Application of Differenced Tracking Data Types to the Zero Declination and Process Noise Problems

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A preliminary analysis of the information content inherent in differenced doppler and differenced range data [Quasi-VLBI (very long baseline interferometry)] is made to illustrate why these data types may be superior to conventional data types, when the spacecraft is at a low declination or is subject to unmodelable accelerations. This simple analysis, based upon a 3 parameter model of the range and range-rate observables, shows that in certain circumstances the differenced data types can be expected to improve the accuracy of the orbit determination solution. Some hardware and calibration requirements which will insure that the data will be of sufficient quality are briefly discussed.

I. Introduction

This article considers the use of differenced simultaneous or near simultaneous tracking data from two widely separated tracking stations as a countermeasure for two particularly troublesome problems that occur in determining the orbit of an interplanetary spacecraft, namely, the zero declination and process noise problems. The process noise problem refers to the difficulties encountered in determining the orbit of a spacecraft that is subject to random non-gravitational acceleration uncertainties. The acceleration uncertainties, although often negligible in their direct effect on the physical orbit of a spacecraft, can severely limit the capability of actually solving for the orbit on the basis of conventional tracking data types. The zero declination problem is a more familiar difficulty, i.e., obtaining accurate short arc solutions with zero declination, declination insensitive doppler data. The problem is particularly acute when the spacecraft random accelerations degrade longer arc solutions. The following presentation indicates that the differenced data techniques promise significant improvements in orbit determination performance, particularly in cases for which the zero declination or process noise problems are a limiting factor. The degree of improvement is, however, contingent on projected, although not overly optimistic, tracking instrumentation and system calibration capabilities.

Presently only two-way doppler and three-way doppler are simultaneously available at separate tracking stations. This discussion broadens the selection in considering simultaneous two-way and three-way range and nearly simultaneous two-way range measurements, one before and one after an interstation handover. Three-way range has never been used as an explicit data type, yet it is equivalent to station-to-station timing techniques that have been used for lunar spacecraft tracking. There should be no difficulty in implementing the three-way ranging with the planetary instrumentation (see Ref. 1). This preliminary analysis treats the simultaneous data in differenced form, i.e., two-way minus three-way doppler, two-way minus three-way range, and two-way range minus near simultaneous two-way range. This approach need only be an artifice for revealing the advantages of the simultaneous tracking data in circumventing the process noise and zero declination problems. Although explicit differencing may prove to be a satisfactory mode of incorporating the simultaneous data, a more efficient "optimal" use of the data entails a direct combination of both data types with a suitably designed orbit determination filter.

The differenced data types, two-way minus three-way doppler and two-way minus three-way range are analogous to the VLBI (very long baseline interferometery) data types, fringe rate, and time delay, respectively, and hence are sometimes referred to as quasi-VLBI data. (Two-way minus two-way range contains the same information as time delay VLBI, yet has different error characteristics as explained later.) Williams in Ref. 2 discusses the characteristics of VLBI tracking, primarily with regard to geophysical parameter determinations and he points out that in spite of the remarkable precision available to VLBI techniques their direct application to spacecraft orbit determination is limited by the same tracking platform and propagation media uncertainties affecting the conventional tracking data. The direct use of actual VLBI measurements for spacecraft navigation is in addition hindered by the rather special data processing requirements associated with interferometery. The conventional tracking data VLBI analogs, however, provide the special VLBI characteristics discussed in this article with the conventional tracking data acquisition ease and adequate measurement precision (with respect to expected navigation requirements and calibration accuracies). These comments are not intended to minimize the promise of VLBI in aiding Earth-based interplanetary navigation since, although VLBI may be inconvenient for direct spacecraft tracking, it is expected to be valuable in tracking platform calibration.

The discussion of differenced tracking data proceeds in the following with an analysis of two-way minus three-way doppler as a means for circumventing the process noise problem. The treatment serves principally as a motivation for the use of the simultaneous two-way and three-way data and as an identification of associated major error sources. The next segment of the discussion considers differenced range data types for use in alleviating the zero declination problem, and delineates the major expected error sources.

