SLAC–PUB–9566
November 2002

GPS Activities at SLAC*

Dirk Behrend, Cristóbal Bañuelos, Catherine Le Cocq
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

Abstract

The Alignment Engineering Group of the Stanford Linear Accelerator Center (SLAC) started to use RTK (real-time kinematic) GPS equipment in order to perform structure mapping and GIS-related tasks on the SLAC campus. In a first step a continuously observing GPS station (SLAC M40) was set up. This station serves as master control station for all differential GPS activities on site and its coordinates have been determined in the well-defined global geodetic datum ITRF2000 at a given reference epoch. Some trials have been performed to test the RTK method. The tests have proven RTK to be very fast and efficient.

Contributed to 7th International Workshop on Accelerator Alignment (IWAA2002)

Spring-8/JASRI, Sayo-gun, Hyogo, Japan, November 11-14, 2002

* Work supported by Department of Energy contract DE–AC03–76SF00515.

GPS ACTIVITIES AT SLAC*

Dirk Behrend, Cristóbal Bañuelos, Catherine Le Cocq
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

1. INTRODUCTION

The Stanford Linear Accelerator Center (SLAC) roughly covers an area of 430 acres forming a significant part of the Stanford University campus. Apart from its alignment tasks in the physics labs, the Alignment Engineering Group also provides services to the SLAC community in all tasks that are related to surveying. These surveying tasks cover a large range of accuracy requirements going from micrometers to decimeters. While control surveys and alignment jobs require the highest accuracy level, structure mapping and GIS-related tasks have a low accuracy demand. Although conventional techniques and instrumentation (total stations, leveling instruments, laser trackers) could be employed for all of the above tasks, geodetic Global Positioning System (GPS) surveying techniques might constitute a better choice for some tasks, especially when considering time efficiency.

With the incentive to create an information system for all structures of the SLAC campus, the Alignment Engineering Group in cooperation with Site Engineering and Maintenance acquired a GPS system with RTK (real-time kinematic) capabilities at the end of 2001. Yielding a relative position accuracy of 1 cm over distances up to 10 km (Leica, 2001), the absolute accuracy is limited by the quality of the position information of the reference point. Thus, in order to provide geo-referencing in a well-defined reference frame, the reference station must be known to the highest possible accuracy level in that frame.

Hence, it was decided to install a continuously operating GPS receiver at a suitable site. In this way, the coordinates of this station are available to a few millimeters (in the chosen reference frame), the rate of change of the coordinates can be determined after a sufficiently long observation period (more than a year), and, finally, discontinuities in the coordinate (and velocity) time series might be discernible. This site serves as the master control station for the SLAC campus and all differential GPS measurements are referenced to it.

2. GPS EQUIPMENT AND SOFTWARE

Basic geodetic GPS equipment consists of a (dual-frequency) receiver and an external antenna. While the antenna captures the electromagnetic waves arriving from the GPS satellites and

* Work supported by Department of Energy contract DE-AC03-76SF00515.

converts them into electric current, the receiver tracks the signal (code and phase), determines a position, stores the raw data on a storage device and/or outputs it via an interface to a computer. The processing within the receiver is associated with a certain noise floor that should be as low as possible. The receiver noise can be evaluated in a zero baseline test in which two receivers (or more) are connected to the same antenna with the help of a signal splitter. In this way external error sources are canceled out. After processing, if the measured length of the baseline is confirmed to be zero, the health of both of the receivers' electronics is corroborated (van Sickle, 1996).

GPS antennas are omnidirectional, i.e. they pick up the microwave signals emanating from the satellite and coming in from all azimuth and elevation directions in the hemisphere above the local horizon. For high precision applications, the antenna should have a stable phase center (electrical center of the antenna) and should not be severely affected by reflected signals (multipath mitigation) and radiointerference (jamming resistance). Choke rings are particularly effective in reducing the effects of multipath. A choke ring (see Figure 1) consists of several concentric hoops, or thin-walled hollow cylinders, of metal mounted on a circular base at the center of which is placed a microstrip patch antenna (Langley, 1998).

Figure 1 Station SLAC M40 at the end of the LINAC housing with the Leica AT-504 choke ring antenna in the setup before (left) and after (right) the mount change.

For geodetic purposes, dual-frequency receivers with 12 channels and with the ability to perform code and phase measurements are employed. The alignment group at SLAC opted for a Leica system with the major components being summarized in Table 1. The choice was based on the requirements of a high quality GPS receiver plus full RTK (real-time kinematic) capabilities (see Section 4).

