model is described in Fontaine (1978).

3.3. *Estimation of the accuracy of Doppler positioning*

Three positioning techniques are considered here: (I) point positioning with broadcast ephemerides (p.p.–b.e.); (II) point positioning with precise ephemerides (p.p.–p.e.); (III) short arc positioning with constraints on orbital parameters with the use of b.e.

As with every estimation technique of positions in geodesy, it is necessary to emphasize how the reference system, with regard to which coordinates are computed, is operationally defined (the datum problem; see, for example, Grafarend 1977). In Doppler techniques, the natural reference systems are average geocentric terrestrial systems. The three positioning techniques are semi-dynamical, i.e. they use preliminary ephemerides. Basically, those ephemerides permit the definition of the reference system. Precisely three items are to be defined: a computation technique, including fundamental constants such as c and GM; a set of coordinates of basic tracking station network; and a gravity field model.

For b.e., Black *et al.* (1975) give information on the software of the Navy Astronautical Group Computing Center, the set of four stations (OPNET), and the WGS 72 gravity field. The resulting system does not seem to be identical to the WGS 72 reference system (which is well defined with regard to NWL 9D as identical to NWL 10F; see, for example, Anderle 1976).

For p.e., the three items are: CELEST software (O'Toole 1976), the TRANET network in NWL 9D system (NSWC 9Z-2 from June 1977), and the NWL 10E gravity field (NWL 10E-1 from June 1977).

The errors in ephemerides induce in station coordinates determined by p.p. a bias, the value of which characterizes the absolute accuracy. Globally, we can assume that the total error in position, with the use of a data set collected at one station and one epoch, can be split into three parts: D_1 depending on the data set, D_2 depending on the geographical location, and D_3 depending on the epoch. D_1 can decrease by adding data (convergency of the sequential adjustment). D_2 takes into account regional bias; when stations are close (a few hundreds of kilometres), D_2 is more or less the same (translocation). D_3 takes into account time variations of the reference system.

In order to try to estimate these errors, we can state five things.

(1) Using a large data set from several close simultaneous stations for which we have terrestrial coordinates $X_{T,i}$, and Doppler coordinates $X_{D,i}$, we can compute

$$DX_i = X_{D,i} - X_{T,i},$$

and the average value DX. Residuals $DX_i - DX$ can allow estimation of D_1. Variations of DX from several data sets can estimate $D_2 + D_3$.

(2) The mean square value of $DX_i - DX$ can be considered as an estimation of standard deviation of D_1, assumed to be of zero mean.

(3) For b.e., we found σ_{D_1} to be of the order of ± 1 m (Fontaine 1978). The repeatability seems of the order of 3–4 m. In this case, some large-scale campaigns could permit D_2 to be separated from D_3.

(4) Obviously, errors in X_T influence these estimates. Terrestrial errors can be of this order for long distances, whence the importance of using the best available external standards (high precision traverse, v.l.b.i., lunar laser ranging, Doppler, best terrestrial adjustments).

(5) In p.e., σ_{D_1} is found by the same methods to be of the order of ± 0.8 m (Wilson *et al.* 1978, table 15) and the repeatability $(D_2 + D_3)$ better than 2 m.

Table 1 summarizes for p.p. techniques and gives information on convergency. As previously stated, estimates for p.e. are certainly pessimistic.

Table 1. Point positioning techniques and convergency

	b.e.	p.e.
passes	40	30
σ_{D_1}/m	+1.0	+0.8
max $\lvert D_2 + D_3 \rvert$/m	3–4	2

For s.a., results show similar accuracy to that for p.p.–p.e. (Wilson *et al.* 1978, table 15), for a network with sides of less than a few hundred kilometres. Over this limit, the s.a. option of GDP has failed (Lesard experiment; Piuzzi *et al.* 1978). We consider that this fact is due to the approximate short arc model chosen, and, by the way, could be overcome by using a more accurate model.

In concluding this section, I should mention that the order of magnitude of the *a posteriori* standard variation of Doppler observation, ϕ, is ± 0.15–0.20 count for p.p.–b.e. and 0.06–0.08 for p.p.–p.e. or s.a.

4. Status and developments of geodetic uses

Geodetic and geodynamical applications of the satellite Doppler technique are very varied and efficient: positioning, Earth's gravity field, polar motion, and geophysical parameters such as Love numbers. We shall only consider here the first item, for which a variety of applications can be mentioned: (*a*) 'zero order' network for the establishment (or readjustment) of a new terrestrial datum; (*b*) analysis of distortions of existing horizontal networks; (*c*) readjustment and strengthening of an existing horizontal network; (*d*) extension of an existing network, determinations of new stations in such a network (e.g. boundary delimitation, link of islands, offshore positioning); (*e*) geoidal computation; (*f*) levelling.