II. Differenced Doppler

Differenced simultaneous doppler (two-way doppler minus three-way doppler) promises to be less sensitive to short-term spacecraft random accelerations than conventional two-way doppler. This effect is easily motivated with the familiar Hamilton/Melbourne range rate representation of doppler residuals (see Ref. 3):

$$\Delta\dot{\rho} = a + b\sin\omega t + c\cos\omega t + n(t)$$

with

$$a = \Delta\dot{r}(t)$$
$$b = -r_s\omega\sin\delta\Delta\delta(t)$$
$$c = -r_s\omega\cos\delta\Delta\alpha(t)$$

where $\Delta\dot{r}$, $\Delta\delta$, and $\Delta\alpha$ are instantaneous corrections to the distant spacecraft's geocentric range rate, declination, and right ascension over the duration of the pass. Parameters r_s, ω, and δ are station radius from the spin axis, Earth rotation rate, and spacecraft nominal declination, respectively. The time $t = 0$ corresponds to nominal meridian crossing to allow simpler expressions for b and c. The function $n(t)$ represents a data noise process. This representation implies that the information available from a single pass of doppler data can be expressed in terms of estimates of the spacecraft's geocentric range rate, declination, and right ascension. The difficulties arising from random spacecraft acceleration can be visualized as follows: accelerations affect the data most strongly through the a-term, short-term acceleration variations will introduce short-term velocity variation, and these components then introduce errors into the b and c determinations, thereby corrupting the right ascension and declination solutions.

Consider for example a moderate spacecraft random acceleration of 5×10^{-11} km/s^2. (Acceleration uncertainties can be expected to range from the 10^{-12} km/s^2 affecting ballistic spacecraft to the 10^{-9} km/s^2 affecting a thrusting solar electric spacecraft.) The worst possible 1-day degradation in b and c is produced by a radial acceleration of the form

$$a_r \sim (5 \times 10^{-11})\cos(\omega t + \phi)$$

inducing an effective station location error of magnitude

$$\frac{5 \times 10^{-11}}{\omega^2} \sim 10 \text{ meters}$$

Thus, relatively small acceleration uncertainties can conceivably cause significant spacecraft position measurements.

Consider now topocentric range rate observed from two separated tracking stations

$$\Delta\dot{\rho}_1(t) = \Delta\dot{r}(t) + b_1 \sin \omega t + c_1 \cos \omega t + n_1$$

$$\Delta\dot{\rho}_2(t) = \Delta\dot{r}(t) + b_2 \sin \omega t + c_2 \cos \omega t + n_2$$

The parameters b_1, b_2, c_1, c_2 are linear expressions in the $\Delta\alpha$ and $\Delta\delta$ corrections, their explicit form depending on the particular time reference used in the above representations. Two-way doppler residuals obtained at station 1 can be expressed as $2\Delta\dot{\rho}_1$. Three-way doppler residuals available at station 3 are of the form $\Delta\dot{\rho}_1 + \Delta\dot{\rho}_2 - C\Delta f/f$ where the $C\Delta f/f$ term arises from the frequency standard discrepancy, Δf between stations 1 and 2. The difference of two-way doppler from station 1 and 3-way doppler from station 2 is represented as

$$\Delta\dot{\rho}_1 - \Delta\dot{\rho}_2 + C\Delta f/f = C\Delta f/f + (b_1 - b_2)\sin \omega t + (c_1 - c_2)\cos \omega t \tag{1}$$

over the overlap $\psi_1 \leqq \omega t \leqq \psi_2$. The geocentric range rate terms subtract out and are replaced by a "velocity bias" $C\Delta f/f$ arising from the relative station to station frequency standard bias $\Delta f/f$ (C = speed of light). Herein lies the motivation for differenced doppler data: in the presence of large unmodelable random acceleration, the differenced doppler allows separation of $\Delta\delta$ and $\Delta\alpha$ determination, through $b_1 - b_2$ and $c_1 - c_2$, from a corrupted $\Delta\dot{r}$ determination. The technique is hindered, however, by the introduction of a velocity bias uncertainty in the place of the geocentric range rate uncertainty. Clearly, the differenced doppler data can be effective in circumventing process noise effects only as long as the uncertainties arising from frequency standard instability are significantly less than the process noise uncertainties expected in the conventional doppler data.

The differenced doppler data is formally identical to VLBI fringe rate data (with respect to the above representation), hence the term quasi-VLBI. This correspondence includes the velocity bias term that arises from the tracking station frequency standard biases. The only essential difference between the differenced doppler and fringe rate VLBI (in the case of spacecraft tracking) lies in the different data resolution capabilities inherent to the two techniques. The geometric relationships characteristic of either fringe rate VLBI or differenced doppler can be visualized as shown in Fig. 1, where $\bar{r}_{s_1}$ and $\bar{r}_{s_2}$ are equatorial projections of the two tracking station radius vectors. Associated with those data types is the projected "base line" $\bar{r}_{s_1} - \bar{r}_{s_2}$. The differenced data can be viewed as conventional doppler (minus the geocentric effects) observed from a "pseudo-station" located at $\frac{1}{2}(\bar{r}_{s_1} - \bar{r}_{s_2})$ during the overlap of stations 1 and 2.

