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DOPPLER SATELLITE POSITIONING OF OFFSHORE STRUCTURES

by L.D. Hothem and W.E. Strange
National Geodetic Survey, National Ocean Survey
National Oceanic and Atmospheric Administration
Rockville, Md., USA

ABSTRACT

Both for reasons of accuracy of results and economy of operation, Doppler satellite positioning has become an important technique for extending geodetic control surveys into the offshore areas. Fixed-site Doppler satellite surveys to position offshore structures have been reported in areas of the Canadian coastal waters, North Sea and Gulf of Mexico. The navigation or two-dimensional positioning mode and the more accurate three-dimensional positioning mode are the basic Doppler satellite positioning techniques. The Doppler station accuracy is a function of the orbital data accuracy and the method of data reduction. Provided site conditions are met and equipment operation is normal, the accuracy of Doppler satellite positioning of offshore structures is estimated to be 0.5 to 1.5 meters rms in each coordinate.

In order to make use of the accuracy inherent in Doppler positioning, care must be taken in relating the positions to the local datum coordinate system.

INTRODUCTION

Development of the resources of the continental shelf has led to placing of fixed offshore structures at increasingly longer distances from shore. Since the change of a lease or political subdivision boundary by one or two meters can sometimes make a difference of several million dollars, it becomes important to have precise positions for these offshore structures. Beyond the line of sight from shore, positioning with the accuracy desired, using conventional methods, becomes extremely difficult and expensive, if not impossible. Thus, both for reasons of accuracy of results and economy of operation, the Doppler satellite positioning method is coming into increasing use as a means of positioning offshore structures.

There are two basic modes of determining a location using Doppler satellite positioning techniques — the navigation or two-dimensional positioning mode and the three-dimensional positioning mode. For positioning of fixed offshore structures, the more accurate three-dimensional positioning mode is normally used.

The positioning of a fixed offshore structure is not essentially different from positioning of a Doppler station on land. However, because of the environment on an offshore platform, the noise level of the data is often higher than for a land station and the question of possible degradation of accuracy must be examined.

In defining the accuracy of a position of an offshore structure, a user is normally interested in accuracy relative to geodetic positions on an adjacent land area. To maintain the inherent accuracy capabilities of Doppler positioning, care must be taken in relating the various coordinate systems involved and in recognizing that systematic differences can exist between two Doppler positions because of the type of ephemeris used or because of the data reduction program employed.

THE DOPPLER SATELLITE EPHEMERIDES

The accuracy of a station position derived by a Doppler satellite positioning method is, to a large extent, a function of the accuracy of the orbital data used in the reduction. Also, the coordinate system in which station positions are expressed is that earth-centered (geocentric) coordinate system in which the orbit is expressed. Therefore, it is important to consider the two Doppler satellite ephemeris systems in common use in terms of orbital accuracies and coordinate systems. Both of these quantities depend primarily upon the gravity field used to generate the orbits and the positions assigned to the stations whose data is used to generate the orbits.

The broadcast or operational ephemerides are those injected into the six satellites of the Navy Navigational Satellite (NAVSAT) or Transit System. These predicted ephemerides are computed using tracking data from four stations located in Minnesota, Maine, California, and Hawaii. The station positions and gravity field used to produce the broadcast ephemeris have been changed from time to time during the history of the NAVSAT System. From June 1968 through late 1975, the broadcast ephemerides were computed using the APL 4.5 gravity model and a particular set of coordinates for the four tracking stations.

By late 1975, the latest change in the geopotential model used to compute the operational ephemeris was implemented. The new geopotential model used is the World Geodetic System 1972 (WGS-72) model. The dates of implementation of the WGS-72 gravity model, to compute the orbit of the six Doppler satellites, are given in Table 1. The positions of the four tracking stations were modified, effective August 1975. The station position changes were small, being less than 7 meters in any coordinate. The significance of these changes is twofold. First, the error in the broadcast ephemerides has been reduced. The accuracy of the predicted reference orbit is now estimated to be about 12 to 28 meters (BLACK, 1975). BLACK (1976, *per. comm.*) has found this improvement in the ephemerides is directly reflected in substantially decreased scatter of single pass position determinations. This has led to improved accuracies in 3-D position solutions using the broadcast ephemeris, although not on a one-for-one basis (LEROY & MURPHY, 1976).

TABLE 1

WGS-72 gravity model implementation schedule

APL Satellite No.	Effective date
30120	Day 344, 1975 at 0202 UT
30130	Day 346, 1975 at 0857 UT
30140	Day 342, 1975 at 2341 UT
30180	Day 217, 1975
30190	Day 345, 1975 at 0455 UT
30200	Day 346, 1975 at 0942 UT

The second significance of the change to the broadcast ephemerides is that orbits produced using the WGS-72 gravity model and the new station coordinates will have systematic difference from those using the APL 4.5 gravity model and the old station coordinates. This means that station positions, obtained since late 1975 using the broadcast ephemeris, can differ systematically from those obtained prior to this time.

The existence of position differences brought about by the gravity field and station position changes has been noted but the exact nature of the differences, on a worldwide basis, has not been defined. Because the stations used to provide data for orbit generation are not worldwide, it is possible that the systematic orbit differences may cause station position differences, dependent upon location (ANDERLE, 1976, *per. comm.*).

The precise ephemerides are two-day orbits computed after the fact using data from a worldwide network of approximately 20 stations. Prior to April 1975, these precise ephemerides were produced by the Naval Weapons Laboratory (NWL) and since then, by the Defense Mapping Agency Topographic Center (DMATC). Normally, these precise ephemerides are produced for no more than two of the six Doppler satellites with the designated satellites changing from time to time.