The rover unit of the Leica SR-530 system with an AT-502 antenna is shown in Figure 2. The achievable accuracy is claimed to be at 10 mm + 2 ppm in kinematic mode (Leica, 2001). The DISTO handheld distance meter facilitates the measuring of building corners and the like that would otherwise not be accessible due to signal blockage.

Table 1 Basic components of SLAC's alignment engineering group's GPS equipment.

component type	part	remark
receiver	Leica SR-530	3 units
base antenna	Leica AT-504	choke ring
rover antenna	Leica AT-502	2 units
	Leica AT-503	2 units
radio link	Pacific Crest PDL	
distance meter	DISTO Pro A	hand held

A (rigorous and accurate) GPS survey is largely software driven and encompasses the following basic steps: project planning, data gathering, data reduction, data processing and post-processing. To fulfill all these tasks the alignment group makes use of two software packages: SKI-Pro and Bernese.

Figure 2 Leica SR-530 rover unit with AT-502 antenna and DISTO Pro A distance meter employed in a survey at SLAC.

Leica's SKI-Pro software was part of the original equipment purchase. It is a windows-based, largely automated suite of programs that is used for all observation related tasks. SKI-Pro facilitates the importing of real-time data and combines this data with post-processed results (Leica, 2002). While it is well suited for real-time applications with baseline lengths up to 10 km, it yields limited accuracy in regional and global applications where a station should be tied in to a well-defined reference frame (at the sub-centimeter level in an absolute sense). This is likely caused by not fully exploiting the GPS modeling capabilities (ionospheric and tropospheric delay models, ocean loading effects as examples).

BERNESE V. 4.2 GPS software was acquired in February 2002 to perform in depth analysis and long-term studies. Bernese is a platform independent software package based on standard

FORTRAN-77 and FORTRAN-90 modules that are being driven by a menu system (Hugentobler, 2001). The data analysis can be automized to a large extent by means of batch processes of the Bernese Processing Engine (BPE). The highest accuracy requirements are met by processing dual frequency code and phase measurements as well as by modeling or introducing models for the ionospheric and tropospheric signal delay, antenna phase center variations, and ocean tide loading effects as examples. Bernese constitutes a state-of-the-art scientific software package which is also being employed worldwide by survey agencies to evaluate permanent local or regional GPS networks.

3. REGIONAL ANALYSIS

Until the purchase of GPS equipment, SLAC has had no on-site monument in a well-defined global reference frame. Thus, it was decided to establish such a station using GPS technology. With ongoing RTK applications planned, it was further decided to establish a continuously operating GPS station. This will facilitate a permanent control of the site and, eventually, provide a velocity estimate in a global reference frame.

SLAC's new GPS master control station is located next to the Sector 30 gate at the end of the LINAC and is named SLAC M40 (see Figures 1 and 3). The actual control point is located on top of a 60 cm diameter concrete pillar with the top about 3 m off the ground. A wooden deck surrounding the concrete cylinder provides access (Figure 3). The actual receiver is a Leica System 530 Base Receiver that is housed in a weatherproof box attached to the deck (Figure 3). The AT-504 choke ring antenna is attached to the top of the pillar using a Kern forced centering mount (Figure 1).

Figure 3 SLAC M40 with the wooden deck surrounding the 60 cm diameter concrete pillar and the weatherproof box for the Leica System 530 base receiver.

This control monument was chosen for several reasons:

- central SLAC location;
- monument within controlled area of SLAC;

▪ amount of visible sky is large enabling better GPS geometry;
▪ RTK radio-modem coverage of SLAC nearly perfect;
▪ permanent power access and potential network connectivity;
▪ easy access for monitoring the equipment;
▪ pillar and deck are in good condition.

The initial antenna mount was changed at the end of March 2002. At the same time the weather radome was removed.

The tie to the global reference frame ITRF2000 is done in a regional analysis of GPS data with a network of well-established permanent GPS stations. The chosen network consists of seven stations of the International GPS Service (IGS) plus the station SLAC M40. Figure 4 shows the geographical distribution of all eight sites.

