SESSION 8:

RECEIVER AND SATELLITE ANTENNA CALIBRATIONS

Receiver and Satellite Antenna Phase Center Offsets and Variations

Markus Rothacher, Forschungseinrichtung Satellitengeodäsie, TU Munich
Gerry Mader, US Department of Commerce, NOAA, Geoscience Research Division

Position Paper of the "Antenna Session"
IGS Workshop in Ottawa, April 8-11, 2002

Draft of April 5, 2002

1 Introduction

If highest precision is required, antenna phase center and multipath effects are crucial error sources in GPS site position determination. Especially the vertical component is heavily affected by erroneous antenna phase patterns and multipath. In many geodetic and geophysical applications (like, e.g., reference frame maintenance, global sea level change and post-glacial rebound) very high accuracy (site positions on the few millimeter level and site velocities at about 1 mm/year) is aimed at.

In order to achieve these aims, very accurate and consistent antenna phase center variations (PCVs) are needed for both, the receiver and satellite antennae and site-dependent effects (such as multipath) have to be reduced to the extent possible or determined from calibration measurements.

In Section 2 we consider the status of receiver antenna calibration results from various calibration methods (relative and absolute field calibrations and chamber measurements). The quality is limited by site-dependent effects (multipath, ...) that cannot easily be accounted for.

Section 3 summarizes the present knowledge on the satellite antennae and the methods to determine satellite antenna offsets and patterns and shows the relationship between receiver and antenna phase center variations.

After an overview of interesting new developments in the field (Section 4) the necessity of a new format for antenna information and clear responsibilities for the maintenance of antenna information are discussed in Section 5. The Appendix consists of the description of the new antenna information file format called ANTEX.

2 Receiver Antenna Calibrations

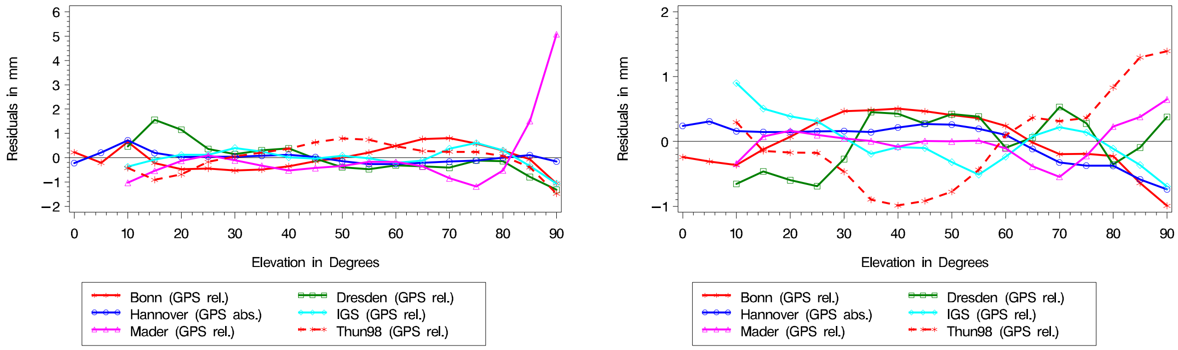
2.1 Relative Receiver Antenna Calibrations

This method for receiver antenna calibration has been used for a long time now (see, e.g., [*Mader*, 1999; *Rothacher et al.*, 1995, 1996]). Elevation-dependent (and azimuth-dependent) patterns are estimated from the GPS data collected on a very short baseline with accurately known endpoints. In order to be able to determine azimuth-dependent variations, the antenna to be calibrated has to be rotated between sessions (because of the north and south "hole" in the GPS satellite constellation). The official IGS antenna patterns stem from such relative field measurements and have a precision of about 1-2 mm (see also Figure 1 in Section 2.2).

For long baselines or if the antenna is tilted, however, absolute antenna phase patterns are needed to be able to correctly take into account elevation- and azimuth-dependent PCVs.

