FINAL TECHNICAL REPORT

1. USGS Award Number	G10AC00075
2. Project Title	Installation of Permanent GPS Networks in Northern California to Support Crustal Deformation Monitoring by the U.S. Geological Survey (dated October 19, 2009, revised January 8, 2010 and January 26, 2010)
3. Principal Investigator	Karl Feaux UNAVCO, Inc. 6350 Nautilus Drive Boulder, CO 80301 Phone: (303) 381-7556 Fax: (303) 381 – 7451 Email: kfeaux@unavco.org
4. Project Period	February 15, 2010 to December 15, 2011

Abstract
This final report summarizes the work completed by UNAVCO as part of the U.S. Geological Survey (USGS) Award No. G10AC00075. This USGS grant was awarded (under the American Recovery and Reinvestment Act of 2009) to UNAVCO based on a UNAVCO proposal submitted as a response to the USGS Program Announcement 10HQPA0008 (Proposals for Upgrades to the USGS Crustal Deformation Monitoring Systems under the American Recovery and Reinvestment Act). Under this award, UNAVCO completed reconnaissance, permitting, construction, and data telemetry for eight new permanent GPS stations in Northern California, a subset of the list of potential stations in the Announcement Attachment B3 ("Proposed New U.S. GPS Stations"). Each of these eight GPS stations consists of a state-of-the-art geodetic GPS receiver with choke-ring antenna, a very stable geodetic-quality monument, a power system capable of year round operation, and a data communications system capable of delivering 1-Hz, IP-based GPS data streams.

Project Overview
UNAVCO installed eight GPS stations in the San Francisco Bay Area to enhance the performance of USGS crustal deformation monitoring in the region by providing real-time delivery of 1-Hz GPS data. These GPS stations will improve the ability to detect transient geodetic signals as well as to report co-seismic and post-seismic deformation to support timely and accurate earthquake solutions. Between February 2010 and December 2011, UNAVCO conducted reconnaissance, permitting, and construction of the following permanent GPS stations in the San Francisco Bay Area: DUBP, MILP, MSHP, ROCP, SCCP, SWEP, T3RP, TRCP (Table 1). For each target area, UNAVCO often completed reconnaissance in multiple locations to meet the strict siting requirements, including line of site radio telemetry, sky view, accessibility, geologic stability, scientific goals and other criteria. Once the final location was determined and the landowner tentatively agreed to grant a permit for station construction, UNAVCO completed reconnaissance reports for each site. UNAVCO also completed an installation report for each completed station. All written reports were submitted to the USGS via email.

Table 1. Key dates for reconnaissance, permitting, and station installations.

Alt Name	Type	Landowner	NEPA Review	Recon Date	Site Permit Submitted	Permitted Date	Install Date	Permit Expiration	Stream
TRCP	SDBM	Private, Corp-1	y	June 30, 2010	July 12 2010	October 5, 2010	November 12, 2010	Aug 25 2021	y
SCCP	SDBM	Private, Corp-2	y	December 16, 2010	Dec 20 2010	February 20, 2011	April 12, 2011	Feb 18 2021	y
DUBP	SDBM	Public, Utility	y	March 10, 2010	May 27 2010	February 4, 2011	April 29, 2011	Jan 20 2016	y
MSHP	DDBM	Private, individual-3	y	September 16, 2011	Sept 14 2011	October 10, 2011	October 20, 2011	Sept 21 2021	y
MILP	DDBM	Private, individual	y	April 9, 2010	May 13 2010	June 7, 2010	August 20, 2010	June 7 2020	y
T3RP	SDBM	Public, Utility - 4	y	April 15, 2010	June 17 2010	November 4, 2011	October 31, 2011	Oct 5 2021	y
ROCP	DDBM	Public, Utility -5	y	April 1, 2010	June 15 2010	May 27, 2011	July 6, 2011	Feb 28 2012	y
SWEP	SDBM	Government, NPS	y	March 1, 2010	Aug 25 2010	December 10, 2010	January 12, 2011	Dec 31 2015	y
1 - 1st recon 4/15/2010 and permit submission 7/14/2010 with initial landowner rejected; USGS revised target area									
2- 1st recon 4/8/2010 and permit submission 4/15/2010 with initial landowner rejected; USGS revised target area									
3 - 1st recon 3/1/2010 and permit submission 7/15/2010 with initial landowner rejected; USGS revised target area									
4 - recon location and permit negotiation required several iterations with accommodating landowner									
5 - original USGS permit ammended									