The short overlap durations and the offset tracking configurations associated with the geometries of widely separated tracking stations can diminish the precision of the $\Delta\delta$ and $\Delta\alpha$ determinations. In contrast to the usual Hamilton/Melbourne analysis, determinations of the parameters $b = b_1 - b_2$ and $c = c_1 - c_2$ as well as $\Delta\delta$ and $\Delta\alpha$ cannot generally be considered as independent, complicating a detailed error analysis such as provided by Ref. 3. In any case

$$\sigma_b^2 + \sigma_c^2 = \omega^2 r_B^2 (\sin^2 \delta\, \sigma_a^2 + \cos^2 \delta\, \sigma_\delta^2)$$

depends only on the pass width and the data noise where σ_a^2, σ_b^2, σ_α^2, σ_δ^2 are the variances of the a, b, $\Delta\alpha$, and $\Delta\delta$ determinations based on the data in Eq. (1) (assuming a particular data noise variance σ_n^2). r_B is the baseline projection length $|\bar{r}_{s_1} - \bar{r}_{s_2}|$. Estimates that are sufficient for the purposes of this discussion can then be obtained from

$$\sin^2 \delta\, \sigma_\delta^2 \leqq (\sigma_b^2 + \sigma_c^2)/r_B^2\omega^2$$

$$\cos^2 \delta\, \sigma_\alpha^2 \leqq (\sigma_b^2 + \sigma_c^2)/r_B^2\omega^2$$

The α and δ variances, therefore, have bounds that depend on the overlap width $\psi_2 - \psi_1$ and the projected baseline length r_B. These quantities vary considerably with the particular tracking station pair. Table 1 presents the baseline and projected baseline (obtained from Ref. 2) length and overlap variations for a selection of DSN tracking station pairs. The overlap varies approximately linearly with spacecraft nominal declination for pairs in the same northern or southern hemisphere. The strength of a given station pair increases with the available overlap width, yet large overlap widths go with short baseline projections, e.g., station pair 51–61, which tend to diminish the strength of the station pair. The α and δ variances also depend on the spacecraft nominal declination, with declination solutions becoming degenerate near $\delta = 0$ in analogy to conventional doppler.

Figure 2 presents curves of $(\sigma_b^2 + \sigma_c^2)^{1/2}/\omega$ (scaled as effective station location errors) as functions of overlap half-width and *a priori* velocity bias uncertainty. The values are based on 1 mm/s data taken at 1-minute intervals. The *a priori* velocity bias uncertainty as well as the overlap width are seen to strongly affect the precision of the a and b, and accordingly the $\Delta\alpha$ and $\Delta\delta$ determinations. The effect of good *a priori* velocity bias information is particularly dramatic for the short overlap widths that are available from typical station pairs. For instance, an *a priori* velocity bias certainty of 0.1 mm/s ($\Delta f/f < 3 \times 10^{-13}$) allows 3-meter effective station location error determinations of $\Delta\alpha$ and $\Delta\delta$ for a nominal 30-deg half pass width. This dependence on velocity bias *a priori* implies that long-term frequency standard stability is a critical factor affecting the capability of the differenced data in determining the spacecraft's right ascension and declination.

Short-term frequency instabilities, particularly diurnal variations, produce $\Delta\delta$ and $\Delta\alpha$ errors in the same way short-term acceleration variations affect two-way doppler. Figure 3 shows the relation between short-term frequency stability and rss b and c accuracy (assuming otherwise perfect b and c determinations). The domains of two available frequency standards (hydrogen and Rubidium) are also indicated (see Ref. 4). Rubidium associated accuracies are on the order of 30 meters in effective station location whereas the hydrogen accuracies are bounded by 3 meters. (Hydrogen maser stability of 5×10^{-13} is conservative.) Three-meter accuracies are compatible with the performance requirements of modern interplanetary navigation while 30-meter accuracies are not. This and the above comments regarding long-term stabilities imply that the useful application of two-way/three-way doppler tracking requires hydrogen frequency standards at each tracking station.

The preceding analysis is not intended to imply that the sole use of two-way minus three-way doppler or, equivalently, fringe rate VLBI is an efficient use of the data received at both stations from the spacecraft. The differenced data is effective in allowing separation of topocentric and geocentric tracking information—even in the case of a spacecraft experiencing large random accelerations. Ultimately, maximum information is extracted if concurrent two-way and three-way data are processed together with a suitably designed orbit determination filter that takes advantage of the known random acceleration characteristics. The differenced data provides, nevertheless, an adequate conceptualization for preliminary analysis as well as a straightforward first approximation to an "optimal" treatment of concurrent two-way and three-way doppler data.

