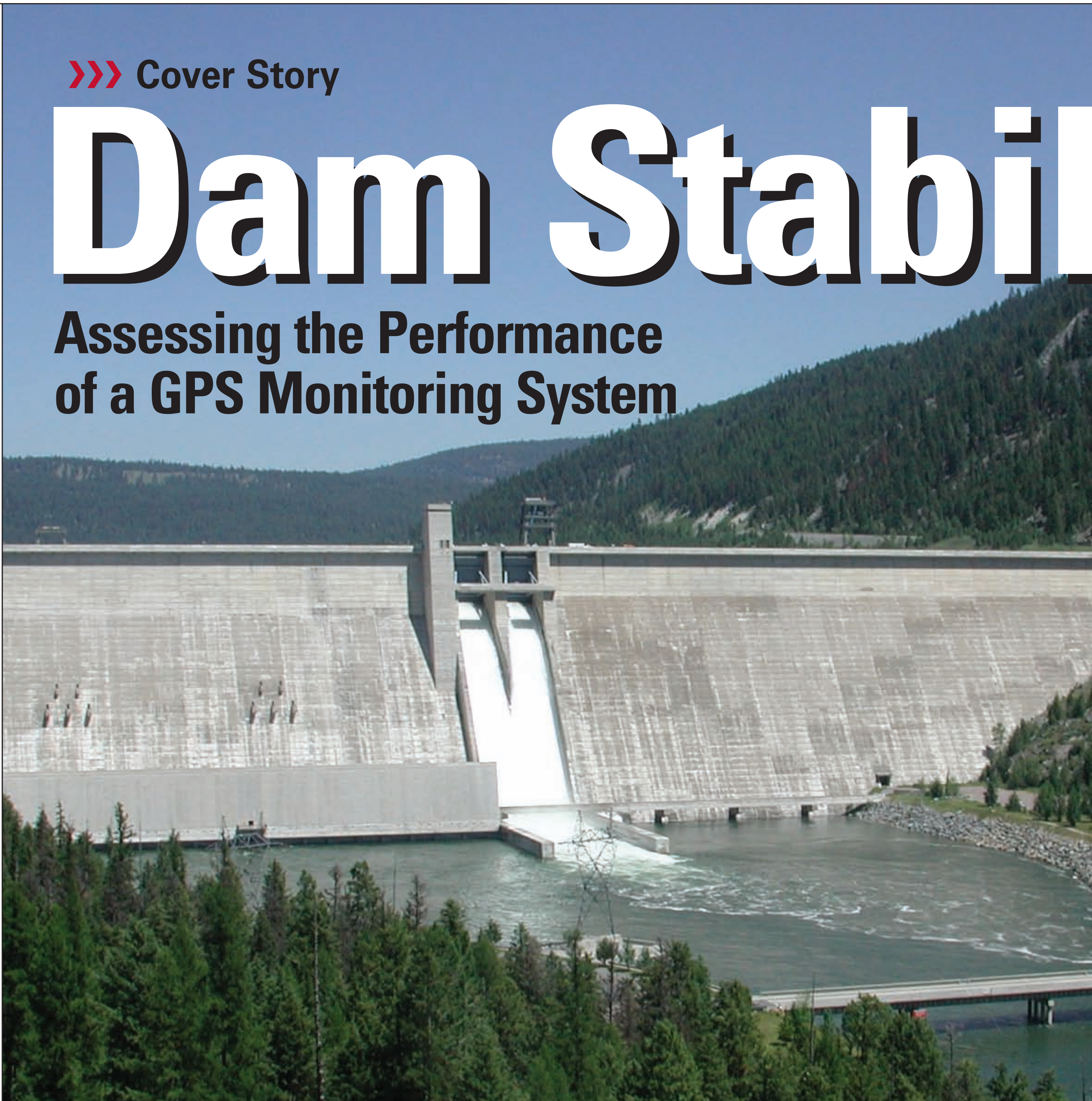
››› Cover Story

Dam Stabil

Assessing the Performance of a GPS Monitoring System



INNOVATION INSIGHTS
with Richard Langley

WHEN THE Global Positioning System was being designed back in the early 1970s, it was assumed that a GPS receiver's position would be determined from pseudorange measurements using the pseudorandom-noise-code modulation on the GPS satellite signals. In fact, that is how most GPS-based positioning and navigation is done even today. But the accuracy with which positions can be determined using pseudorange measurements is fundamentally limited by measurement noise and multipath which in turn is determined by the effective wavelength of the code. However, it was realized around 1978 or so, that relative positions between pairs

"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments and topic suggestions. To contact him, see the "Columnists" section on page 10 of this issue.

