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ESTABLISHING HYDROGRAPHIC CONTROL USING DOPPLER

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ABSTRACT

Two Doppler Satellite surveys conducted for the purpose of establishing hydrographic control stations are reviewed. One survey was conducted in Monterey, Calif., the other established shore control for an upcoming hydrographic survey of Lake Superior to be performed by the National Ocean Service (NOS). A brief discussion of the positional accuracies obtained using relative positioning programs MAGNET and GEODOP V is included. The Lake Superior project is discussed regarding methods used and total cost incurred.

INTRODUCTION

In most cases the establishment of a hydrographic control station is more difficult than establishing a geodetic control station of similar accuracy. This additional degree of difficulty exists because the location of the hydrographic control station is dictated first by the requirements of the hydrographic survey; ease of establishment is a secondary consideration. Because of this increased difficulty, Doppler positioning techniques can be extremely efficient when compared to conventional surveying methods. Doppler methods allow the establishment of needed control with little or no intermediate stations (some sites may require an offset).

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Many areas of the United States have sufficient amounts of established control that a two-person party can reconnoiter and establish a shore station in a single day. Clearly, those areas are better suited for conventional survey methods. Doppler methods are most advantageous in areas where there is little or no established control, or where interstation visibility is lacking. Examples of such areas are heavily wooded shorelines, surveys in and among island groups, and marshy coastlines where the established control is inland. This article discusses two Doppler surveys which were conducted to establish hydrographic control. The Monterey survey was a thesis project of the author and was not in support of any upcoming hydrographic survey. The Lake Superior survey was conducted in preparation for an upcoming hydrographic survey to be carried out by the National Ocean Service (NOS).

In most discussions of satellite positioning techniques, the term accuracy is generally not used correctly. Accuracy implies that multiple measurements of a standard have been made, that all systematic differences and blunders have been removed, and the remaining values have been used to compute the accuracy of the measurement system. However, the accuracies normally presented in discussions of satellite systems are actually estimates of the true accuracy based on the statistics of the range determinations. A more appropriate term is the uncertainty of the position or range measurements. Uncertainty will be used in this paper instead of estimated accuracy. Thus "a survey with good relative uncertainties" could be read as "a survey with good estimated relative accuracies".

MONTEREY PROJECT

In May and June of 1982 a Doppler survey was conducted in the vicinity of Monterey, Calif. The object of the survey was to determine the suitability of Doppler survey techniques for establishment of hydrographic shore control. The working area consisted of the Pacific coastline from Santa Cruz to Big Sur, Calif., a shoreline distance of approximately 90 miles. Within the survey area nine stations were selected for occupation. Six of these were established control stations. The other three stations were established as reference marks for an already existing station. Of the six existing stations, one was first order, four were second order, and the sixth was a third order station. All but two stations were near shore stations which would have been acceptable as hydrographic control stations. During this test, as many as four Magnavox MX-1502 Doppler receivers were operated simultaneously. The two inland stations were occupied in order to demonstrate : (1) the effect of various station geometries, and (2) the system's ability to measure elevation. Since all servicing of units (changing tapes, batteries, etc.) had to be done by the author on an after-hours basis, accessibility was also a key factor in station selection. Two stations required 24-hour attendance due to security considerations. This problem was solved by camping on site during the station occupation periods (See figure 1 for survey area).