The scope of this article's treatment of differenced doppler data is the influence of process noise on the information available from only a single tracking pass, i.e., the data available over periods of less than one day. Orbit determination solutions require data over several days and, although short-term accuracies do determine ultimate orbit determination performance, the correspondence between short-term and longer-term accuracy is by no means a simple one. This is particularly true in the case of acceleration uncertainties since they directly affect the spacecraft's position and velocity. The topic of longer arc orbit determination is presented in the next article[1] of this volume.

III. Differenced Range

The two-way minus three-way doppler is analogous to fringe rate or narrow band VLBI. A time delay or wideband VLBI analogue can be implemented by differencing range measurements taken at separate tracking stations.

As mentioned previously, two modes are considered for differenced range time delay measurement, namely, two-way range minus simultaneous three-way range and two-way minus near simultaneous two-way range. The two-way minus two-way technique is motivated by the difficulties encountered in obtaining sufficiently precise tracking station clock synchronization for acceptable three-way range accuracies. Three-way synchronization errors are directly involved in the signal arrival measurement so that a timing error Δt produces a range difference error of $C\Delta t$, i.e., at a rate of 300 meters/microsecond. Two-way minus two-way station synchronization, however, introduces an error into the measurement epoch specification producing range difference errors $\dot{\rho}\Delta t$, where $\dot{\rho}$ is the spacecraft's range rate, thus resulting in only ~10-mm errors per microsecond timing error. Since best synchronization accuracies to date (see Ref. 1) are in the 5-microsecond range, the use of the simultaneous differenced range requires advanced methods (e.g., stellar source VLBI or extraction from the tracking data). The timing bias can be expected to drift at 13 meters/day for oscillator stabilities at 5×10^{-13}, implying that the timing bias calibrations or solutions will require frequent updating. It is unclear if two-way minus three-way range is superior to differenced doppler in the case that timing bias is extracted from the spacecraft tracking data.

The measurement geometry associated with either the pseudo or "real" wide-band VLBI is illustrated in Fig. 4.

[1]Ondrasik, V. J., and Rourke, K. H., "An Analytical Study of the Advantages Which Differenced Tracking Data May Offer for Ameliorating the Effects of Unknown Spacecraft Accelerations" (this volume).

The signal time delay, baseline length and signal source direction are seen to be related as follows:

$$\tau = \frac{D}{C} \cos \phi$$

The time delay expression can be related in equatorial coordinates as

$$\tau = \frac{1}{C} [z_B \sin \delta + r_B \cos \delta \cos (\alpha - \alpha_B)]$$

where z_B, r_B, and α_B are baseline z height, equatorial projection length, and right ascension at the time of the delay measurement. Since the delay measurement allows short arc solutions of equatorial angles, differenced range data exhibits the same advantages of insensitivity to process noise as does differenced doppler. In contrast to differenced doppler, however, the time delay permits zero declination, declination solutions, since near zero declination

$$C\Delta\tau \sim z_B \cos \delta \, \Delta\delta$$

so that general time delay errors, $C\Delta\tau$, produce declination errors

$$\Delta\delta \sim \frac{1}{\cos \delta} \frac{C\Delta\tau}{z_B}$$

Short arc determinations on the basis of doppler data (conventional or differenced) are on the other hand degraded by errors of the form

$$\Delta\delta \sim \frac{1}{\tan \delta} \frac{\Delta r_s}{r_s}$$

where Δr_s and Δr_B, in the case of the differenced data, are assumed to be the limiting error sources (see Ref. 3). Figure 5 displays these relationships in terms of position errors at 10^8 km for varying nominal declinations and $C\Delta\tau$ error levels. Typical values are assigned to z_B, r_s, and Δr_s: 7000 km (Goldstone, Canberra), 5000 km, and 1.5 meters, respectively. The figure makes clear the potential of differenced range measurements for alleviating the zero declination problem—assuming that $C\Delta\tau$ errors can be restricted to the sub-10-meter domain. Such an assumption, however, cannot be taken lightly. The conventional application of range measurements regards 10-meter accuracy as entirely adequate (provided that stabilities permit DRVID calibrations, see Ref. 5). Differenced range quasi-VLBI finds 10-meter range measurement marginal with 1-meter measurement system accuracies an attractive goal.

Differenced range measurement errors can be placed in the following general categories:

(1) General baseline errors, including geocentric station location errors, polar motion, and UT1 errors.

(2) Transmission media errors, including ionosphere and space plasma charged-particle effects and tropospheric refraction errors.

(3) General instrumentation errors, including those of signal arrival time measurement, local clock synchronization and rate stability, spacecraft transponder delay, and ground delay.