Permitting
Permitting was one of the most time-consuming and difficult parts of the project. Once a suitable site was found, UNAVCO submitted permit applications to the landowner on behalf of the USGS. Usually, weeks to months of negotiations were required before both the USGS and the landowner would agree to all conditions of the land-use agreement. The USGS is the permittee for all land-use agreements obtained during this project. UNAVCO delivered

hard copies of the permits to Dr. Jessica Murray-Moraleda (USGS/Menlo Park). Of the eight sites, three were permitted with public utilities agencies, two with private individuals, two with private corporations, and one with the National Park Service. On average, sites with public utilities companies took the longest amount of time to permit (~12 months) and land held by a private corporation or individual required the least amount time to permit (~2 months). The National Park Service was also fairly expedient, with a straightforward application process that spanned four months. Several sites required more than a year to permit due to more stringent requirements from the landowner. The permit renewal dates for each site (Table 1) vary depending on landowner requirements and/or different signing dates. In most cases, the permits do not have to be renewed until 2016 or later. All sites went through the NEPA (National Environmental Policy Act) review process before they were approved for construction.

Monumentation and Hardware

Each GPS station consists of either a SCIGN (Southern California Integrated Geodetic Network) deep-drilled braced monument (DDBM – Appendix I) or a SCIGN short-drilled braced monument (SDBM – Appendix II). UNAVCO contracted Lundgren Drilling Systems to complete the drilling and grouting operations at the DDBM sites. UNAVCO field crews completed the SDBM drilling using a Hilti hand-held roto-hammer drill.

The USGS furnished twelve Topcon NET-G3A Topcon receivers and Topcon CR-G3 GNSS chokering antennas, four of which will be utilized as spares. For each station, the GPS antenna is fixed to the monument utilizing a SCIGN antenna mount and a protective SCIGN radome. Other station hardware includes an IP-based Ethernet bridge (radio), charge controller, four 100 amp-hour batteries, lightning protection, and three 80-watt solar panels. Stainless steel protective armor is mounted onto the enclosure to thwart vandalism or theft (the exception is ROCP where equipment is located within the USGS hut). Fencing is installed where necessary and approved by the landowner. Customized informational placards are installed at two of the stations. The standard layout for each station is shown in Figure 1. UNAVCO submitted station metadata and installation reports to the USGS after station installation as required by the award.

