# Sub-millimeter Precision GPS Survey System at the Holloman High Speed Test Track

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## ABSTRACT

The National Geospatial-Intelligence Agency (NGA) provides high-accuracy survey support for the Air Force's Holloman High Speed Test Track (HHSTT), a test facility that supports ground-level aerodynamic and impact testing at speeds in excess of Mach 8. Specifically, NGA provides three-axis positions of 1,018 survey benchmarks installed along the HHSTT. High performance traditional survey methods have been skillfully employed for many years and yield satisfactory measurement accuracy (approximately 1.0 mm in each axis), but these methods are manpower-intensive and slow. The high cost and high latency associated with these methods motivated NGA to task Applied Research Laboratories, The University of Texas at Austin (ARL:UT) to develop an alternative GPS-only survey method. In response, ARL:UT developed and deployed the Benchmark Survey System (BSS), a GPS system consisting of twenty-five portable devices that may be used to survey approximately forty-eight HHSTT baselines in a ten-hour work shift, to a precision of better than 1.0 mm in each axis. Relative to earlier methods, the BSS provides a substantial improvement in throughput, and the accuracy is at least comparable.

This paper presents the Benchmark Survey System with a focus on the three key aspects of the system that are critical to the achievement of sub-millimeter baseline measurement performance. First, a method for precisely estimating GPS antenna phase center characteristics is presented. This method facilitates rapid and low cost characterization of antennas and has a proven repeatability of better than ±0.35 mm in each axis. Second, the mechanical design and requisite characterization methods necessary to ensure precise positioning of each GPS antenna relative to each survey benchmark is presented. This positioning process is faster than traditional methods, does not require bulky hardware, and is repeatable to better than ±0.05 mm in each axis. Third, an ARL:UT-developed GPS double-differenced carrier phase network positioning processor is presented. Testing of this processor has focused on the 30-meter baseline lengths representative of the benchmark spacing at the HHSTT, and baseline solution repeatability of better than ±0.32 mm in each axis has been consistently demonstrated using 3 hours of single frequency data. Finally, the paper presents results from the first full-system deployment test of the BSS at the HHSTT. BSS survey results will be compared with NGA-derived survey results obtained through the employment of traditional methods.

## INTRODUCTION

The Holloman High Speed Test Track (HHSTT), located at Holloman Air Force Base, New Mexico, supports ground-level hypersonic testing of various propulsion systems, aerodynamic platforms, ejection seat systems, weapons systems, and targets [1]. Its 9.6 mile length (15.5 km) supports testing at speeds in excess of Mach 8; the HHSTT holds the current land speed world record at 9,465 feet/second (2885 meters/second).

The HHSTT is a pair of continuously welded heavy duty crane rail sections, spaced approximately 2 meters apart and supported by a U-shaped concrete foundation. Track alignment fixtures are located every 42 inches (1.1 meters) along the entire length of each rail to secure it to the foundation. These fixtures permit incremental lateral and vertical adjustment of the rails. Figure 1 provides a cross section view of the HHSTT.

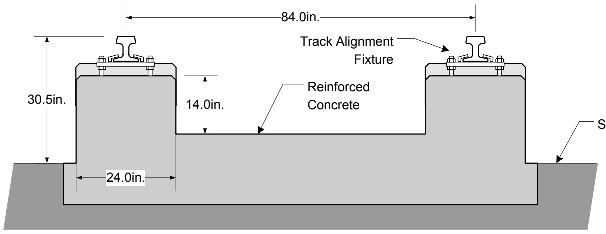


**Figure 1** Cross section view of Holloman High Speed Test Track.

The very high velocities obtained on the HHSTT mandate exacting control of the rails' straightness and alignment. The Air Force routinely manipulates the rail, meter-by-meter via the track alignment fixtures, to maintain straightness and rail-to-rail spacing. All measurements made in support of these adjustment activities are referenced to 1,018 survey benchmarks installed along the entire length of the track. The Air Force requires survey positions for all the benchmarks that are accurate at the single millimeter level, relative to a local reference frame.

## Legacy Methods

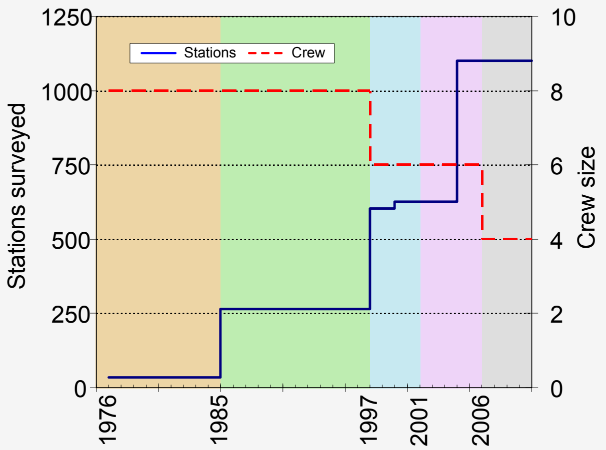
The National Geospatial-Intelligence Agency (NGA) has coupled precise geodetic survey instrumentation and standardized acquisition methods to meet their customers' challenges at locations throughout the world for several decades. In 1974, NGA (then the Defense Mapping Agency) conducted a study of HHSTT and the geodetic survey requirements imposed by the Air Force's 6585th Test Group (now the 46th Test Group) at Holloman. This study determined that an eight man crew, with a large inventory of geodetic survey equipment, would be needed on a continuing basis in order to meet the production schedules of the HHSTT – this based on the shorter 35,000-foot (10.7 km) track length at the time.

Since 1976, NGA has successfully supported precise geodetic survey applications at the HHSTT. Each survey element had individual stringent standard error criteria developed to meet or exceed the Air Force's accuracy requirements; current NGA survey techniques at the HHSTT yield an accuracy of approximately 1 millimeter (2-$\sigma$, each axis). Figure 2 depicts the evolution of this process from 1976 to the present. NGA's overall goal at the HHSTT has been to establish a database capable of serving as a tool to continuously monitor the HHSTT and its environment; the NGA geodetic survey results allow the 46th Test Group to keep the two HHSTT rails precisely aligned in support of ever-increasing test velocities.

## The Benchmark Survey System

Although the measurement quality achieved through NGA's current survey process is satisfactory, the process is manpower-intensive and slow. This has motivated NGA to seek a more efficient method. In July 2004, under the sponsorship of NGA, Applied Research Laboratories, The University of Texas at Austin (ARL:UT) began the development of an alternative GPS-only survey system for the HHSTT, called the Benchmark Survey System (BSS).

Two fundamental requirements were imposed on the BSS at the outset of the development: high accuracy and high throughput. The BSS has been designed to measure benchmark-to-benchmark vectors to an accuracy of 1.0 mm or better (1-$\sigma$, horizontal and vertical components), and to support a full survey of the HHSTT in six weeks with a crew of four.



| | |
|---|---|
| 🟫 | Principal Methods: Trilateration, traverse, astronomical azimuth & position, differential levels, gravity anomalies<br>Primary Equipment: Laser geodimeters, prism banks, calibrated steel tapes, theodolites, timing systems, gravity meters |
| 🟩 | Trilateration, traverse, astronomical azimuth & position, differential levels, gravity anomalies<br>Spectra-Physics geodolite, prism banks, Wild precise levels, chronometers, gravity meters |
| 🟦 | GPS Dual-frequency differential, trilateration, astronomical azimuth & position, differential levels<br>Ashtech Z-12, Spectra-Physics geodolite, A35M Geodetic astrolabe, Leica digital levels |
| 🟪 | GPS Dual-frequency differential, trilateration, astronomical azimuth & position, differential levels<br>Ashtech Z-12, Leica TC2003 total station, A35M Geodetic astrolabe, Leica digital levels |
| ⬜ | GPS Single- & Dual-frequency differential, astronomical position, differential levels<br>Ashtech Z-12, A35M Geodetic astrolabe, Leica digital levels, Benchmark Survey System |

**Figure 2** Evolution of the requirements and methods employed by NGA at the HHSTT.

ARL:UT has developed and deployed the entire system; it includes commercial hardware components such as the GPS receiver and antenna, custom-designed mounting hardware specific to the HHSTT, and custom data processing software consisting of both a graphical interface and a GPS network position estimation package. The basic components of the system are described in the next four sections, followed by a description of the procedures used to test the system, and several test results. Results produced by the BSS are compared with the legacy NGA survey results, showing that the BSS has achieved the accuracy and throughput goals in the requirements.

## PRINCIPLES OF OPERATION

The Benchmark Survey System hardware consists of 25 self-contained GPS data collection and storage units, or "survey nodes," which are deployed together so that GPS observations are recorded concurrently at 25 benchmarks along the HHSTT. Each survey node consists of a ruggedized electronics enclosure containing a NovAtel OEM4-G2L GPS receiver, a single-board computer, a rechargeable battery pack and supporting electronics, plus a NovAtel 701 GPS antenna with a mechanical mount that supports the antenna and provides precise control of the antenna's location relative to the survey benchmark.

BSS survey operations are typically conducted at night in order to minimize the measurement errors induced by solar heating and by the ionosphere, as well as to avoid exposing the operators to the (typically extreme) daytime temperatures at Holloman. An extended 10-hour work shift allows for two 3-hour deployments of the 25 nodes, after accounting for other logistical tasks. The 3-hour occupation time represents a compromise between higher throughput, which could be achieved through lower occupation times, and improved measurement precision, which could be achieved through longer occupation times.

At the end of 2005 a complete conventional survey of the HHSTT required a six-person crew working an entire year, although standard procedure included a second (redundant) complete survey for quality assurance purposes. With the deployment of the BSS, it is estimated that the same survey will require only a four-person crew working for 6 weeks. Even with the conservative assumption of just one-half year for a single legacy survey, the BSS will yield a 400% increase in throughput while *reducing* manpower expenditure by 85%.

The three-dimensional vector, or baseline, between two HHSTT benchmarks is measured by the BSS via GPS carrier phase measurements and double-difference processing. As depicted in Figure 3, the GPS baseline represents the vector between the effective phase centers of the two antennas and will not necessarily be equal to the actual benchmark-to-benchmark baseline. To derive the actual baseline from the GPS-determined baseline, the user must account for variations in the phase centers of the antennas, as well as offsets due to the mechanical assemblies. These corrections are applied to the GPS-derived baseline estimate in post-processing.

The careful characterization of instance-to-instance variation in antenna phase center offsets and mechanical mounts is critical to achieving sub-millimeter accuracy from the BSS. The next two sections of this paper address these challenges in some detail.

## ANTENNA CHARACTERIZATION

The phase response of GPS antennas can greatly affect GPS measurement accuracy; it has been shown that biases up to the centimeter level may result when different GPS antenna types are mixed in a baseline measurement [2]. Some variation in phase response should also be expected in antennas of a like type due to manufacturing variability. This effect can become a limiting factor in applications that require very high accuracy.

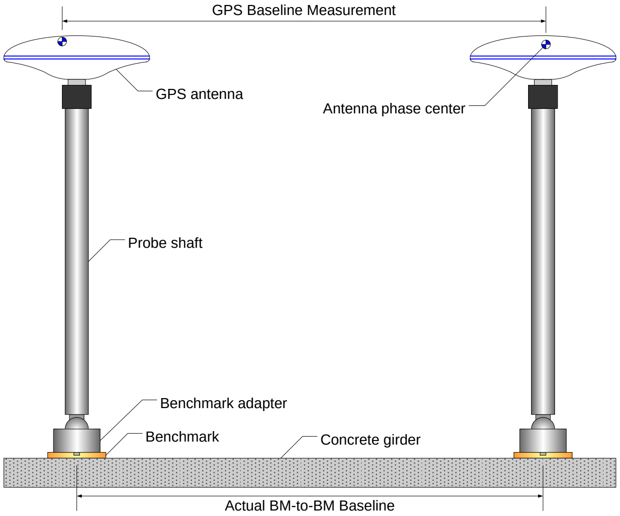


**Figure 3** GPS baseline measurement, error due to antenna variation exaggerated.

A calibration method was developed in order to measure variations in phase response between different BSS antennas. The effective phase center offset (PCO) in both the horizontal and vertical planes of each antenna is determined relative to a common reference antenna, similar to the GPS antenna PCO calibration method described in reference [3]. A relative PCO calibration for a given antenna under test (AUT) is obtained by collecting GPS measurements using the AUT and the reference antenna over a very stable and repeatable baseline. The precise baseline between the two antenna phase centers is then determined using processing software. This procedure is repeated for all AUTs, using the same reference antenna and baseline. For any two AUTs characterized in this manner (labeled $A$ and $B$), the relative PCO vector for the two antennas is given by

$$\Delta\vec{x}_{AB} = \vec{b}_{REF,B} - \vec{b}_{REF,A}$$

where $\vec{b}_{REF,y}$ is the measured baseline between antenna $y$ and the reference antenna. Only the relative PCO of antennas $A$ and $B$ remains in this result; all other effects difference out, due to the repeatability of the reference antenna and the baseline. With this result, any baseline measurement that uses antennas $A$ and $B$ ($\vec{b}_{AB}$) may be corrected for antenna PCOs using the measured relative offset:

$$\vec{b}_{AB,corr} = \vec{b}_{AB} - \Delta\vec{x}_{AB}.$$

While a useful calibration can be achieved by this method, some restrictions apply. All antennas that will be used together in the system must be calibrated with a common horizontal orientation, relative to the reference antenna. Similarly, a common horizontal orientation must be maintained between all calibrated antennas in the application of the system. Finally, this calibration result is only valid for relatively short baseline lengths. The accuracy of the calibration will decrease with increasing baseline length, due to the difference in observation angles of the GPS satellites at each antenna. These restrictions do not present a problem for the BSS, however, because the antennas can be aligned easily and accurately using the HHSTT track itself as a visual reference, and because the baselines measured by the BSS are very short.