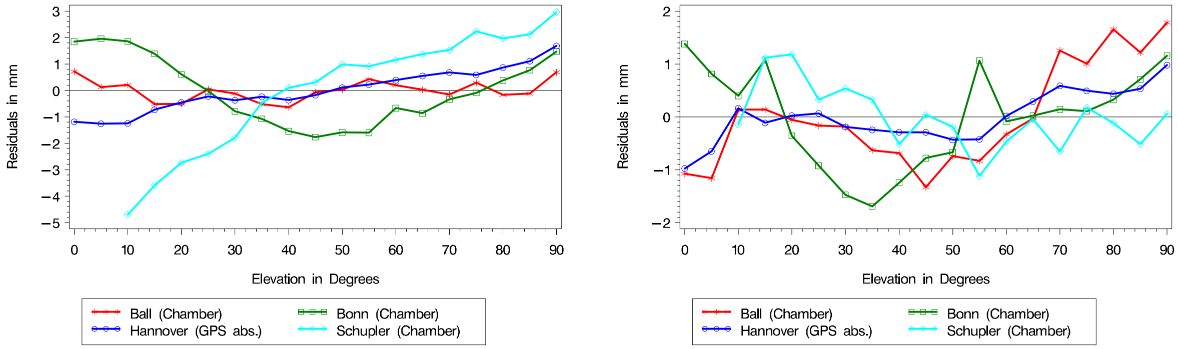
2.2 Absolute Receiver Antenna Calibrations

There exist two independent methods to obtain absolute receiver antenna PCVs nowadays: the measurements in an anechoic chamber (see, e.g., [*Schupler et al.*, 1995] or [*Rocken et al.*, 1996]) and the field measurements on a short baseline using a robot to tilt and rotate one of the antennae (see [*Wübbena et al.*, 2000]). The advantage of the robot measurements is, that real GPS signals are tracked with a real receiver and an antenna in the "usual" field environment.



(a) L_1 Frequency (b) L_2 Frequency

Figure 1: Differences between relative elevation-dependent antenna PCVs from different calibration sources. PCVs of the TRM14532.00 antenna relative to the AOAD/M_T antenna are shown.



(a) `AOAD/M_T`, L_1 Frequency (b) `AOAD/M_T`, L_2 Frequency

Figure 2: Differences between absolute elevation-dependent antenna PCVs from different calibration methods: chamber measurements from BALL, BONN, and SCHUPLER, and robot results of HANNOVER (IfE and Geo++).

In contrast to the relative antenna calibrations in the field, the robot measurements allow (1) the determination of patterns down to zero degree elevation or even below, (2) the elimination of multipath effects to a large extent, and (3) a dense and quite homogeneous coverage of the GPS antenna hemisphere.

The comparison of the different methods shows that GPS receiver antennae may be calibrated nowadays with a precision of about 1 mm nowadays, including the elevation as well as the azimuth dependence of the antenna phase center location. The absolute calibration results from the robot (a cooperation between the Institut für Erdmessung (IfE) and the company Geo++) are in very good agreement with the relative field calibration results on short baselines (see Figure 1 as an example, where the PCV differences with respect to a mean pattern are shown for a number of field calibrations; more details may be found in [*Rothacher*, 2001; *Mader*, 2001]). For some of the anechoic chamber patterns still unexplained differences compared to the absolute or relative field calibrations are seen. For the `AOAD/M_T` antenna different absolute calibration methods and measurement campaigns differ by about 1–4 mm (see Figure 2 and [*Rothacher*, 2001]). It is nice to see that especially the BALL chamber measurements and the Hannover values are in very good agreement (1–2 mm level).

2.3 Problematic Effects (Radoms, Snow, Multipath, ...)

Errors due to site-dependent effects (like, e.g., site-induced antenna phase center variations and multipath) are very difficult to reduce and may thus be considered as a major accuracy limiting factor (besides tropospheric refraction) for position determination with GPS in general and for heights in special.

When mixing different antenna types, you have no guarantee to obtain height estimates with sub-centimeter accuracy, even after correcting the observations for antenna specific phase center variations (as available at the IGS Central Bureau). For longer baselines you have the adverse circumstances that you have to make use of the ionosphere-free linear combination, which tends to amplify the phase center effects, and that you also have to estimate troposphere zenith delay parameters which are highly correlated with the antenna phase patterns. The conclusion is, that for precise site coordinate determination, whenever possible, the same antenna type should be used for all sites. This is especially true for the permanent stations of the IGS.