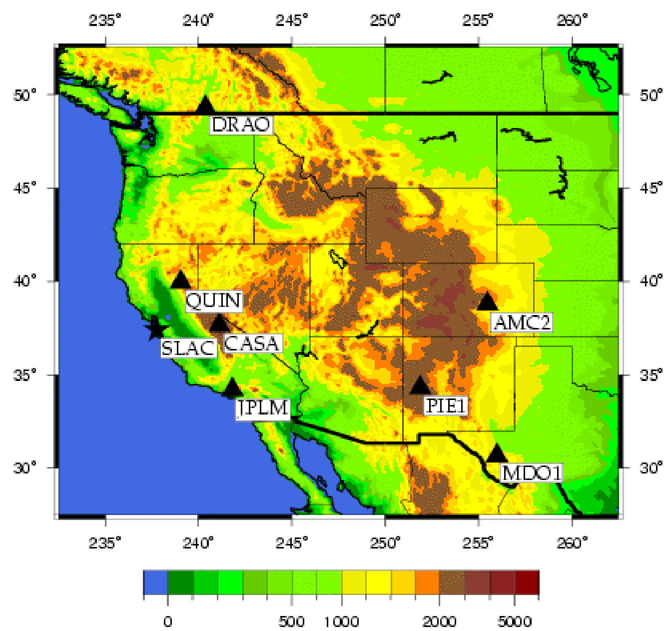

Figure 4 Geographical distribution of the permanent IGS sites used in the regional analysis. The four character site codes represent the following stations: Colorado Springs (AMC2), Mammoth Lake (CASA), Penticton (DRAO), Pasadena (JPLM), Fort Davis (MDO1), Pietown (PIE1), Quincy (QUIN), Stanford (SLAC).

A detailed description of the processing steps being performed to derive accurate coordinates for SLAC M40 is beyond the scope of this paper. We limit the description to the following itemized list:

▪ Download RINEX, orbits, and ERP files,

- Orbit computation,
- Synchronization of receiver clocks,
- Creation of baselines,
- Data cleaning,
- Ambiguity resolution,
- Daily free network solution,
- Combination of daily network solutions and datum fixing.

The GPS observation files are exchanged in the Receiver INdependent EXchange format (RINEX). ERP files contain the Earth orientation parameters (pole coordinates, UT1-UTC, UTC-GPStime).

The coordinates obtained for SLAC M40 refer to the antenna reference point (ARP) of the Leica AT-504 GPS antenna. The ARP is located at the bottom of the preamplifier as indicated in the antenna diagram (Figure 5). By choosing the ARP instead of the physical marker of the monument, subsequent GPS RTK surveys need not be concerned about antenna height information of the master control station.

```
                  +-------+                          <-- 0.1393
                 /    +    \                         <-- 0.1282 L2
                |     +     |                        <-- 0.1093 L1
  +-------------+-----------+---------------+        <-- 0.1020 TCR
  |                                          |
  |                                          |
  |                                          |
  |                                          |
+-+------------------------------------------+-+    <-- 0.0380
+---------------+-----------+-----------------+     <-- 0.0350 BCR
                |           |
                |           |
                +-----x-----+                        <-- 0.000  BPA=ARP

<--                  0.3794                  -->


  ARP: Antenna Reference Point
  L1 : L1 Phase Center               L2 : L2 Phase Center
  TCR: Top of Chokering              BCR: Bottom of Chokering
  TGP: Top of Ground Plane           BGP: Bottom of Ground Plane
  TPA: Top of Preamplifier           BPA: Bottom of Preamplifier
  TOP: Top of Pole

  All dimensions are in meters.
```

Figure 5 Antenna diagram of the Leica AT-504 choke ring antenna. Coordinates refer to the ARP (antenna reference point) located at the bottom of the preamplifier.

Figures 6 and 7 show the coordinate time series plus velocity estimates of the North, East, and Up components of the arbitrarily chosen stations SLAC, CASA, and JPLM. Since the vertical component is usually determined less accurately, the 'Up panels' were given a smaller scale. Although only some 5 months of data have been used, a clear trend is discernible in all horizontal coordinate components. The horizontal performance of SLAC is comparable to JPLM, both being slightly better than CASA. The vertical component, on the other hand, is relatively noisy as compared to JPLM. Still, a value of 3-4 is common for the relationship between vertical and horizontal accuracy.

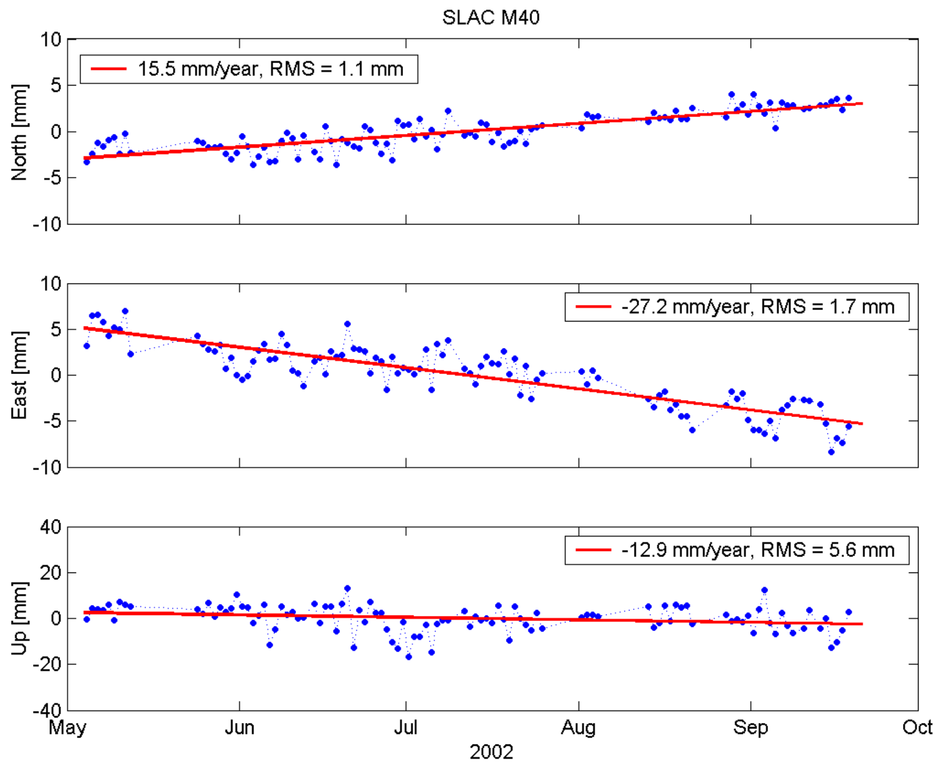

Figure 6 Coordinate time series and velocity estimates for the station SLAC M40 over the time span from May to October 2002.

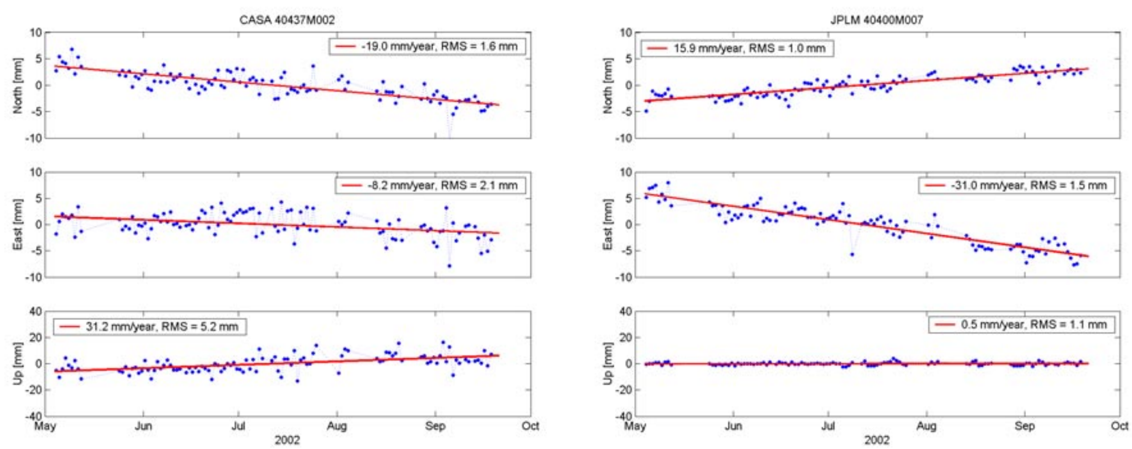

Figure 7 Coordinate time series and velocity estimates for the stations CASA (Mammoth Lake) and JPLM (Pasadena) over the time span from May to October 2002.

The velocity estimates for the stations of the regional network as derived directly from the time series are compiled in Table 2. Table 3, in turn, contains the IGS published velocity values for the same stations. The velocities found for SLAC agree with the nearby station of SUAA to within a few mm/yr in all components. This is an indication that the velocity estimate for SLAC is realistic, although it is only based on five months of data. Nonetheless, the limited amount of data manifests itself in larger discrepancies at other stations: CASA and DRAO, for instance, show differences as large as 30 mm/yr in the vertical and 15 mm/yr in the horizontal components. This will hopefully be cured with more data becoming available.

Table 2 ITRF2000 station velocities (North, East and Up components) for the eight stations of the regional network as derived from the time series.

Station	North	East	Up
AMC2	-10.5 mm/yr	-23.9 mm/yr	-4.3 mm/yr
CASA	-19.0 mm/yr	-8.2 mm/yr	31.2 mm/yr
DRAO	-24.6 mm/yr	-3.7 mm/yr	0.7 mm/yr
JPLM	15.9 mm/yr	-31.0 mm/yr	0.5 mm/yr
MDO1	-3.6 mm/yr	-20.4 mm/yr	0.3 mm/yr
PIE1	-11.8 mm/yr	-18.2 mm/yr	-17.4 mm/yr
QUIN	-7.2 mm/yr	-0.7 mm/yr	11.9 mm/yr
SLAC	***15.5 mm/yr***	***-27.2 mm/yr***	***-12.9 mm/yr***

Table 3 ITRF2000 station velocities (North, East and Up components) for the eight stations of the regional network as published by the IGS. Since for SLAC no published velocity value is available, the station SUAA was chosen which is located within a distance of less than 8 km from SLAC M40.

Station	North	East	Up
AMC2	-10.8 mm/yr	-17.6 mm/yr	-4.2 mm/yr
CASA	-9.8 mm/yr	-21.7 mm/yr	-1.9 mm/yr
DRAO	-11.7 mm/yr	-13.4 mm/yr	1.2 mm/yr
JPLM	11.2 mm/yr	-37.1 mm/yr	-1.6 mm/yr
MDO1	-7.2 mm/yr	-12.1 mm/yr	-0.6 mm/yr
PIE1	-9.8 mm/yr	-13.8 mm/yr	-0.5 mm/yr
QUIN	-5.6 mm/yr	-21.3 mm/yr	-6.9 mm/yr
SUAA	***10.6 mm/yr***	***-24.5 mm/yr***	***-14.1 mm/yr***

4. RTK EXAMPLE

RTK is a method of surveying that allows for the use of GPS measurements from a well-determined station to be transferred to a rover thus providing real-time centimeter accuracy without long point occupation times. The necessary hardware (cf. section 2) consists of two or more GPS receivers and radio-modems. One receiver occupies a known reference station (such as SLAC M40) and broadcasts a correction message to one or more of the roving receivers. The roving receivers process the information from the reference station to solve for WGS-84 vectors by real-time integer solutions. This gives an accurate position of the rover with respect to the reference station. Clearly a well determined reference station is needed to produce accurate roving results.

In terms of the time necessary for accurate data gathering, RTK allows a surveyor to occupy a point of interest for only a few seconds instead of the numerous minutes otherwise needed. RTK is a GPS differential mode of operation using the very accurate carrier phase measurements for point position determination. The phase observations require a preliminary ambiguity resolution before being useable. When phase lock is lost such as when measuring near trees or at a building corner, RTK can be limited in its ability to measure those points. Thus at SLAC we have added Leica’s DISTO system to our RTK package (Leica System 530). Combining RTK with traditional survey methods allows for the mapping of objects that would otherwise not be accessible by ordinary GPS methods.

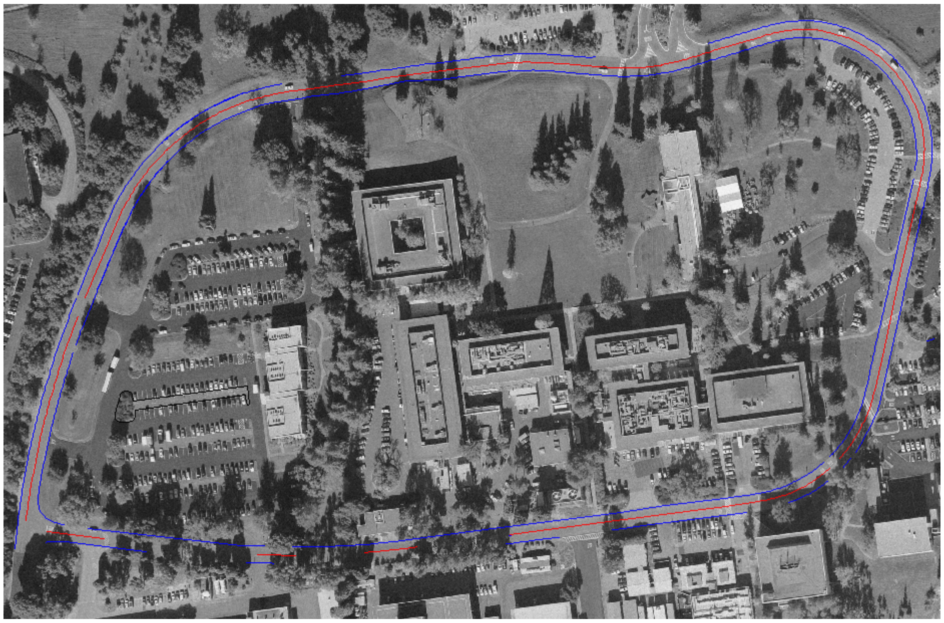

Figure 8 Overlay of RTK GPS results on top of an orthophoto of the SLAC campus. The red line represents the loop road centerline, the two blue lines are the pavement edges.

As an example we show results of an RTK test survey of the loop road of the SLAC campus (Figure 8). The purpose of the survey was to map the centerline as well as the pavement edges of the loop road along with getting familiar with the equipment and procedures of the Leica system. The GPS results were transformed from the ITRF2000 reference datum to the NAD83 datum using published transformation parameters (e.g., Soler, 2002). The resulting line work was overlaid onto an orthophoto of the SLAC campus that was provided in the same reference datum (NAD83).

From an eyeball inspection, no systematic discrepancies are discernible between the two data sets; i.e., there appears to be no datum problem. The overall agreement can be described as good. The time needed to obtain the three lines of about 4.6 km length each can be summarized as follows: 1 hour to prepare setup, 12 hours of field work, and 4 hours of office work. Hence, altogether two working days of a single person are needed.

5. CONCLUSIONS

The Alignment Engineering Group of the Stanford Linear Accelerator Center (SLAC) started to use RTK (real-time kinematic) GPS equipment in order to perform structure mapping and GIS-related tasks on the SLAC campus. In a first step a continuously observing GPS station (SLAC M40) was set up. This station serves as master control station for all differential GPS activities on site and its coordinates have been determined in the well-defined global geodetic datum ITRF2000 at a given reference epoch. Some trials have been performed to test the RTK method. The tests have proven RTK to be very fast and efficient.

From the first 5 months of data, an initial estimate of the station velocity of SLAC M40 has been done giving a good indication of the true site velocity. Still, at least a complete year, preferably several years, of uninterrupted data coverage is needed for allocating an accurate and reliable velocity value to SLAC M40. A good estimate of this velocity, however, is a prerequisite for making coordinate determinations comparable over time.

ACKNOWLEDGEMENTS

The authors would like to thank all members of the Alignment Engineering group for their support and assistance. No results would have been possible without their efforts. A special thanks goes to Brian Fuss for setting up the group's GPS web page and his constant preparedness to give a helping hand if needed. The Stanford Linear Accelerator Center is operated by Stanford University for the U.S. Department of Energy.

REFERENCES

Beutler, G., A. Geiger, M. Rothacher, S. Schaer, D. Schneider, A. Wiget (1995): *Dreidimensionales Testnetz Turtmann 1985-1993 – Teil II (GPS-Netz).* Geodätisch-geophysikalische Arbeiten in der Schweiz, Volume 51, Schweizerische Geodätische Kommission, Zürich, 1995.

Hugentobler, U., S. Schaer, P. Fridez (2001): *Bernese GPS Software Version 4.2.* Astronomical Institute of the University of Berne, Berne, February 2001.

Langley, R.B. (1998): *GPS Receivers and the Observables.* In: P.J.G. Teunissen and A. Kleusberg (Eds.): GPS for Geodesy – 2nd Edition. Springer-Verlag, Berlin, 1998.

Leica (2001): http://www.leica-geosystems.com/gps/product/sr530.htm.

Leica (2002): http://www.leica-geosystems.com/gps/product/ski-pro.htm.

van Sickle, Jan (1996): *GPS for Land Surveyors*. Ann Arbor Press, Chelsea, Michigan, 1996.

Soler, T. (2002): *Computing NAD83 Coordinates Using ITRF-Derived Vector Components*. ACSM-ASPRS 2002 Annual Conference Proceedings, Washington, DC, April 2002.