The influence of baseline errors on the differenced range time delay measurement can be presented in terms of the following differential expression of differenced range:

$$\begin{aligned}\Delta\rho_1 - \Delta\rho_2 &= C\Delta\tau \\ &= z_B \cos \delta - r_B \sin \delta \cos (\alpha - \alpha_B) \Delta\delta \\ &\quad - r_B \cos \delta \sin (\alpha - \alpha_B) (\Delta\alpha - \Delta\alpha_B) + \sin \delta \Delta z_B \\ &\quad + \cos \delta \cos (\alpha - \alpha_B) \Delta r_B\end{aligned}$$

where Δz_B, Δr_B, and $\Delta\alpha_B$ are corrections to the baseline parameters z_B, r_B and $\Delta\alpha_B$. The baseline errors Δr_B and $r_B \Delta\alpha_B$ are less than 3 meters on the basis of station r_s and λ accuracies of 1.5 and 3 meters, respectively (see Ref. 5). The $\sin \delta \Delta z_B$ error is a maximum of 8.5 meters at $\delta = 23.5°$ assuming individual station z height accuracies of 15 meters. The z_B errors can be improved on the basis of preliminary differenced range determinations. Note that declination determinations at zero declination are insensitive to z_B errors.

The influence of baseline errors on differenced range orbit determination accuracy is in any case essentially equivalent to the influence of station location errors on conventional tracking data orbit determination accuracy (except that the differenced data exhibits no singularity at zero declination). The crucial accuracies affecting the feasibility of effective differenced range measurements lie in the media and instrumentation error categories. Adequate estimates of these accuracies are difficult to obtain at this time, since, as mentioned previously, meter-level ranging accuracies have heretofore been considered unnecessary. Thus, current specifications are expected to be overly pessimistic with regard to differenced range applications. Table 2 presents media calibration and instrumentation accuracies for both simultaneous and near simultaneous techniques. In light of the uncertainty regarding the actual possible accuracies, several values are quoted for each error source, including expected present capability and upper and lower values for projected future capability. The future quotations include earliest availability dates. The projected accuracies are illustrated in Fig. 6. Specific references are cited where possible. (The future accuracy capabilities are drawn from Ref. 9 that addresses several specific quasi-VLBI configurations.) These values indicate that meaningful demonstrations of differenced range techniques can be conducted at present and that the future goal of 1-meter level differenced range measurements is indeed a plausible one. The promise of differenced range techniques will become more clear with more detailed analysis and experimental verification of range instrument capabilities in the 3-meter domain, and sub-meter charged particle and troposphere calibration capability.

IV. Concluding Remarks

This article presents reasons why data taken simultaneously or nearly simultaneously from widely separated stations is a partial solution to the zero declination and process noise problems. This analysis should not, however, be conceived of as proving the value of the differenced data. To be able to state with assurance that the differenced data will substantially improve spacecraft navigation, it will be necessary to undertake a thorough accuracy study using analysis tools which are a direct analogue of operational software. Such a study is currently underway and will be reported on in the future. The faith which one may put in the results of this study will be highly dependent on the quality of the information which describes the performance of the frequency standards, ranging machines, and calibration procedures. Ultimately, credible information regarding measurement system performance can only be obtained by an analysis of actual radio tracking measurements taken from an interplanetary spacecraft. Presently plans are underway for acquiring this data during the *Mariner IX* mission.

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Table 1. Differenced tracking data parameters for principal DSN station pairs

Station pair	Baseline length D, km	Baseline z height z_B, km	Equatorial projection length r_B, km	Overlap, deg	
				$\delta = 23.5°$	$\delta = -23.5°$
DSSs 14–42 (Goldstone–Canberra)	10590	7350	7630	85.9	85.9
DSSs 14–61 (Goldstone–Madrid)	8390	441	8380	106.8	27.9
DSSs 14–51 (Goldstone–Johannesburg)	12260	6440	10430	35.4	35.4
DSSs 42–51 (Canberra–Johannesburg)	9589	906	9546	28.7	88.7
DSSs 42–61 (Canberra–Madrid)	12515	7790	9795	26.8	26.8
DSSs 51–61 (Johannesburg–Madrid)	7524	6884	3038	148.1	148.1

Table 2. Differenced range measurement errors

Error source	Present capability, m		Present configuration	Projected capability, m				Projected configuration
				Upper value		Lower value		
	Simultaneous	Near simultaneous		Simultaneous	Near simultaneous	Simultaneous	Near simultaneous	
Charged particles	1[a,b]	1	Faraday rotation	0.1	0.5			S-X down link, 1976
Troposphere	1[a,c,d]	1	Constant model	0.5	0.5			Historical data improved mapping, 1973
Signal arrival time/ground delay	10[e]	10[e]	Mariner Mars 1971 planetary systems	10	10	1	1	
Clock sync	1000[e]	1	3 μs	1	1			Star source VLBI, 1976
Clock rate at 1 AU	3[f]	3	Rb standard $\sim 10^{-11}$	0.3	0.3			H standard, 1973
Transponder delay instability	0.1	1	Mariner Mars 1971	0.1	1			

[a]Reference 5.
[b]Reference 6.
[c]Reference 7.
[d]Reference 8.
[e]Reference 9.
[f]Reference 4.