Without going into much detail, we would like to mention that multipath and the antenna environment have a crucial impact on the GPS results, too. Snow on the antenna, wet ground after rainfall, the height of the antenna above the ground, the monument design, the antenna ground plane, radoms, and any multipath producing or absorbing material around the antenna — to name just a few of the factors involved — may result in height changes of up to a few centimeters (see [*Jaldehag*, 1995; *Böder et al.*, 2001] and publications at UNAVCO `http://www.unavco.ucar.edu`). A recent example have been the changes in the height time series of about 5 cm of the IGS site Hoefn in Iceland, that were most probably caused by changes of the antenna type and setup. Unfortunately, it is extremely difficult to correct or model this type of antenna and environment effects and we will probably always have to live with some remaining effects from the antennae and from multipath that will adversely affect the GPS site coordinate estimates, especially the heights.

Out of these reasons it is very important, therefore, not to change the antenna equipment at an IGS site unless absolutely necessary. A change of the antenna characteristics is comparable in its consequences on coordinate and velocity estimates as moving the site to another location.

The work of the Hannover group and new developments at Haystack and at NGS(see Section 4) might give new insights into the possibilities to calibrate site-dependent effects.

3 Satellite Antenna Calibrations

In the last few years research groups started to realize that not only the receiver antennae, but also the satellite antennae show phase center variations. These variations are most certainly the reason for the scale factor that results in global GPS solutions, when absolute phase center patterns (from anechoic chamber or robot field measurements) are applied. Scale errors of the order of 15 ppb corresponding to an overall height change of about 10 cm are observed.

It is important to mention in this context that a very basic relationship exists between satellite and receiver antenna elevation-dependent PCVs. The nadir angle z' at the satellite (to the station) is related to the zenith angle z for the receiver at the ground (to the satellite) by

$$\sin z' = \frac{R}{r} \sin z \tag{1}$$

where R is the Earth's radius and r the geocentric distance of the satellite. Whereas the zenith angle z at the receiver ranges from 0 to 90 degrees, the corresponding nadir angle z', as seen from the satellite, only varies between 0 and approximately 14 degrees. An elevation-dependent phase center pattern $\Delta\phi(z)$ of the receiver antenna may thus be interpreted as a phase center pattern $\Delta\phi'(z')$ of the satellite antenna and vice versa with

$$\Delta\phi'(z') = \Delta\phi(z) \tag{2}$$

The consequence is, that errors in the satellite antenna patterns may be seen in the receiver patterns and vice versa.

3.1 Manufacturer Information on Satellite Antenna Offsets

The information available about the GPS satellite antennae and, especially, about the location of the antenna phase center is very sparse. Some details on the antenna characteristics may be found in *Aparicio et al.* [1996]. It is, however, not even known, whether the phase center offsets (from the center of mass of the satellite) from the manufacturers are offsets for L_1, L_2, or the ionosphere-free linear combination. From the estimation of satellite antenna offsets by various IGS analysis centers it also became clear that the satellite antenna offset information by manufacturer is not reliable (thinking, e.g., of the Block IIR satellites).

The offsets presently used by all IGS analysis centers are given in Table 1.

Due to these circumstances, people started to think about satellite antenna calibration methods to improve this situation. Due to the high correlation between receiver and satellite patterns, the global scale, absolute station heights, and troposphere zenith delays very accurate offsets and PCVs are extremely important. The possible approaches are discussed in the sections to come.

Table 1: Satellite antenna offsets used by the IGS.

Satellite Block	X (m)	Y (m)	Z (m)
I	0.210	0.000	0.854
II/IIA	0.279	0.000	1.023
IIR	0.000	0.000	0.000

3.2 Satellite Antenna Measurements on the Ground

Estimates of the L1, L2 and LC phase centers for the Block IIA GPS satellite antennae have been determined. These results indicate that the L1, L2, and LC phase centers have z-axis (toward the earth) offsets that differ significantly from the currently assumed offset values.