Calibration measurements of the BSS antennas were performed on two special survey monuments located on the ARL:UT grounds; these monuments provide both good mechanical stability and repeatable antenna mounting. The monuments were built in accordance with National Geodetic Survey (NGS) recommendations for Continuously Operating Reference Stations (CORS) site monumentation [4]. Each monument consists of a large column of reinforced concrete below ground, integral to a shorter and narrower reinforced concrete column extending above ground. The monuments at ARL:UT extend 5 feet (1.5 m) above ground, and 10 feet (3.0 m) below ground, embedded in solid limestone. The above ground height is recommended by NGS as a good trade-off between mulitpath error, monument stability, and user accessibility. A plate with mounting pins is set into the concrete at the top of each monument. A high quality tribrach adapter is placed onto these mounting pins and leveled, then a standard 5/8 inch threaded adapter plug is inserted into the tribrach adapter, and the GPS antenna is installed on the tribrach. The monuments at ARL:UT were installed approximately 30 meters apart in a flat, open field, as pictured in Figure 4. A Delrin® plate, inscribed so as to indicate horizontal direction relative to local North, is mounted on top of each monument and used to orient the antenna. GPS data were collected on the monuments over a five month period in order to assess their stability; the result was that the offset between monuments is stable to well under 0.5 mm per axis.

The BSS hardware includes 30 NovAtel 701 antennas (25 operational plus 5 spares); each of these was calibrated on the ARL:UT monuments using another NovAtel 701 antenna as reference. The principal axis (defined by the 701 tape tab feature) on both the AUT and the reference antennas was pointed to local North during each calibration measurement. Each AUT and the reference antenna were connected to NovAtel OEM4-G2L receivers, which were used to collect 24 hours of L1 carrier phase data at 1 Hz. This dataset length was chosen to provide a reasonable collection time while maintaining the accuracy of the calibration. The carrier phase measurements collected during each test were processed using DDBase (cf. section below) to determine the baseline between the AUT and the reference antenna; an elevation mask of $15^{\circ}$ was assumed. The baseline solution vector in Earth-centered Earth-fixed (ECEF) Cartesian coordinates was rotated into an antenna-fixed reference system (l,c,v), where ‘l’ is the principal axis or the horizontal direction aligned to local North during data collection, ‘v’ is local vertical and ‘c’ is horizontal and completes an orthonormal triad.

**Figure 4** Survey monuments at ARL:UT used to characterize BSS antenna PCO.

Eight tests were conducted over a two month period to assess the repeatability of this relative PCO calibration method. A single AUT and the reference antenna were used in all the tests, and the measurement and data processing procedures described above were used. The resulting measured PCOs are shown in Figure 5. (For clarity in presentation, the PCO for an AUT is computed as the difference between the baseline measurement using the AUT and the reference antenna and the known truth baseline.) The variation in the PCO is relatively small over all of the tests, with a maximum deviation of 0.4 mm in the horizontal and 0.6 mm in the vertical. The standard deviations of these results are summarized in Table 1. Good repeatability is achieved with the presented calibration method, since the 2-$\sigma$ values for each component are well below 0.5 mm.

**Table 1** Standard deviation of PCO component estimates from repeated calibrations of a single NovAtel 701 antenna, in millimeters. Results are given in antenna-based coordinates.

| $\sigma_l(mm)$ | $\sigma_c(mm)$ | $\sigma_v(mm)$ |
|---|---|---|
| 0.10 | 0.12 | 0.17 |

The PCO estimates for all of the BSS antennas are presented in Figure 6, with their component standard deviations given in Table 2. (The biases evident in Figure 6 are the combined result of the PCO of the reference antenna and a small offset in the truth baseline.) These results show generally good repeatability among the 30 antennas. The anomalous PCOs here are much larger than the variations found in repeated calibration tests of a single antenna

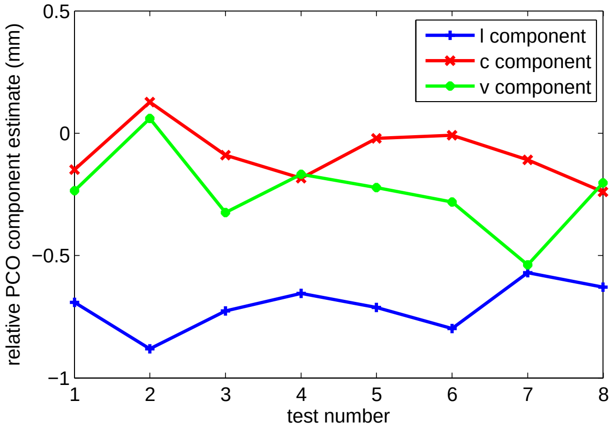


**Figure 5** Antenna phase center offsets resulting from repeating the calibration procedure for a single NovAtel 701 antenna eight times. Results are given in antenna-based coordinates (l,c,v).

(Figure 5). Also, the standard deviations in Table 2 are 50-100% larger than those in Table 1. This suggests that the anomalies shown here are due to actual PCO variations among the different antennas, that the calibration procedure is effective, and that BSS baseline solutions are improved at the 0.5 mm level when corrected for antenna PCOs.

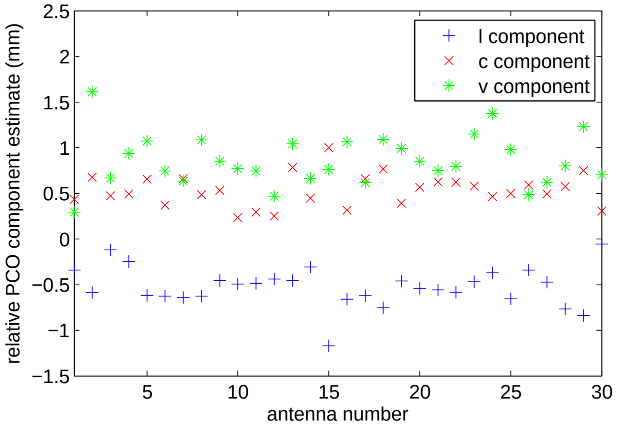


**Figure 6** Antenna phase center offsets resulting from the calibration procedure for all 30 BSS antennas. Results are given in antenna-based coordinates (l,c,v).