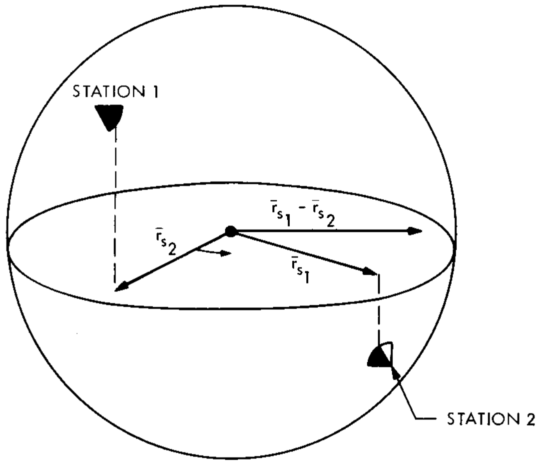

Fig. 1. Differenced data geometry

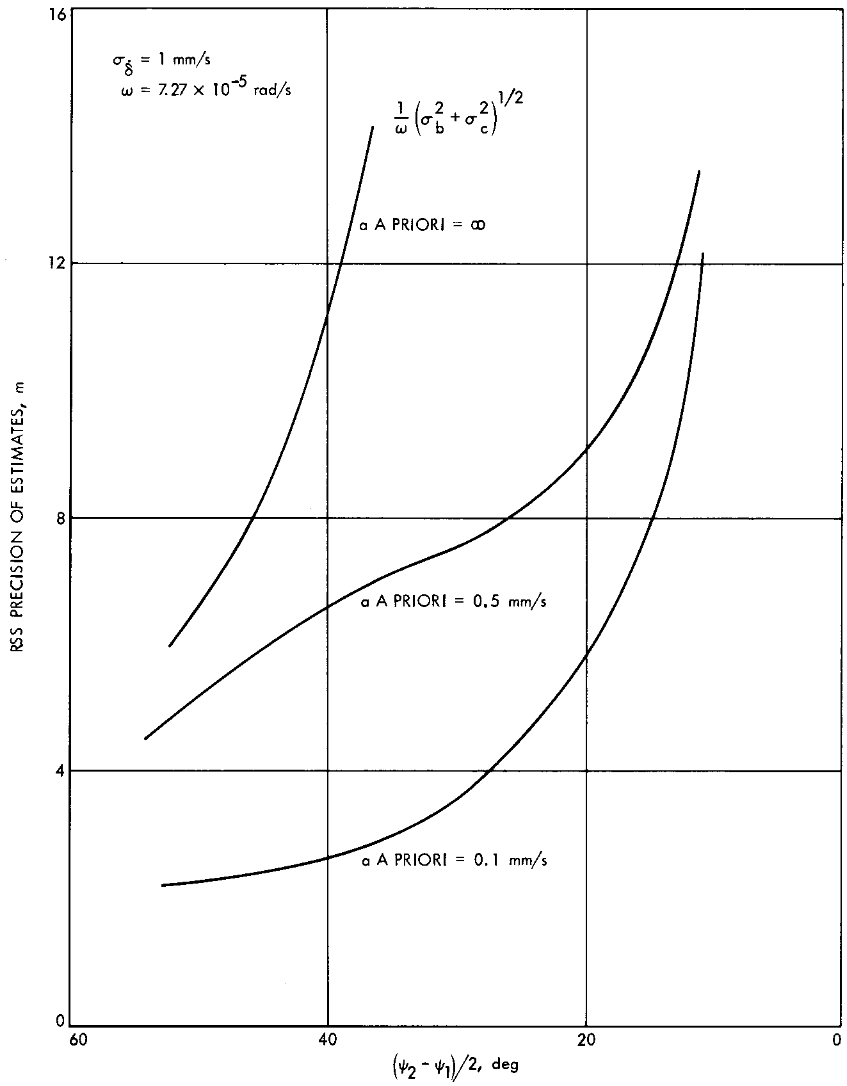

Fig. 2. Precision of *b* and c parameters as a function of overlap halfwidth and *a a priori*