The geopotential model now used to produce the precise ephemerides is called NWL 10E. The coordinate system for the worldwide tracking network is referred to the NWL 9D reference system. The differences between the designations applied to the gravity field and coordinate system reflect the fact that the two were not derived in a single simultaneous adjustment. Additional details concerning the method of computation of the precise ephemeris can be found in ANDERLE (1974a) and BEUGLASS & ANDERLE (1972). Between 1971, when highly portable precise positioning Doppler equipment became available and January 1, 1973, when the NWL 10E gravity model and NWL 9D coordinate system were adopted, there were several changes in gravity models and station coordinate systems. Comparisons have shown the various changes have led to systematic station position differences of only ± 1 to 2 meters in North America. Since a worldwide network of tracking stations contributes to the orbit computations, it seems unlikely that the systematic differences vary greatly with location in the world.

The significance of the above discussion is that, if one is aiming at the 1 to 2 meter accuracy level in locating offshore structures, recognition must be given to the fact that not all Doppler station position results are necessarily expressed in the same coordinate system. Of considerable interest will be the definition of the conversion factors between the present precise ephemeris system and those of the present and immediately preceding broadcast ephemeris systems. A word of caution is important. ANDERLE (1976) has suggested modifying station positions obtained using the precise ephemeris, by application of a longitude rotation and a scale change. ANDERLE refers to the rotated and scaled system as being the NWL 10F system which he states is equivalent to the WGS-72 coordinate system. This should not necessarily be taken to mean that station positions obtained using the present broadcast ephemerides can be transformed to the same coordinate system as those obtained using the present precise ephemeris by applying the ANDERLE transformations in reverse. While the present broadcast ephemeris is computed using the WGS-72 gravity model, it is not necessarily true that the station positions of the four stations used in generating the orbit are in the WGS-72 coordinate system.

METHODS OF DOPPLER DATA REDUCTION

There are two basic modes of reduction for determining a location using Doppler satellite positioning techniques -- the navigational mode and the three-dimensional positioning mode. In the navigation mode, two-dimensional (2-D) positioning is accomplished by using observations of a single pass of a satellite, together with the broadcast ephemeris to compute a latitude (ϕ) and a longitude (λ). To obtain a single pass 2-D solution, the geocentric (earth centered system) radial position of the ground station antenna's electrical center is also required as input to the solution.

To compute the geocentric radial position of the antenna's electrical center, it is usual to input to the computational program the parameters of a reference ellipsoid and a height above this ellipsoid. Table 2 is a summary of the parameters of reference ellipsoids mentioned in this paper. The height above ellipsoid consists of a geoid height relative to the ellipsoid and an elevation above the geoid (mean sea level). It is important that the geoid heights (separations) and ellipsoid parameters used are compatible so as to provide an accurate geocentric radius vector. The particular ellipsoid used is unimportant so long as a compatible set of geoid heights is maintained. The geoid heights used should be those which provide the best geocentric radius vector; they need not be derived from the gravity field used to generate the satellite ephemerides. Indeed, at the present time, the gravity fields which produce the most accurate orbits for the polar Doppler satellites are not the gravity fields which produce the most accurate geoid heights. Finally, it should be recognized that it is the accuracy of the distance of the antenna's electrical center from the satellite's earth-centered coordinate system that is important rather than the mathematical steps used in its determination.

TABLE 2

Reference ellipsoids

Datum	Semi-major axis (a) (km)	Flattening (f)
APL 4.5	6378.144	1/298.23
WGS-72	6378.135	1/298.26
NWL 9D (WGS 1966)	6378.145	1/298.25
NAD 1927 (Clarke 1866)	6378.2064	1/294.979

Discussions of the navigational mode of Doppler satellite positioning, combined with other offshore navigation systems, are found in KIRKHAM & THOMSON (1974), EATON *et al.* (1976), DENNIS (1976), OTT (1976) and WASILEW & VIVIAN (1976). The primary use of the navigation mode of positioning is for the determination of positions of moving ships. The navigation mode has also been used for positioning when moving offshore oil platforms into position (KIRKHAM & THOMSON, 1974). One can also determine ϕ and λ for a fixed point by computing the mean values of ϕ and λ obtained from a number of 2-D single pass solutions (MOFFETT, 1973; EATON *et al.*, 1976), but these are less accurate than those obtained in the 3-D positioning mode.

In the three-dimensional (3-D) positioning mode of Doppler data reduction, a substantial number of satellite passes are processed simultaneously to obtain a set of Cartesian coordinates (X, Y, Z) describing the position of the fixed station in a geocentric coordinate system. The orientation of the coordinate axes and the scale of the resulting positions are defined by the coordinate system and scale of the satellite ephemeris positions. These coordinates can be expressed in a geodetic coordinate system (ϕ, λ, H) relative to a chosen geocentric reference ellipsoid, the parameters selected for the ellipsoid being entirely arbitrary.

A number of approaches differ in terms of the method of data reduction and in terms of the source of the satellite ephemerides used. The methods of reduction can be characterized in two ways. One characterization is in terms of whether or not the orbit parameters are held fixed or allowed to adjust during the solution. The second characterization is based upon whether station positions are determined individually or data from two or more stations is processed simultaneously.

The most common method in use for 3-D position determination is *point positioning*. With this technique, the position of each ground station is determined independently. The satellite orbits are assumed error free and, with 20 to 50 satellite passes, the station position is recovered using a differential correction process in which the unknowns are corrections to initial estimates of station position and certain system biases. A *point* *positioning* solution can be carried out using either the broadcast or precise ephemeris.

Two of the more important sources of error in Doppler satellite station positioning are orbit error and error due to imperfect modelling of the ionospheric refraction. If positions for two or more stations, separated by no more than a few hundred kilometers, are determined using data from the same satellites during the same time period, the orbit and ionospheric refraction modelling errors would be expected to be highly correlated for the two stations. Thus, the differential positions would be determined with higher accuracy than if computed from point positioning solutions based on different data sets separated in time and/or taken from observing different satellites. In many instances, such as relating the position of an offshore platform to local control on the adjacent land area, the differential position is the quantity of primary interest. Because of the opportunity for improvement in differential station position determination, a number of methods of reduction have been developed assuming simultaneous observations of the same satellite(s) by two or more stations.