These calibrations used the Block IIA antenna as a receiving, rather than a transmitting antenna. The Block IIA antenna was pointed at the zenith from the roof of the Boeing facility in Seal Beach, CA, and was connected to a standard dual-frequency, geodetic-quality GPS receiver. By computing baseline vectors from a nearby reference antenna, first to a standard geodetic-quality GPS antenna, and then to the Block IIA antenna, the phase centers of the Block IIA antenna relative to the standard antenna could be determined. This calibration procedure is essentially identical to that used by NGS numerous times on previous antenna calibrations. The primary difference for this calibration was to limit the data used to satellites above 60^o elevation due to the highly directive antenna beam and to include only those periods when at least two satellites were in view.

Graphs of the phase residuals versus elevation from these solutions show greater azimuthal variations for L1 than for L2. These effects may be unique for these particular antennae and may depend on the tuning done to produce the desired amplitude response. These results mitigate much of the scale factor error introduced when absolute antenna calibrations are used for the global network of terrestrial antennae.

3.3 Estimation of Satellite Antenna Offsets and Patterns

The estimation of satellite antenna offsets from global GPS solutions has been performed by quite a few IGS analysis centers (see, e.g., [*Springer*, 1999]). It has been shown that it is difficult to get good absolute satellite antenna offsets, especially in the z-direction (towards the Earth), because of the bad separability between satellite clock estimates and satellite antenna offsets. The repeatability is of the order of a few decimeters. In contrast to this, relative offsets between different satellite blocks may be determined on a 1-5 cm level.

In view of the fact that the GPS satellite antennae consist of two large antenna rings, it has to be expected that not only antenna offsets but also antenna patterns have to be taken into account. An indication that this is indeed necessary is the fact that the absolute receiver antenna patterns lead to a scale of about 15 ppb, if the IGS satellite antenna offsets are used. The offset values determined by Gerry Mader, NGS (see Section 3.2) reduce this scale considerably, but not completely.

Therefore, at the TU in Munich, the necessary software modifications were done to allow for the estimation of satellite antenna patterns, i.e., variations of the phase center depending on the nadir angle z'. The results of such an estimation using the global IGS data is shown in Figure 3. We see that different patterns are obtained for Block II/IIA and Block IIR satellites. The patterns can be estimated with a precision of about 1-2 mm (repeatability from day to day). In order to be able to estimate these satellite PCVs the global scale has to be fixed (e.g. on the ITRF scale). More details will be given in a paper presently written by *Schmid and Rothacher* [2002].

Using these satellite antenna patterns, the problem of the global scale is “solved” and absolute receiver antenna patterns may be used at the ground. It would make sense for the IGS to adopt at one and the same time (1) a set of satellite antenna offsets (e.g., by NGS) together with a set of consistent satellite PCVs determined by TU Munich and (2) the absolute receiver PCVs from the robot measurements from Hannover. In this way, the most consistent set of both, receiver and satellite antenna PCVs available now could be applied.

4 New Developments

4.1 Antenna and Multipath Calibration System at Haystack

Despite the many efforts devoted by investigators to the calibration of site-specific errors, signal scattering and multipath remain an unsolved problem. Therefore, groups at the Harvard-Smithsonian Center for Astrophysics, MIT Haystack Observatory, and UNAVCO/UCAR (Kwan-Dong Park, James L. Davis, Per Jarlemark, Brian Corey, and many others) developed an Antenna and Multipath Calibration System (AMCS) for characterizing