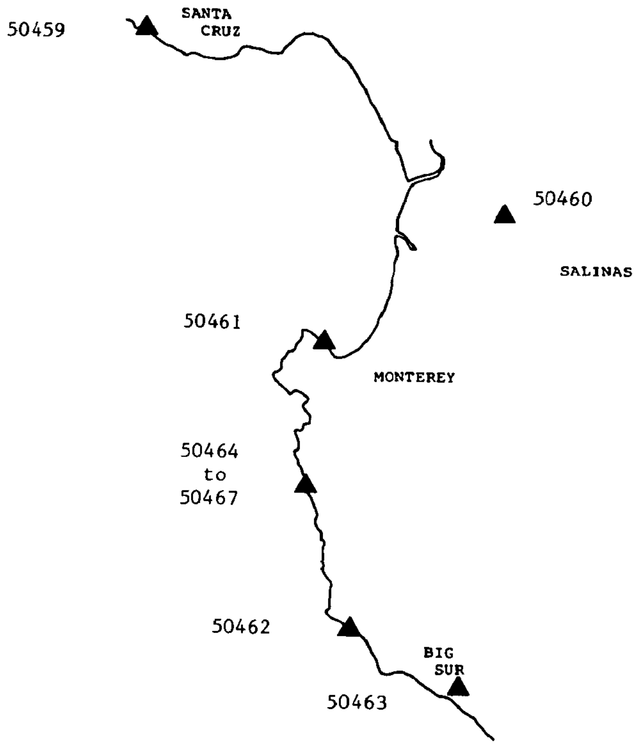

FIG. 1. — Monterey survey.

Data reduction

Reduction of the raw Doppler data to geocentric Cartesian co-ordinates was performed by three methods. Point position solutions based on precise ephemeris data were computed by the National Geodetic Survey (NGS) using program DOPPLR. A second set of station co-ordinates was computed by Magnavox via their relative positioning program MAGNET (Magnavox, 1980). The third set of station solutions was computed by the author via program GEODOP V (KOUBA, 1979).

Station co-ordinates were also computed by the author using the on board Field Translocation Memory Board of the MX-1502. These results are not included, as there is a large disparity between this solution set and the aforementioned solution sets. This difference is felt to be due to operator error, not the firmware of the MX-1502. Other solutions using the MX-1502 firmware (HOTHEM, 1980) indicate that the error was operator induced. These solutions are to be recomputed and compared to the other solution statistics at a later date.

Both DOPPLR and MAGNET derived station solutions were obtained using all passes recorded at each station during the entire observation period. Because the pass count at a single station was as high as 465, the solution uncertainties were not used as "real life" examples. However, comparison of the two solution sets does show the strength of a relative positioning program which uses the broadcast ephemeris (MAGNET). Using both solution sets (X, Y, Z co-ordinates), base line vectors were computed and their magnitudes compared. The largest difference between base lines was 0.09 m over a base line 45,551 m. This level of agreement can generally be reached with a data set of 30 to 40 passes since solution convergence is reached at approximately 40 passes. See Table 1 for a comparison of the Doppler derived base lines with the base lines computed from the published positions.

TABLE 1

Base line lengths compared to terrestrial values (LOCAL)
Base line comparison

Station	MAGNET	Local	GEODOP V	DOPPLR
50460	49733.63	49732.83	49733.67	49733.65
50461	45551.47	45551.00	45551.40	45551.38
50462	81723.73	81723.84	81723.78 *	81723.73
50463	92152.99	92152.98	92153.13	92153.07
50464	63381.41	63381.66	63381.52	63381.41

Base line distances are in metres from station 50459
* Station 50462 base line computed via station 50461

Comparison of MAGNET with GEODOP V (both programs use the broadcast ephemeris) also showed good agreement. The largest base line difference was 0.14 m over the 92 km base line. The GEODOP V results are representative results based on two days of data (34 accepted passes). Program QMAT (written by T. VINCENTY, NGS) was used to compute relative positional uncertainties from the GEODOP V output.

Comparison of the Doppler base lines to the terrestrial base lines indicates a lack of consistency in the local established control. If all stations had been established by the same survey, one would expect the internal consistency to be higher. This variation in the local control points out the need to occupy the established geodetic control in a survey area so that the Doppler established network can be tied to the local geodetic network.

GEODOP V station solutions indicate that a two-day observation period should be adequate for establishment of shore control. Using a value $\pm$ 3 metres as the normal accuracy of ranging systems used by NOS (UMBACH, 1981) the estimated DRMS of a position with a 90° intersection between lines of position is 4.2 m (assumed to be a 1 sigma value). A two-day data set with 3 stations observing will normally yield station solutions with relative positional uncertainties (in X, Y, Z) in the mid to low 20's (cm). In this case the solution is more than an order of magnitude better than the aforementioned hydrographic fix. Using the equation found in (ROSS, 1982) :

$$\text{SIGMA} = 150/(N(S-1))^{1/2}$$

(where N equals the number of simultaneous passes, S equals the number of stations, and SIGMA equals the positional uncertainty of station solutions) one can estimate the number of passes required to achieve a desired uncertainty level. Table 2 is a tabulation of GEODOP V solutions from the Monterey data set. The above equation is sufficient for planning purposes if the data are to be reduced with a relative positioning program.