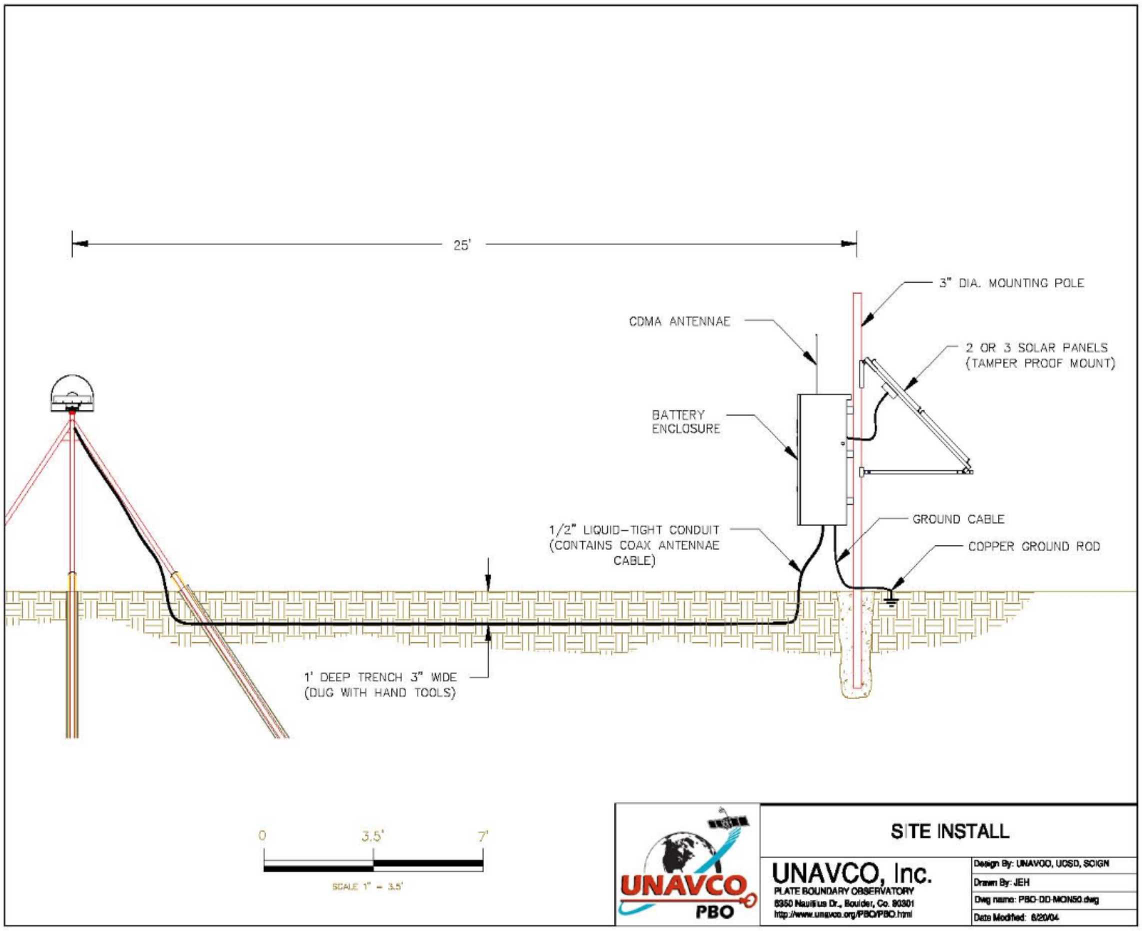


Figure 1. Standard GPS station design. Dimensions were modified for site-specific conditions and landowner requirements. Typically, fences were not constructed due to landowner request.

Data Telemetry / Realtime Performance

The primary goal of the project was to deliver high-rate (1-Hz) GPS data streams with low-latency to the USGS Menlo Park facility. To increase post-event reliability, reduce the ongoing operations and maintenance costs, cellular technology could not be utilized. Instead, UNAVCO engineers used 900MHz IP-based radios (Intuicom EB3+ series) at most of the stations. One exception is station ROCP, which utilizes an existing microwave radio link to telemeter GPS data streams to the Menlo Park USGS office. The radio network topology was fairly straightforward (Figure 2), but did require the use of multiple repeaters and quite a bit of testing throughout the project.

Table 2. Performance parameters for high-rate GPS data streams on March 11, 2012. Average return time of a 400 byte packet sent to the radio which is roughly equivalent to the amount of binex data at 1Hz pushed through the network (per USGS website).

	Name	Estimated TX Latency (sec) 03-11-2012	Streaming Data Completeness 1 day average (%) (1)
DUBP	Dublin	0.18	100
MILP	Milpitas/Starbird	0.18	100
MSHP	Mission Hills	0.70	96
ROCP	Rocky Ridge	0.02	100
SCCP	Stonebrae CC	0.40	92
SWEP	Sweeny Ridge	0.18	100
T3RP	MtTam Middle Peak	0.15	100
TRCP	Tamarancho Camp	0.25	100

24 hr day average 00:00 UTC Mar 11, 2012 – 23:59 UTC Mar 11, 2012
http://escweb.wr.usgs.gov/share/highrate-gps/graphics/perform.php?site=SC

The GPS stations TRCP, T3RP, SWEP and ROCP typically maintain 100% data completeness (Table 2). Data completeness at station DUBP, on the other hand, can vary depending on time of day. The station MILP also performs well at 100% data completeness. When run individually, SCCP has near 100% completeness, although retransmits at MSHP can affect the link to the shared master radio at Menlo Park and reduce data completeness at both stations. Statistics for latency, completeness and radio diagnostics are maintained by the USGS at http://escweb.wr.usgs.gov/share/highrate-gps/.