David R. Rutledge, Steven Z. Meyerholtz, Neil E. Brown, and Cory S. Baldwin

A precise and modernized monitoring program is an important component of the U.S. Army Corps of Engineers' long-term risk-management plan for hydroelectric structures. Recent work at Libby Dam in Montana demonstrates that GPS deformation monitoring systems can accurately track displacements at critical points, making it an important asset in ensuring dam safety.

The U.S. Army Corps of Engineers is responsible for investigating, developing, and maintaining the water and related environmental resources throughout the United States. In February 2002, the Corps deployed a GPS monitoring system at Libby Dam. Six GPS monitoring stations are located along the crest of the dam to measure horizontal and vertical motion. A GPS reference station is located on each side of the dam to provide differential correction information. Processing software collects raw measurements from all eight GPS stations and computes high-precision GPS solutions in real time.

GPS vs. Plumb-Line Data

Four of the GPS monitoring stations on the crest of the dam were installed coincident with existing gravity-based plumb lines in order to directly compare the horizontal readings from each measurement system. In this article we present the correlation between the GPS data and the plumb-line data, and discuss the formal process of evaluating GPS repeatability and accuracy.

Libby Dam is located on the Kootenai River in northwest Montana. Its construction formed Lake Koocanusa with a reservoir capacity of 715,000 hectare-meters. It is a straight axis concrete dam composed of 47 monoliths (MLs). The length of Libby Dam is 880 meters, and the structural height is 128.6 meters. The Corps of Engineers owns and manages the dam and actively monitors its performance. This careful monitoring effort is managed by engineers who continually analyze readings from the instrumentation deployed on the dam. Besides the GPS system, the instrumentation at Libby Dam includes plumb lines, joint meters, foundation deformation meters, extensometers, uplift pressure cells, inclinometers, concrete temperature meters, leakage measurements, and a laser alignment system.

Pilot Project. The GPS system was installed at Libby Dam to replace the existing laser alignment system. The laser equipment became increasingly difficult to maintain in the 1990s, and it became apparent that a replacement system was needed. After a careful evaluation of various options, engineers in Seattle decided to install an automated GPS system as part of a pilot project. Several of the GPS instruments were collocated with existing — and reliable— plumb lines so that the two measurement systems could be compared. The pilot installation of an automated GPS alignment system was selected for various reasons. One of the major concerns with the laser alignment survey was that the end points of the dam were assumed to be stable, when in actuality this might not be the case. Corps personnel were aware that any deformation

of GPS receivers could be determined with much higher accuracies by using the signal's carrier rather than its modulation. By differencing the phases simultaneously measured by a pair of receivers, essentially an interferometric technique, it was predicted that relative position accuracies equal to a small fraction of the carrier wavelength would be possible, although the instability of the receivers' clocks would be an issue. That issue was dealt with by forming a second measurement difference: differencing between satellites. Carrier-phase integer ambiguities also had to be dealt with by estimating them or eliminating them through a third differencing: differencing sequentially in time. And so by the early 1980s, the standard double and triple differencing carrier-phase approaches to high-accuracy relative positioning were in use. Since then, carrier-phase positioning has become a standard technique for both real-time and post-processed high accuracy positioning. In addition to many conventional applications, it has been used to detect slowly occurring or "silent" earthquakes, to control heavy machinery, and to monitor the displacements of engineered structures such as suspension bridges, tall buildings, and as discussed in this month's column, dams.

▲ **FIGURE 1** Plan view of the Libby Dam GPS system

of the monoliths being used as anchor points (ML 5 and 46) would contaminate the results from the laser alignment survey. The Corps concluded that a GPS system could solve this problem by making use of stable reference points located away from the dam. The GPS system has the added benefit that the integrity of its reference points can be checked easily.

The Corps also decided to pursue a system that could provide continuous measurements from key monoliths. These continuous data were deemed to be more valuable for analysis than the twice-yearly laser survey, and would allow data to be collected for true peak-loading conditions. The ability of GPS to operate in real time fulfilled these requirements, and could even provide rapid feedback to Corps engineers and geologists in the event of a major flood or earthquake. In short, the GPS system offered the promise of continuous surveillance, high accuracy, and reasonable cost.