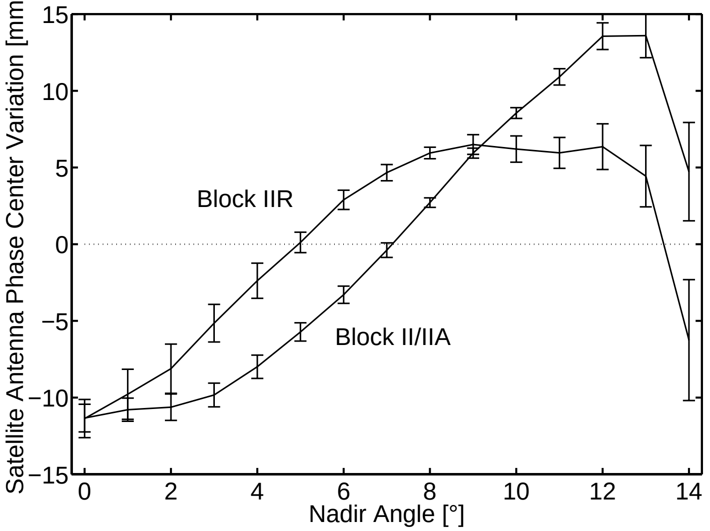


Figure 3: Antenna Phase Patterns (ionosphere-free LC) for Block II/IIA and Block IIR GPS Satellites Estimated from 8 Consecutive Global 1-Day Solutions (with standard deviation).

site-specific GPS phase measurement errors. The system consists of a high-gain, multipath-free, 3-m diameter parabolic antenna, two test antennae, and two Trimble GPS receivers. The parabolic antenna can track GPS satellites in the azimuth angle range of 7-357 degrees and the elevation angle range of 5-87 degrees with pointing precision of better than 0.5 degree.

There are two modes of operating the AMCS: Zero-baseline (ZBL) and AMCS modes. In ZBL-mode, the two receivers simultaneously record the signal from the test GPS antenna. In this operating mode, one can determine the receiver clock offsets and the phase biases for each satellite. Typical RMS accuracies of ZBL-mode phase residuals are sub-millimeter level, ranging from 0.4 to 0.7 mm. In the AMCS-mode, one GPS receiver records the signal received at the test antenna, and the other records the signal from the parabola. Thus, one can compare the phases from the two receivers, and determine the antenna and multipath calibration errors of the test antenna.

To assess the antenna and multipath calibration errors in AMCS-mode several experimental configurations have been tested. For example, the parabolic antenna can be parked pointing towards a fixed sky position (static-parabola) while a satellite drifts in and out of the antenna beam. The resulting RMS of the phase differences (or residuals) from these tests is usually two or three times larger than the RMS of the ZBL-mode. However, by modeling the azimuth and elevation angle dependence of the phase residuals, the RMS may be reduced to 1.2 mm. The system can also be programmed so that the parabolic antenna tracks a GPS satellite. The phase residuals obtained by tracking the same satellite over several days shows large amplitude variations over small elevation angle ranges with highly repeatable patterns. Modeling and subtracting the repeating patterns from the phase residuals results in an RMS of about 1.2 mm.

Recently, a second GPS antenna has been installed at a nearby location where the multipath effects are presumably less significant than at the location of the first GPS antenna. The second antenna is equipped with all-weather microwave absorber to further reduce multipath effects. The amplitude of the phase residuals obtained for the second antenna location are significantly smaller than for the first antenna, implying that the second antenna is less affected by multipath. These independent results also served to confirm that the origin of the phase patterns measured is multipath.

4.2 Phased Array Antenna/Receiver (NAVSYS)

NAVSYS Corporation has developed a 16 element digital beam-steering antenna array that is used with a high gain receiver to track the P(Y) code. Up to 12 GPS satellites on both L1 and L2 can be tracked. The beam steering array provides a nominal 10 dB increase in GPS signal strength compared to a conventional survey type antenna. The directivity of the digital beams created from the antenna array also reduces multipath errors, further improving the accuracy of the DGPS corrections generated by the GPS receiver and the navigation and timing solution computed. For C/N0 values above 52 dB-Hz, the P(Y) code receiver provides pseudo-range accuracies of 5 cm (1-sigma). The US Naval Observatory has purchased this type of receiver for evaluation in time transfer applications. Carrier phase outputs are also available for geodetic applications and NAVSYS is considering a semi-codeless version for the civil user.

A further enhancement of the beam steering receiver is to detect the multipath fields around the antenna array and to dynamically minimize these regions by applying nulls in the direction of the multipath signal sources detected for each satellite being tracked. NGS is planning an evaluation this spring of the NAVSYS digital beam steering receiver using the multipath nulling capability in a post-processing mode at the CORS site in Longmont, Colorado.

4.3 Possible VLBI Contribution

A working group of the IVS including members of the IGS and the ILRS was formed to study, whether the GPS satellite antenna phase centers might be determined using VLBI measurements of GPS satellites, or more precisely, using differential phase delay measurements between the GPS satellite and near-by quasars. A report of this working group is presently put together and will soon become available. According to this report the quality of a “map” of a GPS satellite antenna (similar to a radio source map) would only have a quality of the order of 40–50 cm and individual antenna elements could therefore not be distinguished.

It seems, however, that the position of a GPS satellite could probably be determined with an accuracy of about 3 cm. If this is true, a few VLBI observations to GPS satellites could be used to obtain the position of the satellites in the International Celestial Reference Frame (ICRF). The combined analysis of the GPS and VLBI data could then be used to directly get UT1 estimates that are in general not available from satellite data (only length of day (LOD)); but these ideas are outside the scope of this position paper.

4.4 GLONASS, Galileo, and GPS III

The satellite systems GLONASS and in future Galileo should also be considered here. At the moment, the same receiver antenna offsets and patterns are used for GLONASS and for GPS. This can be justified, since the frequencies are quite similar for the two satellite systems and no specific GLONASS calibration values are presently available to our knowledge. In the new antenna format proposed in the Appendix the generalization for GLONASS and Galileo antenna patterns has already been taken into account. The format is also ready to allow for a third GPS frequency.

5 New Format and Calibration Responsibilities

5.1 New Format

The format presently used by the IGS for PCVs (see file `igs_01.pcv` at the IGS Central Bureau Information System) is very simple and basic, but does not really serve the more general needs of various GPS communities. Because the IGS PCV values are generally accepted as the recommended phase center patterns and the format is used by most, if not all, commercial GPS software packages, the various institutions and communities involved in the antenna calibration issues would like to stick to a unique IGS PCV format, but more flexibility is required. The most important additions/modifications that should be included in a new PCV format are:

- Azimuth-dependent variations
- Antenna serial number to allow for individual patterns
- Flexible tabular interval
- Elevation cut-off information
- Information about the calibration source
- Generalization for GLONASS and Galileo
- Inclusion of satellite antenna offsets and patterns
- Formal errors of the phase center values

Further requirements are, that it should be possible to add new "blocks" of information to the format without causing problems. Especially the possibilities to allow for patterns of individual antennae and for azimuth dependent variations are very important for many commercial software packages. In Germany, e.g., each individual GPS antenna to be used in the official survey work of the federal states has to be calibrated and corrected for individual antenna phase patterns.

The old and new format should be maintained in parallel for a reasonably long overlap period to allow for a smooth transition to the new format.

The description and an example of the new format is given in the Appendix.

Table 2: Tasks in the Field of Receiver and Satellite Antenna Information

Topic	Institution(s)
Receiver and antenna names	IGS CB ?
Antenna reference point (ARP)	IGS CB ?
Antenna graphics or pictures	IGS CB ?
Antenna phase center patterns	Hannover ?
Satellite antenna offsets	NGS ?
Satellite antenna patterns	TU Munich ?

5.2 Responsibility for Antenna Information and Calibrations

At present, the IGS Central Bureau is updating the list of receiver and antenna names as well as the calibration results that are most often coming from Gerry Mader at NGS, but clear responsibilities have never really been defined. Because a lot of international and regional institutions rely on the IGS for the availability of consistent receiver antenna patterns, it makes sense to come up with a list of tasks that have to be performed to keep track of antenna and receiver names, antenna patterns etc. and to assign responsible institutions for these tasks. Table 2 contains a draft of such a list.

All information concerning satellite and receiver antennae should consistently be available at the IGS Central Bureau and it might make sense to have an official IGS antenna group to deal with the various issues in the field of antennae.

Ideally, results from at least two independent methods or groups should be compared/combined before an official IGS antenna "product" is released.