TABLE 2

Sample results from Monterey project						
Station	Days	Passes	Unc X	Unc Y	Unc Z	Base line (m)
50460	156 & 157	24	22.96	23.64	15.71	49733.73
50463		24	23.24	23.70	16.18	92153.13
50461	142 & 143	29	18.18	13.76	12.67	45551.43
50463		30	20.85	15.64	14.54	92152.77
50461	142 & 143	25	20.04	14.11	13.82	45551.39
50463		25	25.10	15.89	16.28	92152.90
50464		25	27.56	26.27	19.64	63381.55
50460	155, 156,	40	17.13	15.10	11.59	49733.78
50463	157	40	17.33	15.33	11.81	92153.38

Uncertainties (Unc's) are in centimetres.
Base lines are in metres from station 50459.

Because the satellites are in polar orbits, the number of usable passes received in a single day will vary as a function of latitude and time (due to orbit precession). The above data sets were separated based on days instead of number of passes since the editing program uses time instead of number of passes as input. Clearly, a procedural specification for number of passes instead of days would be more useful.

LAKE SUPERIOR PROJECT

An excellent example of an area well suited for use of Doppler survey methods is the Lake Superior area. The north shore is rocky and rugged with dense forest starting at the water continuing back into the low mountains inland. Accessibility is at a minimum. The south shore of the survey area is predominantly wooded also. Both shores have many areas where the shoreline is a cliff face 20 to 150 ft in height. Accessibility on the south shore is not as bad as the north, but still very poor. An absolute minimum estimate of time and manpower required to establish hydrographic control for the survey area was one working year for 8-12 persons. This estimate was for an operation using conventional methods. Because of the estimate, alternative methods were investigated by NOS. It was decided that a Doppler survey would be the most efficient method for establishing the required control.

Based on time and budget constraints an observing scenario using four receivers for the month of September 1982 was decided upon. Three units were leased, the fourth was supplied by NGS. Partial reconnaissance of the survey area was performed in August by the field crew, while working on another project in the Bayfield, Wisc., area. Because the receivers do not need continual attendance, the rest of the reconnaissance of the survey area was carried out as the Doppler survey progressed. The working schedule decided upon was to begin on the north shore near Grand Portage, Minn., and proceed around the west end of the lake, continuing east along the south shore to the Keweenaw Peninsula. (See Figure 2). The party was to cease operations at the end of the lease period, independent of how far they had progressed. Within the first week of field operations, it was clear that the entire survey area would be covered. This caused a schedule revision and the addition of more stations to the survey. The survey party consisted of four men with four vehicles. All four units were placed on power on August 27 to stabilize the oscillators. August 28 was used to familiarize three of the party members with the set-up and operating procedures of the units. Field operations commenced on August 29 and terminated on September 28. During the survey, no holidays or weekends were observed.

The observation scenario decided upon was to hold two stations fixed on established first order stations (base stations), while the other two receivers were used to establish the hydrographic stations. This would tie the shore control to the network while providing first order Doppler positions (via precise ephemeris point position reduction) on the base stations. Additionally, with two fixed stations all shore stations would be interconnected, allowing a relative position reduction to be performed. One base station (50281) was located on the north shore at the west end of the lake, the other station (50299) was on the south shore at the east end of the survey area. This bracketing of the survey area was imposed so as to yield an acceptable tie to the local geodetic network. Later, the receiver at the north base station was moved to a geodetic control station (50298) located on the northern tip of the Keweenaw Peninsula due to logistical requirements.