GPS System Installation

The GPS system at Libby Dam was installed during the winter of 2001-2002. The entire installation was completed in about three weeks at a cost of just under $150,000, including the GPS and radio hardware. All eight GPS stations are powered by photovoltaic equipment, and communicate to a central PC via a digital radio network. Each station is self-contained and autonomous from the existing electrical and mechanical systems at Libby Dam.

Six GPS monitoring stations were installed on the crest of the dam on carefully selected monoliths. One GPS reference station was installed on stable ground on each side of the dam. The GPS station locations are shown in **FIGURE 1**. Each GPS monument was designed to limit any thermal deflection, while still being straightforward to install.

The GPS receiver, radio, gel-cell batteries, and power controllers at each station are housed in a weather-tight enclosure attached to the dam parapet wall. Each GPS monitoring station was designed to run for approximately 20 days on battery power during inclement weather. If the power drops below a pre-set threshold, the station will gracefully shut down, and then automatically restart when the batteries are recharged by solar power. A master antenna array located just outside the instrumentation room is used to receive the telemetry from the eight GPS stations. The master radios stream raw GPS data in real time to the processing software located on a standard Windows-based PC in an on-site instrumentation room. This architecture has proven to be robust. The GPS system computes a three-dimensional measurement every 5 seconds for each station.

The processing engine is a delayed-state Kalman filter processing carrier-phase measurements as triple differences. Double-difference code measurements are used as well.

Plumb-Line Correlation

GPS measurements and plumb-line measurements collected at ML35 and 23 are presented alongside one another in **FIGURES 2 through 4**. The positive region of the graph represents upstream motion, while the negative region represents downstream motion. Three years of data are displayed. These figures clearly show the strong correlation between the GPS data and the plumb-line data.

The offsets between the GPS data and the plumb-line data are obvious in these figures. These offsets result from the installation of each measurement system at a different time, and come in two forms. The first involves the natural elastic cycle of deformation that occurs at Libby Dam. The GPS system and the plumb-line system were not installed at the same point in this cycle and therefore have separate and unique initial readings. This type of offset could have been mostly eliminated by installing each GPS monitoring point at the same time of year that its corresponding plumb line was installed — a luxury not available because of the added installation cost. The second type of offset can result from the presence of inelastic deformation recorded by the plumb-line system before the installation of the GPS system.

Figure 2 shows the upstream-downstream motion of Libby Dam at ML35 as measured by both the GPS system and the plumb-line system. The Corps rotated the GPS frame so that the two horizontal axes were perpendicular and longitudinal to the axes of Libby Dam. This useful step allows us to precisely track both upstream-downstream displacement and longitudinal displacement (the long axis of the dam). Plumb-line data are displayed in black and GPS data are displayed in purple. Plumb line 35 is read automatically on a daily basis, whereas the GPS station at ML35 computes a solution every 5 seconds. A daily average of the 5-second solutions is plotted in Figure 2 as a thin green line. A 7-day moving average is plotted as a thick purple line, with data collected from March 2002 through February 2005.

All GPS data shown in Figure 2 were computed by using the GPS reference station LREF, located near the left abutment of Libby Dam. Measurements computed using LREF agree extremely well with the plumb-line data. A high level of correlation is present between the two measurement sets, and both show the same pattern of normal elastic deformation. A similar correlation between plumb-line measurements and GPS results is obtained when using the right abutment reference station, or RREF.

Figure 3 is a roundup of the data from both the LREF and RREF reference stations, and data from the ML35 plumb line. We present this figure to show the excellent agreement between GPS data derived from two separate and independent GPS reference stations. This strong correlation between the LREF and RREF measurements adds another level of system integrity monitoring, and firmly establishes the validity of not just the GPS system, but also the plumb-line system. These data suggest that a GPS network comprising two or more reference stations is highly desirable when a second corroborating instrument such as a plumb line is not present.

Upstream-downstream displacement associated with ML23 is displayed in Figure 4. The same high level of correlation is present in these data. The plumb line located at ML23 differs from the one at ML35: it's not automated; instead it's read manually once per month. This results in an incomplete recording of the magnitude and pattern of the displacement by the plumb line. The GPS measurements provide a more accurate representation of the displacement because of the continuous record.

It is a natural step to mathematically describe the agreement between the plumb line and the GPS. The following equation is used to calculate a linear correlation coefficient that quantifies the agreement between the plumb-line data and the GPS data:

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}}$$

where x_i and y_i are the ith samples of plumb-line and GPS data and $\bar{x}$ and $\bar{y}$ are the corresponding sample means.