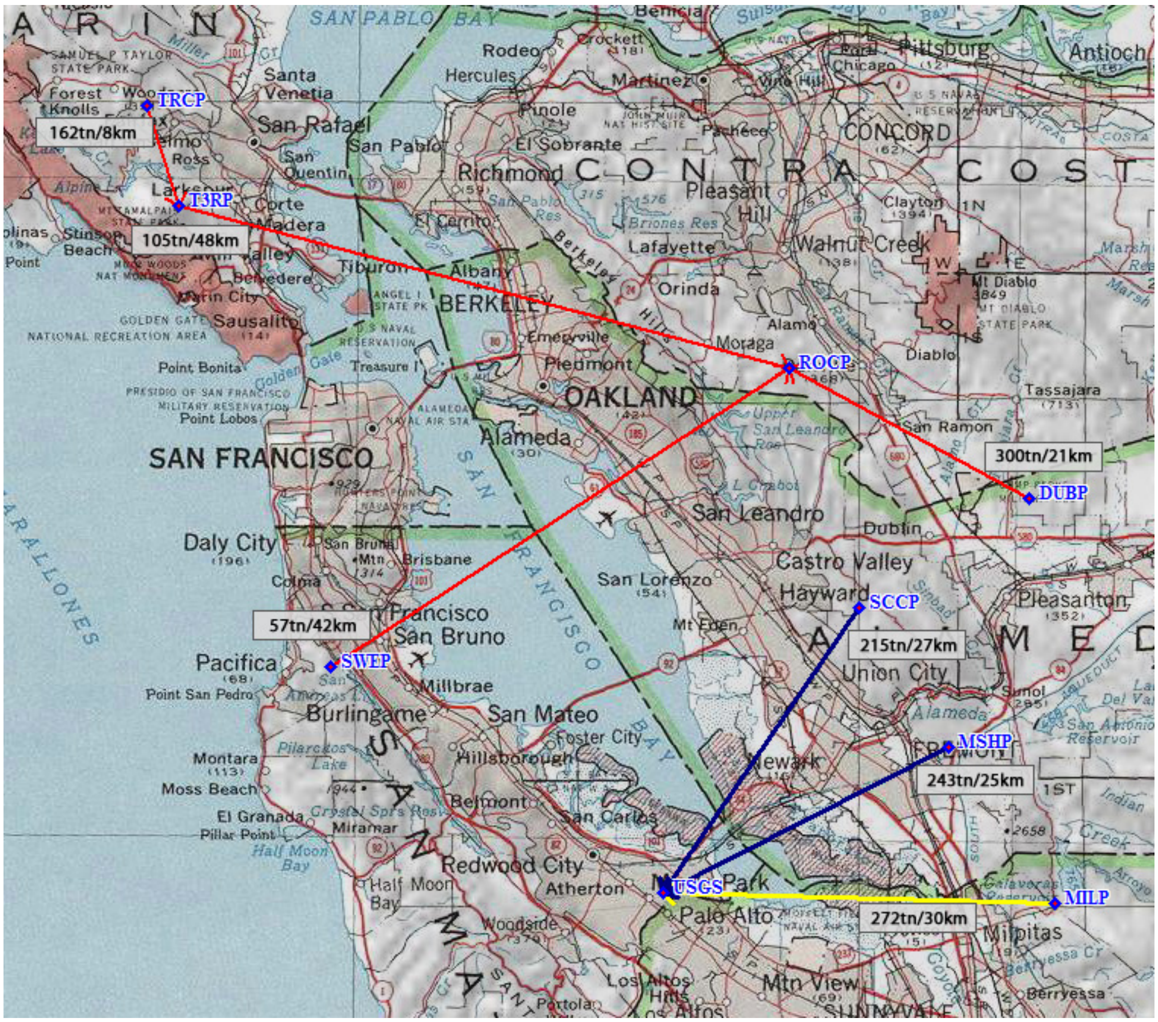


Figure 2. Network topology, showing data paths for the high-rate GPS data streams. Red lines delineate the ROCP sub-network that utilizes the USGS microwave backhaul link. Blue and yellow lines indicate dedicated radio links on the tower at USGS Menlo Park.