The simplest approach to improved differential position determination is to have two or more stations observe simultaneously the same satellite passes and then reduce each station independently in the point positioning mode. The relative positions are then simply determined by differencing the results. This approach might be termed *simultaneous point positioning*. Another approach is to observe simultaneously from two stations in order to obtain a common set of passes for determining the relative positions of two stations (ΔX, ΔY, ΔZ). This approach to data reduction is known as *translocation*.

A considerable variety in details of data reduction and data editing is found in carrying out *point positioning* and *translocation* solutions. More details on these methods can be found in DoD (1972), WELLS (1974), ANDERLE (1974, 1976), SMITH *et al.* (1976) and BROWN (1976). In the *point positioning* and *translocation* approaches described above, the satellite ephemerides are held fixed and not allowed to adjust in the solution. However, where two or more stations have observed the same satellite(s) during the same time period, it is possible to allow for small adjustments in the orbits during the differential adjustment process. In the *multistation solution* approach (KOUBA *et al.*, 1974; KOUBA & WELLS, 1976), several stations observe simultaneously at all times. At least one station continuously observes during an entire observation period with one or more other stations moving from point to point. The data from the stations are then processed simultaneously with the orbital parameters allowed to adjust for each pass within preset limits. A very similar approach is the *short arc adjustment* method described by BROWN (1976).

ACCURACIES OF DOPPLER POSITIONING ON LAND

Since establishment of a Doppler station on an offshore structure is, in most respects, similar to establishment of a station on land, it is worthwhile to review the accuracies of positioning on land.

For *point positioning*, using the precise ephemeris and 30 or more satellite passes, an rms accuracy of better than 1 meter in the NWL 9D system has been found (ANDERLE, 1974, 1976; STRANGE *et al.*, 1975). With *point positioning*, utilizing the broadcast ephemerides, the estimated position uncertainty is at present 2 to 6 meters rms (KOUBA, 1975; BROWN, 1976; SPRADLEY, 1976). These figures for broadcast positioning are based mainly on experience obtained from positioning in North America in relatively close proximity to the four Transit tracking stations whose data is used in generating the broadcast ephemerides. The accuracy of broadcast ephemeris *point positioning* may be lower outside North America.

Based on analyses carried out by the authors, the rms accuracies for relative positions using precise ephemeris *simultaneous point positioning* are $\sigma_{\Delta\phi} = 0.4$ m, $\sigma_{\Delta\lambda} = 0.9$ m and $\sigma_{\Delta H} = 0.5$ m. *Translocation* solutions using the precise ephemeris will yield rms accuracies of 0.5 to 1.5 meters for relative positions (DMATC 1972), hence, there is no improvement over the precise ephemeris *point positioning* or *simultaneous point positioning* method. However, when using the broadcast ephemeris with the *translocation* method, the estimated rms accuracies for relative positions are about 3 meters (WELLS, 1974, BROWN, 1976) which represents some improvement over broadcast ephemeris *point positioning* results.

Multistation or *short arc geodetic adjustment* solutions using broadcast ephemeris are equivalent to corresponding precise ephemeris solutions as far as accuracy of relative positions is concerned. KOUBA *et al.* (1976) and BROWN (1976) report rms accuracies of 0.2 to 1.7 meters in each coordinate for relative positions when utilizing the broadcast ephemerides and 20 to 30 passes per station.

It should be noted that the above stated "accuracies" are in fact precisions in that they define the results that can be achieved by a single investigator using a specific reduction program. It has been found in practice that different investigators using different reduction methods, although they may arrive at essentially the same relative positions of stations, often have systematic differences of 1 to 3 meters in the geocentric positions obtained. On a worldwide basis, systematic differences because of coordinate system differences can be even larger where one user has employed the broadcast ephemeris and another the precise ephemeris in data reduction.

SPECIAL ASPECTS OF OFFSHORE STRUCTURE POSITIONING

Although, in most respects, the Doppler positioning of offshore structures is similar to station positioning on land, there is a difference in the operational environment. On an offshore structure, one is often operating on a metal deck and metal superstructures are often present in the near vicinity of the Doppler equipment antenna.

HOTHEM (1975) found that, in certain cases, the metal deck can cause signal interference due to reflected signals. The interference was most

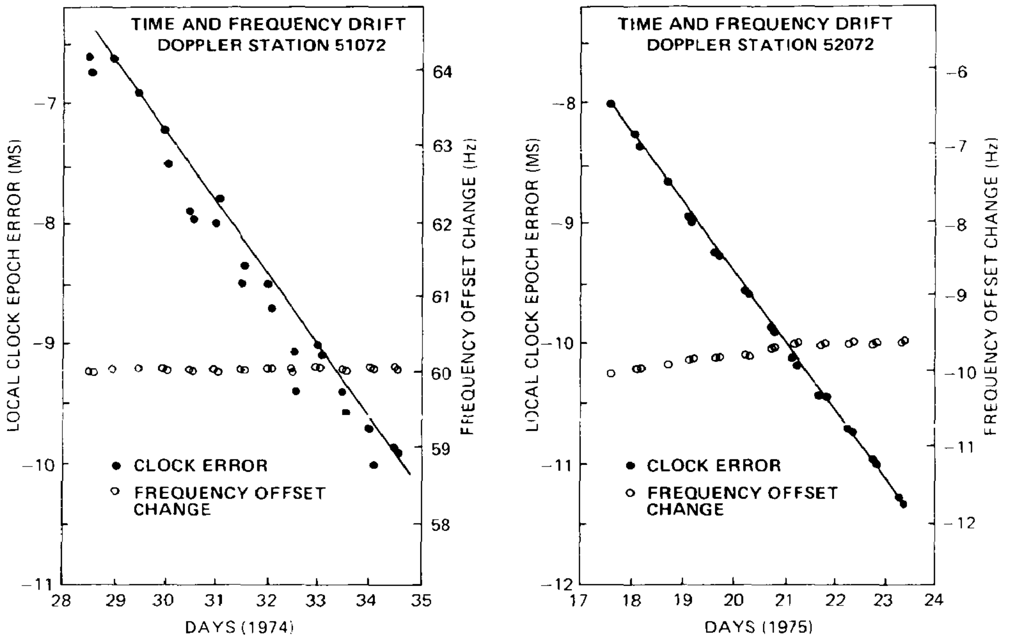

FIG. 1. — *Time and Frequency Drift.* Graph of the Doppler satellite tracking equipment's clock error (●) and reference frequency drift (o) from data observed at offshore Doppler stations 51072 and 52072. Station 52072 is a reobservation of the point for station 51072. The improvement in the clock error values for station 52072 was the result of modifying the observation procedures commonly used on land.

clearly visible in its effect on the clock time error, a pass specific bias determined in carrying out a *point positioning* solution. The clock time error is simply the time offset between the ground instrument clock and the satellite clock. Normally, there is a linear drift in the ground instrument clock during the one to two weeks of a station occupation, the random scatter of determinations of clock differences about a linear relationship being ± 25 µsec. Fig. 1, taken from HOTHEM (1975), shows the clock time error obtained during two separate occupations of the same site on an offshore oil platform. During the first occupation, designated 51072, the antenna was on a tripod as is the normal case on land. During the second occupation, designated 52072, the antenna was set directly on the metal platform deck. The decrease in scatter of the recovered clock time error about a linear change is clearly evident. Thus, with Geoceiver Doppler tracking equipment, the problem was solved by setting the antenna directly on the metal deck rather than on a tripod. In this way, the metal deck would act as the ground plane for the antenna. In order for the metal deck to be fully effective as a ground plane, the antenna must be placed at least two meters from the edge of the platform.

Even with the elimination of the reflection problem, noted above, the random noise level for data gathered on offshore platforms is often larger than for land stations (HOTHEM & STRANGE, 1976). These authors found the increased noise level to be reflected in the larger number of Doppler counts rejected in a solution (5 to 12 % on some platforms vs.

less than 4 % on land) and, on the average, in a higher formal standard error of observed range differences. The higher noise levels were found to be directly related to metal superstructure obstructions. Some platforms, with no obstructions, showed almost no difference in random error statistics from land stations. However, stations with severe obstructions, for example, a steel microwave tower within 5 meters of the antenna, had formal standard errors twice as large as the average for land stations. It is clear that, to the extent possible, the Doppler station on an offshore platform should be placed so that no metal superstructure obstructs a line of view at greater than 10° above the horizon. If this is not possible, it is best to have the obstruction directly north or south of the antenna so that only directly overhead passes are obstructed during the rise or set portion of the satellite pass.

EVALUATION OF POSITIONING ACCURACY OF OFFSHORE PLATFORM STATIONS

The first use of the Doppler satellite system for positioning fixed platforms at sea, known to the authors, was employed by the Canadians in 1968 (Hittel, 1969). By 1971, Doppler satellite positioning had become a standard method of positioning offshore oil drilling rigs in Canadian waters, with an accuracy of ± 15 m (Hittel, 1971; Kirkham & Thomson, 1974). To achieve this accuracy with the broadcast ephemeris, the *multi-station* method of observations and data reduction was used.

Only two other areas are known to the authors where extensive positioning of offshore platforms by Doppler satellites has been reported. These are the Gulf of Mexico where fifteen platforms have been positioned (Hothem & Strange, 1976) and in the North Sea where a substantial number of platforms have been positioned (Williams & Bordley, 1976; Blankenburgh, 1976). Offshore platform positioning is being conducted in other parts of the world but, at present, the authors are not aware of any reports on results.

Because of the generally higher noise level of data gathered on the offshore platforms, the question is raised as to whether or not the accuracy of positions obtained on platforms is less than the accuracy of positions obtained on land. The following is an examination of this question by reviewing the results obtained in the Gulf of Mexico where positions established by conventional methods were available for comparative purposes. More details on this comparison may be found in Hothem & Strange (1976).

During the period from January 1974 through March 1976, fifteen Doppler stations were established on offshore platforms in the Gulf of Mexico. These are listed in Table 3 together with estimates of the quality of the results obtained. In addition, Table 3 lists the same information for a number of nearby land Doppler stations. All data was observed with the Magnavox 'Geoceiver' and reduced using the precise ephemeris *point positioning* method.

TABLE 3

Summary of Doppler stations on offshore oil platforms and at nearby land stations

Station Number		Period of Occupation	σ_0 (meters)	Overall Data Quality (1)	Remarks
51153	McDade, Texas	12/4-17/4/76	0.17	Excellent	
51024	Freeport, Texas	25/1-9/2/74	0.14	Excellent	
51025	Newton, Texas	8/3-18/3/74	0.19	Very Good	
51121	Opelousas, Louisiana	3/3-9/3/75	0.14	Excellent	
51167	Columbia, Mississippi	2/3-15/3/76	0.17	Very Good	
51125	Milton, Florida	14/3-20/3/75	0.16	Excellent	
51162	Gulf of Mexico	31/3-7/4/76	0.18	Excellent	
51167	,, ,, ,,	22/1-8/2/74	0.23	Good	(2) (3)
52072	,, ,, ,,	17/1-23/1/75	0.21	Good	
51163	,, ,, ,,	23/3-28/3/76	0.21	Very Good	
51164	,, ,, ,,	10/3-15/3/76	0.27	Good	(4)
51165	,, ,, ,,	28/2-7/3/76	0.19	Excellent	
51071	,, ,, ,,	12/2-23/2/74	0.31	Good	(2) (3) (4)
51108	,, ,, ,,	26/1-31/1/75	0.21	Very Good	(4)
51109	,, ,, ,,	19/2-24/2/75	0.25	Fair	(3) (4)
51110	,, ,, ,,	27/1-1/2/75	0.17	Very Good	
51111	,, ,, ,,	19/1-26/1/75	0.16	Good	
51112	,, ,, ,,	9/2-15/2/75	0.17	Very Good	
51113	,, ,, ,,	11/2-17/2/75	0.17	Excellent	
51115	,, ,, ,,	20/2-26/2/75	0.29	Good	(4)
51116	,, ,, ,,	25/2-3/3/75	0.15	Very Good	
51117	,, ,, ,,	3/3-8/3/75	0.17	Very Good	