This equation yields a linear coefficient that approaches 1 if the two datasets are perfectly correlated and 0 if they are uncorrelated. The linear coefficient for LREF-ML35 and the plumb-line data is 0.87. The linear coefficient for RREF-ML35 and the plumb-line data is 0.91. This good agreement clearly shows that:

- the GPS measurement system and the plumb-line measurement system track the same basic displacement, and
- a component of this displacement is not common-mode.

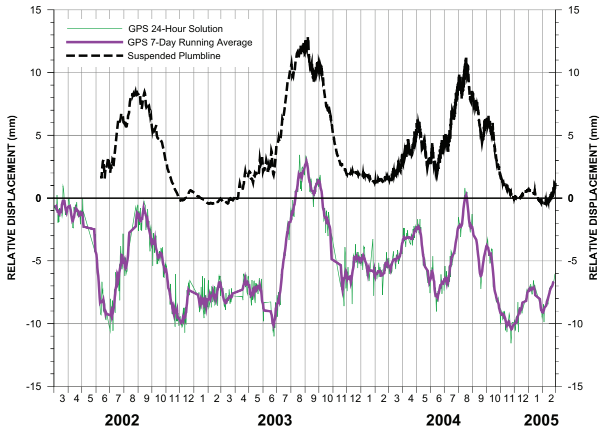
Calculating the linear coefficient between two different measurement systems is an effective step to quantify agreement, and in this case clearly demonstrates that both systems function very well.

Uncommon Displacement. It is, however, worth considering the displacement that is not common. There are several possible explanations for this. One is that this difference is caused by some combination of noise in the measurement capabilities of the two systems. The other is that the uncommon signal represents displacement that one system tracks but the other does not.

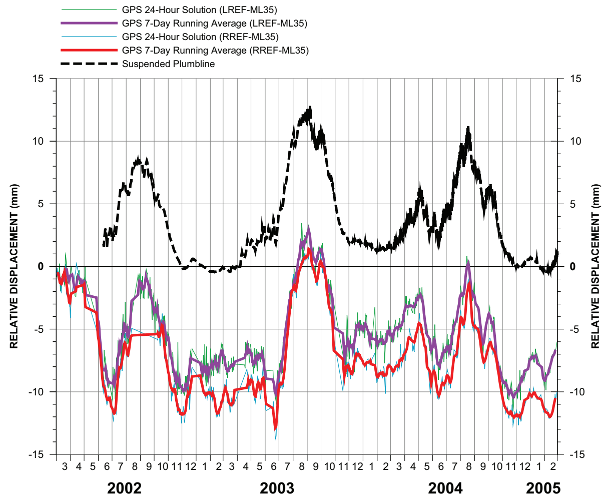
Calculating the linear coefficient between the two separate GPS solutions for ML35 (LREF and RREF) offers some insight. The higher linear coefficient of 0.95 between the two GPS solutions suggests that the two systems are measuring slightly different signals. A study of the two GPS reference stations reveals a small relative motion (**FIGURE 5**), possibly because of regional structural geology. Removing this periodic variation would drive the GPS to GPS linear coefficient closer to 1. This suggests that — even after process noise and geology are accounted for — some difference in signal tracking capabilities exists between the two systems. More will be said about the different measurement capabilities in the next section.

Figures 2–5 considered horizontal displacement only. Vertical displacement at ML35 is displayed in **FIGURE 6** (Vertical displacement at ML23 shows a similar result). GPS data from LREF and RREF are plotted next to one another. Data from LREF are plotted as purple and data from RREF are plotted as red. The plumb-line data is absent in these figures because the plumb lines at the dam are capable of tracking horizontal motion only. The installation of the GPS network marks the beginning of vertical displacement surveillance. This surveillance has revealed what appears to be a normal yearly displacement cycle of uplift and subsidence at the dam crest.