**Table 2** Standard deviation of PCO component estimate for the calibration of all BSS antennas. Results are given in antenna-based coordinates.

| $\sigma_l(mm)$ | $\sigma_c(mm)$ | $\sigma_v(mm)$ |
|---|---|---|
| 0.21 | 0.17 | 0.28 |

## MECHANICAL DESIGN

### Principle of Operation

The basic principle of the mechanical design of the BSS hardware is to replicate the spacing between benchmarks by positioning each GPS antenna identically relative to the subject benchmark. The simplest way to accomplish this is by placing the nominal phase center of the antenna on a plumb line passing through the benchmark, at a fixed height above the benchmark plate. There are three aspects to this task: providing an interface to the benchmark, the design of the mechanical mount which supports the antenna and precisely controls its position, and characterization of the manufacturing and assembly tolerances of the mount so that uncertainties in the positioning of the antenna can be minimized.

### GPS Antenna Mount Configuration

The interface between the GPS antenna probe shaft and the HHSTT benchmark plate is provided by a benchmark adapter which rests on the plate, with an index pin aligning the adapter to the reference hole in the plate, as shown in Figure 7. The adapter has a conical socket in its top surface which receives a spherical tooling ball at the base of the probe shaft. The nominal design of this interface places the center of the ball on the centerline of the plate reference hole, at a distance of 1.000 in. (25.4 mm) perpendicular from the surface of the plate. This location, the benchmark reference point (BRP), matches the measurement point used in the conventional survey procedures. The ball-in-socket configuration allows free rotation in all planes, provides distributed contact for positive location of the probe, and the measurement datum remains fixed as the angle of the probe shaft changes. This interface is robust and durable; the probe ball is a commercially available item, allowing for easy replacement if necessary.

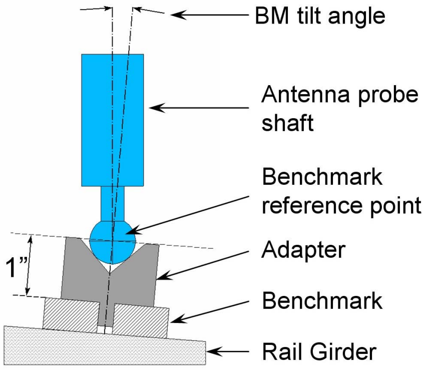


**Figure 7** Benchmark interface.

The GPS antenna probe is supported and positioned by a mount which clamps to the adjacent track rail; see Figure 8. A support arm links the mount to the probe; a spherical bearing allows the angle of the probe to vary as it is positioned. The extension of the arm can be adjusted to accommodate variation in the distance from the rail to the benchmark. Likewise, the shaft of the probe slides through the bore of the bearing to allow for height variations.

**Figure 8** BSS node at rail benchmark.

The antenna is positioned using a micrometer-driven cross-slide. Precision level vials with a resolution of 60 arc-seconds per division are mounted to the probe to indicate when the shaft is plumb. The goal is to position the nominal phase center of the antenna within 0.1 mm (0.004 in.) of the plumb line through the BRP, which is an order of magnitude below the desired baseline measurement accuracy. This requires the shaft to be plumb to within 40 arc-seconds. Operational testing of the full set of probes has shown that positioning of the antenna is repeatable to within 0.05 mm (0.002 in.) per axis. Despite this stringent positioning precision requirement, the nodes can be set up quickly, with the process typically taking less than 5 minutes from unpacking to the start of data collection.

In actual survey operations at the track, thermally-induced movement of the rail often produces drift of the antenna position during the 3-hour occupation. The level vials are checked for bubble movement at the end of each occupation; a change of 2 divisions or more (corresponding to a phase center movement greater than 0.25 mm) is the criterion for rejecting the data due to positioning uncertainty. Baselines are not computed for these nodes, and occupations are repeated as necessary during subsequent deployments.

### Antenna Mount Characterization

Because the antenna probe is assembled from several components, each of which has manufacturing dimensional tolerances (typically ±0.005 in.), the overall length of the probe may be outside the 0.1 mm (0.004 in.) antenna positioning target range. Similarly, due to geometric tolerances, the plate with the level vials may not be exactly perpendicular to a line connecting the center of the tooling ball and the antenna reference point (ARP) at the top of the probe shaft. While it is possible to correct these variations by precise finish machining of the assembled probe, it is more practical to measure and characterize them so that each probe may be precisely calibrated. Therefore, it was necessary to determine the actual length of the probe and the horizontal offset of the ARP from a plumb line through the benchmark reference point when the probe is positioned so that the precision level vials indicate a nominally plumb orientation. This characterization process produced an offset vector from the BRP to the nominal antenna phase center, which is used to adjust the GPS-derived baseline measurements to reflect the true benchmark baselines.

The effective height of each adapter BRP and the length of each assembled probe is measured with digital calipers to a resolution of 0.0005 in. using standard metrology techniques. The procedure for characterizing the horizontal offset is to place the probe and its supporting mount on a mockup of the track rail with a benchmark plate, position the probe so that the bubbles in the level vials are centered, then adjust the mount to bring the center of the top of the probe shaft to a plumb line established above the BRP with a high-resolution optical plummet, and measure the amount of offset. The micrometer heads on the rail mount give direct indication of the along- and across-track adjustment at the height of the support arm; these figures are then scaled to give the actual offset at the antenna phase center. The probe length and horizontal offset figures are combined to produce the offset vector for each antenna probe.

## DDBASE – OPEN SOURCE GPS PROCESSOR

DDBase is the core software baseline processor in the Benchmark Survey System. It is a full network processor, designed to estimate precise relative positions at all baseline lengths using double differenced GPS carrier phase data. While the BSS Processing Software (see next section) provides a convenient graphical interface for the user, DDBase itself is a platform-independent console application designed to be run independently. DDBase has been tested extensively at short baselines, both as part of the BSS and independently, in the field and at ARL:UT; it consistently yields sub-millimeter results with little or no manual intervention. DDBase has been included as part of the GPS Toolkit (GPSTk) open source software project (see below).

DDBase was developed in C++ using the GPSTk and the standard template library (STL). Originally it was the result of a rapid development program at ARL:UT for the BSS in early 2005. Other, existing software projects and commercial products were evaluated, but it was decided that existing software packages available to ARL:UT at the time would not satisfy the BSS requirements of high precision, high throughput, little or no manual operation and short datasets, while still providing the necessary sub-millimeter accuracy.

DDBase is modular and object-oriented in its design. It consists of a single executable that takes input from the command line and optional configuration file(s), and produces output to a log file and several optional intermediate data files. Data input to DDBase is in the form of RINEX observation files, either RINEX navigation or SP3 format file(s), and Earth orientation parameter file(s) in any of several standard formats. The basic design of DDBase is presented in the flow chart of Figure 9.