Each of the base stations was manned by a single individual while the other two men worked singly or together depending on location and requirements. Occasionally, one individual would maintain a base station while establishing and/or maintaining a mobile unit. Based on discussions held prior to the survey, it was decided that 20 usable passes per station would yield solutions of acceptable accuracy (positional uncertainty of 1 m or less). Allowing for rejection of some passes, a value of 30 3-D passes[*] recorded at each station was adopted as a minimum requirement. This procedure allowed the operator to easily predict (based on ephemeris predictions) when the unit would be ready for movement to the next site. Generally, 30 3-D passes took approximately 48 hours. During the 30 days of the survey, 25 stations were occupied along approximately 420 miles of shoreline. Station sites were selected which could be used both for hydrographic control and as the origins of traverses to establish more control. Whenever Doppler stations are used in a traverse, station spacing must be adjusted to meet azimuth accuracy requirements.

(*) The MX-1502 categorizes passes as either 2-D or 3-D, based on the residuals of the position solution and other criteria. A 3-D pass has smaller residuals.

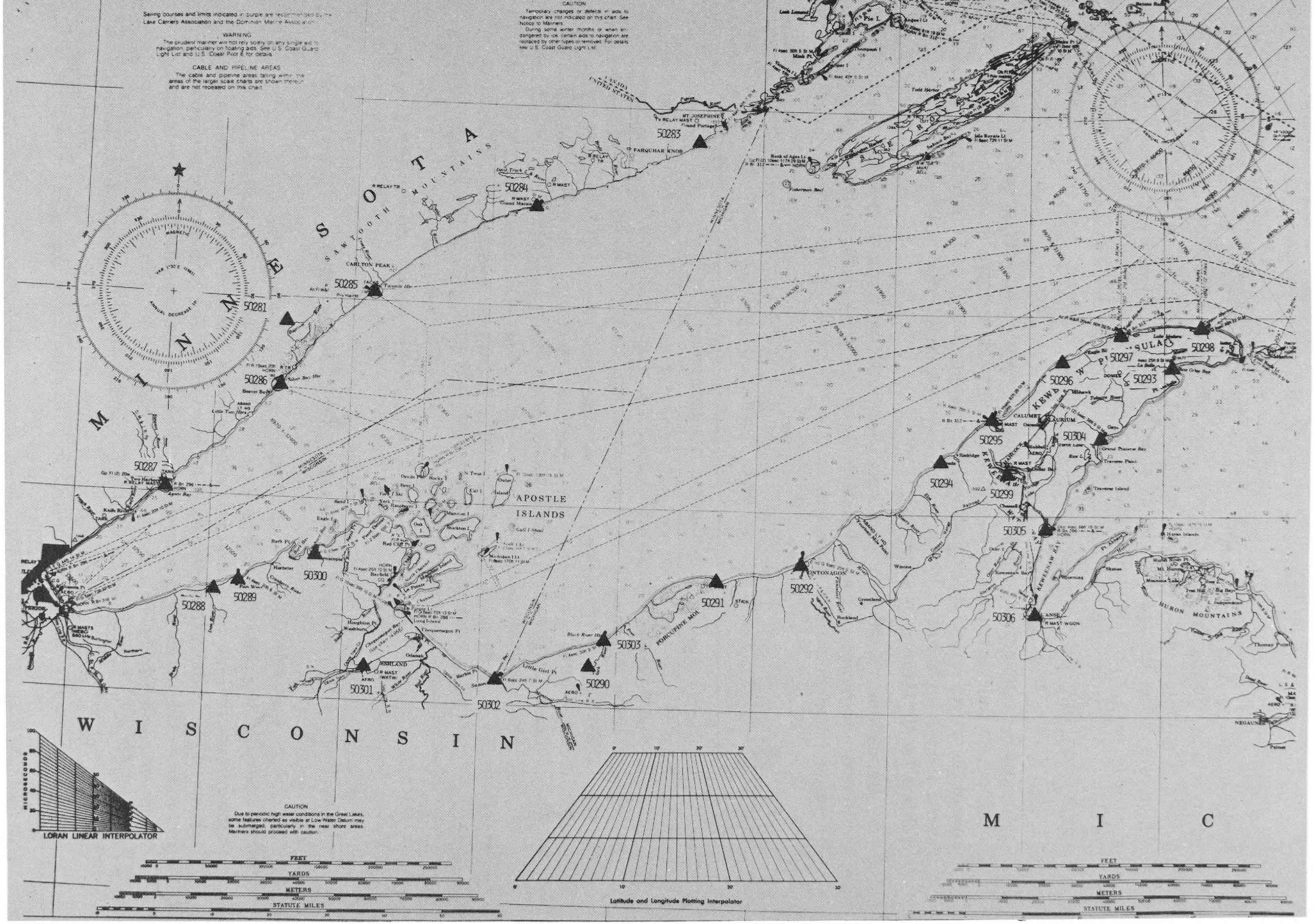

FIG. 2. — Lake Superior survey.

Little time was lost to inclement weather. Operation of the unit is virtually weather independent, but threatening surf did force removal of two units for safety's sake. During the entire survey there was only one incident of equipment failure. The failure occurred when a unit atop a ski jump (285 ft above ground), which was being located for use as a landmark, was subjected to high static electricity as a thunderstorm passed through the area. Apparently the unit's shielding was overcome and damage to various components occurred. This is supposition, since there was no observable damage, but many memory-controlled operations did not function.

Based on actual per diem expenses for two men, average salary (with overtime) for four men, lease rates, and miscellaneous expenses, the total estimated cost of the survey is $ 43.2 K. Obviously this is significantly less than the cost that would have been incurred by an 8- to 12-person crew working for a year. (See Table 3 for breakdown of expenses).

Reductions of selected data sets with GEODOP V have yielded relative positional uncertainties of approximately 25 cm (or less) in any co-ordinate axis. These uncertainties were as expected.

TABLE 3

Breakdown of expenses	
Salary (averaged)	$ 6,800.00
Per diem	7,524.00 *
Overtime	7,074.00 *
Data tapes	270.00
Lease (3 receivers)	21,000.00
Miscellaneous	566.10
TOTAL	$ 43,234.10

* Based on actual expenses for 2 people.

SITE AND NETWORK CONSIDERATIONS

Though site selection for a Doppler station is not as difficult as for conventional stations, there are some requirements that need be considered in all instances. Further site restrictions can be imposed by the type of data processing to be used. The following is a brief discussion of these considerations, with most examples coming from the Lake Superior project.

One of the most important considerations for site selection is horizon visibility. Because the satellite signals are line of sight, they can be deflected, refracted, or totally obscured by obstructions between the antenna and the satellite. The sky should be clear of obstructions 8° above the horizon. Because it is advantageous to use Doppler instead of conventional methods in areas of poor station intervisibility, horizon visibility is often a problem. An occasional tree projecting above this 8° mark will probably have no effect. A dense stand of trees, however, could cause complete or partial blockage of a satellite pass; the degree of blockage is most critical to the east and west of the station. Obstructions to the east or west could completely block passes in that quadrant, resulting in a poor pass balance, thereby affecting the accuracy of the final position solution. Obstructions to the north are not as critical, since they would only block the rising or setting of a pass; however, they still need to be considered. Though it is best to have the antenna as near the ground as possible to minimize multipath interference, elevation of the antenna is sometimes the only solution. Where horizon visibility was marginal on the Lake Superior project, 8-foot collapsible tripods were used instead of conventional tripods. All antennas had been fitted with adaptors which allowed use of conventional tribrachs with optical plummets. When the 8-foot tripods would not suffice, one or two sections of antenna mast (*) were used to elevate the antenna.

The base station on the north shore required two such tower sections to clear nearby obstructions (see Figure 3). The antenna was mounted to a 2 × 6 inch plank which projected out of the tower approximately 2 ft. The tower was offset from the station mark so that a vertical collimator could be used to plumb the antenna over the station mark. Adjustment of guy lines brought the antenna into plumb. Two men assembled and erected the tower in two hours. No problems with ground reflections were observed at any of the elevated stations.