The study of models relating Doppler and terrestrial reference systems is now under investigation at the I.G.N. Some general or preliminary results are given here, rather as a basis for discussion. We shall basically consider here the three-dimensional framework. Coordinates of a station in the geocentric system associated to the Doppler technique (I, II or III) are denoted by $X_D = (X_{D,1}, X_{D,2}, X_{D,3})$, and by $X_G = (X_{G,1}, X_{G,2}, X_{G,3})$ in a terrestrial system (G). The relation between X_D and X_G will be expressed as

$$X_G = F(X_D, T),$$

where $T = (T_1, T_2, \ldots, T_k)$ are transformation parameters. A classical model is the seven parameter model ($k = 7$): translation + rotation + scale factor.

Using one of the three options I, II or III, we get for each station (i) a set of Doppler coordinates $\hat{X}_D$ which differ from the true value X_D by

$$\hat{X}_{D,i} = X_{D,i} + D_{1,i} + D_{2,i} + D_{3,i}.$$

Similarly, X_G is estimated by $\hat{X}_G$, a function of horizontal position $(\hat{\lambda}, \hat{\phi})$ and vertical information $\hat{h}_e = \hat{h} + \hat{N}$.

We can now review the various situations and give some results:

Case (a). The new datum is defined by a choice of values for T, $\hat{T}$. In this case, the estimation of geodetic coordinates is directly given in three dimensions by

$$\hat{X}_{G,i} = F(\hat{X}_{D,i}, \hat{T}).$$

The accuracy of the result is given by $D_{1,i} + D_{2,i} + D_{3,i}$.

For I, $D_{2,i}$ can be neglected. Moreover, if the Doppler measurements have been made in a short time span, $D_{3,i}$ is independent of i, in such a way that the relative accuracy is improved.

For II, similar comments can be made, though $D_{2,i}$ cannot be neglected. For Doppler measurements performed simultaneously, $D_{3,i} + D_{2,i}$ is independent of i.

For III, either a simultaneous data set can be used, or several data sets with common stations, which can be merged into a unique global data set.

Generally, in case (a), the resulting geodetic system is an average geocentric terrestrial system. In this case, at least for I and II, usually no translations are used, and estimations of T can be found from several investigations such as comparisons with other space techniques or physical geodesy. In option III, satisfactory solution is to compute the data set in p.p. (I or II) and to estimate the transformation $\hat{T}_1$: III $\rightarrow$ p.p., then to use a standard transformation $\hat{T}_2$: p.p. $\rightarrow$ G and finally to use $\hat{T} = \hat{T}_1 + \hat{T}_2$: III $\rightarrow$ G.

Case (b). Using $\hat{X}_{D,i}$ and $\hat{X}_{G,i}$ for each station, we can estimate T by using the transformation formula and suitable weight. Residuals, $\hat{X}_{G,i} - F(\hat{X}_{D,i}\hat{T})$, can be interpreted as distortions and either plotted by contour maps or approximated by a suitable mathematical expression. The components of the distortions can be alternatively expressed in a global geocentric or a local natural frame.

Case (c). In this case, it is possible to merge Doppler measurements with terrestrial ones (vertical and horizontal angles, distances). A suitable model is a three-dimensional model, with $X_{G,1}, X_{G,2} X_{G,3}$ as unknowns for each station. T is also introduced as unknown. As previously seen, X_D is determined in the three options. The solution of the datum problem with the X_G coordinates is then equivalent to the determination of T. For instance, it is possible to hold T at an *a priori* value (cf. case(a)), or to add observations to some points of known geodetic coordinates. Such use is under study at the I.G.N. for applications in various countries (Libya, Jordan, France).

Case (d). For positioning in an existing system G, each option can provide coordinates from X_D with the use of either standard values for T or values estimated from simultaneous occupation of stations of known coordinates in G. This last solution improves the accuracy, especially when distortions exist in G.

Cases (e) *and* (f). After the use of Doppler techniques for determination of coordinates in G, and the choice of a spheroid, one can compute the height above ellipsoid: $h_e = h + N$. This result can be used either for levelling (determination of h) when geoidal information is available or for computation of N when heights are known.

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