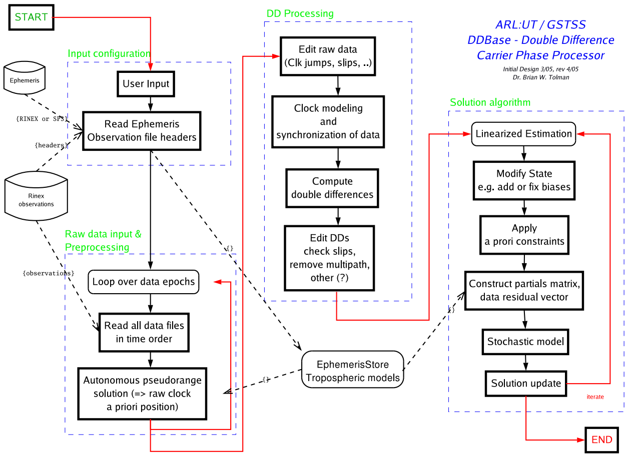


**Figure 9** Design of DDBase source code.

DDBase begins by reading all user input and determining its validity; for example all input data files are opened and the RINEX headers are read. The raw data are then read and preprocessed; this consists of data editing and computation of a pseudorange solution. The pseudorange solution is used for editing and to obtain the receiver clock offset. Then the carrier phase double differences are formed, using an automatic reference satellite selection algorithm, and outliers and cycleslips are removed. Finally, DDBase uses the edited data in an estimation algorithm, which is an iterated, linearized least squares processor. The estimator solves for positions, phase biases and (optionally) residual zenith tropospheric delays. When using single-frequency data, DDBase can fix the phase biases to integer values on the last iteration of the estimator. DDBase is well documented, both inside the code and in a separate User's Guide that includes examples and a complete command reference.

DDBase has routinely produced sub-millimeter accuracy on very short baselines, and few-millimeter or better repeatability on baselines in the field up to 5 kilometers in length. The following results present the output of DDBase using a script with no manual editing of the input data or the results, or special configuration of DDBase input parameters.

Figure 10 presents the difference between the final DDBase solution and a precise conventional survey (stated accuracy ±0.4mm, each component), on the 30-meter baseline of the antenna testbed at ARL:UT. The data are 68 consecutive 1-hour sets of 1-second L1 only data, collected using BSS hardware. The average offset is (0.37, -0.33, 0.53) mm ECEF XYZ; this bias is attributable to two things, the lack of antenna PCO corrections, and an offset in the survey that is known to be at the 0.2 mm level per component. The standard deviations, (0.25, 0.45, 0.34) mm ECEF XYZ, are all under 0.5 millimeter. Experience has shown that processing more data will improve these results slightly; generally one hour of data is a minimum for DDBase but is entirely acceptable with good data on a very short baseline. DDBase has not yet been tested extensively on long baselines.

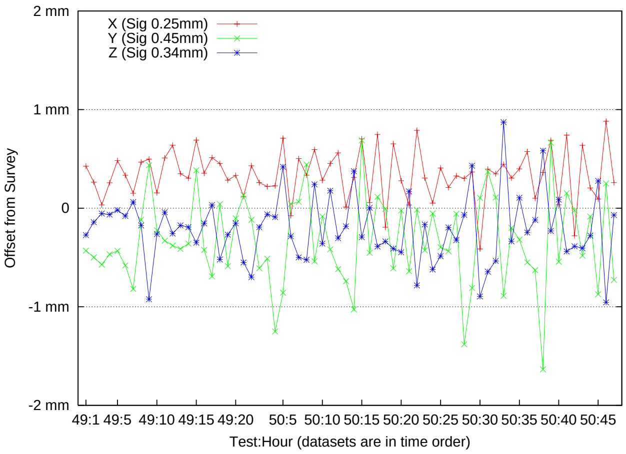


**Figure 10** DDBase positioning results, differenced with a precise conventional survey, from 68 hours of L1 only data in 1-hour blocks, collected on a very short baseline at the ARL:UT antenna testbed (the bias is understood and expected).

## The GPS Toolkit

The GPS Toolkit (GPSTk) was instrumental in the rapid development of DDBase; recently the DDBase source code has, in turn, been released to become part of the standard distribution of the GPSTk. The GPSTk (cf. www.gpstk.org and reference [5]) is intended to provide a world class open source software suite for GPS users and analysts. It is completely self-contained, object-oriented ANSI C++ source code that is highly modular, platform independent, well documented and easily extensible and maintainable. It consists of both a library of core functionality and a suite of stand-alone applications. The GPSTk is released under the Lesser GNU Public License (LGPL).

The DDBase source code implements several critical functions in terms of classes in the GPSTk library. All of the DDBase data input is handled using toolkit classes and RINEX data readers; after preprocessing, the data are stored and manipulated using STL containers. The navigation data are input in either RINEX or SP3 format, and standard ephemeris calculations are performed using GPSTk readers, storage objects and methods. Because the toolkit uses C++ inheritance, no distinction needs to be made within the DDBase code for the two different types of ephemeris input. During preprocessing, DDBase makes use of the toolkit class PRSolution (the autonomous pseudorange solution) and class TropModel (several standard tropospheric models). Throughout the code, DDBase makes use of position and time objects (class Position and class DayTime) to handle transformations, algebra and I/O operations on these standard quantities. The least squares estimator used by DDBase is the measurement update portion of a full implementation of the Square Root Information Filter (SRIF) form of the Kalman filter; this DDBase Kalman filter code now has become part of the GPSTk library.

Development of DDBase is on-going at ARL:UT, both as part of the BSS and independently as part of the GPSTk. This work includes study of antenna phase center variations and multipath within DDBase, and its application to much longer baselines. We look forward to refinement and extension of DDBase for the BSS, and its application to other projects at ARL:UT, as well as the interest and involvement of the GPSTk community.

## SYSTEM OPERATIONS AND LOGISTICS

Operation of the Benchmark Survey System may be categorized into three segments: “Deployment,” “Data Offload, Configuration, and Charging,” and “Baseline Processing,” as illustrated in Figure 11. The design of each of these has been focussed on ensuring efficiency and maximizing throughput. The following subsections describe each of these operational segments.

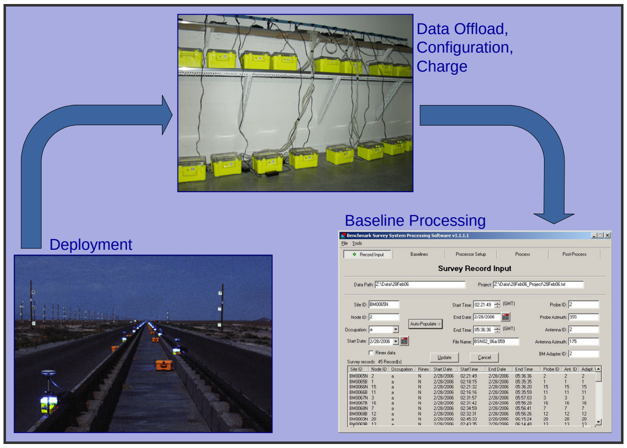


**Figure 11** Operational segments of the Benchmark Survey System

### Deployment

All survey nodes are deployed along the track using a small crew. A flatbed trailer facilitates rapid deployment of each BSS node to a location very near a survey benchmark. The crew then walks down the track, mounting the BSS hardware on each benchmark and activating collection. As the survey nodes collect GPS data, the crew is available to perform other functions (e.g., analysis of previous nights’ data) for approximately two hours. Then the BSS nodes are broken down and redeployed down the track. The full complement of 25 BSS nodes can be deployed, set up, and activated in approximately 45 minutes with a crew of four. System retrieval is essentially the reverse of deployment and requires even less time; a crew of four can retrieve the full system in 30 minutes.

### Data Offload, Configuration, and Charge

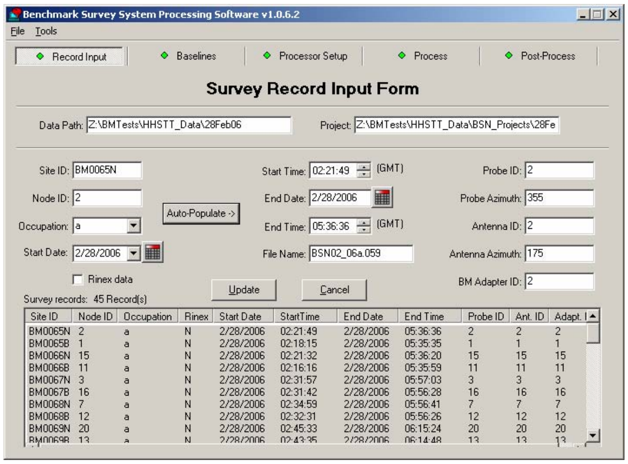
The BSS survey nodes are retrieved and transported to an operations center, where data files are offloaded and batteries are charged. The operators must attach one power cable and one data cable to each survey node. A user-friendly graphical software application facilitates data offload and permits changes to the data collection parameters. Ethernet communications support offloading of a night’s data (25 nodes $\times$ 3 hours $\times$ 2 deployments) in approximately 15 minutes. Battery charging is automatic once the power cable is attached.

### Baseline Processing

The Benchmark Survey System Processing Software (BSSPS) is designed to provide a streamlined method for processing GPS baselines from data collected using the BSS survey nodes. The actual baseline processing is performed by DDBase (cf. previous section). BSSPS provides a simple user interface that facilitates or automates all of the steps required to obtain final baseline results from the downloaded data files and user-created survey records. BSSPS creates output text log files for each processed baseline, a summary file containing all raw results for all baselines, and another summary file containing all of the baselines corrected for hardware offsets (mount calibration offsets and antenna PCOs). There are five steps involved in using BSSPS to process data collected by the BSS. Each step has a corresponding page (or tab) in the program’s user interface.

- Survey record input
- Build baselines to process
- Set processing options
- Format and process data
- Correct baselines for hardware offsets

Figure 12 shows the BSSPS user interface. The emphasis of the design has been to minimize the time required for the user to associate a given GPS measurement file with the corresponding survey benchmark occupied by the BSS node that generated that file. Through attention to layout and the auto-population of most of the fields based on the first user entries, the time required to enter a survey record is very short. All survey records corresponding to a typical night of operations (25 nodes × 2 deployments) can be entered in less than 15 minutes.



Survey Record Input Form

Data Path: Z:\BMTests\HHSTT_Data\28Feb06
Project: Z:\BMTests\HHSTT_Data\BSN_Projects\28Fe

Site ID: BM0065N
Node ID: 2
Occupation: a
Start Date: 2/28/2006
☐ Rinex data
Start Time: 02:21:49 (GMT)
End Date: 2/28/2006
End Time: 05:36:36 (GMT)
File Name: BSN02_06a.059
Probe ID: 2
Probe Azimuth: 355
Antenna ID: 2
Antenna Azimuth: 175
BM Adapter ID: 2

Survey records: 45 Record(s)

| Site ID | Node ID | Occupation | Rinex | Start Date | StartTime | End Date | End Time | Probe ID | Ant. ID | Adapt. I |
|---|---|---|---|---|---|---|---|---|---|---|
| BM0065N | 2 | a | N | 2/28/2006 | 02:21:49 | 2/28/2006 | 05:36:36 | 2 | 2 | 2 |
| BM0065B | 1 | a | N | 2/28/2006 | 02:18:15 | 2/28/2006 | 05:35:35 | 1 | 1 | 1 |
| BM0066N | 15 | a | N | 2/28/2006 | 02:21:32 | 2/28/2006 | 05:36:20 | 15 | 15 | 15 |
| BM0066B | 11 | a | N | 2/28/2006 | 02:16:16 | 2/28/2006 | 05:35:59 | 11 | 11 | 11 |
| BM0067N | 3 | a | N | 2/28/2006 | 02:31:57 | 2/28/2006 | 05:57:03 | 3 | 3 | 3 |
| BM0067B | 16 | a | N | 2/28/2006 | 02:31:42 | 2/28/2006 | 05:56:28 | 16 | 16 | 16 |
| BM0068N | 7 | a | N | 2/28/2006 | 02:34:59 | 2/28/2006 | 05:56:41 | 7 | 7 | 7 |
| BM0068B | 12 | a | N | 2/28/2006 | 02:32:31 | 2/28/2006 | 05:56:26 | 12 | 12 | 12 |
| BM0069N | 20 | a | N | 2/28/2006 | 02:45:33 | 2/28/2006 | 06:15:24 | 20 | 20 | 20 |
| BM0069B | 13 | a | N | 2/28/2006 | 02:43:35 | 2/28/2006 | 06:14:48 | 13 | 13 | 13 |

**Figure 12** Benchmark Survey System Processing Software user interface

All other steps require a total of about 60 seconds of the user's time, unless the user needs to specify non-standard processing options. One key step which BSSPS automates is the specification of which baselines DDBase is to process. A simple algorithm generates this list automatically, for each benchmark occupied, by locating the nearest benchmarks (in both directions along the track) for which simultaneous measurement data have been collected.

After the survey records have been entered and processing options set, the BSSPS preparation is complete, and baseline processing may begin. The full complement of 48 3-hour baselines requires several hours of processing time on a modern computer, but this step requires no user intervention; generally this takes place during the day between crew shifts.