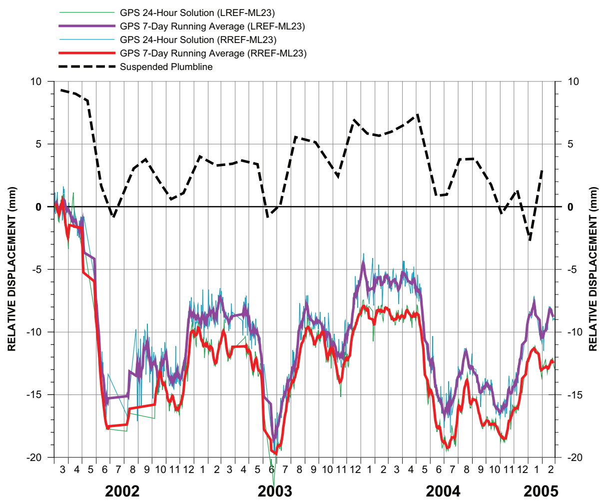
The vertical measurements computed from RREF are much more precise than those computed from LREF. This is also true for the horizontal measurements, but to a lesser degree. This is a direct result of the use of different real-time GPS processing parameters for each reference station. How a GPS system is designed and configured is a tradeoff between responsiveness and accuracy. The real-time processing of



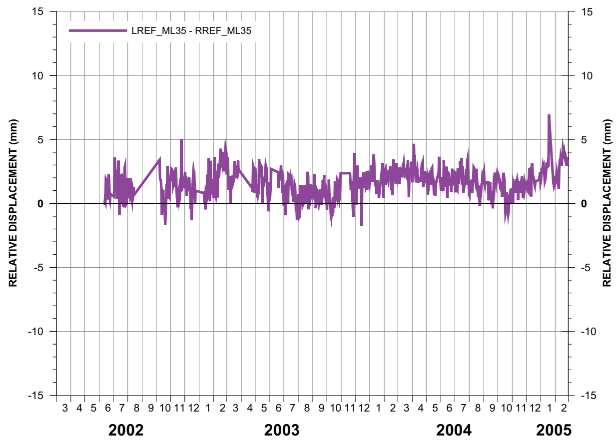
▲ **FIGURE 2** Upstream-downstream displacement at ML35, plumb line and GPS (LREF)



▲ **FIGURE 3** Upstream-downstream displacement at ML35, plumb line, LREF GPS, and RREF GPS



▲ **FIGURE 4** Upstream-downstream displacement at ML23, plumb line, LREF GPS, and RREF GPS



▲ **FIGURE 5** Relative displacement between LREF GPS and RREF GPS at ML35

the RREF station introduces less process noise into the Kalman filter, resulting in a more precise but less reactive solution than the LREF processing.

These two different processing configurations are used at Libby Dam in order to simultaneously provide a fast response time to critical displacements and a very high precision record of long-term horizontal and vertical displacements.

Repeatability and Accuracy

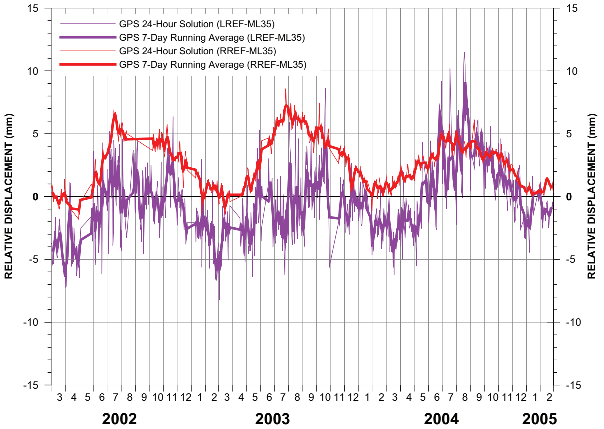
The establishment of a strong correlation between the GPS data and the plumb-line data leads naturally to a formal evaluation of the GPS repeatability and accuracy. This evaluation is greatly simplified when both systems sample on a regular interval. Since the GPS instruments are mounted on a structure that moves less than 1 millimeter per day it is possible to look at repeatability by comparing the standard deviations of the daily solutions.

TABLE 1 displays the long-term repeatability of the GPS data for each monitoring station (computed from RREF). These statistics were generated using a two-step process. The first step consisted of computing a standard deviation (SD) for each 24-hour set of data from each station. The population size for each daily dataset is roughly 17,280 measurements (the number of possible solutions at our selected five-second sampling interval). These SD calculations were made daily over a three-year period for each GPS station.