Another important consideration in site selection is possible sources of radio interference. All sites which had any type of active transmitting antennas nearby were ruled out since equipment damage could occur. One station was located approximately 10 ft from the shoulder of a state road which had medium usage. No problems due to ignition noise were observed. This antenna was on an 8-foot tripod. Whether this and the antenna characteristics of the MX-1502 prevented interference is not known.

Security is a major consideration at all stations. Though many stations were remote, loss of a unit was still considered at all stations. Because the party consisted of four men with four units, around the clock attendance was not feasible. When possible, units were chained and locked to any nearby substantial object. At other sites, eyebolts were set along with the station marks. The units were then chained to the eyebolts. In Monterey, 4- × 6-foot covered trailers were leased, towed to the site, and the units locked inside. Some stations in the Monterey project required 24-hour attendance for security purposes.

If processing of the survey data will entail use of a relative positioning program, the geometry of the survey should be considered. A survey with long base lines (200 km or more) should be designed to maximize the strength of figure. This consideration will yield improved relative positional uncertainties in the reduction. In addition to the configuration of the survey, one should also consider the orientation. Small surveys will have the best positional uncertainties when aligned in a north-south direction, due to the satellites' orbits. As the survey becomes

(*) Lightweight triangular tower sections used by NOS for construction of shore station antennas; sections are 10 ft in length, 1 ft on a side.

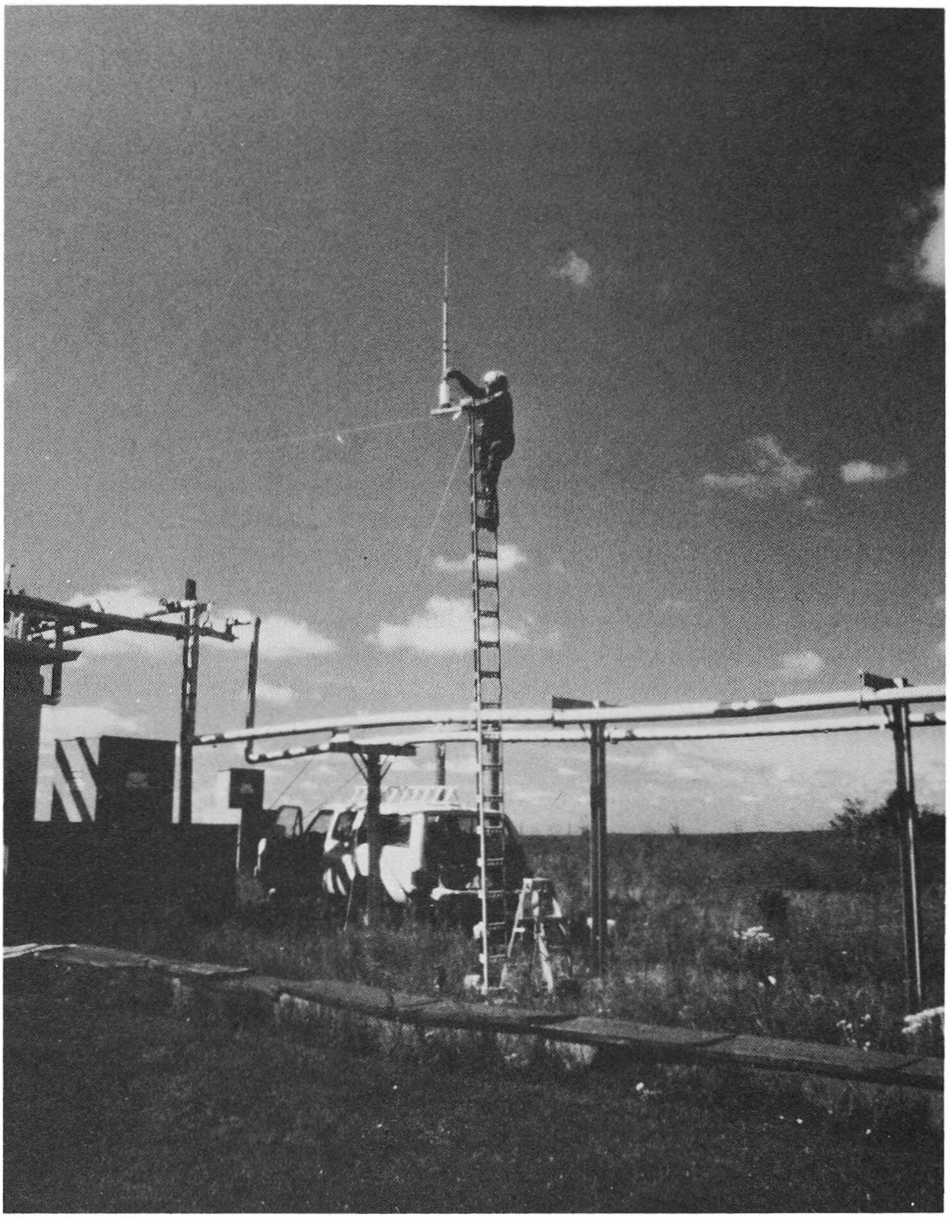

FIG. 3. — Antenna tower.

larger, the orientation of the major axis of the survey, defined by the base lines between base stations, should be rotated to an east-west orientation. This ensures that the base stations will be tracking the satellites simultaneously.

Occupation of established local geodetic control stations (base stations) is essential when performing a Doppler survey to establish hydrographic control. Using predicted mean datum shift values to transform the Doppler derived co-ordinates to the local datum can cause positional errors of 10 m or more (MINKEL, 1984). If one does not have access to the precise ephemerides, local control must be occupied since the broadcast ephemeris is only acceptable when used in a relative positioning mode. The best procedure, when using a relative positioning reduction program, is to determine the co-ordinate differences between the base stations and the unknown stations in the Cartesian system of the satellite datum. These differences can then be applied to the published Cartesian co-ordinates of the base stations in the local datum. These sets of co-ordinates can then be easily converted to geodetic co-ordinates. In this method one does not have to either assume or determine a datum shift for the survey area.

CONCLUSION

Use of satellite survey techniques to establish shore control by NOS is not common at present. Because this technique is new to NOS, rigorous accuracy specifications have not yet been made. At present the required positional accuracy of shore stations is specified only in terms of a proportional error. A more useful specification would be to state the required positional accuracy as a 1 sigma value(s) independent of distance between stations. This would allow the total positional error in a sounding to be estimated. An uncertainty level of 70 cm in any co-ordinate axis would meet both NOS and International Hydrographic Organization (IHO) specifications for hydrographic shore control (MINKEL, 1983). Clearly, the need for revised accuracy standards will increase as satellite techniques (both TRANSIT and GPS) become more widely used by NOS for establishment of shore control, and as high accuracy satellite positioning systems become available to the mariner.

ACKNOWLEDGEMENTS

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REFERENCES

HOTHEM, L.D. (1980) : *Report on test and demonstration of semi-short-arc translocation firmware for the Magnavox MX 1502 satellite surveyor.* Report to Instrumentation Subcommittee, Federal Geodetic Control Committee, National Geodetic Survey, NOS/NOAA, Rockville, Maryland.

HOULDER, R.H. (1982) : *Project report for Doppler survey of Lake Superior* (internal report), National Ocean Service, NOAA, Rockville, Maryland.

KOUBA, J. (1979) : *Improvements in Canadian geodetic Doppler programs.* Proceedings of the Second International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, New Mexico.

MINKEL, D.H. (1984) : *Establishment of hydrographic shore control by Doppler satellite techniques.* Masters thesis, Naval Postgraduate School, Monterey, California.

Magnavox (1980) : *Network adjustment computer program MAGNET.* Magnavox Advanced Products and Systems Company, Torrance, California.

ROSS, W.T. (1982) : *MAGNET, Magnavox network adjustment post processing software.* Proceedings of the Third International Symposium on Satellite Doppler Positioning, Las Cruces, New Mexico.

UMBACH, M.J. (1976 Ed.) : Revised 1981. *Hydrographic Manual,* National Ocean Service, NOAA, Rockville, Maryland.

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