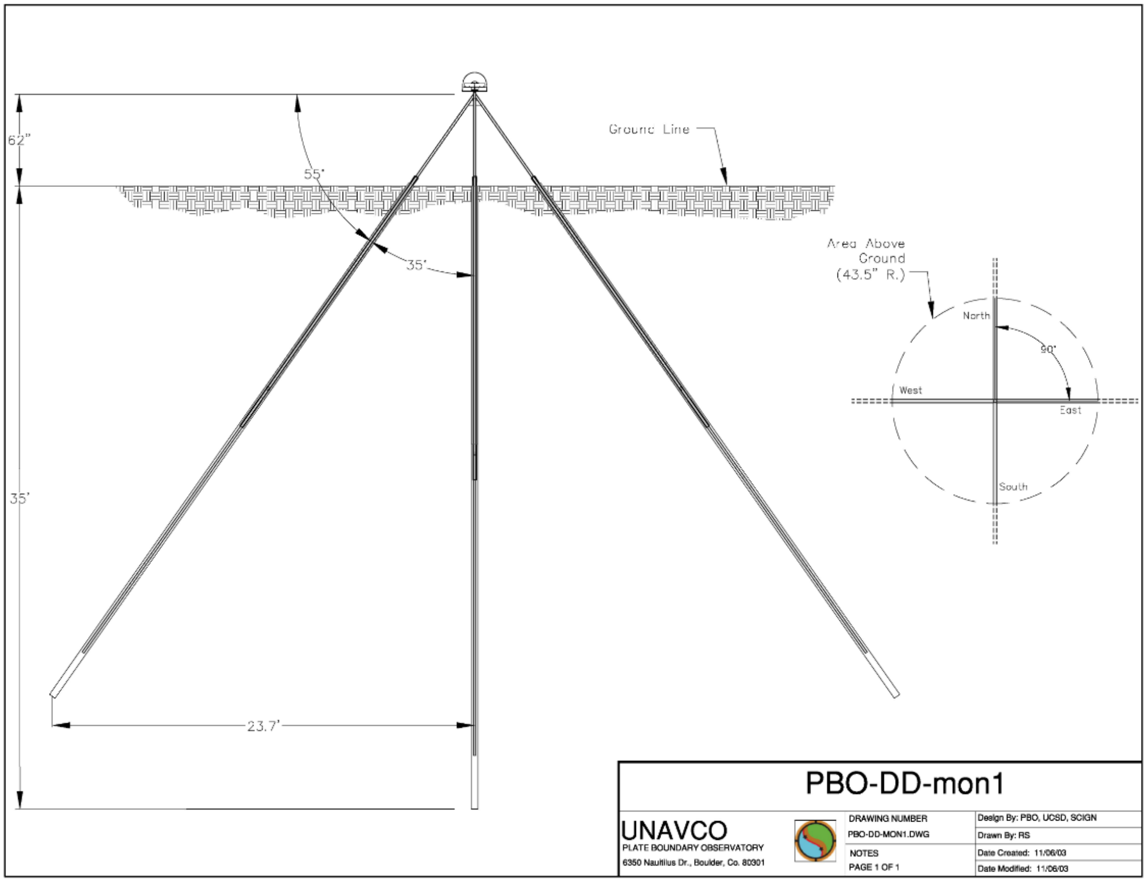
Conclusions / Benefits

This project was completed on-schedule (within the 3-month no-cost extension granted in July 2011) and slightly under-budget. This project provided direct economic benefit to California and Colorado where field engineers and permitting staff were employed, which was one of the primary goals of the American Recovery and Reinvestment Act of 2009. Construction of this GPS network also improved the geodetic infrastructure in the region by enhancing access to geodetic data within a region subject to secular and transient crustal deformation. Furthermore, these GPS stations enhance the capabilities of the earthquake science community, local government, and the private sector.

Acknowledgements
UNAVCO is thankful to all the individuals who helped make this project a success. We especially would like to thank all of the landowners, including private citizens, public utility and Federal agencies, whose generosity made this project possible. Contributing personnel include Andre Basset, Chelsea Jarvis, Chris Walls, Doerte Mann, Shawn Lawrence, Kyle Bohnenstiehl, Adrian Borsa (UNAVCO), Michael Jackson (original co-PI, Trimble Navigation) as well as Jessica Murray-Moraleda, Dave Croker, Nicole Knepprath, Chris Guillemot, John Langbein and Nancy King (USGS).