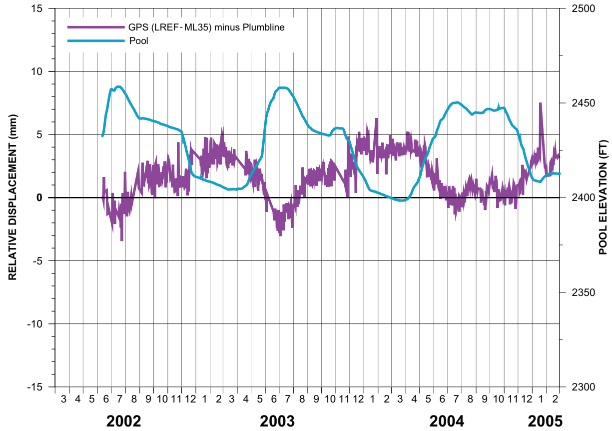
The average daily SD for three years of data was computed to give a single measure of repeatability. For the purposes of this statistical analysis, the dam was modeled as having zero motion over a 24-hour period. This allows us to consider any scatter in the 24-hour data set to be residual noise from the real-time GPS processing, and not displacement. This is generally a good starting point as the fastest displacement rate recorded at Libby Dam during the past two years was 0.23 millimeters per day (at ML 35). At this extreme, we might a priori expect some component of the SD during these peak rate periods to be displacement and not noise.

The long-term repeatability of the GPS data for each station computed from LREF is noisier than that from RREF because the processing software is programmed to let in more process noise into the Kalman filter. The average long term repeatability (all components) of GPS measurements computed relative to LREF is 2.11 millimeters at 1 SD, and the average long-term repeatability of GPS measurements computed relative to RREF is 0.29 millimeters at 1 SD.

Establishing Accuracy. Establishing the accuracy of the GPS system is more challeng-



▲ **FIGURE 6** Vertical displacement at ML35, LREF GPS, and RREF GPS



▲ **FIGURE 7** Bias between ML35 plumb line and ML35 GPS (LREF) plus pool elevation

ing than establishing the repeatability, and requires the selection of a standard. A considerable amount of good science already exists regarding the theoretical establishment of GPS accuracy and will not be reproduced here. For the purposes of this research, the plumb line turned out to be a very useful standard to which the GPS data can be compared. This exercise yields meaningful information on GPS accuracy, and reveals key differences in tracking capabilities between these contrasting measurement systems.

Declaring that the plumb line is the standard allows us to form a difference between the two data sets by subtracting the two curves, and then evaluating the result in terms of GPS accuracy. **FIGURE 7** shows the difference — or bias — between the plumb-line data at ML35 and the LREF GPS data at ML35.

The bias between the two shows a clear upstream-downstream yearly cycle that is unrelated to GPS accuracy. The components of the bias include a prominent low frequency, a high frequency (GPS accuracy), and the relative motion between the two reference stations. Figure 7 demonstrates that the plumb line at ML35 measures a slightly different displacement signal than the GPS.

This is demonstrated first by the better GPS-to-GPS linear coefficient versus the GPS-to-plumb-line linear coefficient, and

TABLE 1 Long-term Repeatability of GPS Measurements (Using RREF)

Measurement	Axis	Mean of 17280 daily SDs (millimeters)	SD of daily SDs (millimeters)	95% Confidence (1.97 x SD) (millimeters)
LREF-RREF	Upstream/Downstream	0.31	0.18	0.61
	Right/Left	0.37	0.21	0.73
	Vertical	0.38	0.22	0.74
RREF-ML06	Upstream/Downstream	0.32	0.18	0.62
	Right/Left	0.28	0.17	0.55
	Vertical	0.32	0.17	0.63
RREF-ML19	Upstream/Downstream	0.28	0.20	0.54
	Right/Left	0.29	0.21	0.58
	Vertical	0.27	0.19	0.54
RREF-ML23	Upstream/Downstream	0.30	0.14	0.59
	Right/Left	0.30	0.14	0.59
	Vertical	0.25	0.13	0.50
RREF-ML29	Upstream/Downstream	0.28	0.16	0.56
	Right/Left	0.26	0.14	0.51
	Vertical	0.25	0.15	0.48
RREF-ML35	Upstream/Downstream	0.33	0.17	0.64
	Right/Left	0.28	0.14	0.55
	Vertical	0.28	0.14	0.56
RREF-ML46	Upstream/Downstream	0.25	0.25	0.49
	Right/Left	0.27	0.23	0.52
	Vertical	0.25	0.17	0.49
Average	Upstream/Downstream	0.29	0.18	0.58
	Right/Left	0.29	0.18	0.57
	Vertical	0.29	0.17	0.56
	Overall Average	0.29	0.18	0.57

second by the presence of the strong low frequency signal in the GPS-to-plumb-line bias. Figure 7 also displays the yearly pool elevation at Libby Dam. The good anti-correlation between these datasets confirms that the low frequency signal is not related to GPS accuracy and suggests that it is related to pool elevation.