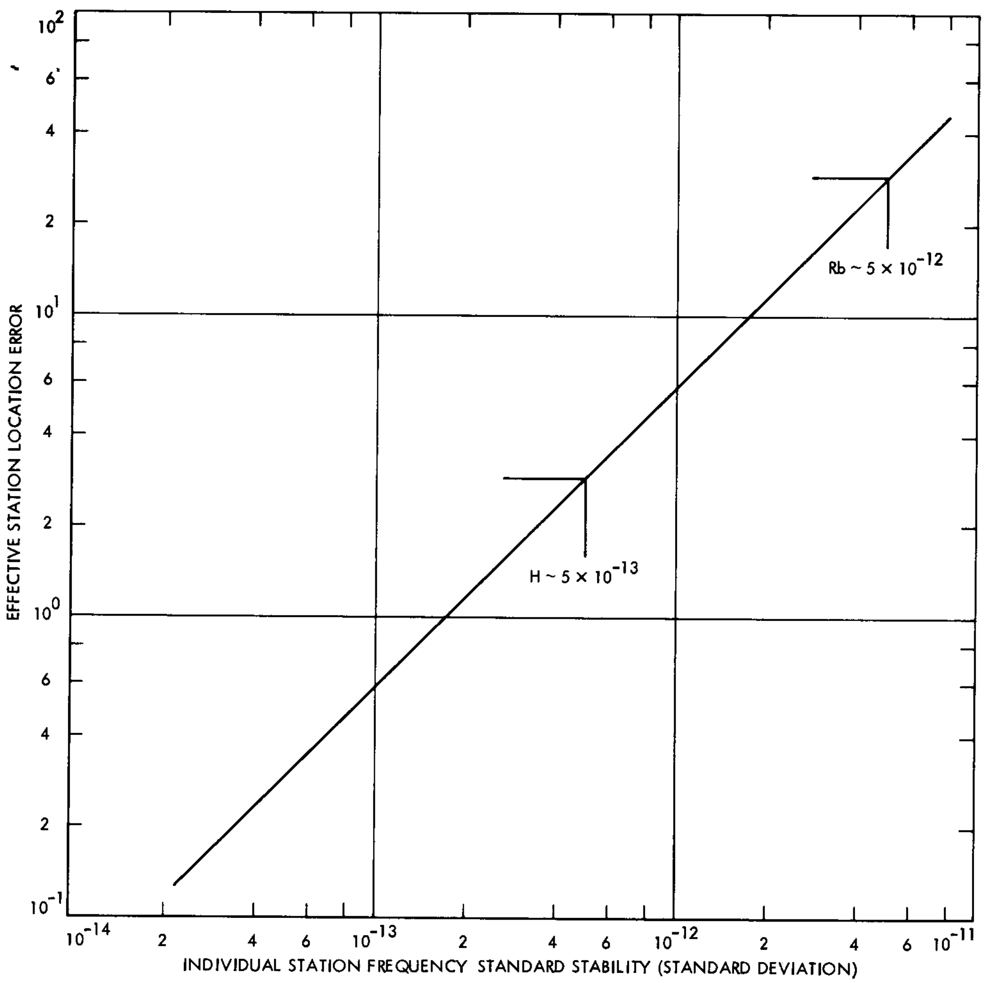

Fig. 3. Effective station location error due to worst case frequency standard drift