(1) All data was reduced using the National Geodetic Survey's Doppler data reduction programs. The data quality was based upon an objective analysis of the statistics from the reduction results. This included such factors as the standard error of the range differences, the passes and Doppler counts rejected in a solution, the stability of the ground instrument's reference frequency, the scatter of the clock error values relative to a linear relationship, the number of iterations in the solution, etc.

(2) Observations affected by reflected signals.

(3) Abnormal number of passes where the clock error values relative to a linear relationship was greater than ± 25 μsec.

(4) Observations affected by obstructions.

(5) σ_0 = standard error of unit weight for the range differences or observation residuals.

Doppler stations 51072/52072, 51162, 51163, 51164, and 51165 were on platforms previously connected to the North American 1927 Datum (NAD 1927) using conventional geodetic triangulation methods. The 1963 control points are obtained from adjusted second-order triangulation with an expected accuracy of about 1 part in 20 000.

All the land stations are connected to the national horizontal control network on the NAD 1927 datum where the expected accuracy is 1:50 000 to 1:100 000. Additionally, land stations 51153, 51025, 51121, 51167 and 51125 are tied to a precise transcontinental geodimeter traverse (TCT) where there are available preliminary adjusted positions on a so-called MEADES RANCH 1972 (MR 1972) datum (MEADE, 1974). The ultra high accuracy of the MR 1972 traverse positions (about 1 part per 1 000 000) provided an excellent standard for evaluating the relative positional accuracy of the land Doppler positions.

One of the simplest modes of comparing Doppler and local datum (NAD 1927 or MR 1972) positions is to compute the differences, ΔX, ΔY, ΔZ, between the Doppler and local datum X, Y, Z values at each station. Provided the axes of the two coordinate systems are not rotated relative to one another, the variation of ΔX, ΔY, ΔZ from station to station is the result of distortions in the local datum and errors in the Doppler station positions. In fact, rotations do exist in relating the Doppler coordinate system to either the NAD 1927 or the MR 1972 coordinate system (STRANGE *et al.*, 1975). However, they are sufficiently small that they can be ignored for the purposes of this paper since they introduce negligible error in making local comparisons.

TABLE 4

Datum shifts

Station Number	Location	Lat. (N) (Degrees)	Long. (W) (Degrees)	Datum Shifts (1)		
				ΔX (m)	ΔY (m)	ΔZ (m)
51153	Texas	30.28	97.25	27.80	− 151.42	− 176.65
51025	Texas	30.91	93.60	26.88	− 151.68	− 176.60
51121	Louisiana	30.63	92.17	26.73	− 150.21	− 175.98
51167	Mississippi	31.20	89.70	26.95	− 149.27	− 175.71
51125	Florida	30.60	86.97	25.33	− 148.84	− 175.79
			Mean	26.74	− 150.28	− 176.15
			Standard Error of Mean ($\overline{\sigma}$) =	0.89	1.26	0.43

(1) Datum Shifts = Geodetic Position (MR 1972 Datum) minus Doppler Satellite Position (NWL 9D Datum).

Table 4 presents the ΔX, ΔY, ΔZ differences between the Doppler and MR 1972 positions for those land stations located on the transcontinental geodimeter traverse. To illustrate the variations of horizontal position from station-to-station implied by the differences in ΔX, ΔY, ΔZ, the ΔX, ΔY, ΔZ values for station 51121 were used to transform the Doppler positions for stations 51133, 51025, 51121, 51167 and 51125. The differences in latitude and longitude between the transformed Doppler positions and the MR 1972 positions were then computed. Table 5 presents these latitude and longitude differences ($\Delta\phi$ and $\Delta\lambda$) in meters as well as the resolution of the two into a two-dimensional vector. Figure 2 illustrates the vector differences. These vectors can be interpreted as the lack of agreement between the transformed Doppler positions using the ΔX, ΔY, ΔZ transformations at station 51121 and the MR 1972 positions. The sense of the vectors is to point *from* the transformed Doppler position using the station 51121 transformation parameters *to* the MR 1972 position of the station. With this approach in deriving the vectors, the quantity of importance is the change in vector magnitude and direction from station-to-station. The exact value of a vector is not important since the selection of station 51121 rather than one of the other stations to provide the reference transformation values used was arbitrary.

TABLE 5

Summary of position differences

Station Number	$\Delta\phi$ (m)	$\Delta\lambda$ (m)	Horizontal Resultant (meter)	Direction of vector (degrees)
51153	− 1.11	1.20	1.64	312.6
51025	1.29	0.24	1.30	349.3
51121	0	0	0	0
51167	0.71	0.22	0.76	197.3
51125	0.90	− 1.33	1.60	124.1

(1) The position differences are from the transformed Doppler station positions to the MR 1972 datum positions.
(2) Datum Shift = Shift at Station 51121, Opelousas, La.
(3) Direction of vectors is clockwise from South.

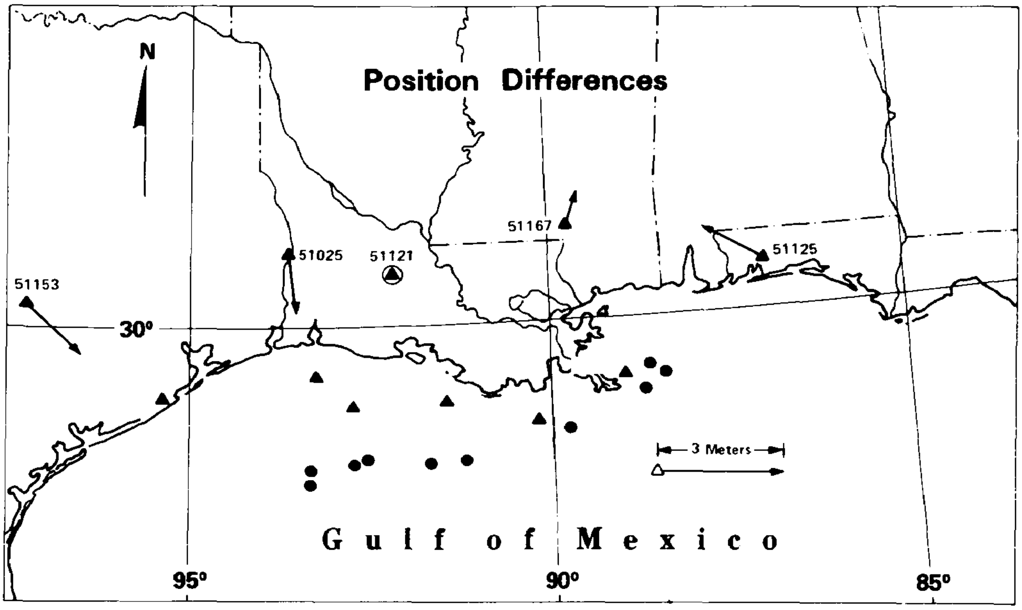

FIG. 2. — Position Differences. The vectors indicate the magnitude and direction of the position differences from the transformed Doppler station positions (▲) to the Transcontinental Geodimeter Traverse (MR 1972 Datum) positions. The Doppler station positions (NWL 9D coordinate system) were transformed using the datum shift computed at Doppler stations 51121.

It can be seen from figure 2 that there is excellent agreement between the transformed Doppler and MR 1972 positions at all stations, with the maximum disagreement being less than 2 meters. This is compatible with comparisons between preliminary MR 1972 positions and Doppler positions throughout the United States. Meade (1974) and Strange *et al.* (1975) found agreement of 1 to 2 meters over short distances and about 4 meters over intercontinental distances for such comparisons.

Tables 6 and 7 and figure 3 present results for comparisons between Doppler and NAD 1927 positions which are similar to those found in Tables 4 and 5 and figure 2. Table 6 presents the ΔX, ΔY, ΔZ differences between the Doppler and 1927 NAD positions for land stations and for those offshore platform stations where 1927 NAD positions, established by the National Geodetic Survey, were available. Again, using the transformation parameters of station 51121, the reference residuals in latitude and longitude were computed and are given in Table 7. Figure 3 presents a vector representation of the residuals.

TABLE 6

Datum shifts

Station Number	Location	Lat. (N) Degrees	Long. (W) Degrees	Datum shifts (1)		
				ΔX (m)	ΔY (m)	ΔZ (m)
Offshore doppler stations (2)						
51162	Gulf of Mexico, Louisiana	29.37	93.18	29.46	−149.00	−174.13
51072	Gulf of Mexico, Louisiana	28.94	92.75	30.09	−149.05	−173.34
52072	Gulf of Mexico, Louisiana	28.94	92.75	30.03	−148.64	−173.59
	Mean 51072 and 52072			30.06	−148.84	−173.46
51163	Gulf of Mexico, Louisiana	28.98	91.47	29.77	−147.19	−171.46
51164	Gulf of Mexico, Louisiana	28.79	90.20	27.82	−147.70	−172.70
51165	Gulf of Mexico, Louisiana	29.37	89 01	30.16	−146.94	−171.89
			Mean	29.45	−147.93	−172.73
			Standard Error of Mean (σ)	0.95	0.94	1.10
Doppler stations on land (3)						
51153	McDade, Texas	30.28	97.25	29.38	150.86	−175.37
51024	Freeport, Texas	29.03	95.33	29.17	−149.71	−175.17
51025	Newton, Texas	30.91	93.60	28.63	−150.97	−175.80
51121	Opelousas, Louisiana	30.63	92.17	27.35	−149.07	−174.02
51167	Columbia, Mississippi	31.20	89.70	29.68	−148.07	−173.74
51125	Milton, Florida	30.60	86.97	24.45	−147.30	−173.13

(1) Datum Shifts = Geodetic Position (NAD 1927 Datum) minus Doppler Satellite Position (NWL 9D Datum).

(2) All stations were established on oil platforms where points on the National Horizontal Control Network (NAD 1927 Datum) had been established by the National Geodetic Survey in 1955 or 1963.

(3) Geodetic Positions on the NAD 1927 Datum, Clarke 1866 Ellipsoid.

The deviations between transformed Doppler and NAD 1927 positions for the land stations are much greater than was the case for the transformed Doppler/MR 1972 comparisons. This reflects the fact that the NAD

TABLE 7

Summary of position differences

Station Number	Δφ (m)	Δλ (m)	Horizontal Resultant (meter)	Direction of vector (degrees)
51024	– 1.22	1.87	2.23	303.2
51153	– 1.93	2.24	2.96	310.9
51025	– 2.46	1.39	2.83	330.5
51121	0	0	0	0
51167	0.74	2.34	2.46	252.3
51125	1.74	– 2.79	3.29	122.0
51162	0	2.11	2.11	270.1
51072	0.67	2.73	2.82	256.3
52072	0.65	2.65	2.73	256.2
Mean 51072 and 52072	0.66	2.69	2.78	256.2
51163	3.18	2.37	3.97	216.7
51164	1.82	0.46	1.88	194.1
51165	2.88	2.85	4.05	224.7

(1) The position differences are from the transformed Doppler station positions to the NAD 1927 Datum positions.

(2) Datum Shift = Shift at Station 51121, Opelousas, La.

(3) Direction of vectors is clockwise from South.

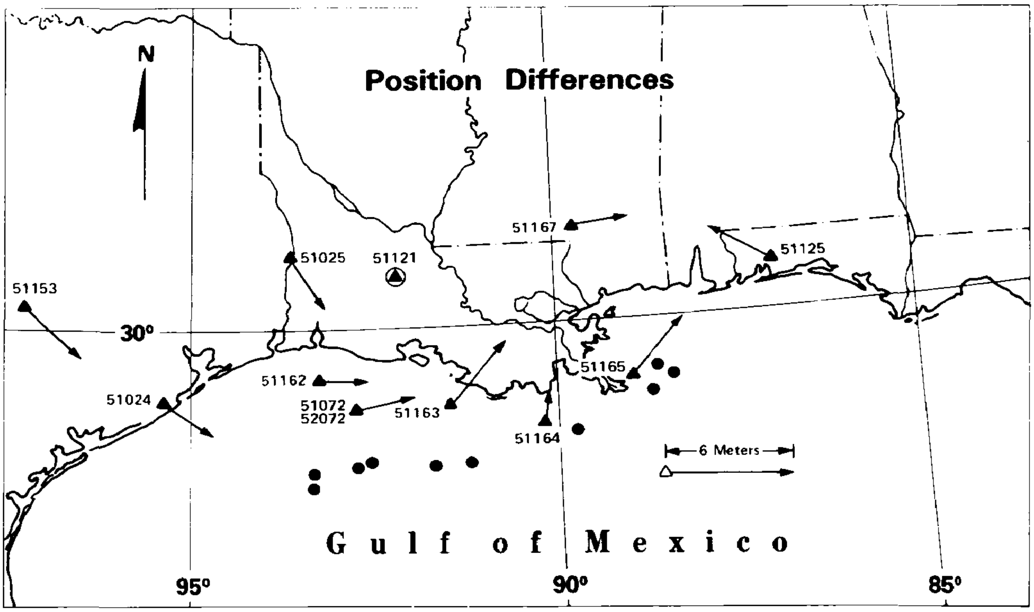

FIG. 3. — Position Differences. The vectors indicate the magnitude and direction of the position differences from the transformed Doppler station positions to the NAD 1927 Datum positions. The Doppler station positions (NWL 9D coordinate system) were transformed using the datum shift computed at Doppler station 51121. The symbol (▲) indicates the Doppler stations which were on adjusted NAD 1927 Datum positions.

1927 has only about 1:100 000 accuracy rather than the 1:1 000 000 accuracy of the MR 1972. For the offshore stations, the disagreement between the NAD 1927 and transformed Doppler is slightly greater than for the land stations. However, it is well within what might be expected based on the estimated 1:20 000 accuracy of the NAD 1927 survey results there. The systematic nature of the differences, with respect to location, indicates that the bulk of the difference is due to systematic distortions in the NAD 1927 Horizontal Network.

Figure 4 repeats the vectors shown in figure 3, with the addition of the vector differences for the other offshore Doppler stations, where the transformed Doppler station positions were compared to unadjusted NAD 1927 coordinates established by non-NGS surveys. Again, the systematic nature of the vector differences indicates the errors are in the unadjusted NAD 1927 positions.

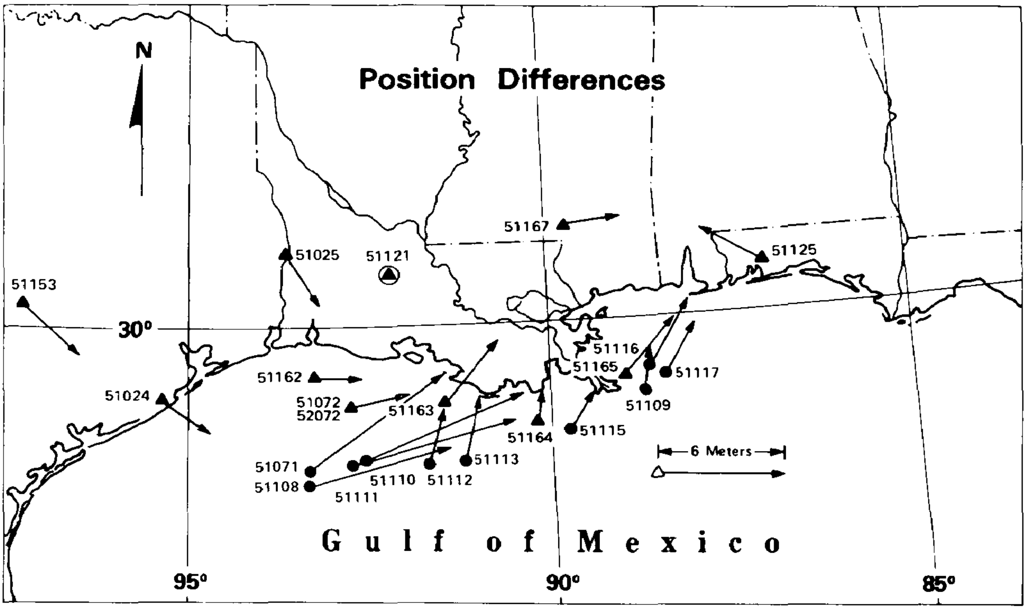

FIG. 4. — Position Differences. This illustration is the same as fig. 3 except for the addition of offshore Doppler stations which had unadjusted NAD 1927 Datum positions established by non-NGS surveys. The symbol (●) indicates these stations.

In figure 4, there is a clear change between the orientation of the vector differences at the six westernmost offshore stations and the remainder of the offshore stations. This is consistent with a known weakness in connecting the eastern and western parts of the adjusted segment of the offshore ground survey. Despite the higher noise level in the observed Doppler data, it is believed that the accuracy of the Doppler positions on offshore platforms are not substantially different from those on land, for the following reasons. The difference between the transformed Doppler positions and NAD 1927 positions for those offshore platforms where adjusted NAD 1927 positions are available are not significantly different from land stations. In the case where comparisons are made with unadjusted NAD 1927 positions, the position differences are larger. However, for stations near one another, the differences are almost identical, indicating that the reason for poorer agreement lies in systematic distortions in the ground survey data. In no case is the agreement outside what might be expected based on the estimated accuracy of the ground survey. It appears, therefore, that offshore platforms can be positioned by the Doppler positioning method with an accuracy of ± 0.5 to 1.5 meters relative to the local datum.

RELATION OF OFFSHORE AND COASTAL DOPPLER POSITIONS TO LOCAL DATUMS

The difference or datum shift between a Doppler station position and a position from the local geodetic control often causes confusion. EATON *et al.* (1976) outlines the reasons the datum shift must be known if the Doppler position is to be transformed to coordinates on the local geodetic datum. SEPPELIN (1974) compares the NWL 9D and WGS-72 geocentric coordinate systems to local datums around the world. Table 8 lists the reference ellipsoid parameters for several local datums and the coordinate shifts between the ellipsoid centers of the NWL 9D and WGS-72 geocentric (satellite) coordinate system and the local datums. These datum shifts represent mean values. However, as noted previously, there are distortions in the local datums.

TABLE 8

Datum shift constants

Local Geodetic Datum	Reference ellipsoid		Datum shift components (1)					
			NWL-9D			WGS 72		
	a (m)	f	ΔX (m)	ΔY (m)	ΔZ (m)	ΔX (m)	ΔY (m)	ΔZ (m)
North American 1927	6378206.4	1/294.9786982	24	– 154	– 179	22	157	– 176
European	6378388	1/297	81	104	126	84	103	127
Australian Geodetic	6378160	1/298.25	127	34	145	122	41	– 146
South American 1969	6378160	1/298.28				77	3	45
Tokyo	6377397.155	1/299.1528128	140	518	— 673	140	– 516	– 673

(1) *NWL 9D or WGS-72 to Geodetic Datum.*

Table 9 summarizes the range of datum shifts between the NAD 1927 datum and the NWL 9D datum along the coasts of continental United States, western Canada, and Alaska. The NWL 9D datum is the datum to which Doppler positions derived using the precise ephemeris are referenced. HOTHEM & STRANGE (1976) found the mean of the coastal datum shifts (ΔX, ΔY, ΔZ) in the conterminous U.S. was 28.4, – 153.3, and – 179.3 meters, with a standard error of the mean of 3.5, 4.7, and 5.1 meters, respectively. The large range in the datum shifts is consistent with the distortion throughout the North American 1927 datum as reported in Meade (1974), Seppelin (1974), and Strange *et al.* (1975). The results quoted in Table 9, as well as the results shown in figure 3, point out that the variation of datum shifts, not only between geodetic datums but also within datums, must be considered by the users of Doppler satellite positioning methods to achieve 1 to 2 meter accuracy.

Table 9

Datum shifts

(NWL 9D to NAD 1927 Datum)

Area	Datum shifts		
	ΔX (m)	ΔY (m)	ΔZ (m)
East Coast, United States	22.9 to 29.8	−150.2 to −157.8	−174.5 to −187.6
Gulf Coast, United States	24.2 to 29.7	−146.4 to −151.0	−172.7 to −175.8
West Coast, United States	28.7 to 37.3	−158.1 to −164.0	−178.5 to −187.1
West Coast, Canada	28.1 to 28.7	−163.1 to −163.2	−181.9 to −184.0
Southeastern Alaska	−1.9 to 20.8	−142.7 to −152.9	−179.3 to −186.2
South Central and Alaska Peninsula	15.8 to 26.0	−136.2 to −160.7	−177.1 to −183.0
West Coast Alaska	9.9 to 13.7	−135.5 to −139.9	−180.8 to −184.2
Arctic Coast Alaska	6.8 to 17.7	−137.1 to −139.6	−179.4 to −180.6
Alaskan Islands	−17.6 to 44.1	−142.7 to −288.1	−160.1 to −219.6

Because of the variations in datum shift within local geodetic datums, the only satisfactory mode of referencing an offshore platform Doppler position to onshore surveys at the 1 to 2 meter accuracy level is to occupy an onshore geodetic point near the platform. To assure continuity with later surveys in the area, the datum shifts used to transform the Doppler station position and the basis for the transformation constants should be stated when giving the local datum position derived using Doppler results.

SUMMARY

Doppler satellite positioning has become an important technique for offshore geodetic control surveys. It has the advantage over the conventional methods for extending precise offshore control, since individual stations can be established independent of observations at adjacent stations, observations are not dependent upon inter-visibility between stations, transportation to support the observation teams is substantially reduced and, finally, the Doppler satellite system is effectively an all-weather system.

Fixed site Doppler satellite surveys to extend the offshore geodetic control by the National Geodetic Survey were centered along the Gulf of Mexico coast of the United States. All Doppler station positions were derived from single station observations reduced with the precise ephemeris *point positioning* method. Evaluation of the results indicated the level of accuracy was comparable to the estimated accuracy of Doppler satellite positioning on land. This has been estimated to be from 0.5 to 1.5 meter *rms* in each coordinate.

To achieve comparable accuracies when utilizing the broadcast ephemeris, the field procedures and data reduction methods for the techniques of *translocation, multi-station solution* or *short-arc geodetic adjustment* must be considered. The desired absolute accuracies for offshore control stations, given by SAXENA (1975), of ± 10 meters can be accomplished with the single station broadcast ephemeris *point-positioning* method. However, single station observations reduced with the broadcast ephemeris will not give the desired accuracies of ± 1 meter for positions of offshore geodetic control stations relative to local control on land.

Finally, the importance of understanding the concepts and procedures for converting the Doppler station satellite derived position to a position on the local datum control must be emphasized. The process for deriving the coordinate shifts and transforming the Doppler station positions is an important consideration in Doppler satellite positioning of offshore structures.

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