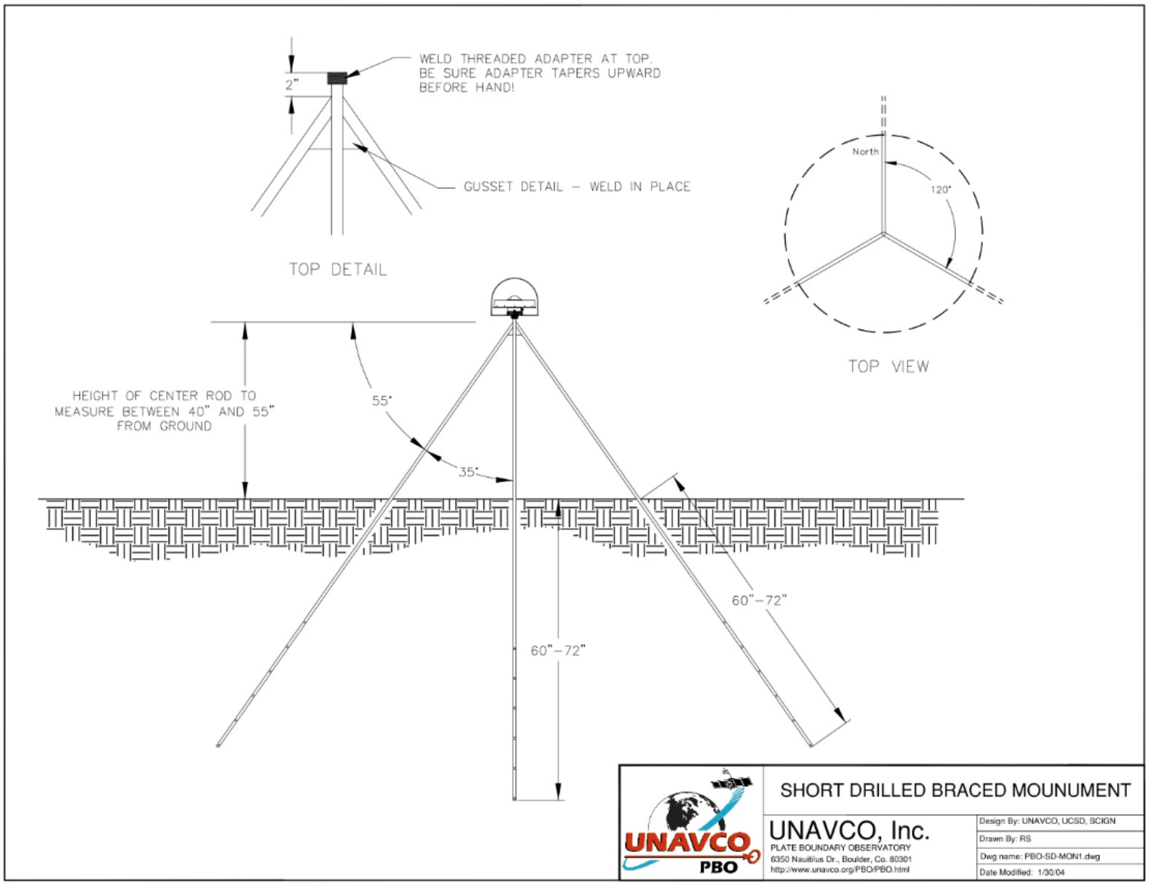
Appendices

Appendix I – Deep Drilled-Braced Monument



The deep-drilled braced monuments (DDBM) installed in this project were the SCIGN (Southern California Integrated Geodetic Network) deep drilled-braced monument modified by UNAVCO from the Wyatt-Agnew quincunx design. This design isolates the monument from near-surface material, but allows a solid bond to the bedrock at depth. The DDBM monument consists of a vertical main leg, braced by 4 angled legs at an inclination of 55 degrees below horizontal, with each leg separated by 90 degrees in azimuth. Each leg consists of 35-40' coupled sections of 1.25" diameter schedule 40 stainless steel pipe. The five-leg design provides redundancy in the event of an incompetent leg or improper grout placement at depth. The drilling subcontractor drills the 5 holes for the monument legs to a depth of 40 ft, installs the steel pipe in place, and then mixes and pumps the grout into the legs to create the subsurface bond. After the legs are grouted in place, the construction crew builds the above ground portion of the monument, first welding the legs together at the intersection point. A SCIGN antenna mount is then used to mount and level the choke ring antenna, which is covered by a radome for security and protection.

Appendix II - SCIGN Short Drilled-Braced Monument



The SCIGN short drilled-braced monument is typically installed in competent bedrock (at a depth of approximately 5 to 6 feet) in situations when site access or permitting issues will not allow a deep drilled braced monument to be constructed. The construction consists of a vertical "main" leg (stainless steel rod) braced by angled legs, typically 35 degrees from vertical. Three angled rods, 120 degrees from one another, are used to constrain the intersection point in three dimensions.

Appendix III - GPS Station Photos
DUBP:

MILP:

MSHP:

ROCP:

SCCP:

SWEP:

T3RP:

TRCP: