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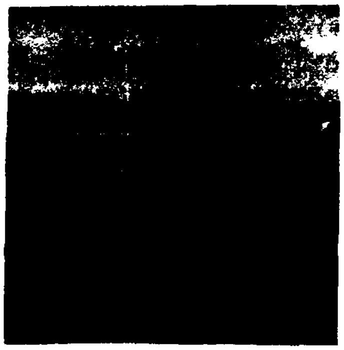

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CONTINUOUS DEFORMATION MONITORING SYSTEM (CDMS)

by

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COVER PHOTOS:

TOP – *Deformation* output example.

CENTER – Deformation simulation platform.

BOTTOM – Dworshak Dam.

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13. ABSTRACT *(Maximum 200 words)*

The US Army Topographic Engineering Center (TEC) has developed an automated deformation monitoring technology known as the Continuous Deformation Monitoring System (CDMS). The CDMS is capable of computing structural deformation using the Global Positioning System (GPS) survey technology while operating in a continuous fashion over time. A network of two personal computers control GPS survey equipment and process the satellite data gathered to compute apparent structural deformation up to 24 times a day without the presence of an operator. Structural monitoring can take place at the project site or at a distant office. Performance testing by TEC has determined deformation measurement precision in the subcentimeter range. The CDMS was installed at Dworshak Dam in northern Idaho and tracked the upstream movement of the dam while undergoing reservoir drawdown.

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Contents

Preface

The work described in this report was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Work Unit 32370, "Continuous Monitoring System for Structural Safety of Large Dams." Dr. Tony C. Liu, HQUSACE, was the REMR Technical Monitor for this work.

Mr. Jesse A. Pfeiffer, Jr., HQUSACE, was the REMR Coordinator of the Directorate of Research and Development, HQUSACE. Mr. James E. Crews, HQUSACE, and Dr. Liu served as the REMR Overview Committee. Mr. William F. McCleese, US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, was the REMR Program Manager. Mr. James E. McDonald, Structures Laboratory, WES, was the Problem Area Leader.

Mr. Stephen DeLoach, Topographic Engineering Center (TEC), Fort Belvoir, VA, was Principal Investigator, and Mr. Carl A. Lanigan, TEC, was Project Engineer. The work was performed at TEC, and this report was prepared by Mr. Lanigan under the general supervision of Mr. Regis J. Orsinger, Director, Topographic Developments Laboratory, and under the direct supervision of Mr. Peter J. Cervarich, Chief, Surveying Division.

Recognition is due to the Continuous Deformation Monitoring System (CDMS) development team at Trimble Navigation Ltd., who developed the system software. That team consisted of Messrs. Bruce Peetz, Mike Potterfield, Brian Frohring, and David Dew. Part of the final report submitted by Trimble Navigation was used in this study with the permission of the authors.

TEC would like to thank the US Army Corps of Engineers team members at Dworshak Dam who provided exceptional support during the demonstration portion of this project.

Colonel David F. Maune was Commander and Director and Mr. Walter E. Boge was Technical Director of TEC when this study was accomplished. During the publication of this report, Dr. Robert W. Whalin was Director of WES. COL Leonard G. Hassell, EN, was Commander.

1 Continuous Deformation Monitoring System (CDMS) Description

Introduction

Background

The US Army Corps of Engineers (USACE) makes extensive use of instrumentation for measuring the behavior of large structures. One of these instrumentation programs is high-precision geodetic surveys. These surveys are accomplished through the use of classical triangulation and/or trilateration techniques, which provide a direct measure of displacement as a function of time. The final accuracy of the displacement is a function of many factors: network geometry, field procedures, survey crew experience, and equipment. Typically, accuracies of about 5 to 10 mm are obtainable. Unfortunately, geodetic surveys are labor intensive, time consuming, and rather expensive. For these reasons, surveys are made infrequently, normally at 6- to 18- month intervals, or sometimes not at all, unless there is a suspicion of structural distress.

With the deployment of the Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS), the possibility for continuous, automatic monitoring of structures has materialized. Due to the very nature of GPS survey technology, high-precision surveys can now be performed in far less time than with other techniques. This fact, combined with the present day capabilities of computer hardware and software, opens up the possibility of continuous structural deformation monitoring with the use of existing GPS surveying equipment driven solely by personal computers (PC).

GPS description

GPS is a navigation and timing system developed by the Department of Defense (DoD) and primarily used to position military platforms. When installation is completed in 1994, it will contain 24 NAVSTAR satellites. Anywhere from four to seven satellites will be available in the sky at any one time in any location. A minimum of four satellites are needed for positioning. Positioning accuracies of 100 m are provided for civilian users, while 16-m accuracy is available to the military. When the satellite constellation is completed, only the civilian positioning code (known as C/A) will be continuously accessible to the public. To improve the accuracy of the C/A code, a technique known as differential (or relative) surveying is used. Differential GPS surveying can provide accuracies from a few meters to a few centimeters and reduces the effects of the positioning degradation practice imposed by DoD. The Continuous Deformation Monitoring System (CDMS) uses the differential GPS surveying technique based on the carrier phase of the C/A code, which is the part of the GPS radio signal on which the C/A code is transmitted. Carrier phase differential surveying has provided centimeter accuracies to geodetic surveyors for many years. Basically, differential carrier phase surveying requires that two or more GPS receivers track at least four or more NAVSTAR satellites for a period of time. The GPS receivers must contain hardware that allows measurement of the carrier phase. In the CDMS, all the GPS receivers must remain still for about an hour. The satellite data collected by these receivers are downloaded to a computer that contains GPS processing software. Simply put, the GPS processing software computes the NAVSTAR satellite ranges from one GPS receiver relative to another. The software processes the data and computes a precise vector to each of the receivers. The accuracy of this vector is on the order of 1 cm +/-1 to 2 parts per million. If the coordinates of one receiver are known, then it is a simple calculation to determine the coordinates of all the other receivers.

CDMS operation

The basic operation of the CDMS is as follows. The GPS antennas that receive the satellite data are located at those points on the structure where monitoring is desired. They must have a clear view of the sky and should not be placed next to solid walls. These antennas will be connected to GPS receivers, which collect the raw satellite data. The receivers should be located near a power source and away from the weather. A network of two PCs will remotely operate the GPS equipment, telling them when to begin and end surveys. The computer network will take the previously collected raw satellite data from the receivers and process it. The CDMS software will compute three-dimensional (3-D) coordinates of each monitoring station and then compare them with the coordinates of those computed when the system was first turned on. Any significant difference between coordinates will be represented by a deformation vector. The CDMS will repeat the cycle until changed by the user. The system will keep a record of all deformation results so that the user can view the history of the movement of the structure over time.

Equipment and Instrumentation Requirements

All of the hardware components used in the CDMS are commercially available. Unique equipment development was not necessary for system operation except to upgrade the GPS receivers. Tables 1 and 2 list the equipment used in the CDMS at the time of publication. Many of the individual parts used in the CDMS are produced by a number of different manufacturers. It is important to determine which components are supported by the current version of both the

CDMS software and the SCO Xenix Operating System.[1] Figure 1 illustrates a typical CDMS configuration. The CDMS can have a maximum of 10 receivers in a survey network. The minimum number is three. All receivers are connected to a computer network consisting of two PCs that drive the system. Figure 2 is an illustration of how the CDMS would look at an actual project site.

GPS receiver stations

The CDMS can operate only Trimble Navigation 4000[2] series receivers upgraded with the CDMS option. The geodetic GPS antennas should be used with these receivers. The antennas are located on the chosen monitoring sites. The normal distance between the antenna and receiver is 200 ft[3] using the standard RG-213 coaxial cable. Distances of up to 500 ft can be achieved with the use of more specialized cable. The GPS receiver requires a power source, either 110-V AC or 12 to 24-V DC. The antenna is supplied power through the coaxial cable.

Receiver to computer network communications

Three types of communication links connect the receivers to the PC network. These are telephone modems, RS-232 cables, or fiber optic cables.

Telephone link. The phone line(s) linking the GPS receiver station(s) to the PC network must support local dial-up communications. The CDMS needs to have a phone number to dial into the remote GPS station. A separate phone line and number must be available for each GPS receiver linked in this fashion. Both ends of any particular phone link should be protected from power surges and spikes. The telephone modems used in the CDMS need to be protected from the weather. AC power must be available for the modems. Variable baud rates of 1200, 2400, 4800, and 9600 can be used in the CDMS; however, using anything less than 9600 will increase the downloading time between epochs.

RS-232 cable. An RS-232 communication link from a GPS receiver station to the computer network can extend to a maximum of 500 ft in length. The cost of RS-232 cable is very low compared with the other two forms of data link.

Fiber optic cable. Fiber optic cable can support a data transmission distance of up to 3.2 km using the present hardware configuration. This cable has the advantage of being immune to electromagnetic disturbances caused by power plants, high tension lines, etc., which could cause problems with a RS-232 link. A fiber optic line driver must be attached at both ends of the fiber optic cable. This is used to convert the electrical signal to an optical signal and then back

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[1] SCO Xenix Operation System is a trademark of the Santa Cruz Operation, Inc., 400 Encinal Street, PO Box 1900, Santa Cruz, CA 95061.

[2] Trimble 4000SX is a trademark of Trimble Navigation, Ltd., 585 North Mary Avenue, Sunnyvale, CA 94088-3642.

[3] To convert feet into meters, multiply by 0.3048.

This is used to convert the electrical signal to an optical signal and then back again. As shown in Figure 1, an RS-232 to fiber optic multiplexor can be used to combine multiple fiber optic links from the receiver stations and transmit the group signal to another multiplexor at the PC1-PC2 site, where the signals will be resplit. Both the fiber drivers and the multiplexor need an AC power source.

Computer network

The two PCs that operate the CDMS (known as PC1 and PC2) must be located in an office environment and have AC power available. As illustrated in Figure 1, both computers have a high-resolution monitor and a power backup supply. The high-resolution monitors are used to take advantage of the graphics capability of the CDMS. The power backup supplies are used to maintain system operation during a power failure or fluctuation. During an extended power outage, the backup system will gracefully shut CDMS down and then automatically restart the system when power is restored.

PC1. PC1 will receive all the GPS receiver station communication links through its multiport serial board. The major function of the PC1 is receiver operation. It also displays the current satellite availability over the project site.

PC2. PC2 is responsible for data reduction and analysis, user access, and archiving. It has plotter and printer capability, allowing processing results to be displayed on these peripherals. All data generated by both PC1 and PC2 will be stored on compact video cassette tapes through the VAST™ mass storage device attached to PC2. During system operation, these tapes must be replaced once a week. This is the only routine maintenance required for the entire CDMS.

PC3. PC3 is a remote access system that allows monitoring of the PC1-PC2 network from any location that has a usable phone line. Any number of PC3s can be linked to the CDMS at the project site. PC3 will be connected to PC2 via a telephone/modem link. PC3 must have a high-resolution monitor and an archive device. It also has the option of having a printer and/or plotter. The data archiving cassettes produced by PC2 can be used on any PC3.

Site Requirements

Antenna location

All antennas need a clear view of the sky to be able to track NAVSTAR satellites. Partial obstruction of the sky is not fatal, but does have some adverse consequences. For example, if any one point cannot track a satellite, that satellite is effectively unavailable to all the other points for the purposes of arriving at a solution within the CDMS. (To get subcentimeter survey resolution, simultaneous tracking is essential.) When full GPS coverage exists (in about 1994), loss of a satellite or two will not have much significance. Until then, satellite loss could drastically affect viewing time. A more severe problem exists when a nearby object, such as a metal building, does not completely obstruct a satellite, but instead refracts the signal, causing one point to get a longer delay than it should. Such a situation may show a systematic change in apparent location whenever a satellite is behind the object. This problem can be overcome by raising the elevation mask (the angle above the Earth's horizon in which the GPS receiver will accept NAVSTAR signals) to the clear sky level when initializing the network definition. The disadvantage of raising the elevation mask is that it restricts viewing time, as discussed. Any nearby opaque structure may cause problems, especially metal objects, since they can reflect satellite signals and cause multipath. Multipath (the false ranges caused by unwanted reception of NAVSTAR signals that have bounced off a solid object) is much harder to control by changing the elevation mask and should be avoided above all other potential problems.

Reference points

The CDMS, in its present configuration, can control a maximum of only 10 GPS receivers. It is possible that the system could be modified to manage more receivers at a future date. At least two of these receivers are "reference points" against which all other points will be judged for movement. Thus, the stability of the antenna location for the reference points directly affects the results of all points being monitored. There are several considerations in choosing a reference point for stability. The stability of the area or structure of the reference point is a prime consideration. If stability is of the same nature as the object points, the movement vectors produced by the system will not represent a true picture of the movement or deformation of the object points.

A second consideration is the method of securing the antenna to the point. The attachment method must be able to withstand any physical abuse (natural or otherwise) it is likely to suffer. Thermal effects are also a potential source of error. If a columnar base is used to attach points to antennas, temperature or solar radiation can cause expansion and contraction that could be interpreted as movement in the points. This can track out if the same attachment method is used for all points and they all receive the same amount of sun; however, this is not always the case. The fixed geodetic coordinates of the primary reference monument (i.e. WGS-84 or NAD-83 latitude, longitude, and ellipsoid height) must be determined before start-up. These coordinates do not have to be precise, but they will be permanent for the duration of any one survey (it may be changed by authorized personnel at a later time). A "best C/A code" location may also be used for the primary reference monument, but this will require a GPS observational session before start-up; alternatively, known coordinates from previous conventional observations, including published data, may be used. Vertical data will be referenced to the ellipsoid, and if a benchmark is to be used for vertical control, its orthometric height should be transformed to the ellipsoid within an accuracy of 10 m. The fixed rectangular coordinates (for example State Plane coordinates) of the primary reference point must also be decided beforehand, although these may be entirely arbitrary as the rectangular system will function as a local survey grid. As a local system, the distances in the rectangular coordinate system will reflect measured distances; no sea level or grid scale factors will be applicable because of the definition of the oblique Mercator system used within the processing software. The location of the reference receiver to be used for azimuth control must be selected beforehand.

Finally, the rotation angle of the azimuth from the primary reference station to the azimuth reference station must be known in the rectangular system of choice. This rotation angle is optional and is included for the convenience of the user to allow deformation vectors to be expressed in terms of a State Plane coordinate projection, structure-axis grid, or some other user-defined system.

Object points

Object points are the antenna locations where monitoring will take place. These locations need to be determined before CDMS operation can begin. The constraints outlined in C-1 should be considered before choosing these points. The coordinates of these points do not have to be known beforehand.

CDMS Initialization

Project definition

Once the survey network has been defined and all hardware components have been installed, system start up can begin. After logging onto PC2 and getting into the menu system, the user will have to initialize a "project." A project is a way of keeping together all the deformation data and analysis compiled for one site and keeping it separate from another "project" site. The project concept allows a single CDMS to be installed at numerous project locations. Each project site will be given a Project Name.

Network definition

The CDMS network may be uniquely defined and controlled by a set of parameters and data that are collected under the name "Network Definition." These values may be grouped roughly into four categories: geometric control, point descriptions, data communications, and epoch definition. These four groups are reflected in the four "pages" used to create, modify, and view the Network Definition in the CDMS. Except for the Project Name, a deformation network may be "redefined" repeatedly by the user, creating a historical sequence of Network Definitions; the redefinition remains compatible with the previous definition, and analysis under the new definition may take place using base information from the earlier definition. In some cases, the redefinition can create a historical discontinuity in the life of a project, as when the primary reference or azimuthal control points are changed. In these cases, analysis may proceed only with base information collected and processed under the new or other compatible definition. Most of the values in the Network Definition are specified by the user. A few are kept internally by the system.

Continuity between Network Definitions is achieved by preserving the same primary and azimuthal reference points, the same fixed values for geodetic and error between them. Maintaining the same base epoch for two definitions will assure an estimation of propagated error over time. Changing the base epoch will interrupt the continuity of error modeling, but will still make it possible to compare geometric vectors of apparent movement. Changing the rotation angle will not affect continuity in estimates of either movement or error. However, it might cause confusion when research is made into historical epochs (i.e. output from network adjustments and deformation analysis) whose rotation angles were different from those being used currently.

Data Reduction and Deformation Analysis

Epoch definition

The use of the term "epoch" in deformation analysis must be distinguished from the use of this term in GPS observational procedures. In GPS usage, epoch refers to timed intervals at which a GPS receiver will record transmissions from observed satellites. For the purpose of deformation analysis, an epoch is defined as an "instant" in time during which no detectable motion occurs in the structure being monitored. When a sufficient number of satellites (minimum four) is visible at all times, an epoch will be synonymous with a GPS receiver session. Although the assumption is made that during an epoch no movement occurs, in actuality movement may well be taking place, but it will not become detectable until a sufficient number of epochs have elapsed for movement to become measurable relative to the first epoch in the series. Obviously, GPS monitoring is best suited for the measurement of gradual, rather than avulsive, movement. If in fact some sudden, avulsive movement of one of the monitoring receivers occurs during the period of one epoch, the measurement results from that epoch will be indeterminate and unpredictable. The assumption behind the processing of satellite phase observables is that the ground points are stable, with all motion occurring in the satellite configuration. Therefore, the true dimensions of the avulsion will not be assessible until the measurements from the epoch following the avulsive epoch are processed, and then only if no avulsive movement has occurred during this most recent epoch.

There is theoretically (given the full constellation of satellites) no limit to the maximum length of time for an epoch to last, but to achieve the goal of making the most accurate measurements possible, it makes sense to restrict the length of an epoch to the length of time required for a satellite observing session to attain its maximum precision and reliability. In static mode, this currently amounts to 1/2 to 1 hr of observations when satellite geometry is optimum. CDMS uses the base epoch Trimvec[1] solution to establish "known baselines" in the network configuration, which are updated at each subsequent Trimvec™ solution. Using "known baselines" greatly reduces the length of data processing time for Trimvec™ solutions. For the purpose of detecting movement, the measured configuration of object receivers from one epoch is compared against the con-

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[1] Trimvec is a trademark of Trimble Navigation, Ltd., 585 North Mary Avenue, Sunnyvale, CA 94088-3642.

configuration, which are updated at each subsequent Trimvec™ solution. Using "known baselines" greatly reduces the length of data processing time for Trimvec™ solutions. For the purpose of detecting movement, the measured configuration of object receivers from one epoch is compared against the configuration at another epoch. The displacement between epochs represents apparent movement. For the purpose of detecting continuous movement over a defined length of time, a base epoch is chosen as the "zero" configuration, and all subsequent epochs are compared against this standard. It then becomes possible to plot the relative configurations associated with a number of epochs against the base epoch and to show movement as displacement from the zero configuration at a consecutive series of discrete times. Deformation analysis is not only concerned with vectors of apparent movement; a reliable analysis must also propagate an error budget that accurately represents the intrinsic errors in the observing technology. This error estimation is achieved by the process of least squares network adjustment of observations, in which a unique mathematical solution is found for an over-determined system. The configuration of the monitoring system at any one epoch is determined by the Trimvec™ multi-baseline solution of satellite observables.

From this subprocess within the CDMS, unique coordinates are computed for each receiver in the survey network. The error estimate propagated by Trimvec™ is based upon clock and phase residuals within the receivers and will have an uncertain (conventionally scaler) relation to actual geometric errors. A true least squares estimate of geometric errors is derived from the combined network adjustment of two (or more) epochs. The CDMS restricts its network adjustment to two epochs. By including more than one point within the reference network, the distance residuals among the redundant vectors may be used to scale the phase errors to real-world geometric values. These errors can then be compared against the computed vectors of apparent movement to determine whether or not the apparent movement is real or is incorporated in the error budget. Statistical error may appear in an epochal solution not only as a result of clock errors, but also as a result of errors in broadcast ephemerides of satellite position, and all errors may be magnified by weak geometry of the satellite constellation.

The epoch name is created by combining the year, month, day, hour, and sequence of an epoch: yy mm dd hh #, where "#" represents the first epoch measured beginning in that hour. If any other epochs are measured beginning in that hour, they will be numbered sequentially. For example 88SEP0814-1 represents the first (perhaps only) epoch observed in Universal Time Coordinated (UTC) hour 14 on 8 September 1988.

Survey network design and definition

A deformation survey network is divided into two types of control stations, reference and object. The reference monuments are presumed not to be subject to deformation, although the CDMS runs a simple test on the reference vectors as a check on this assumption. For each reference baseline, this test will be a check on the observed slope distances from each epoch; a difference between the two exceeding a user-defined value (e.g. 1 cm) will flag the reference network as suspect. As will be explained, the greater number of reference stations there is, the greater the control and certainty over estimates of movement vectors. Two reference stations provide the minimum redundancy to permit *a posteriori* error estimation. One of the two stations (the primary station) is held fixed, while the horizontal azimuth between it and the secondary referenced monument is also held fixed. The redundancy in the combined adjustment originates in the vector between the two reference stations. A greater number of reference stations will add to the redundancy of the combined adjustment, as will be described. The Trimvec™ processing of phase observables yields baseline vectors expressed in Cartesian coordinates, transformable to the ellipsoid or to a tangent plane (the Local Geodetic Horizon). For the combined adjustment, the entire system is transformed first to the ellipsoid and then to an oblique transverse Mercator mapping projection. This mapping projection, which is rotated so that a cardinal direction on the projection coincides with the azimuth between primary and azimuthal reference stations, makes it possible to hold a fixed azimuth during the combined adjustment. The mapping projection coordinates of each epoch are rotated to fit the fixed azimuth before the combined adjustment is executed, thus removing any horizontal rotational bias in satellite coordinates between the two epochs. Following the combined adjustment, the mapping projection coordinates are rotated horizontally once again, around the primary reference station, using the optional rotation angle specified by the user during network definition. In this way the vectors of apparent movement may be expressed in any convenient horizontal orientation.

Combined least squares adjustment of two epochs

A 3-D survey network adjustment with minimum external constraints conventionally requires at least three fixed parameters, one of them being vertical, to orient the network within a coordinate system, plus an azimuthal constraint. The two parameters for the horizontal plane are satisfied in the CDMS by the two fixed horizontal coordinates of the primary reference monument. Theoretically, the completed azimuthal vector components from Trimvec™ satisfy the azimuth constraint, but they leave open the possibility that between two epochs a systematic azimuthal bias may have been inserted into the survey network as a result of biased orbital predictions for the satellites. It is for this reason that the azimuth of the primary reference baseline is held fixed in the combined adjustment.

The forte of the GPS lies in the accurate computation of the slope distance between the two antenna positions, which is not expected to be affected by the systematic error in the ephemeris. The three vector components of this distance, however, can and do change because of systematic error. Rotation of each epoch horizontally to the fixed azimuth of the reference baseline removes the possible azimuth bias without compromising the adjustment of the relative positions of the object points.

Other possible adjustment options that use more extensive network transformations, such as two or more rotations or adjustments using inner constraints, were rejected because of the likelihood that the introduction of such parameters would absorb residuals more properly distributed to the vector components, and hence could disguise apparent movement. In particular, a rotation or transformation out of the horizontal plane was rejected because of the relatively greater standard deviation in the vertical component (approximately twice that of horizontal components) that results from atmospheric error. The logical implication of this approach is that distances between reference monuments should lie reasonably close to the horizontal plane so that errors in the vertical component do not compromise the reference network. A baseline with a vertical gradient less than 30 deg from horizontal is reasonably close to the horizontal plane. For any one epoch, the total number of measured vectors is equal to $(n - 1)$, where n is the number of control stations. Each vector comprises three observational components (horizontal distance, azimuth, and height difference).

In the Trimvec™ solution, each of the three vector components (expressed in Cartesian coordinates) is unknown, meaning that there are $3(n - 1)$ unknowns from an epoch. In the combined adjustment, these unknowns, transformed to the mapping projection, become observations. When two epochs are combined, and the geometrical configuration is identical for both, there will be a total of $2[3(n - 1)]$, or $6(n - 1)$ observations in the combined network. The number of unknowns in the combined adjustment is equal to the number of coordinates subject to adjustment. The number of degrees of freedom (measured redundancy) in an adjustment is equal to the number of observations less the number of unknowns. The primary reference station contributes no unknowns to this adjustment; all three of its coordinates are presumed to be free of error. The secondary reference monument contributes two unknowns to the adjustment (one horizontal coordinate is presumed to be free of error, thus fixing the reference azimuth). Any further reference stations contribute three unknowns per station to the adjustment, as their coordinates are presumed not to move over time. Each object station, on the other hand, contributes six unknowns to the adjustment: three coordinates from the base epoch and three from the new epoch. The total number of unknowns in a combined adjustment, where there are at least two reference stations, is equal to $6n - 3R - 4$, where R = the number of reference monuments. When there is only one reference station, the number of degrees of freedom is always zero, meaning there is no redundancy. But when there are at least two reference stations, the number of degrees of freedom thus is $6(n - 1) - (6n - 3R - 4)$, or $3R - 2$.

Example

In a deformation network containing six stations but only one reference station, the number of observations is 30 and the number of unknowns is 30, yielding zero degrees of freedom. Where there are two reference stations, the number of observations is 30 but the number of unknowns is 26 ($4 \times 6 + 2$), yielding four degrees of freedom ($3 \times 2 - 2$). Where there are three reference stations, the number of observations is 30 but the number of unknowns is 23 ($3 \times 3\ 6 + 5$), yielding seven degrees of freedom ($3 \times 3 - 2$). In summary, adding the additional reference station to a deformation network adds three degrees of freedom to the combined adjustment, where the minimum number of reference stations is two and the minimum degrees of freedom is four.

Deformation modeling

Vectors of apparent movement. Following the combined adjustments, the base-epoch coordinates of the object points are differenced against the new epoch coordinates of the object points computed in the adjustment to yield vectors of apparent movement. In every combined adjustment, all coordinates are subject to new values except the three fixed coordinates of the primary reference station and one fixed coordinate of the secondary (azimuthal) reference station. What is being sought is relative movement rather than final coordinate values. Following a horizontal rotation of the survey network according to a user-defined rotation angle, the vectors are output in the horizontal orientation of choice. Apparent vertical movement is expressed separately, in a computer monitor display showing vertical arrows representing apparent movement and hatched bars showing random vertical deviation at the 95- and 99-percent levels of significance.

Variance-covariance estimation.

a. *Random deviation in azimuth and distance at 95- and 99-percent levels of significance.* For the purpose of propagating error into the vectors of apparent movement, they are treated as pseudo-observations (as though it were possible to make an observation from one epoch directly to another). Observation equations for azimuth, distance, and height are written for them, then multiplied by the *a posteriori* variance-covariance matrix of the coordinate unknowns to yield the variance covariance matrix for the pseudo-observations. The diagonal terms of this matrix (the "sigmas" of azimuth, distance, and height) can be evaluated at levels of significance of 95 and 99 percent (sigma unmodified represents a level of significance of 68 percent) and compared directly against the magnitude of the movement vector to look for real movement. The 95- and 99-percent errors are represented graphically as circular wedges, in which the radius of each wedge represents the error value in distance and the arcs of the wedges represent the error values in azimuth.

b. *The 95-percent relative error ellipse.* In addition to the sigma, or diagonal, values from the variance-covariance matrix of the pseudo-observations, a third value is also present, namely the horizontal covariant term, or correlated error, between azimuth and distance of the movement vector. Using all three values, an ellipse may be generated that shows the orientation of the correlated error and the magnitude of its bivariate components. Furthermore, the area within this ellipse may be said to represent an area of equal probability (e.g. 39 percent using a constant of 1 multiplied times sigma, 95 percent using a constant of 2.45, 85 percent using a constant of 1.96) for the bivariate distribution of errors in azimuth and distance of the movement vector. The relative error ellipse has been used in deformation-study literature to represent the estimated error in movement vectors, and that is why it is also used in the CDMS. The ellipse does offer useful data about the estimated errors, but it is not useful for direct comparison of the movement vector against its component errors in distance and azimuth.

c. *Coordinate standard error ellipses.* In addition to the variance-covariance matrix of the movement vectors, the combined adjustment also propagates a variance-covariance matrix for the coordinate unknowns, which can be helpful in assessing the precision achieved by the combined adjustment. This matrix can be represented in part by error ellipses for the coordinate unknowns, which reflect the errors in each of two horizontal dimensions at a point as well as the correlated error between them. Movable points will have two ellipses (one for each epoch), while reference points will have a maximum of one. The primary reference point will have no ellipse, since its coordinates are by definition without error, while the secondary reference point will have an error only in the unfixed horizontal coordinate. Any other reference points will have one ellipse representing the error propagated into the point by the two epochs combined. These ellipses are plotted as standard error ellipses (representing 1-sigma), and the area within them represents an area of equal probability of 39 percent. These ellipses are useful for evaluating the magnitude and orientation of the error propagated into the coordinates, relative to the fixed reference point and fixed azimuth.

Graphics Output of Deformation Analysis

Analysis of single epoch against base epoch

Two epochs are compared against each other by the vectors of apparent movement, error wedges and ellipses, and error bars. These displays will be automatically output on the monitor screen of the PC2 at each epoch, although their display may be hidden if any user interaction is also taking place at that time. Hard-copy outputs to a printer, showing numerical representations of the vectors with errors, may be obtained automatically by leaving the printer turned on as shown in the PC2 start-up menu. Otherwise, printer output and graphical output from the plotter are available through special user request from the user menu of the PC2 or PC3. Figure 3 is an illustration of a vector of apparent movement.

Analysis of apparent movement vectors over time

Movement over time is represented by a time-plot of the movement vectors from numerous epochs (those within the chosen span of time) compared against the "zero" values of a chosen base epoch. These are available either on the CRT or on the plotter, by special request, via the user menus.

2 Performance Testing and Demonstration

A prototype CDMS was installed at the Humphreys Engineer Center (HEC) located in Fort Belvoir, VA, for the purpose of reliability and performance testing. The purpose of the testing was to weed out any hardware or software bugs inherent in the CDMS and to determine its deformation accuracy.

Site Preparation

Survey monument fabrication

A survey network consisting of eight monuments were constructed at HEC. Six of these monuments are located between Buildings 2590 and 2595 and consist of standard USACE brass disks set in concrete approximately 1 in.[1] below ground. The concrete extends approximately 2.5 to 3 ft below ground and is belled out near the bottom. The brass disks are named HEC-1 through HEC-6 and are arranged as shown in Figure 4. Two other monuments were fabricated on top of Building 2592 within HEC. They consist of a 3- by 3-ft concrete pedestal 6 in. deep imbedded with a 10-in. PVC pipe (6-in. diam). The pipe rises 6 in. above the pedestal (filled with concrete), fixing a 12-in. stainless steel bolt to which a GPS antenna can be attached. These monuments are known as ETL-1 and ETL-2.

Survey control

A geodetic survey of the HEC survey network was performed during the latter half of November 1988 using GPS surveying equipment. First-order horizontal control was brought in from two control monuments located approximately 5 miles[2] away. Baseline vectors were input into the Geolab[3] least squares

[1] To convert inches into meters, multiply by 0.0254.

[2] To convert miles into kilometers, multiply by 1.609.

[3] Geolab is a registered trademark of Bitwise Ideas, Inc., The Baxter Center, 6-1050 Baxter Road, Ottowa, Ontario, Canada.

adjustment program. Two adjustments were performed to obtain the final results on the survey network. The first adjustment held the NAD83 horizontal coordinates of monuments WIG and SILVER fixed. The second adjustment held only the position of monument HEC-1, derived from the first adjustment, fixed thus preventing distortion of the survey network by any distortions that might be present in the national network. Figure 4 is an illustration of the HEC test network.

Deformation simulation platform

A special GPS antenna mount and platform (created by National Geodetic Survey in Corbin, VA) was used to simulate deformation behavior. This antenna mount is a circular metal plate with a series of holes drilled in it located at a known distance from each other (Figure 5). All holes are machined with a precision of approximately two thousandth of an inch. This plate allows a GPS antenna to be moved in different directions at a known distance. Different length bolts can be inserted into the plate allowing a GPS antenna to be elevated to a given distance by using spacers.

Hardware configuration

All hardware listed in Table 1 are included in the prototype CDMS. The computer network and its peripherals were located inside Building 2595. Six GPS receivers were held in a storage shed next to the field containing monuments HEC-1 through HEC-6. The receivers monitoring ETL-1 and ETL-2 were inside Building 2592. The computers linked the GPS receivers by telephone modem and fiber optic cable. The fiber optic cable was communicating with the "HEC receivers" and the telephone modem link with the "ETL receivers."

Testing Procedures

Diagnostic checking

Before the deformation simulation testing began, all hardware components had undergone diagnostic checks. During this checking period, it was discovered that the archiving devices had to be exchanged for newer models and the baud rate for the telephone modem link had to be set at 4800 baud (instead of 9600 baud) due to poor quality telephone communications used at the test site. The reduction in baud rate caused an increase in downloading time for the GPS receivers linked by modem to the computer network. For example, instead of taking 10 min to download survey data, it took approximately 20 min.

Survey network definition

After the diagnostic checks were completed, the survey network definition was installed into the CDMS menu system. ETL-1 was designated as the primary reference station, and HEC-5 was designated the azimuthal station. The baseline length between these two monuments is 267.7 m. The geodetic and rectangular coordinates (Virginia State Plane coordinates of the primary reference station were taken from the November survey. The deformation simulation plate was oriented to grid north within +/-1 deg using a Wild T-2[1] theodilite. A rotation angle of 2°20′ 24″.8122 was used to shift the default CDMS geodetic reference system to the Virginia State Plane coordinate system. During the 3-month testing period, there were anywhere from three to eight GPS monitoring stations used at the test site at any one time. The initial network definition had eight GPS receivers linked to the computer network.

Epoch definition

When testing took place, the amount of NAVSTAR satellite coverage available for 3-D positioning was approximately 3-1/2 hr for the Fort Belvoir, VA, area. The CDMS requires at least 50 min of actual surveying time to perform its deformation function. It was decided to conduct deformation simulations using two observation time frames. These were 90 and 180 min, respectively. The CDMS network definition was initialized to operate under sidereal time. This allowed the CDMS to advance the surveying epoch approximately 4 min each day in order to keep up with the available 3-D satellite window that advanced each day at the same rate. Once the entire GPS satellite constellation is in place, the need for sidereal time initialization will have lost its usefulness because of the 24-hr worldwide coverage that will be available.

Deformation simulation

Deformation simulation was executed by fixing the GPS antenna to the special antenna mount, previously mentioned, at a predetermined horizontal and vertical location. Once fixed, the CDMS would instruct the GPS receivers to conduct a survey. The operator had to make sure the antenna was fixed before the survey was activated because the system was in constant operation surveying every 90 or 180 min. After a given survey was complete, the antenna would be moved a known distance and direction before the next survey began. The mount allowed horizontal movement in the following increments: 2 mm, 4 to 10 mm (1-mm increments), and 1 to 10 cm (1-cm increments). The following vertical deformations were possible: 3 to 10 mm (1-mm increments), 1 to 10 cm (1-cm increments). The deformation simulation was performed for every epoch when the 3-D satellite window was available. A database containing the actual antenna movement and the deformation computed by the CDMS was developed.

Measurement precautions

Five wooden tripods were used to position the GPS antennas over the HEC-1 through HEC-5 monuments. The feet of each tripod were placed into the ends of 2-ft-long galvanized steel pipes that were driven flush with the ground. Sand bags were used to anchor each tripod leg firmly to the ground. A Wild Automatic Nadir Plummet[2] was used to check the positioning of the GPS antennas over

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1 Wild T-2 is a registered trademark of Wild Herbrugg, Ltd., 9435 Herbrugg, Switzerland.

2 Wild Automatic Nadir Plummet is a registered trademark of Wild Herbrugg, Ltd., 9435 Herbrugg, Switzerland.

the HEC monuments before and after each day's satellite pass. This check was made to ensure that any incidental antenna movement that occurred during a given CDMS survey would be discovered and recorded. If an antenna had moved, it would be recentered and releveled. Due to the level of measurement precision required for the deformation simulation, a 0.5-mm hole was drilled in the center of the cross of each HEC monument disk. This facilitated the precise positioning of the GPS antenna over the monument using the optical plummet. The plummeting accuracy was +/-1 part in 200,000. For this experiment, the investigators were able to maintain positional accuracy to about 0.25 mm.

Testing Results

Data collection

Performance testing of the CDMS began on 26 April 1989 and ended 29 June 1989. During this 65-day period, 45 days were used for deformation simulation during which time 88 epochs were taken by the CDMS. For each epoch, the CDMS computed the apparent deformation of each antenna being used as a monitoring station. During the 45-day period, the antenna over monument HEC-6 was being subjected to either horizontal and/or vertical displacement while the other monitoring stations were being held fixed. After completion of the testing period, a comparison was made between the true displacement of the monitoring antenna (or the lack thereof) and the deformation reported by the CDMS.

Epoch processing failures

Of the 88 epochs taken during the performance interval, only 45 of these could be used for deformation comparison. The majority of these failures were a result of bugs in the software, hardware problems, and operator errors. During the course of the performance testing, these problems were discovered and rectified. Thirteen of these unusable epochs were rejected by CDMS quality control routines. It is the responsibility of the CDMS to halt processing if anomalies are discovered in the data.

CDMS accuracy determination

The first objective in the data analysis was to determine the accuracy of the CDMS. To accomplish this, data were selected from the HEC-6 monument where deformation simulations were taking place. The data included only those epochs where the GPS antenna actually experienced simulated movement. The accuracy determination procedure allowed no more than a 24-hr time separation between epochs used for custom deformations (the custom deformation option in the CDMS was used to calculate the movement imposed on the HEC-6 antenna). A statistical mean and standard deviation of the difference between the actual and reported deformation (by the CDMS) was computed for all epochs used in the analysis. The following formulas were used in the statistical comparison:

$$\text{Mean} = \frac{\underline{Sx}}{n} \quad x = \text{sample} \quad n = \text{count} \qquad \text{Standard Deviation} = [\Sigma(x - \text{Mean})^2/n - 1]^{1/2}$$

$$\text{Root Mean Squared} = [\Sigma(Xm - Xt)^2/n]^{1/2} \quad Xm = \text{Measured Position}$$

$$X\,t = \text{True Position}$$

Out of 26 simulated deformations, the difference between actual and CDMS reported horizontal deformation was:

Mean = 0.002 m

Standard Deviation = +/-0.0054 m

Root Mean Squared = 0.0057 m

The difference between actual and CDMS reported vertical deformation was:

Mean = 0.0007 m

Standard Deviation = +/-0.0026 m

Root Mean Squared = 0.0027 m

The standard deviation for horizontal deformation turned out to be higher than expected. Examination of the epochs revealed that two of the custom deformations used in the data set reported abnormally high deformations on all monitoring stations. The two custom deformations in question were 89JUN2621-89JUN2623 and 89JUN2720-89JUN2722. The CDMS reported horizontal deformation of 1 to 2 cm for all four monitoring stations, even though three of them were not subject to deformation simulation. The nightly optical plummet reading for both of these events indicated that displacement during the actual GPS surveying period had not taken place. The difference in length of reference baseline for both custom deformations reported by the CDMS were within the 1-cm critical tolerance default limit.

One theory that may explain the cause of this "erroneous" deformation reporting is based on the three monitoring stations that were not physically moved. These three stations (HEC-2, 3, and 4) could be considered to act as a "control" to which HEC-6 (where deformation simulation was actually being tested) could be compared. Considering that the three stationary monuments were not undergoing deformation, the CDMS was actually comparing the difference in baseline vectors for these monitoring stations each epoch. When the CDMS reported deformations for all monitoring stations, it became apparent that the error might not be due to the CDMS processing but on the GPS data it had downloaded. The merit of this reasoning is based on the fact that the reported deformations were all of similar magnitude and direction. It is well known that the quality of the surveying data gathered by the GPS receivers can be affected by the quality of NAVSTAR broadcast, which can be of poor quality on occasion. Once these "bad" surveying data are downloaded to the computer network, the deformation results would tend to be biased. Normally, the CDMS quality control routines would reject corrupted survey data, but these routines can recognize only significant data errors. Because of this rare "bad" data phenomena, the investigators feel that placing a monitoring receiver over a stable platform (which will not deform over the project life) will provide reliability assurance for unusual deformation reports. If the monitoring points on the structure reports unusual displacement, this "control" monument can be viewed to see if it had undergone similar displacement.

After the aforementioned investigation into the data set was completed, the two custom deformations were removed and the system accuracy recomputed. Out of 24 custom deformations, the difference between the actual and CDMS reported horizontal deformations was:

Mean = 0.0007 m

Standard Deviation = 0.0023 m

Root Mean Squared = 0.0019 m

The difference between the actual and reported vertical CDMS deformation was:

Mean = 0.0007 m

Standard Deviation = 0.0027 m

Root Mean Squared = 0.0027 m

This reflects the deformation accuracy of the CDMS for a short baseline.

CDMS precision determination

Another statistical comparison was made using those monitoring stations that were not subjected to simulated displacement. The intent of this analysis was to examine the repeatability of GPS baseline measurements. Because none of the "control" monitoring station had undergone movement, the CDMS would be reporting only the difference in baseline measurements each day. Therefore, a statistical mean and standard deviation of these baselines would display the GPS measurement precision. Out of 27 custom analysis using all of the control monitoring stations, the following measurement precision was observed:

Horizontal precision

Mean = 0.0027 m

Standard Deviation = 0.0021 m

Root Mean Squared = 0.0034 m

Vertical precision

Mean: -0.0005 m

Standard Deviation: 0.003 m

Root Mean Squared = 0.003 m

Both of these values are well within the precision requirements of GPS hardware.

CDMS Demonstration

The CDMS was installed and demonstrated at Dworshak Dam in northern Idaho. Dworshak Dam is the highest straight-axis concrete gravity dam in the western world and the largest ever constructed by the USACE. The demonstration period was for 3 months beginning in July and ending in September 1989. During this time frame, the CDMS was left to run on its own. The system was programmed to perform deformation analysis once a day (at that time only about 5 hr of satellite coverage was available). At the end of the demonstration, the CDMS prepared a record of deformation behavior of the dam as the reservoir was experiencing drawdown.

Installation

Six GPS receivers were used in the Dworshak Dam demonstration project. Two were used as reference stations while the remaining four acted as the monitoring stations on the dam. The primary reference station was located on top of the three-story concrete Dworshak Fish Hatchery building. A concrete pedestal with a forced centering device (Figure 6) cemented into it was bolted to the roofing slab. The forced centering device (used for all of the antenna mounts in the Dworshak demonstration) allowed the antenna to be rotated in any direction while maintaining centering. This was necessary because of the requirement for all GPS antennas used in a geodetic survey to be oriented in the same direction (within 15 deg). This is done to compensate for any possible measurement error due to potential defects in antenna construction. Having antennas oriented in the same direction allows software processing to remove this error. All antennas used in the Dworshak demonstration were aligned to magnetic north. The azimuth station was located in the Big Eddy marina upstream of the dam. The antenna was set in a concrete pedestal bolted to the wall of the marina's comfort station. The baseline length between the two reference stations was 3,244.8 m. Neither the primary nor the azimuth reference stations were situated in ideal locations. Both of these stations were on buildings that could themselves be subject to deformations. Unfortunately, locations accessible to the demonstration with telephone lines were limited and therefore necessitated the use of these reference sites.

Figure 7 is a photograph of Dworshak Dam. Both the reference and azimuthal station were linked to the computer network in the dam by telephone modem. The remaining antennas were located on the dam. A monitoring station was installed on top of both elevator towers (monoliths 25 and 17), with forced centering devices imbedded into the concrete roofing slab. The other two monitoring stations (known as monoliths 28 and 22) were located near the roadway on top of the dam. The monolith 28 antenna was set in a concrete pillar on the south walkway, whereas the monolith 22 antenna was set in a similar pillar next to the selector gates of the dam. All CDMS monitoring stations on the dam were linked to the computer network by fiber optic cable. In order to reduce the amount of fiber optic cable needed to link all monitoring stations to the computer network, fiber optic multiplexors were employed. A fiber optic cable was run from all GPS receivers (located in the main gallery below the roadway) to the multiplexor located in the monolith 25 gallery. From that multiplexor, all data coming from the receivers would be combined into a single fiber optic cable connected to another multiplexor adjacent to the computer network in the powerhouse (a distance of approximately 1,600 ft). The multiplexor situated in the powerhouse would then resplit the data streams coming from the four GPS receivers and download the data into four available serial ports of PC1. The PC1-PC2 computer network was located in the powerhouse along with its peripherals. PC3 was installed at TEC in Fort Belvoir, VA, and was connected to the Dworshak Dam CDMS by telephone modem link.

System operation

After the hardware installation was complete, the Dworshak Dam network definition was typed into the CDMS software. The geodetic coordinates of the primary and azimuthal reference station were taken from a previous GPS survey completed a year before installation. Idaho State Plane coordinates were used as the project coordinates. The CDMS was instructed to rotate the survey network 25°44′09.2″ in order to have the survey network oriented to project north (which is upstream of the dam). This allowed vectors of apparent movement to be represented in a upstream/downstream fashion (which would be the expected deformation of the dam). After performing some tests on the system, the base epoch was taken on 28 July 1989. A 5-hr survey data collection time was input to the CDMS. This 5-hr interval encompassed the entire GPS satellite availability (four or more satellites) for that area during the demonstration time period. The entire window was used for two reasons. The first reason was to collect as much data as possible to ensure an accurate deformation reading (Dworshak Dam's normal annual horizontal deformation is about 19 mm). Considering the CDMS was being installed for only 3 months, the investigators wanted to be able to pick up very small deformations. The second reason was due to a problem discovered at the azimuth station. The location of this station was in an area where the landscape was shaped in a bowl. This bowl shape tends to create unusually high multipath effects. Another problem with this location was trees spaced on the top of this bowl. The trees would tend to refract the satellite signal as it was moving just above the horizon. Abnormally high deformations were observed using smaller epoch times; therefore, a long GPS observation time was established that reduced the error introduced by these two phenomena. The weekly archiving was scheduled over the weekend, which allowed an employee to replace the archive tape on Monday morning when he came in to work.

After the base epoch was taken, the CDMS remained on automatic operation until 7 October 1989. The system operated normally during that time except for two difficulties. One of the problems concerned the telephone link with the primary reference station in the Dworshak fish hatchery. The poor line quality forced the modems to communicate at 4800 baud. Occasionally the phone line noise would send a false signal to the GPS receiver that would "lock up" its surveying function. When this phenomenon occurred, a man would have to reset the receiver (turn it off and on). The receiver would then operate normally. The second problem was the failure of one of the eight communication ports in the fiber optic multiplexor. When this happened, the fiber optic cable linking the monolith 28 receiver to the computer network in the powerhouse could not down link its data. All other links were not affected.

Demonstration results

During the 3-month demonstration period, the water surface elevation of the reservoir was being recorded each day. With the use of this information, a graphical comparison was made between the reservoir pool elevation and the apparent deformation reported by the CDMS. The reported deformation was broken up into Northings (upstream and downstream deformations), Eastings (right and left deformations), and vertical deformations. For illustration purposes, Figures 8, 9, and 10 (representing monolith 28) will be used to discuss the results. The comparisons for the other monoliths are given in Appendix A. Some of the deformation data will not appear on the figures due to a number of factors such as start-up testing, survey data rejected by the CDMS, and equipment malfunction. The last few deformation results for monolith 28 are not present due to the fiber optic port failure discussed in the previous section.

Figure 8 represents the clearest evidence of the CDMS monitoring actual deformation of Dworshak Dam. It depicts the upstream and downstream motion of the dam. During the demonstration period, the reservoir was experiencing drawdown and the CDMS recorded a gradual upstream deformation. This upstream motion is apparently due to the reduction of force exerted by the reservoir on the dam. As the force was reduced because of dropping pool elevation, the dam can flex back toward the upstream side of the river, therefore exhibiting a northern deformation. As an independent verification system, an optical plummet (almost exactly the same kind used in the HEC tests) took horizontal deflection readings inside monolith 28 periodically during the demonstration period. The optical plummet was located in the same gallery as the GPS receivers and focused on a target at the base of the dam. Though the elevations of the two deformations monitoring systems were different, Figure 8 illustrates that the optical plummet also recorded a gradual upstream motion of the dam. Please note that the first plummet reading was set to zero and all proceeding values are reported relative to that starting point in the same manner as the CDMS.

Figures 9 and 10 represent Eastings and vertical apparent deformations for monolith 28, respectively. There appeared to be no significant east/west deformation experienced by the Dworshak Dam, as shown by Figure 9. The seeming day-to- day right/left motion illustrated in the figure is most likely due to measurement noise, because the reported deformation was close to the accuracy tolerance of the CDMS. Finally, the downward vertical deformation illustrated in Figure 10 could possibly be caused by the reduction in uplift pressure, experienced by the dam, associated with the reduction of pool elevation. Periodic conventional trilateration and/or triangulation surveys of the monitoring stations could not be conducted because of the unavailability of survey crews and the great expense this would entail. Ironically, a GPS survey would overcome these difficulties.

Conclusions and Recommendations

Conclusions

The results of the testing and demonstration of the CDMS have shown that it can be very useful for measuring structural deformation. The investigators feel that this technology would be most valuable for monitoring those structures where continuous observation is necessary, for example, new dams undergoing initial pool rise, structures suffering unusual distress, and areas undergoing subsidence. The automated nature of the CDMS will offer a notable cost savings compared with current survey methods and will also provide a vast amount of deformation data contributing new insight into the behavior of a structure.

Prototype reliability

Verification of the reliability of the system took place over the almost 6 months of testing and demonstration discussed in this report. After investigating the observed hardware malfunctions, all but one were attributed to improper installation and/or configuration. All hardware problems that occurred could be fixed by personnel at the monitoring site. It should be noted that the GPS receivers themselves did not experience any hardware problems. The CDMS software had a number of bugs discovered in it during the performance testing at the HEC, and a few were discovered at the Dworshak Dam demonstration. All these bugs were rectified (mostly by telephone modem), and by the end of the demonstration, the software was running smoothly. The investigators feel that software bugs were not a reflection on the reliability of the system but were a normal result of prototype development. In conclusion, the performance of the prototype CDMS was acceptable. The investigators feel that a production level system would perform at an acceptable level of reliability.

Security issues

It should be noted that consideration should be made to the security of the GPS hardware. At the Dworshak Dam demonstration, no vandalism was experienced, but that possibility does exist. Care should be taken to make the GPS equipment secure. In the case of the Dworshak Dam demonstration, the GPS receivers were locked away from the public, and most of the antennas were placed in an area that could not be reached without difficulty.

Life-cycle cost estimation

An estimate was made to examine the relative cost of using the CDMS compared with conventional geodetic surveying methods. An estimate was made of the life-cycle cost for geodetic surveys of a dam with a 50-year-life expectancy. The approximate cost for both methods are as follows:

Conventional survey cost

Procure Survey Hardware - Electronic Distance Meter - Precise Level - Prisms, Tripods, etc.	\$20,000
Maintenance/Replacement (M/R) Cost (2% of hardware cost)	\$400/year

Hardware/Maintenance cost per year
= [\$20,000 + (50 years × \$400)]/50 years
= \$800/year

CDMS survey cost

Procure Hardware - 10 GPS Receivers (\$20K/each) - Installation - Computers and Peripherals	\$250,000
Maintenance/Replacement (M/R) Cost (2% of hardware cost)	\$5,000/year

Hardware/Maintenance cost per year
= (\$250,000 + [50 years × \$5,000)]/50 years
= \$10,000/year

By looking only at the hardware/maintenance cost per year, it appears that conventional geodetic surveying methods would be the least costly alternative. However, when the amount of labor required to perform a conventional survey is taken into account, the picture changes. Following is an estimate of the cost to perform a single geodetic survey in a typical dam monitoring scenario:

Cost of One Geodetic Survey - Survey Crew - Travel - Vehicles - Data Processing - Drafting	\$10,000

If the yearly M/R cost is added to this amount ($10,000 + $800 = $10,800), it will exceed the yearly M/R cost of the CDMS ($10,000), which does not have a labor charge. The true importance of this example really lies with the production capabilities of the two methods. It would take approximately 1 week to compute a **single** deformation study using conventional techniques. With the CDMS, 24 separate deformation computations can take place in a single day. If 24 deformation surveys are conducted with conventional means, the cost would be:

$$(24 \times \$10{,}000) + \$800/\text{year} = \$240{,}800$$

This is almost the capital cost of procuring a CDMS. It must be stressed, however, that using the CDMS is not recommended for single structures where monitoring is needed only one or twice a year. For these periodic surveys, conventional GPS surveying would be more cost effective. The CDMS is best suited for situations were continuous monitoring is required or where the system can be moved from site to site.

Recommendations

The next stage of development with the CDMS is to adapt it for measuring dynamic deformations. As previously mentioned, the CDMS can measure only gradual deformations. GPS surveying techniques already exist that can perform precise surveys while in motion. The transition to adapt this technology to the CDMS would be straightforward. The Texas Highway Department has already contacted the Topographic Engineering Center about the possibility of using a "dynamic CDMS" for monitoring bridge deformation. With further development, the CDMS can truly become a vital instrument for monitoring deformation in all kinds of environments.

Table 1
Computers and Internally Driven Peripherals

Component	PC1	PC2	PC3
Computer	Compaq Deskpro[1] 386/20	Compaq Deskpro™ 386/20	Compaq Deskpro™ 386/20
Memory	9 MByte total: 1 MByte System plus 8 MByte add-on	5 MByte total: 1 MByte System plus 4 MByte add-on	5 MByte total: 1 MByte System plus 4 MByte add-on
Co-processor	387/20 floating point math co-processor	387/20 floating point math co-processor	387/20 floating point math co-processor
Floppy disk drive	High-density (1.2 MByte) floppy disk drive	High-density (1.2 MByte) floppy disk drive	High-density (1.2 MByte) floppy disk drive
Hard drive	300 MByte or 130 MByte	300 MByte	100 MByte or greater
Graphics card	EGA or VGA	EGA or VGA	EGA or VGA
Display	High-resolution color	High-resolution color	High-resolution color
Operating system	SCO Xenix™, version 2.2.3 and SCO CGI[2] version 1 plus (opt) DOS	SCO Xenix™, version 2.2.3 and SCO CGI™ version 1 plus (opt) DOS	SCO Xenix™, version 2.2.3 and SCO CGI™ version 1 plus (opt) DOS
Local area network	Excelan network[3] card "LAN Workplace for Xenix, for Compaq 386 systems running SCO Xenix™ 386, version 2.2"	Excelan network™ card "LAN Workplace for Xenix, for Compaq 386 systems running SCO Xenix™ 386, version 2.2"	N/A
Multiport RS-232	Anvil Systems[4] 16-port "Stallion" serial board with revision 2.1.7 drivers	4 or more ports recommended (example: Anvil Systems' "Brumby" or "Stallion")	N/A
Archive		Emerald Systems[5] VAST tape unit, with Xenix drivers	Emerald Systems™ VAST tape unit, with Xenix drivers

[1] Compaq Deskpro 386/20 is a registered trademark of Compaq Computer Corp., PO Box 692000, Houston, TX 77269-2000.
[2] SCO CGI is a trademark of the Santa Cruz Operation, Inc., 400 Encinal Street, PO Box 1900, Santa Cruz, CA.
[3] LAN Workplace is a registered trademark of Excelan, Inc., 2180 Fortune Drive, San Jose, CA 95131.
[4] Stallion and Brumby are registered trademarks of Anvil Designs, Inc., Suite 140, 2118 Walsh Ave., Santa Clara, CA 95050.
[5] The VAST device is a registered trademark of Emerald Systems, 4757 Morena Boulevard, San Jose, CA 92121.

Table 2
Material Other Than Computers

Equipment	Type	Quantity
System software	Continuous monitoring system	1
Receivers	Trimble™ 4000 series with geodetic antennas firmware version 3.12 with CMS option (10 channels, single break reset)	3 to 10
Uninterruptable power supplies	Elgar 400 + 600[1] Unisafe for SCO Xenix 5T- 9P[2] kit number 572207-1	2 (one per computer, optional)
Modems	Hayes Smartmodem V.32 9600[3] (recommended)	0 to 20
Printer	Standard ASCII (examples: HP Inkjet[4], Epsom[5] dot matrix)	1 to 2 (optional)
Plotter	Hewlett Packard Draftpro[6] or Hewlett Packard Draftmaster[7]	1 to 2 (optional)

1 IPS 400+600 is a registered trademark for ELGAR, 9250 Brown Deer Road, San Diego, CA 92121.
2 Unisafe for SCO Xenix 5T-9P is a registered trademark for ELGAR, 9250 Brown Deer Road, San Diego, CA 92121.
3 Smartmodem 9600 is a registered trademark for Hayes Microcomputer Products, Inc., PO Box 105203, Atlanta, GA 30348.
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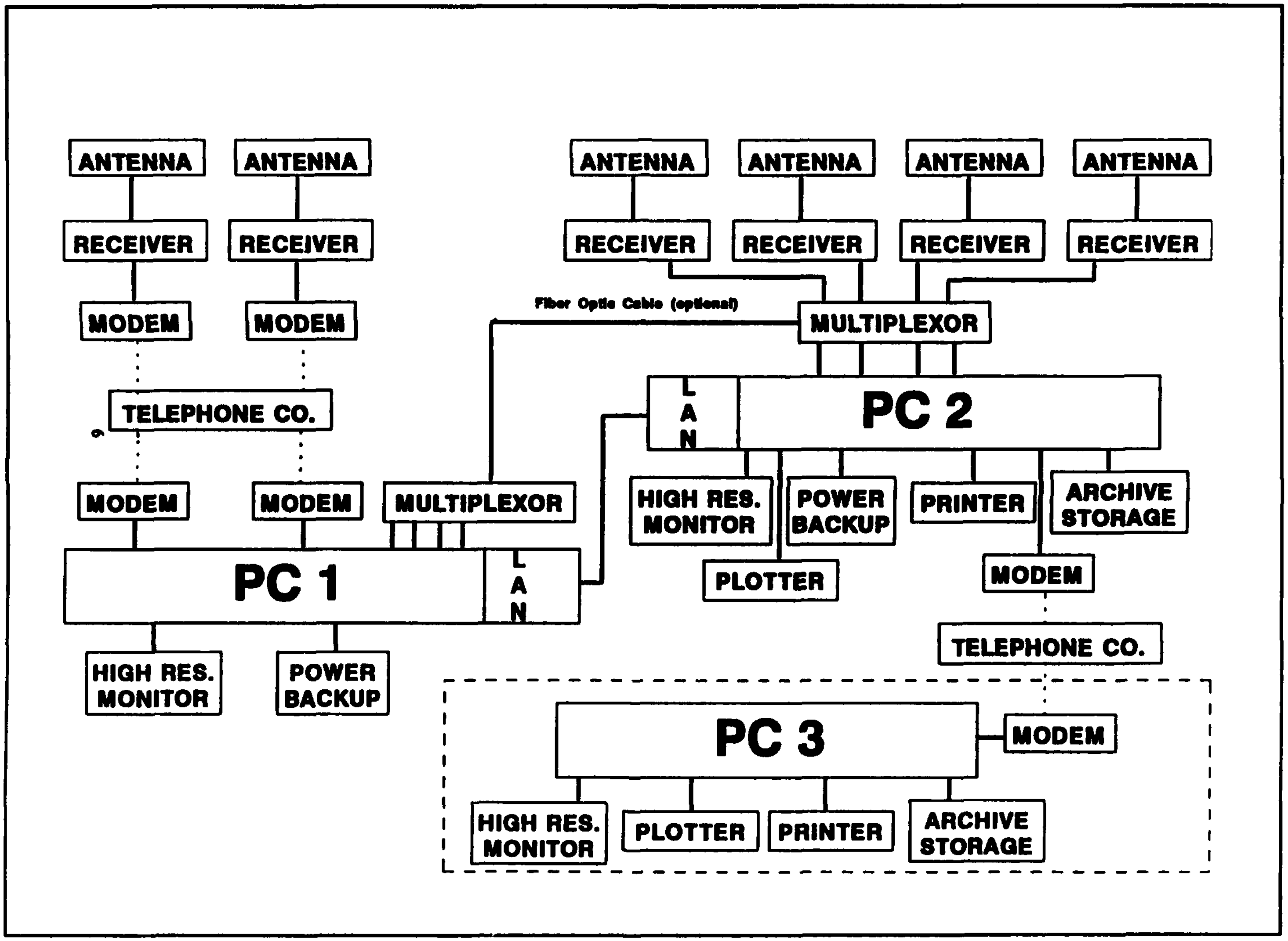


Figure 1. Hardware configuration for the CDMS

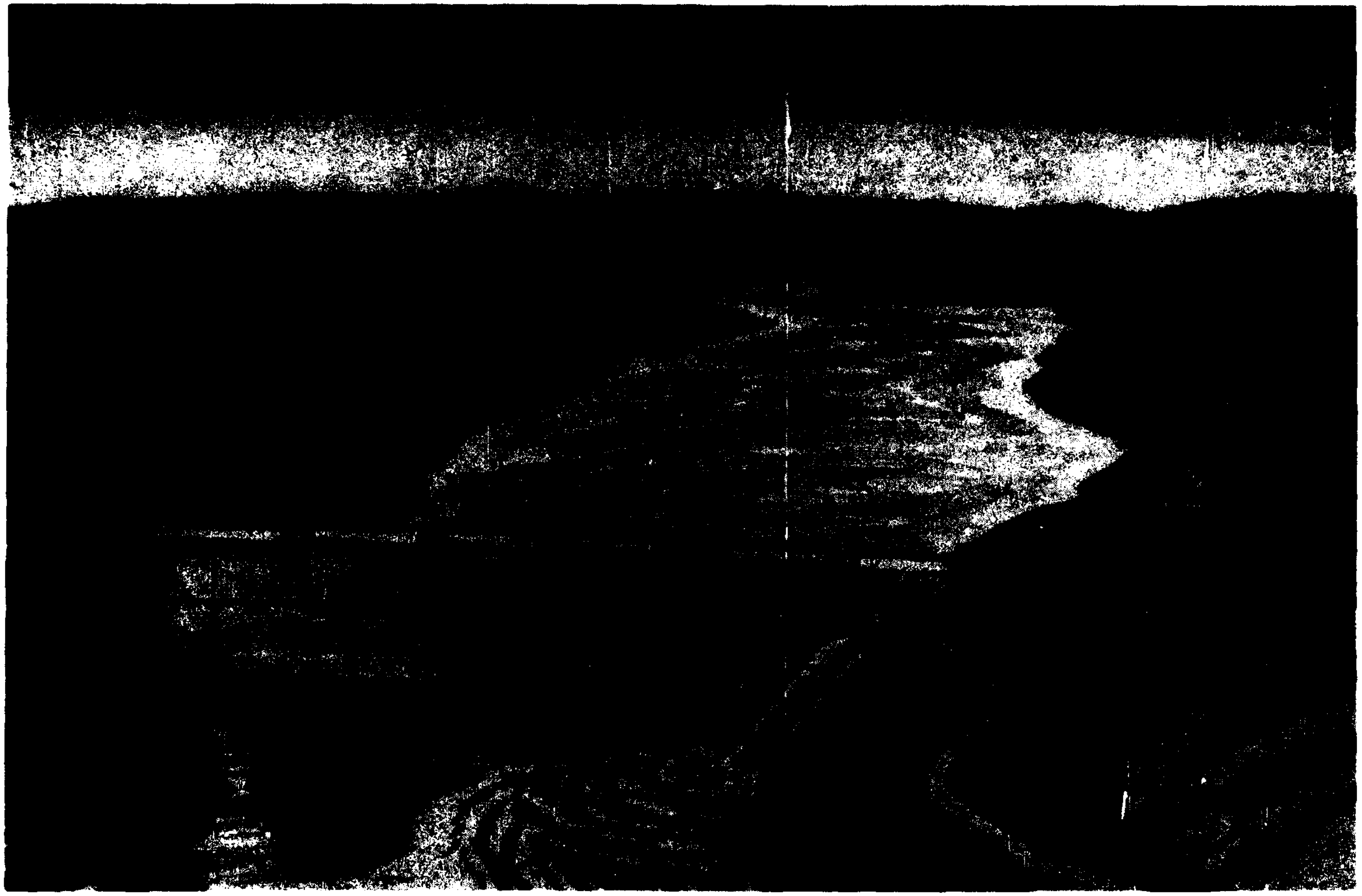


Figure 2. Illustration of CDMS installation

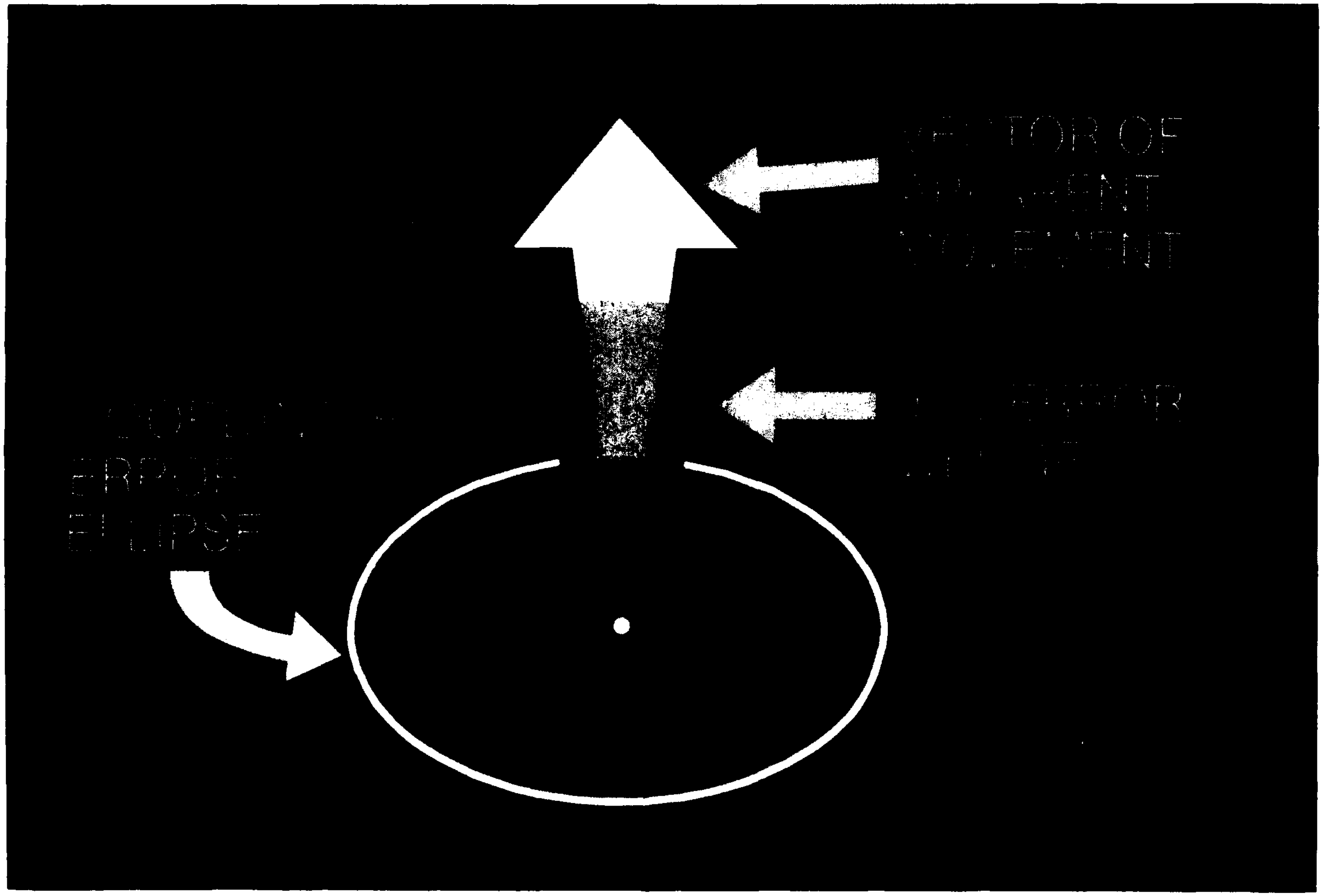


Figure 3. Deformation output example

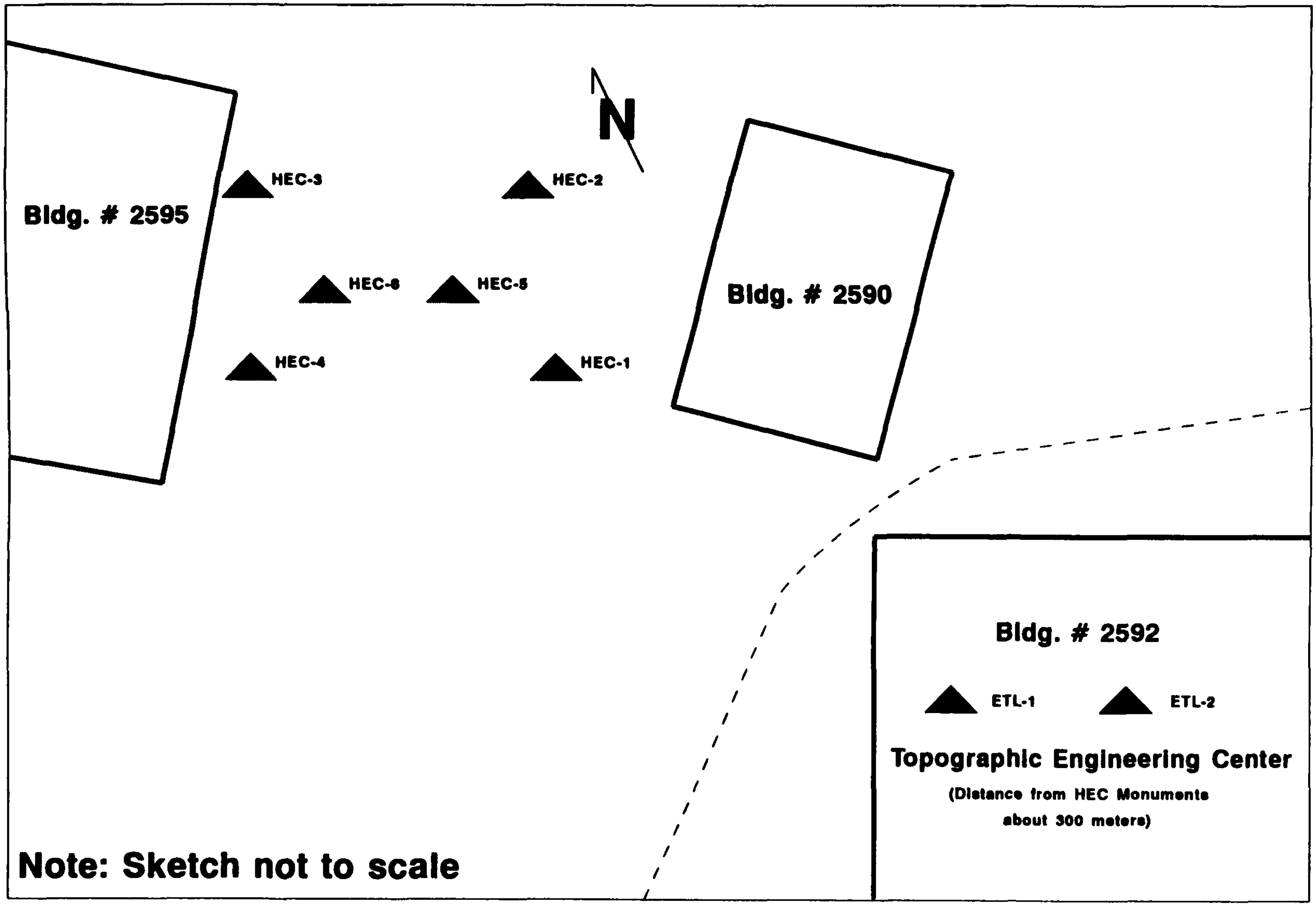


Figure 4. Humphreys Engineer Center test network

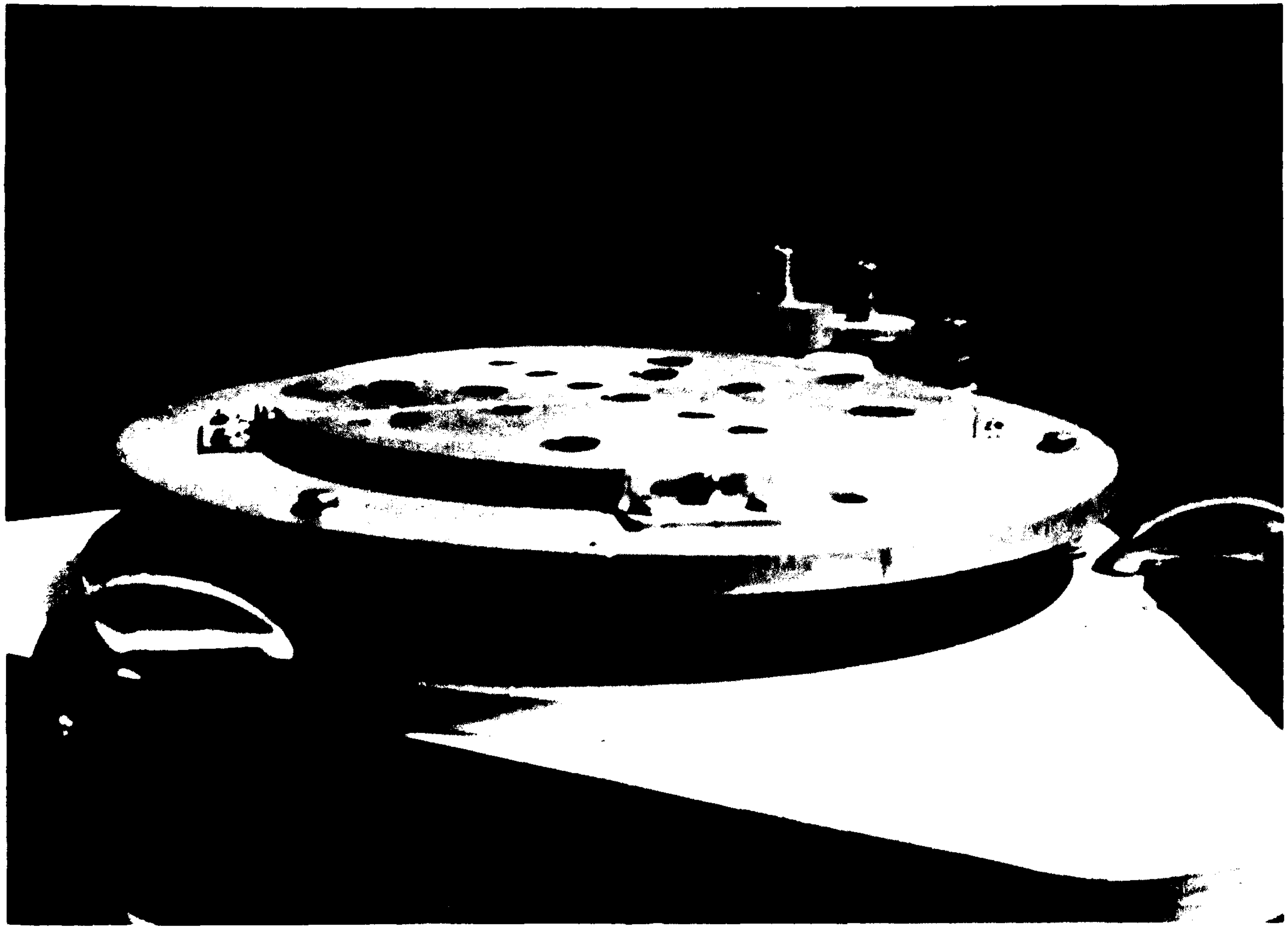


Figure 5. Deformation simulation platform

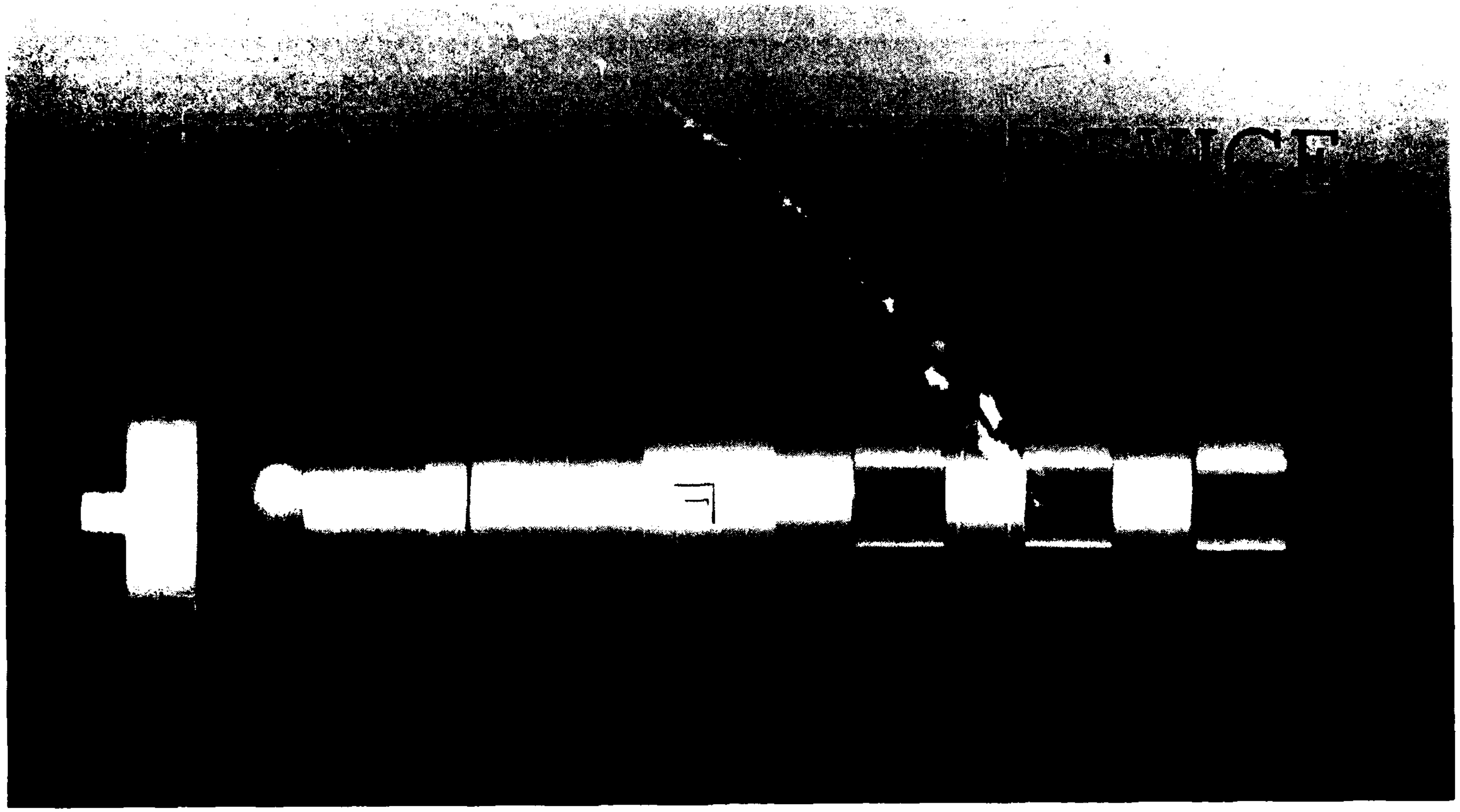


Figure 6. Forced centering device

Figure 7. Dworshak Dam

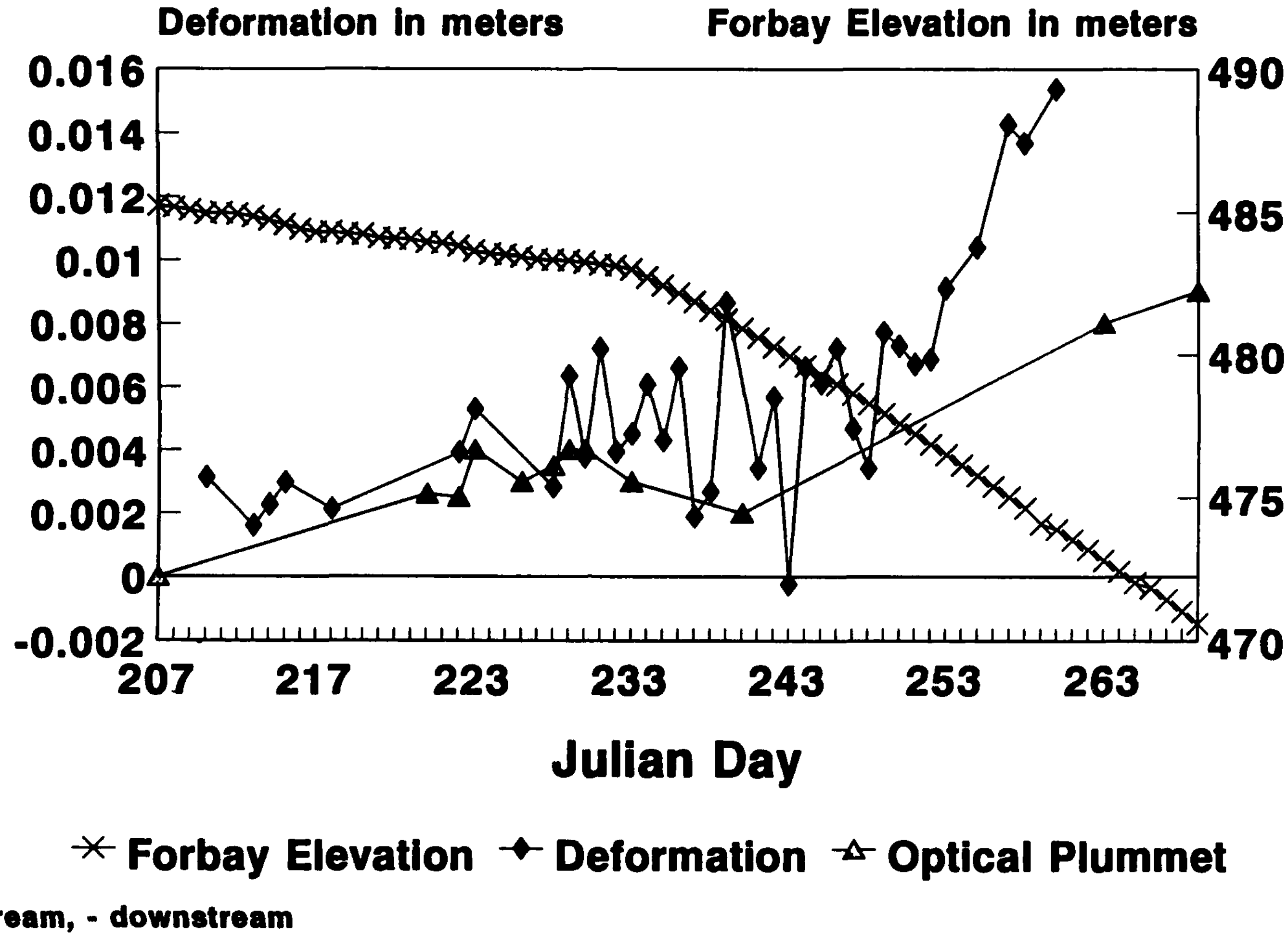


Figure 8. Northings versus pool elevation, monolith 28

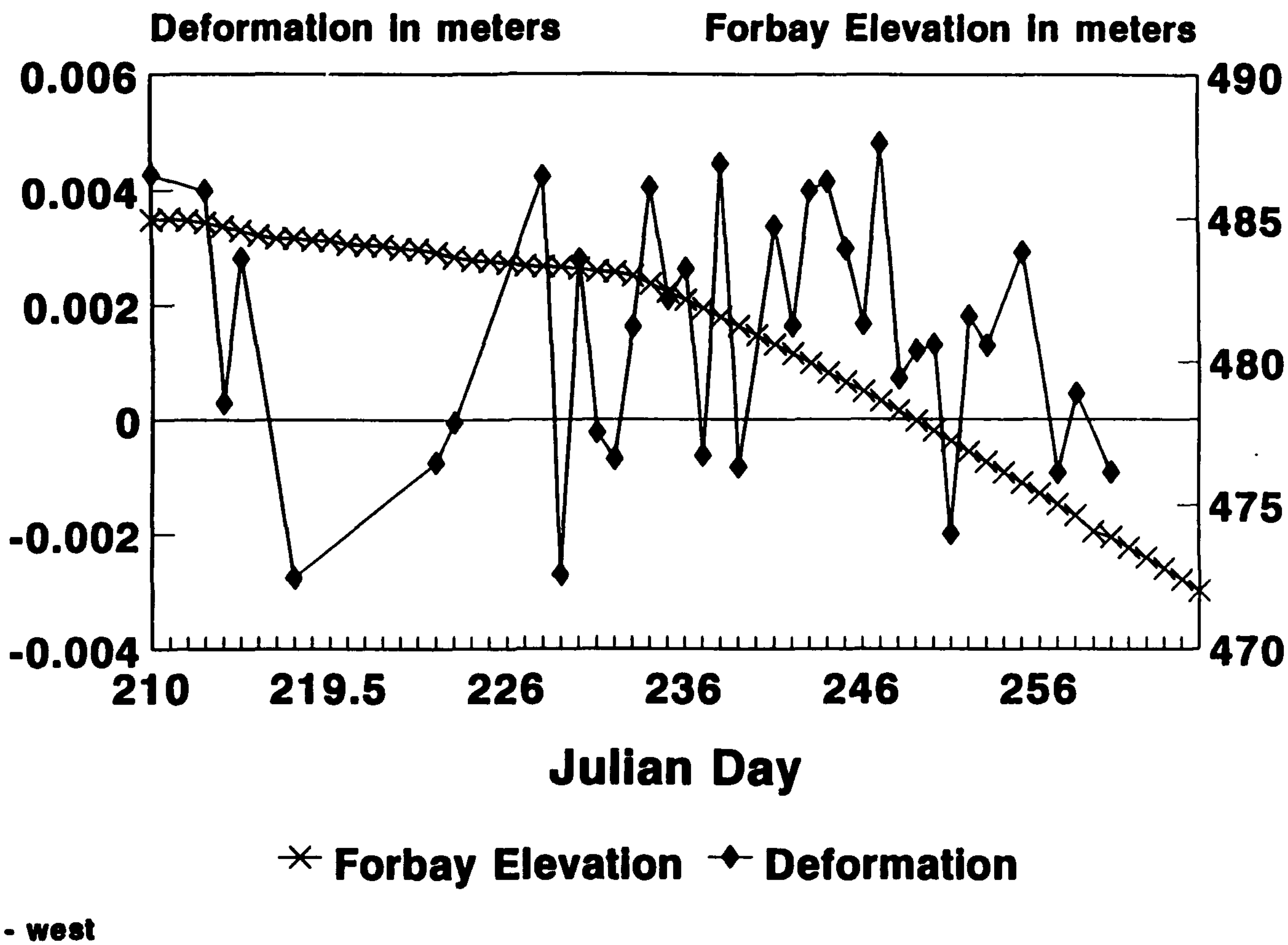


Figure 9. Eastings versus pool elevation, monolith 28

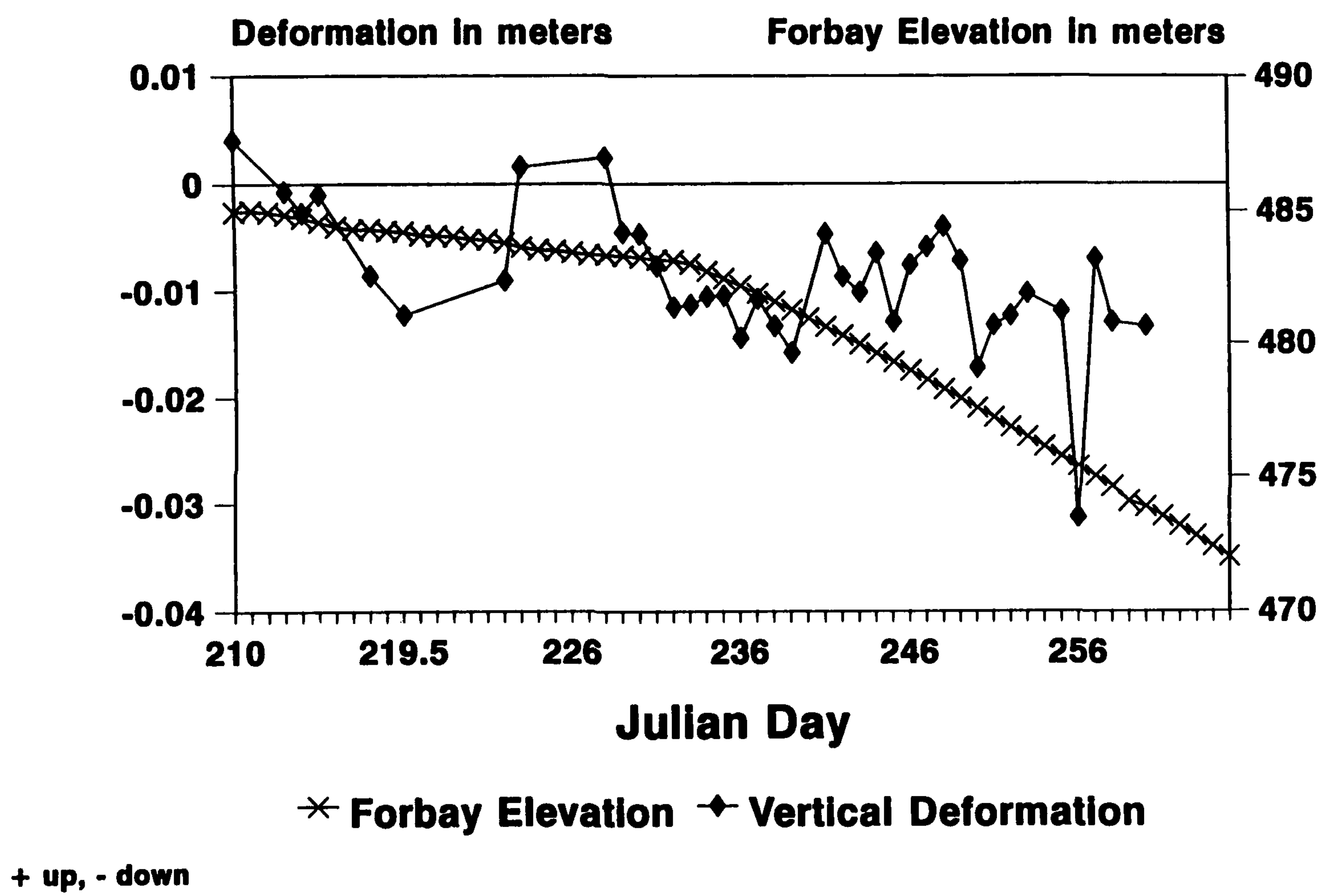
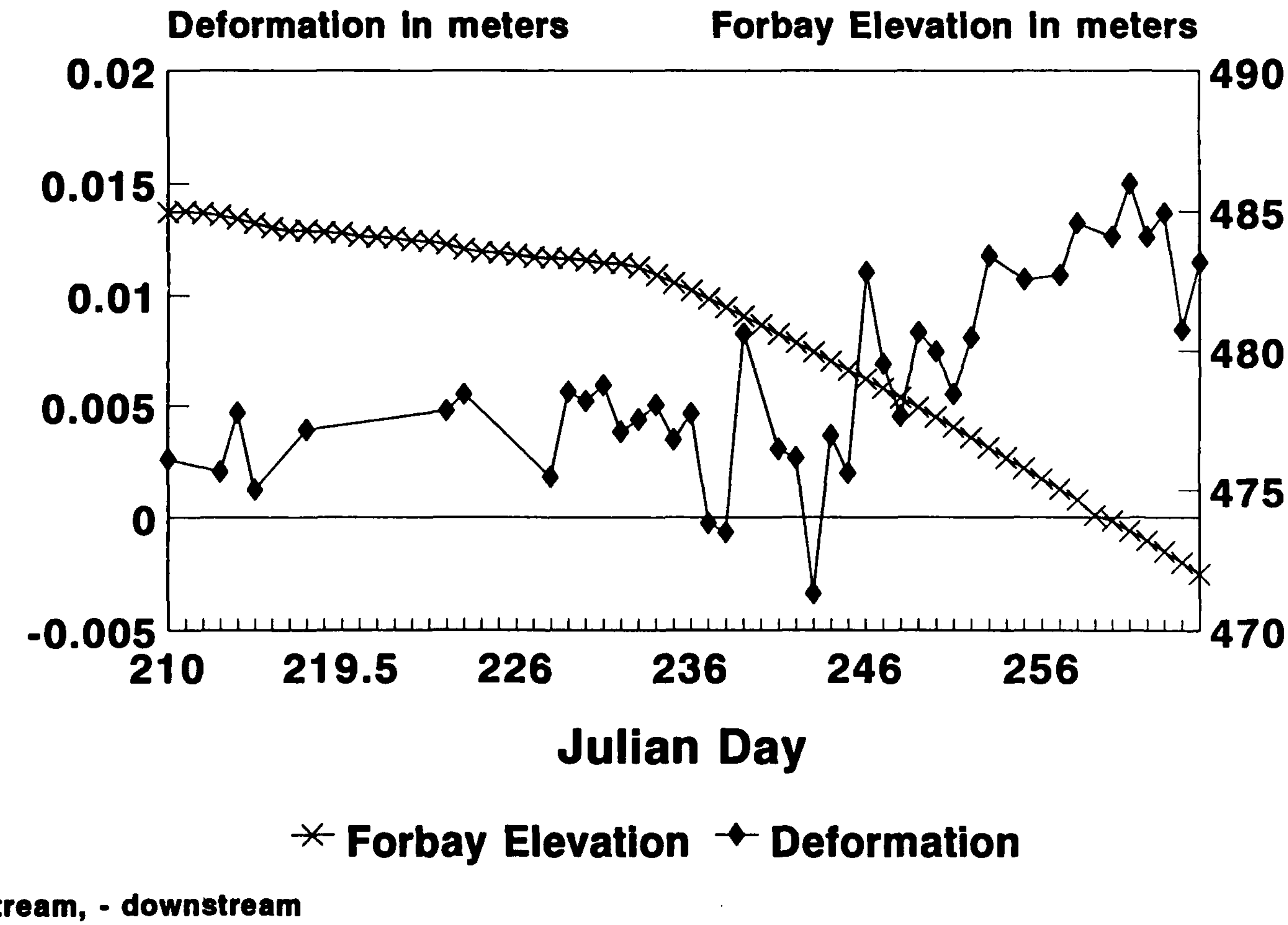


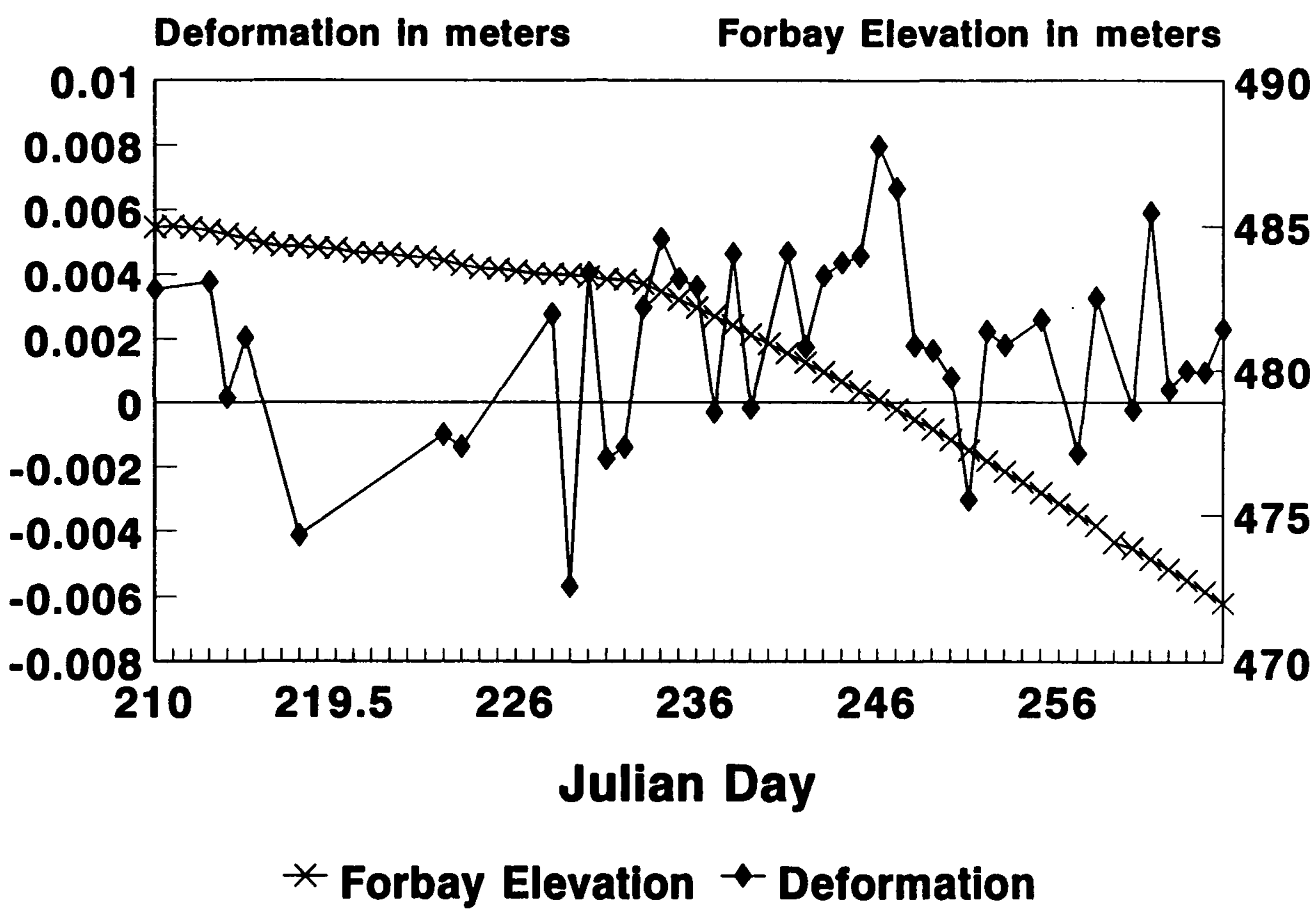
Figure 10. Vertical deformation versus pool elevation, monolith 28

Appendix A: Comparisons for Monoliths 17, 22, and 25

Northings vs Pool Elevation
Monolith 17

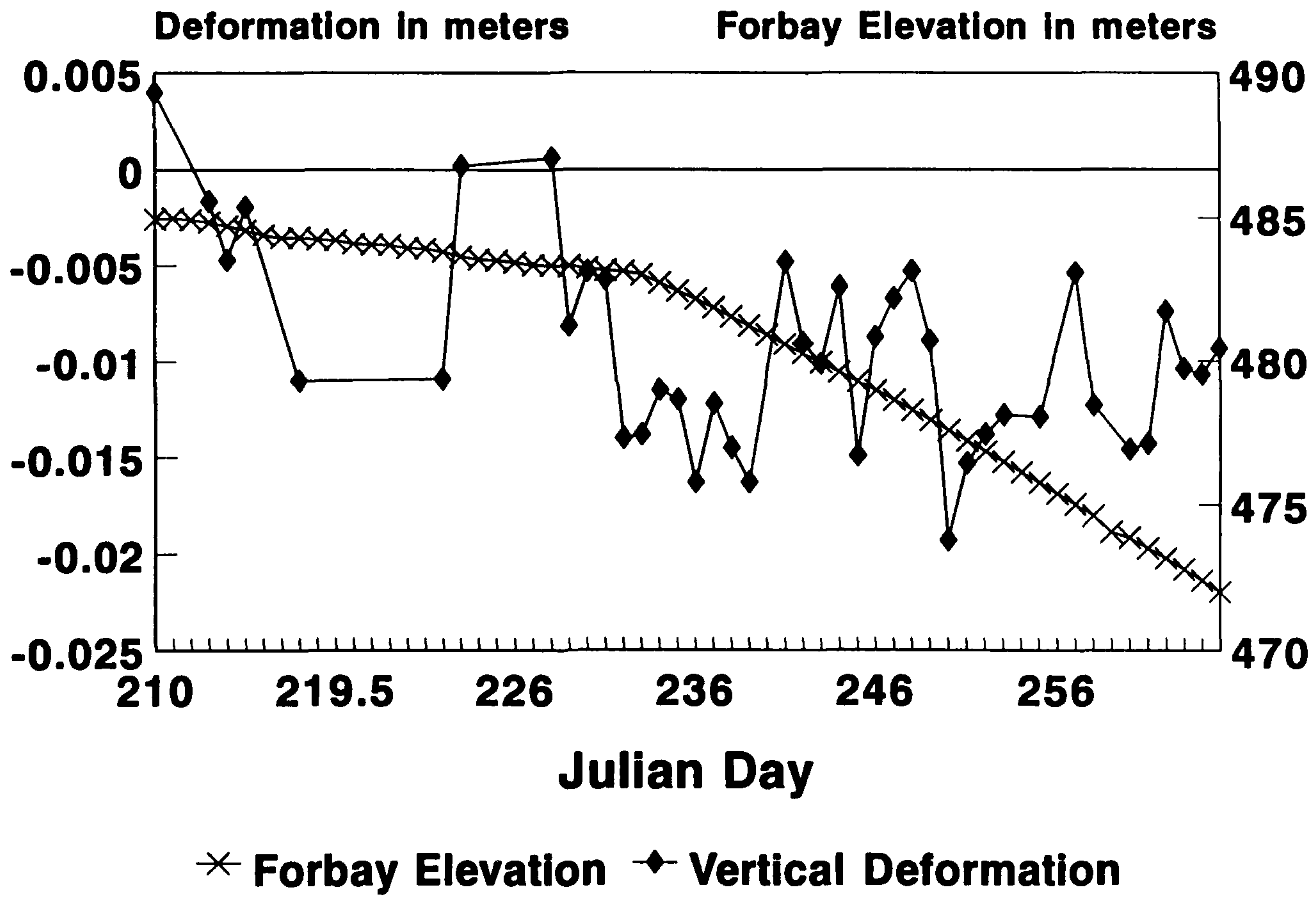


Eastings vs Pool Elevation
Monolith 17



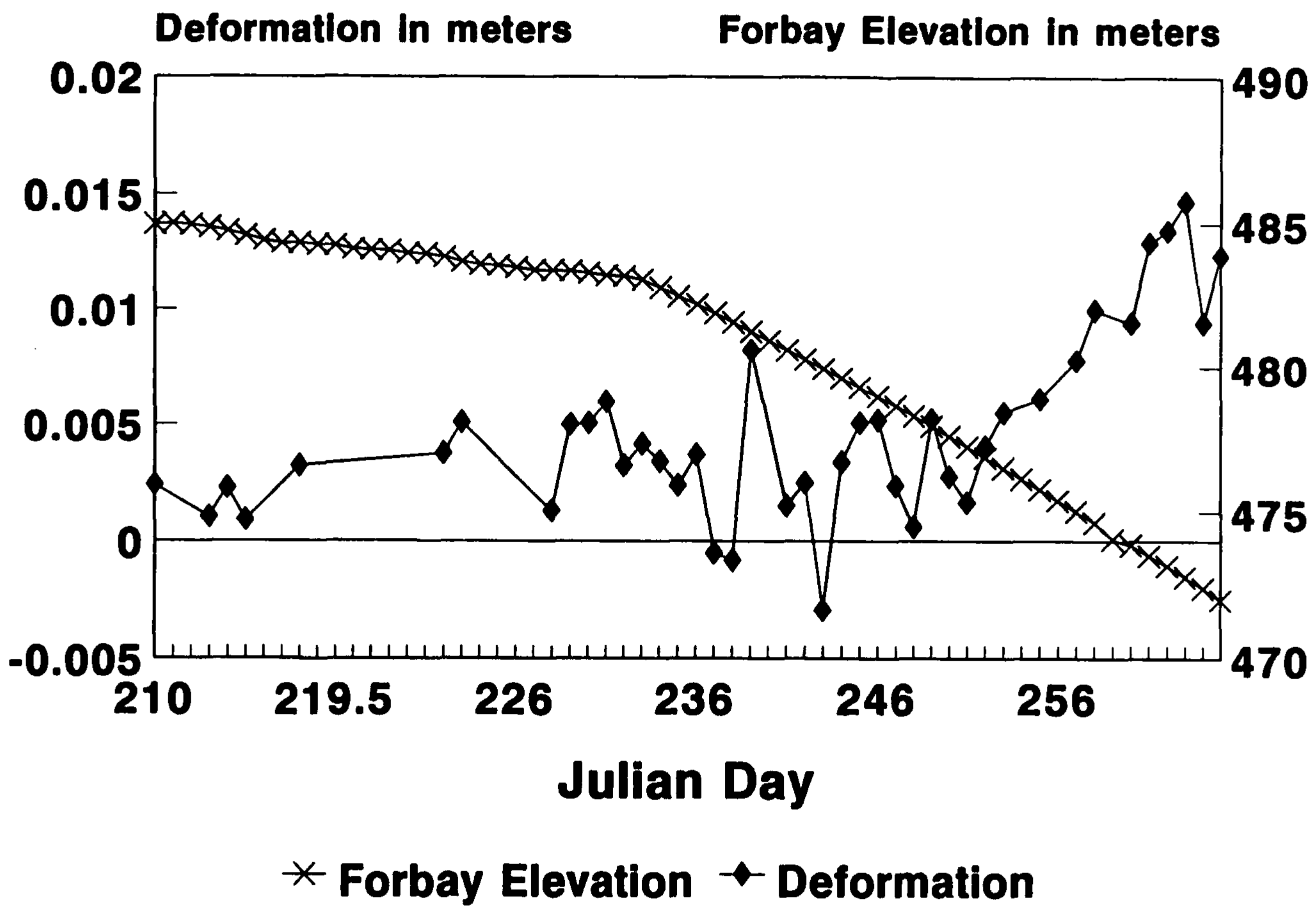
+ east, - west

Vertical Deformation vs Pool Elevation
Monolith 17



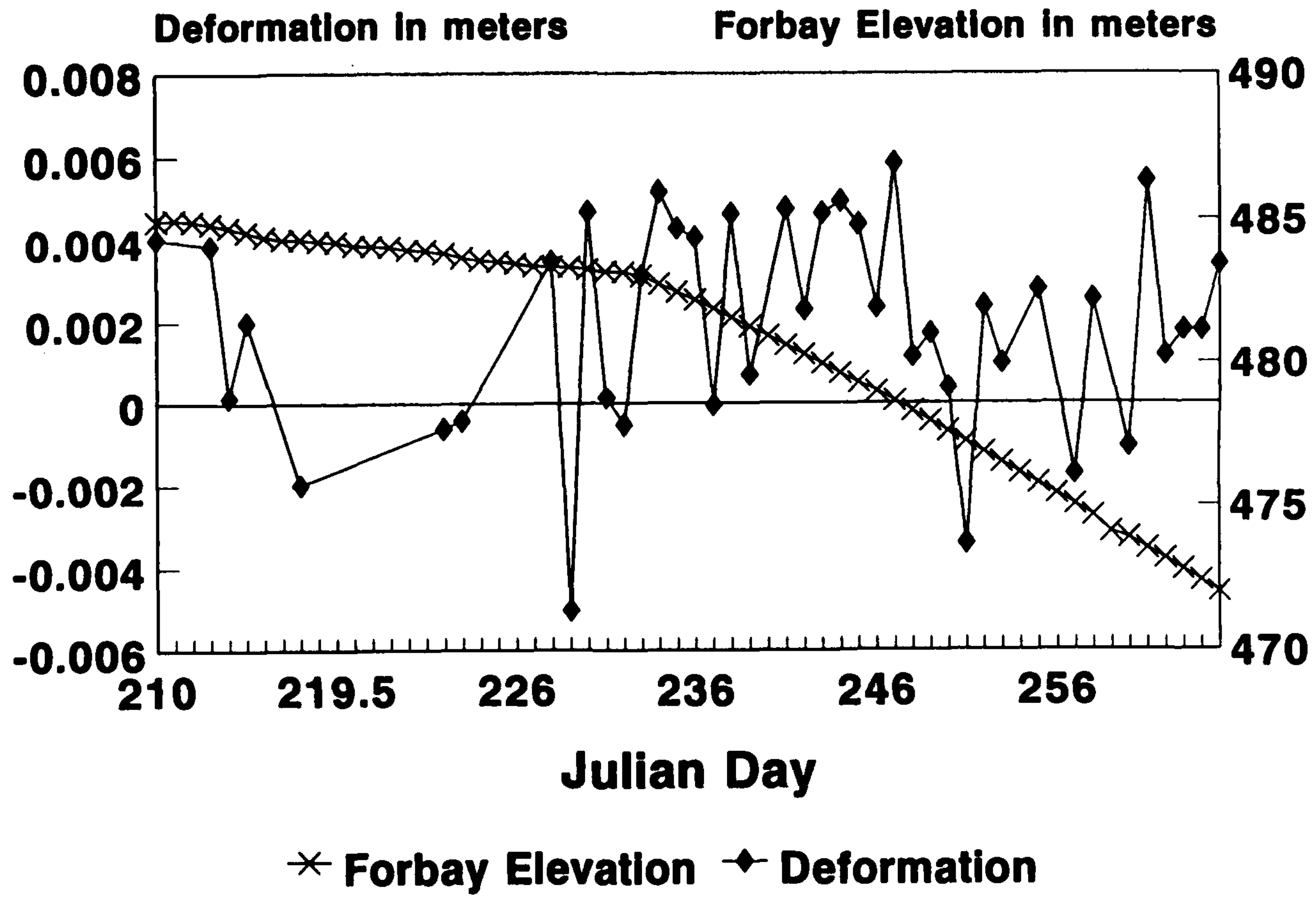
+ up, - down

Northings vs Pool Elevation
Monolith 22



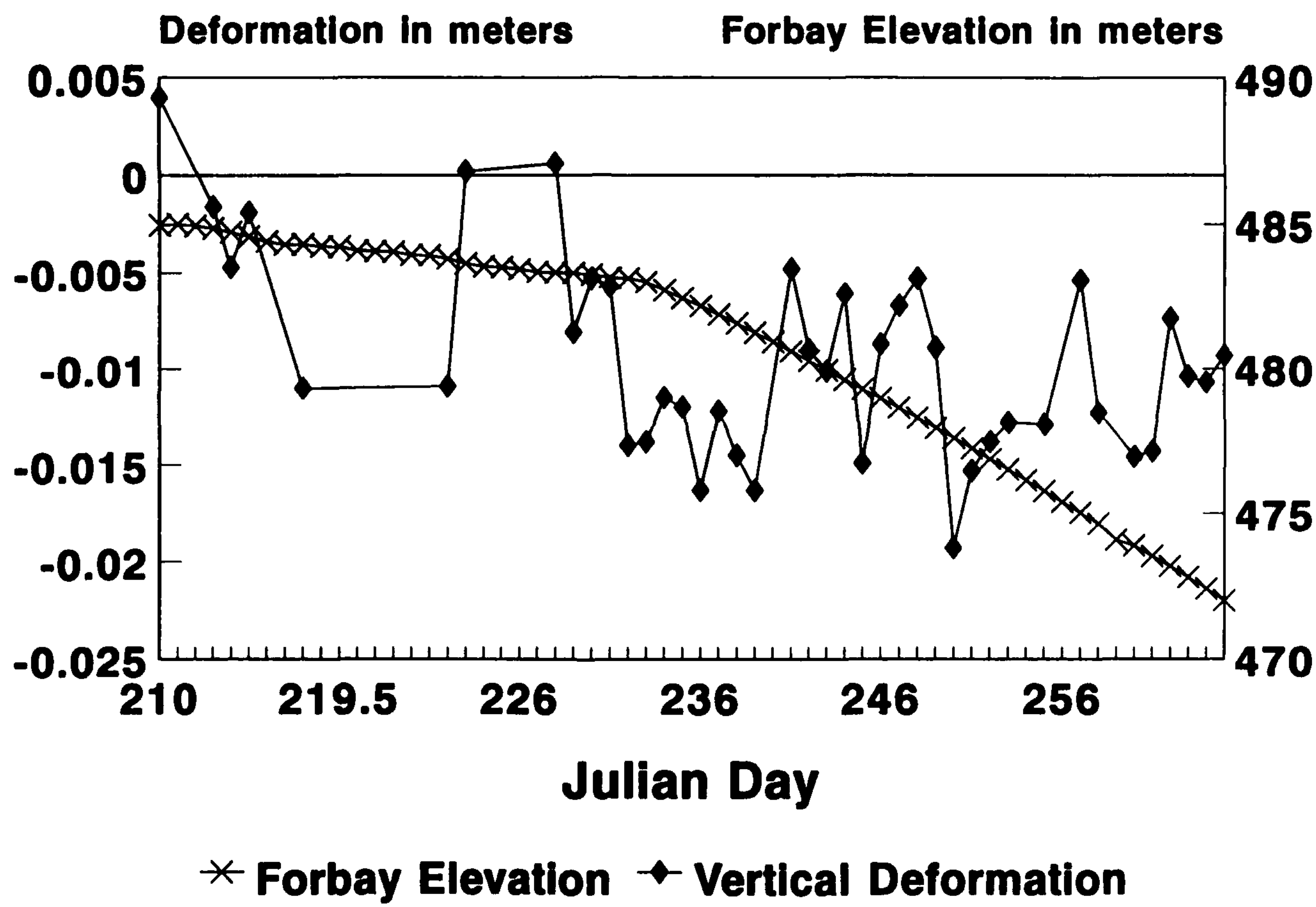
+ upstream, - downstream

Eastings vs Pool Elevation
Monolith 22



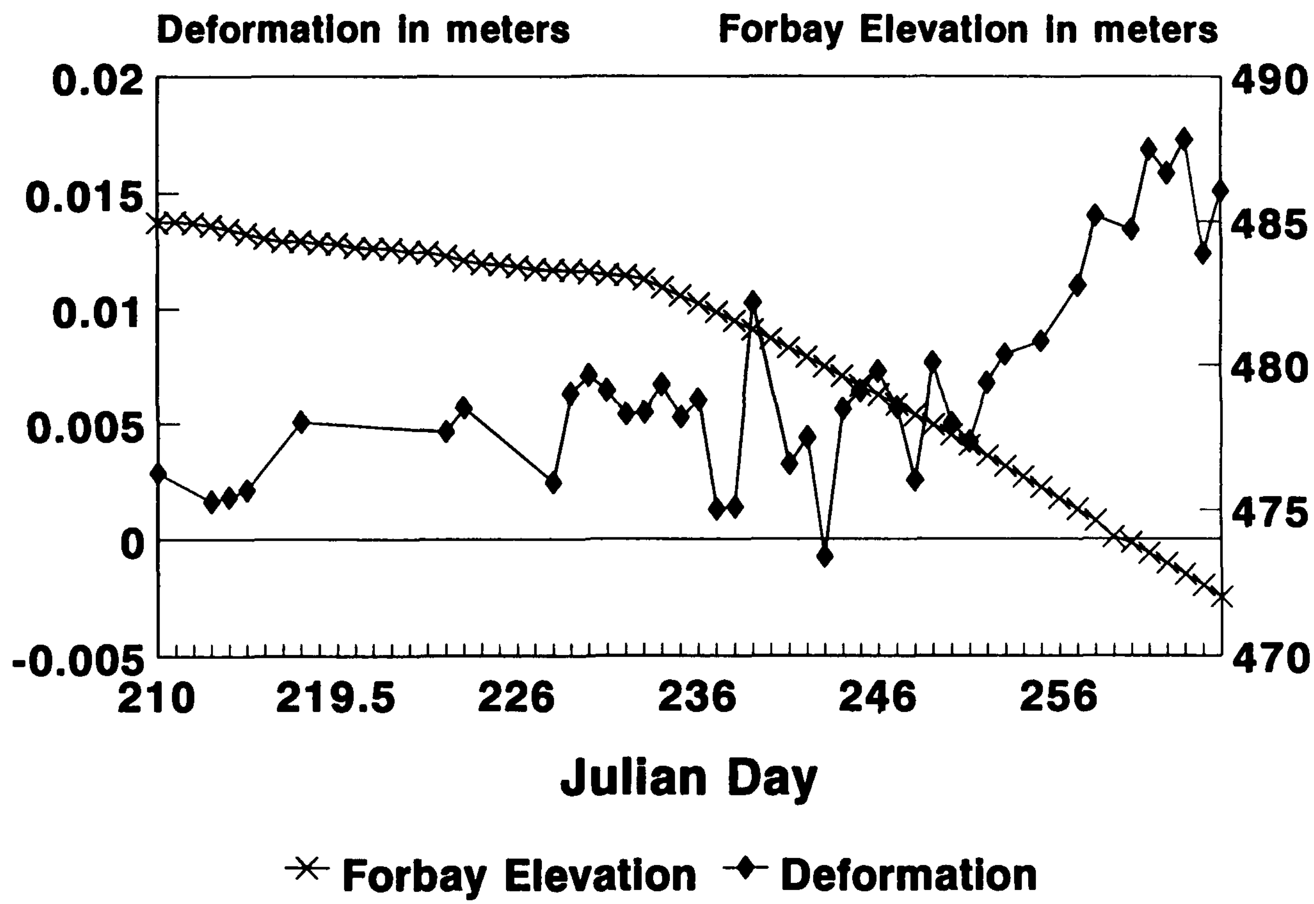
+ east, - west

Vertical Deformation vs Pool Elevation
Monolith 22



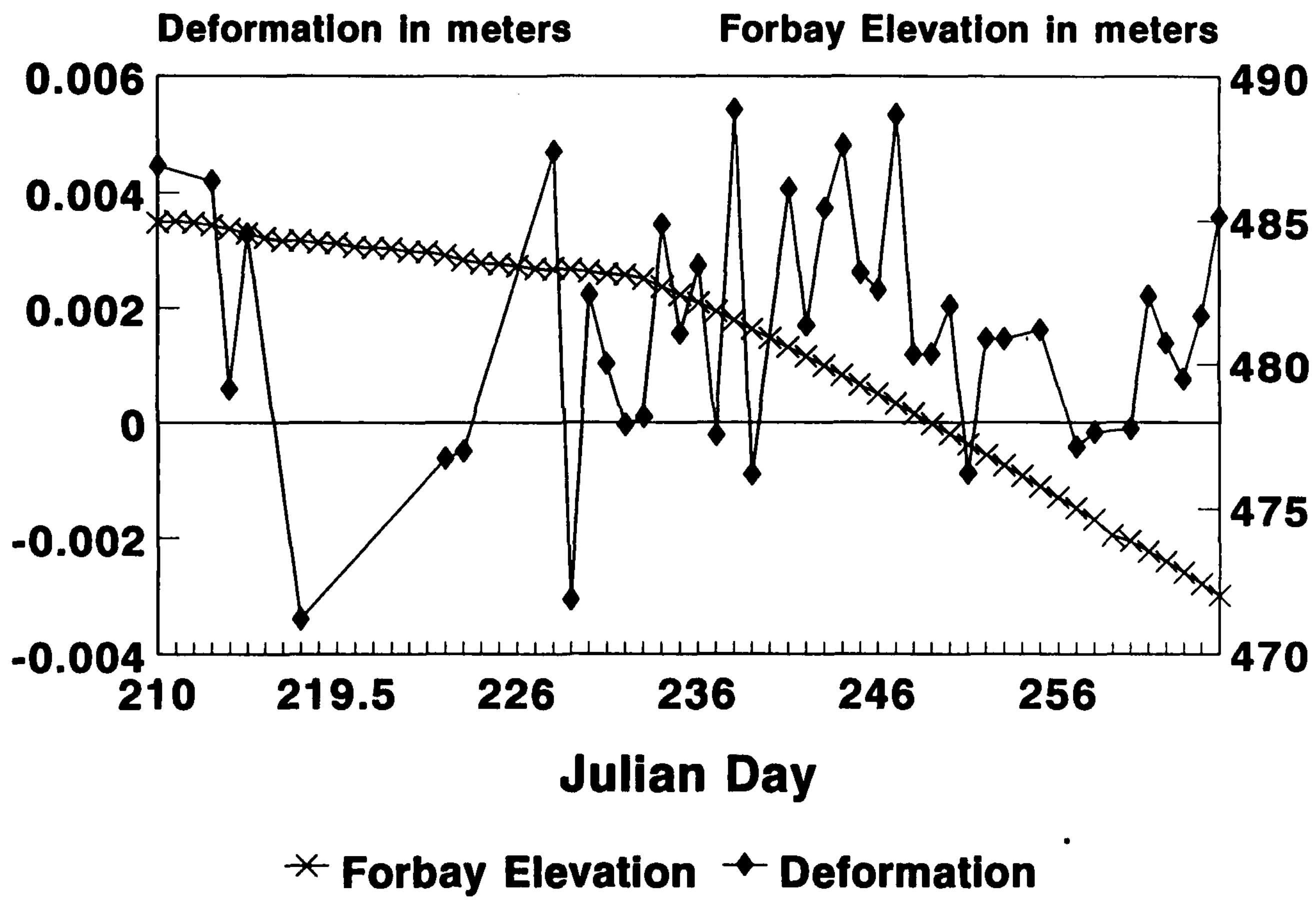
+ up, - down

Northings vs Pool Elevation
Monolith 25



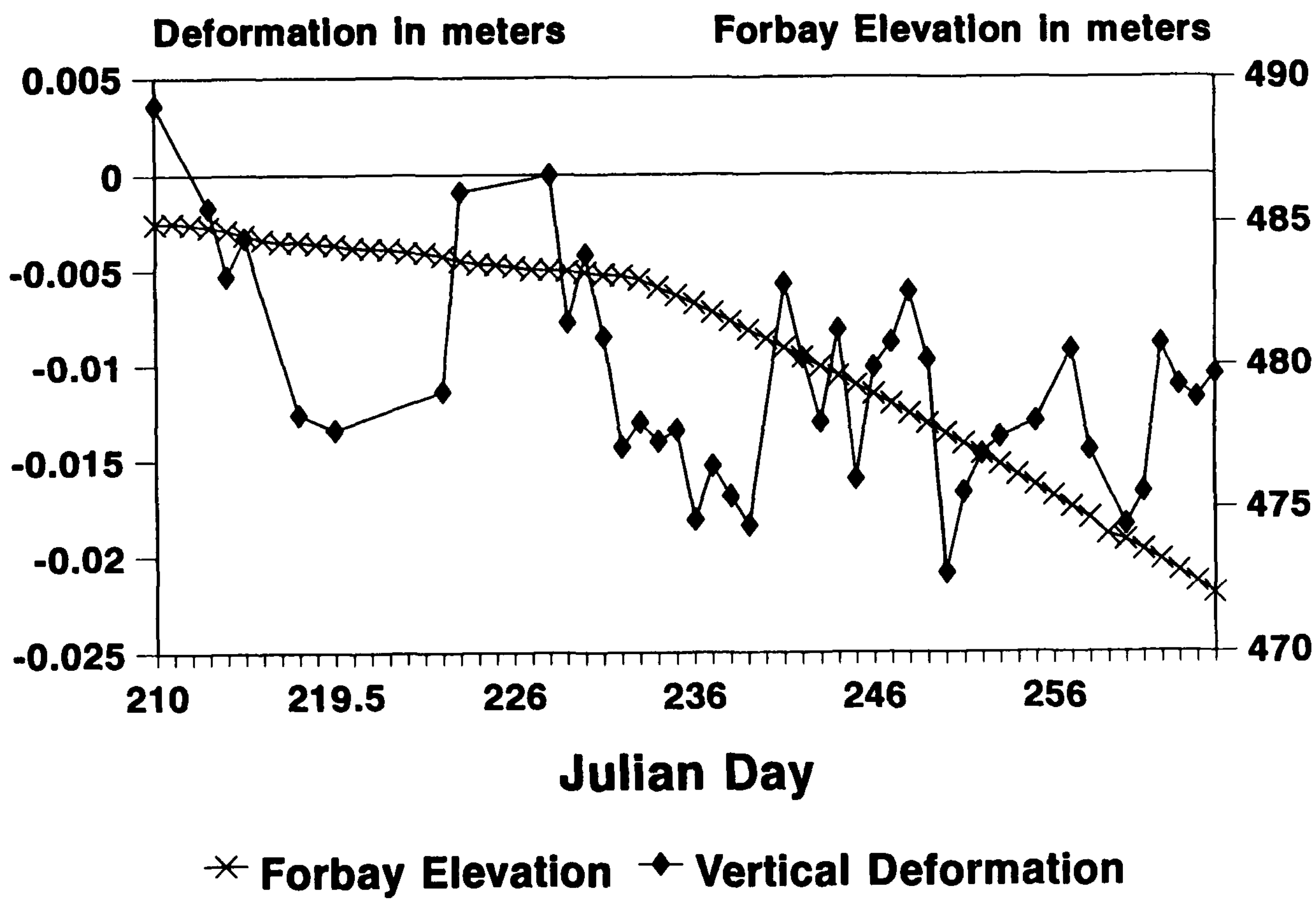
+ upstream, - downstream

Eastings vs Pool Elevation
Monolith 25



+ east, - west

Vertical Deformation vs Pool Elevation
Monolith 25



+ up, - down

Waterways Experiment Station Cataloging-in-Publication Data

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