3D Motion. The GPS system monitors the three-dimensional motion of a point located on the deck of ML35 at elevation 753.5 meters. The suspended plumb line is anchored in the upper service gallery at elevation 750.1 meters. The associated reading station is in the lower service gallery at elevation 683.1 meters. The top of rock elevation is at 637.3 meters. Because of this, the plumb line is only monitoring the relative displacement between its anchor point and reading station, a vertical distance of 67.0 meters (top of dam to bedrock at ML35 measures 116.2 meters).

Although the plumb line is monitoring the majority of displacement associated with the narrow cross-section of the structure, it does not monitor any relative displacement in the lower 45.7 meters of the structure, any movement that could be occurring in the foundation, or any absolute horizontal translation. The low-frequency yearly signal displayed in Figure 7 is the difference between the measurement capabilities of the suspended plumb line at ML35 and the GPS monitoring station. Most likely the bias is dominated by the frequency and amplitude of the relative displacement from elevation 683.1 to elevation 637.3.

Estimation of the GPS accuracy from this bias is possible, but requires either the complete removal of the signal that is not common to each system, or an estimation method that recognizes that the uncorrelated signal has a relatively low frequency.

A simple algorithm was designed that subtracted the daily bias from one day to the next day for the entire ML35 dataset (LREF). This removes the low frequencies (caused by temperature and height-of pool) that are unrelated to GPS accuracy. The results are presented in **TABLE 2**. The removal of the low frequency components from the bias provides a reasonable estimate of the GPS accuracy. It is probable that the accuracy is slightly better than this because:

- the dam is moving slightly during a 24-hour period,
- our algorithm probably does not remove all uncorrelated signals, and
- we are not accounting for the relative motion (structural geology) at the GPS reference stations.

Nevertheless, the information in Table 2 provides a conservative estimate of the GPS accuracy vis-à-vis the plumb-line framework. It also establishes the gravity-based plumb line as an excellent standard for GPS accuracy.

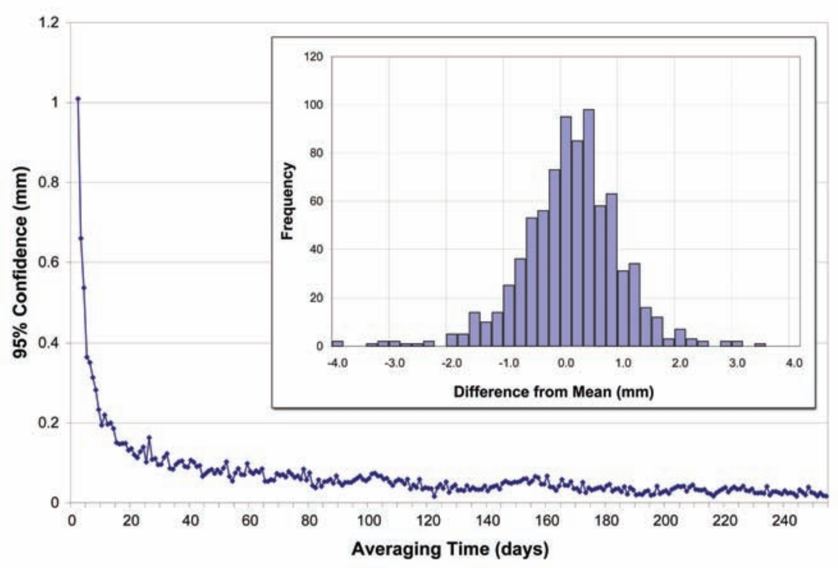
A Gaussian System

Statistics and time series analysis are valuable tools to measure and classify the performance characteristics of the GPS system over time. This is particularly true for accuracy and precision. Accuracy is the difference between the true value and the mean of the underlying process that generates the data. Precision is the spread of the values about the mean. The discrete GPS signal for LREF-ML35 from the accuracy study above was averaged over sequential periods of 1, 2, 3, … 254 days. The standard deviation of the means times 1.97 (equivalent to a 95 percent confidence interval) was then plotted versus the averaging time. These data are displayed in the **FIGURE 8** curve.

The curve in this figure shows accuracy versus averaging time for the ML35 GPS receiver. A significant accuracy gain occurs early on. At 5 days the 95 percent confidence interval is 0.36 millimeters. At 254 days the 95 percent confidence interval is 0.0167 millimeters. At 404 days (not plotted here) the 95 percent confidence interval is 0.0032 millimeters.

The authors were able to reproduce similar time average plots by using datasets from GPS sensors located on other monoliths (with and without the reference to the gravity-based plumb line). This performance characteristic of GPS is partly explained by the large number of samples per day and the fact that multipath tends to average out over long observation periods.

A histogram from the same dataset is inset into Figure 8. The classic normal distribution is clearly visible showing that GPS system errors tend to follow the normal or Gaussian probability distribution over the long haul. The histogram reveals a small bias of about 0.25 millimeters between the results of the GPS and the reference plumb-line system. Figure 8 indicates that when correctly configured, the GPS system can produce deformation results that are both highly precise and highly accurate.



▲ **FIGURE 8** Accuracy versus averaging time for LREF-ML35, with inset histogram

Performance Monitoring Plus

Correlating the GPS data with the plumb-line data demonstrates a high-level of agreement between these two vastly different measurement systems. Both systems are faithfully tracking the overall pattern of horizontal displacement, as well as its magnitude. Establishing a strong linear coefficient between the two datasets is a powerful confirmation that they track the same basic signal. An even better correlation would be obtained if the plumb line were measuring the full 116.2 meters at ML35. Each system confirms that Libby Dam deforms in an elastic fashion, with very little long-term inelastic deformation. The comparison between the two systems provides compelling evidence that GPS is well suited for long-term performance monitoring of dams. What's more, the GPS system at Libby Dam offers the upside of being able to precisely monitor vertical displacement, monitor monoliths without plumb lines, and track pure horizontal and vertical translation. These qualities of GPS are well suited to performance monitoring and have important implications for dam safety. A precise and modernized monitoring program is an important component of the U.S. Army Corps of Engineers' long-term risk-management plan for hydroelectric structures. The gathering of repeatable, high accuracy horizontal and vertical measurements is part of a two-stage feedback loop that verifies design assumptions and establishes normal deformation criteria. A sophisticated monitoring effort first defines normal deformation in order to later identify what is out of bounds. The GPS system at Libby Dam has confirmed the horizontal deformation pattern reported by the plumb lines, and is now being used to reveal the vertical deformation patterns as well. These data will be used for performance monitoring, and will be incorporated into risk-management programs.

The GPS system at Libby Dam was installed with the hope that it would — at a reasonable cost — provide continuous surveillance and high-accuracy measurements. It has. Equally important, the increase in performance transparency that GPS can offer will create positive pressures to more efficiently allocate limited resources. The GPS system at Libby Dam represents an important technological advancement for long-term dam surveillance and performance monitoring, and provides an important window into the increasing role in risk management that GPS systems will play by directly and accurately observing deformation in real time.

TABLE 2 GPS Accuracy vis-à-vis Plumb Line (ML35)

Measurement	Axis	Mean of Day-to-Day Deltas (millimeters)	GPS Accuracy SD of Day-to-Day Deltas (millimeters)	95% Confidence (1.97 x SD) (millimeters)
LREF-ML35	Upstream/Downstream	-0.09	0.90	1.77
RREF-ML35	Upstream/Downstream	-0.03	0.48	0.95

Acknowledgments

This article is based on the paper "Performance Monitoring of Libby Dam with a Differential Global Positioning System" presented at the 25th United States Society on Dams (USSD) Annual Meeting, held in Salt Lake City, Utah, June 6-10, 2005. The authors would like to acknowledge the USSD for allowing some of this material to be reproduced. We would like to thank Dr. Benjamin Remondi of the XYZs of GPS, Inc. for his generous support.

Manufacturers

The equipment used at Libby Dam includes **Thales** *(www.thales.com)* G12 single-frequency GPS receivers (used along the dam as monitoring stations, and used as reference stations) and **FreeWave** *(www.freewave.com)* DGR 900 MHz spread spectrum radios.

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Further Reading

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Assessing the Performance of a GPS Monitoring System

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FURTHER READING

Original Paper

"Performance Monitoring of Libby Dam with a Differential Global Positioning System" by D.R. Rutledge and S.Z. Meyerholtz in Proceedings of the 25th United States Society on Dams (USSD) Annual Meeting, Salt Lake City, Utah, June 6-10, 2005, pp. 493–508.

Deformation Monitoring Instrumentation and Techniques

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Other GPS-based Dam Monitoring Systems

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Information on U.S. Dams

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