## BSS TEST RESULTS

### Test Details

The first full-scale deployment of the Benchmark Survey System took place on the three nights of February 28, March 1 and 2, 2006 at the HHSTT. The first night's deployment was intended to serve as a trial run, providing an opportunity to evaluate deployment schemes and iron out any unforeseen logistical challenges. The second and third nights were designated as the first true system tests; the measurement performance on those nights would be assessed as part of NGA's validation process.

The 1,018 benchmarks installed along the HHSTT are divided among the two primary rails composing the track. The benchmarks are placed every 100 feet (30 meters) along each rail, but they are staggered such that adjacent benchmarks (one benchmark on one rail and the nearest benchmark on the other rail) are approximately 15 meters apart. Because all survey nodes in the system are deployed concurrently, it is possible to process baselines *along* a single rail, *across* the two rails (forming a zig-zag pattern), or as a network comprising many different baselines. For the purpose of assessing the performance of the BSS, the present analysis focuses on the shortest baselines, formed by adjacent benchmarks on different rails.

A full deployment of 25 BSS survey nodes yields 24 baseline measurements between adjacent benchmarks; thus a total of 48 baseline measurements are possible in one night if the whole system is deployed twice. Two nodes were inoperable on the first night of testing, and one of those nodes remained inoperable on the second and third nights. Thus a total of 44 baselines were measured on the first night, and 46 on each of the second and third nights. The same starting location was used on each night, so that night-to-night repeatability could be assessed. Also, survey nodes were deployed with no attention to serial number, to prevent any correlation between particular survey nodes and benchmarks. The data collection period was three hours in length. Each night's data were subsequently processed in batches using the BSSPS and DDBase with default parameters; antenna PCOs and mount offsets were applied automatically in the post-processing step of BSSPS.

### Baseline Comparisons

The differences between the BSS measurements and NGA truth, from all three nights, are presented in Figures 13, 14, and 15. While the differences are calculated in Cartesian ECEF coordinates, here they have been rotated into local coordinates (East, North, Vertical).

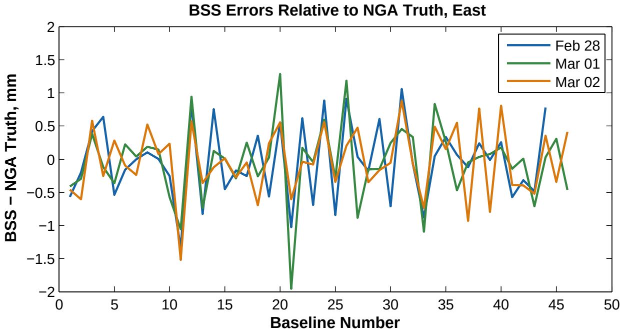


**Figure 13** East component of the differences of BSS measurements and NGA truth.

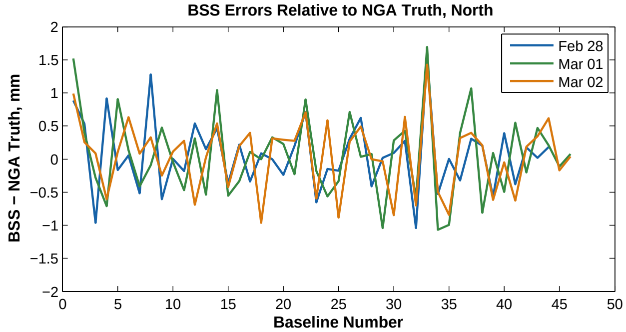


**Figure 14** North component of the differences of BSS measurements and NGA truth.

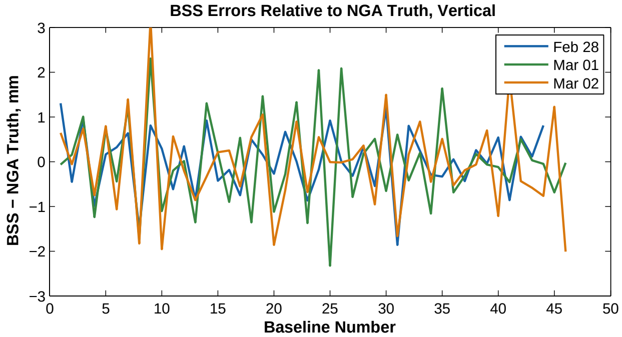


**Figure 15** Vertical component of the differences of BSS measurement and NGA truth.

The differences between BSS measurements and the NGA truth are very small, generally within the uncertainty associated with the NGA values (1 mm 2-$\sigma$ each axis). In the horizontal axes, they are generally bounded by 1.0 mm, and the mean difference is 0.44 mm. Agreement is not quite as good in the vertical component, as expected; here the differences are generally bounded by 2.0 mm, and the mean difference is 0.73 mm. The most extreme outliers tend to be common across all three nights of testing. This repeatability suggests that real errors in the NGA truth baseline estimate may be significant (approaching 1.0 mm) in those cases.

Figures 16, 17, and 18 present these same differences as histograms. The superimposed green curves are Gaussian curve fits to the histograms and are provided simply as a visualization aide.

The histograms presented in Figures 16, 17, and 18 show Gaussian-like distributions centered near zero. For each component, the mean magnitude, standard deviation, and distribution mean are summarized in Table 3.

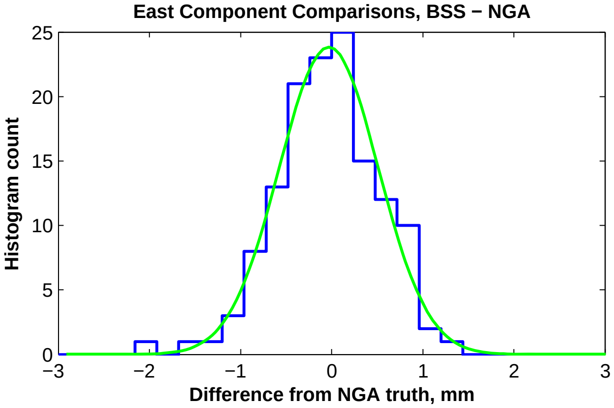


**Figure 16** Distribution of East component of differences.

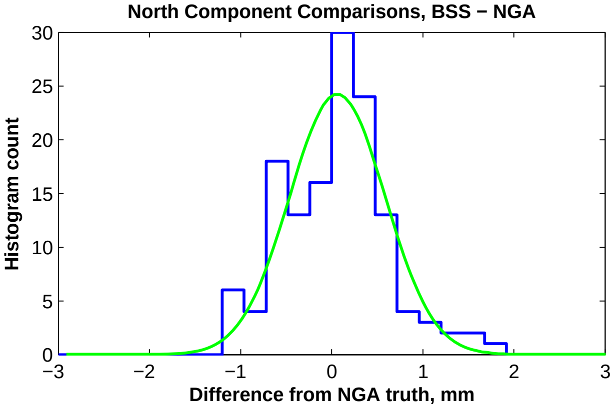


**Figure 17** Distribution of North component of differences.

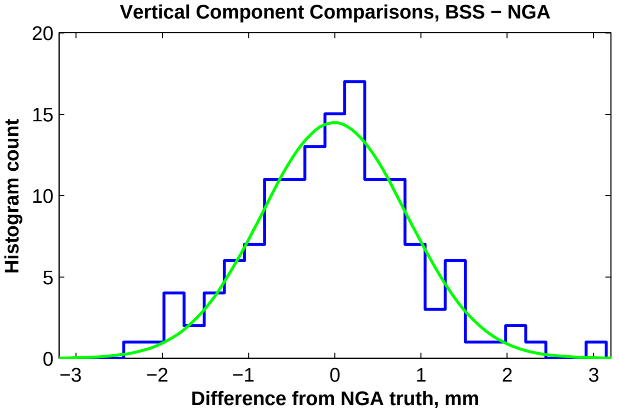


**Figure 18** Distribution of Vertical component of differences.

## BSS Performance at Longer Baseline Lengths

The Benchmark Survey System was designed to achieve better than millimeter measurement accuracy at the minimum along-rail benchmark spacing of 30 meters, and its performance, as described in the previous section, has been very good. It is of interest to consider how the accuracy changes as baseline length increases. While some sources of error in the BSS system are constant (antenna PCO, errors in characterization of the mounts, centering errors), others are expected to vary with baseline (e.g. atmospheric effects). The data collected in the deployment of 2006 al-

**Table 3** Summary of BSS Measurement Errors (all values in mm)

| | Mean Error Magnitudes | Standard Deviations | Distribution Means |
|---|---|---|---|
| $\Delta E$ | 0.43 | 0.56 | $-0.04$ |
| $\Delta N$ | 0.44 | 0.57 | 0.05 |
| $\Delta V$ | 0.73 | 0.94 | $-0.01$ |

low us to consider BSS performance at baseline lengths extending up to 350 meters. All possible unique baselines between benchmarks within the dataset of March 1, 2006 have been processed and differenced with NGA truth vectors. Figure 19 shows the magnitudes of all three components (E,N,V) of these differences, plotted against baseline length.

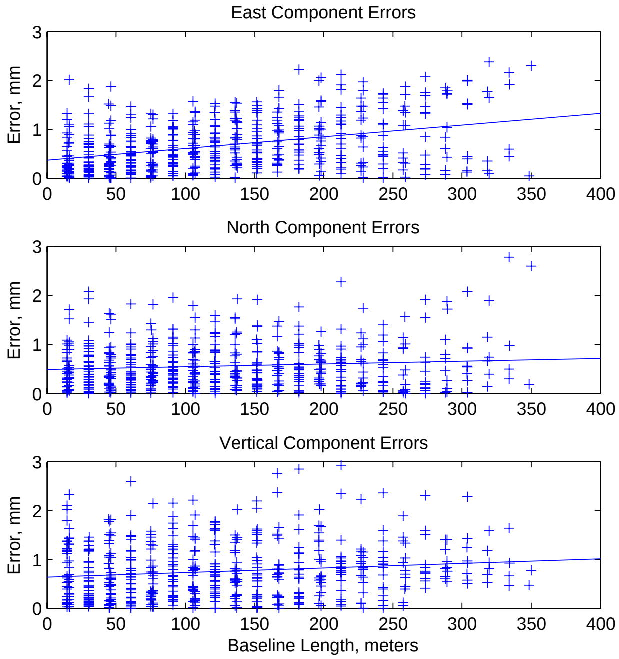


**Figure 19** BSS results differenced with NGA truth, components (top to bottom) East, North, Vertical, as a function of baseline length.

The regularity of the spacing of the benchmarks along the HHSTT is immediately evident in the Figure; the minimum spacing is about 15 meters. A linear fit to this data is plotted as a line over the data points in the Figure, and summarized in Table 4. These results show that the accuracy of BSS results is maintained over longer baselines, at least up to 350 meters, which fully satisfies the needs of NGA at the HHSTT.

**Table 4** Linear fit to magnitudes of the differences between BSS results and NGA truth

| Difference (mm) $= sd + b$, where "$d$" is in meters. ($\sigma_s$ is the uncertainty of the estimate of $s$) | | | |
|---|---|---|---|
| | East | North | Vertical |
| $s(mm/m)$ | $2.4E{-}3$ | $0.6E{-}3$ | $0.9E{-}3$ |
| $\sigma_s(mm/m)$ | $0.24E{-}3$ | $0.23E{-}3$ | $0.29E{-}3$ |
| $b(mm)$ | 0.37 | 0.49 | 0.64 |

## CONCLUSIONS

The Benchmark Survey System is a complete survey system for the HHSTT, custom designed and built by ARL:UT under contract with NGA. The purpose of the BSS development was to replace legacy NGA conventional survey techniques with a GPS-only system, with the goal of maintaining sub-millimeter positioning accuracy while substantially increasing throughput. Three major components of the system design are key to achieving this level of accuracy with a GPS-only system: characterization of the GPS antenna, control and accurate characterization of the mounting of the antenna to the benchmark, and accurate and robust estimation of baselines using the GPS data.

The BSS provides a substantial improvement in survey efficiency at the HHSTT, yielding an estimated 400% increase in throughput with an 85% decrease in manpower, when compared to the existing conventional survey procedures. Analysis of BSS results from three nights of operation in early 2006 shows that the BSS-derived measurements agree with recent NGA precise survey data to better than 0.6 mm (1-$\sigma$) in the horizontal axes and better than 1.0 mm (1-$\sigma$) in the vertical axis.

The BSS has met or exceeded its design goals of accuracy and throughput. ARL:UT continues to improve and expand the BSS while providing support for NGA operations at the HHSTT.

## REFERENCES

[1] "Holloman High Speed Test Track," multimedia compact disk, prepared by the 846th Test Squadron, Holloman AFB, NM, www.46tg.af.mil.

[2] M. Rothacher, S. Schaer, L. Mervart, G. Beutler, "Determination of antenna phase center variations using GPS data," presented at 1995 IGS Workshop, Potsdam, Germany, May 1995.

[3] G. Mader, "GPS antenna calibration at the National Geodetic Survey," GPS Solutions, Vol.3, No. 1, pp. 50-58, 1999.

[4] "National Continuously Operating Reference Station (National CORS) Site Monumentation, Final Report," prepared by National Geodetic Survey, December 2000.

[5] R. B. Harris, et. al., "Open Signals, Open Software: Two Years of Collaborative Analysis Using the GPS Toolkit," ION GNSS 2006.