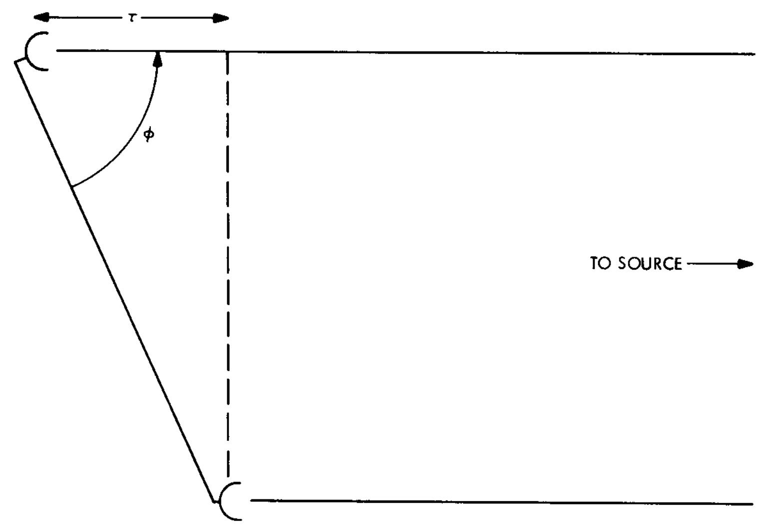

Fig. 4. Signal time delay

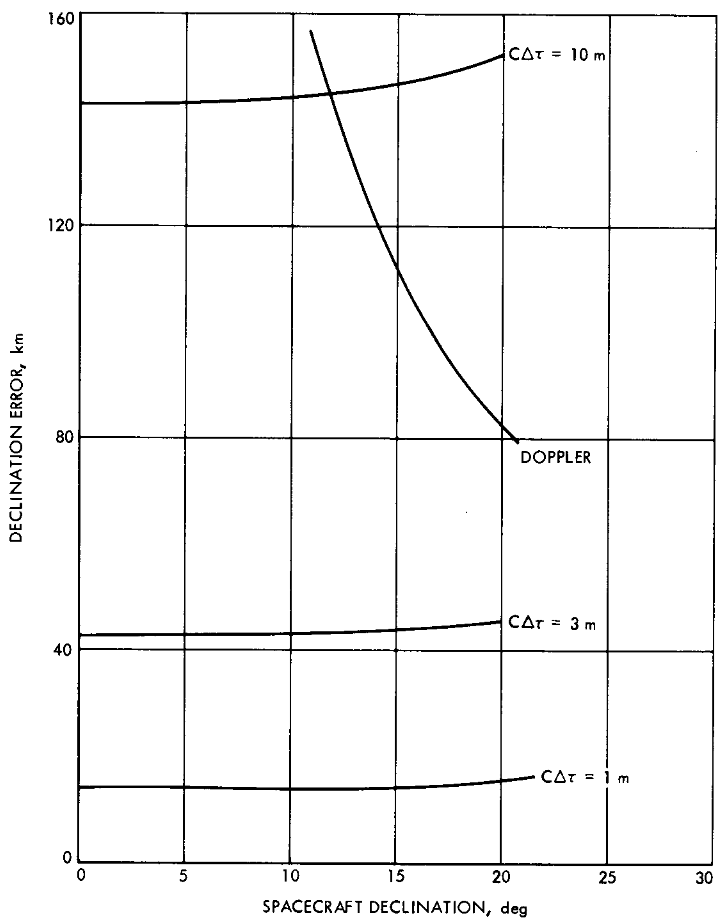

Fig. 5. Doppler and differenced range declination determination error

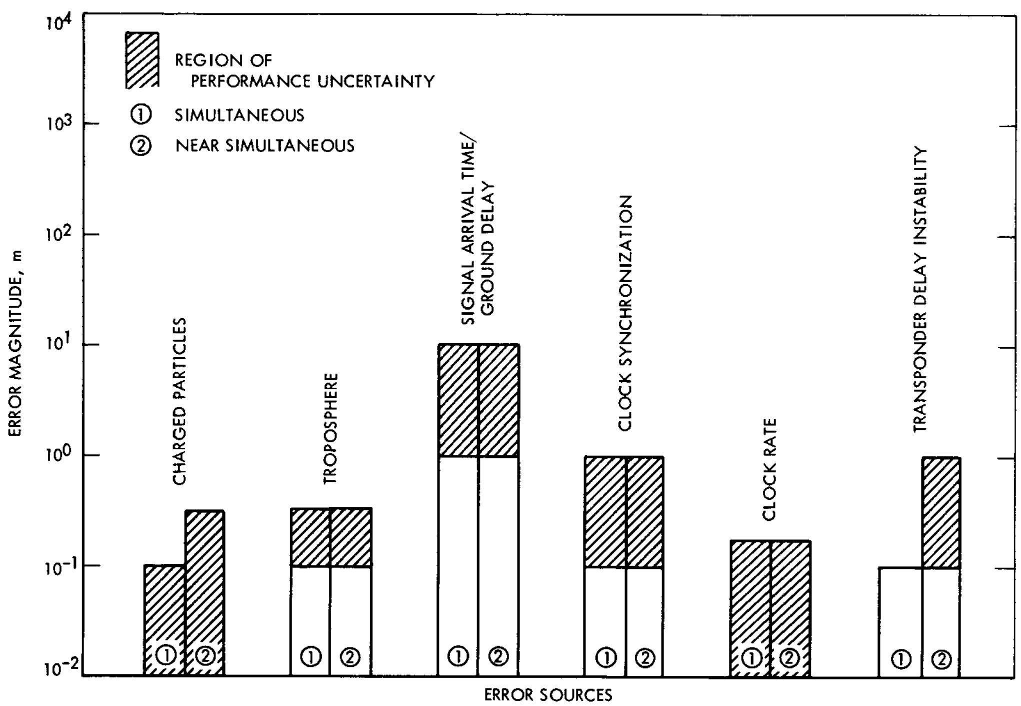

Fig. 6. Future configuration differenced range error sources