Whenever possible, the Hannover (IfE/Geo++) patterns should be used, because with their robot method the influence of multipath effects can be reduced considerably and patterns down to zero degree elevation can be produced. For antennae not calibrated in Hannover, relative patterns from relative field calibrations may be used after conversion to absolute patterns.

Maybe, in future, calibration results from the Haystack Antenna and Multipath Calibration System (AMCS) and the Phased Array Antenna/Receiver may also be used as a source of information.

6 Recommendations (Draft)

The sections above lead to the following recommendations for the "Antenna Session":

1) **Antenna Group:**
Should a group (working group ?) of antenna "experts" be established to take over the task to keep track of antenna issues in general and the transition to absolute phase center variations in special ? Is such a group needed ? Which members , which chair ?

2) **Same Antenna Type, no Antenna Changes:**
Whenever possible, the same antenna type (`AOAD/M_T`) should be installed on all IGS permanent sites.

   The antenna setup (including antenna, radom, orientation, environment) should not be changed unless it is absolutely necessary.

3) **New PCV Format:**
Adoption of a new IGS PCV format for receiver and satellite antenna phase center corrections (offsets and patterns) with the additions/modifications according to Section 5.1.

   May 31, 2002: New format available after review process.

   January 1, 2003: New format as official format; the old format is still available, but no longer updated.

4) **New Receiver Antenna Offsets and Patterns:**
Adoption of absolute antenna PCVs for the receiver antennae. The absolute patterns and offsets (for the Dorne Margolin T antenna `AOAD/M_T`) are given by the robot calibrations obtained by the Hannover group (see Section 5.1).

   May 31, 2002: New receiver offsets and patterns available for all major antenna types for tests by the IGS Analysis Centers.

September 30, 2002: Tests by the IGS Analysis Centers completed.

January 1, 2003: IGS Analysis Centers switch to absolute patterns.

5) **New Satellite Antenna Offsets and Patterns:**
Adoption of new satellite antenna offsets (NGS or Manufacturer) and corresponding, consistent patterns (TU Munich).

   May 31, 2002: Satellite antenna offsets and patterns are available for tests by the IGS Analysis Centers.

   September 30, 2002: Tests by the IGS Analysis Centers completed.

   January 1, 2003: IGS Analysis Centers switch to new satellite antenna offsets and patterns.

6) **Convention on Radoms to be Allowed for IGS Sites:**
Should there be some recommendations on what type of radoms may be used at IGS sites ???

It should be noted that recommendation 4) and 5) have to be implemented at the same time.

Appendix: New Antenna Phase Center Information Format

```
                        3 April 2002


       ANTEX: The Antenna Exchange Format Version 1.0
       **********************************************

                  M. Rothacher, R. Schmid
          Forschungseinrichtung Satellitengeodaesie
                        TU Munich

ANTEX VERSION 1.0 FORMAT DEFINITIONS

 +--------------------+------------------------------------------+------------+
 |    HEADER LABEL    |               DESCRIPTION                |   FORMAT   |
 |  (Columns 61-80)   |                                          |            |
 +--------------------+------------------------------------------+------------+
 |ANTEX VERSION / SYST| - Format version (1.0)                   |  F8.1,12X, |
 |                    | - Satellite System: blank or 'G': GPS    |  A1,39X    |
 |                    |                     'R': GLONASS         |            |
 |                    |                     'E': Galileo         |            |
 |                    |                     'M': Mixed           |            |
 +--------------------+------------------------------------------+------------+
 |PCV TYPE / REFANT   | - Phase center variation type:           |  A1,19X,   |
 |                    |     'A': absolute values                 |            |
 |                    |     'R': relative values                 |            |
 |                    | - Reference antenna for relative values  |  A20,20X   |
 |                    |     (blank: AOAD/M_T)                    |            |
 +--------------------+------------------------------------------+------------+
*|COMMENT             | Comment line(s)                          |    A60     |*
 +--------------------+------------------------------------------+------------+
 |END OF HEADER       | Last record in the header section.       |    60X     |
 +--------------------+------------------------------------------+------------+
 |START OF ANTENNA    | Record indicating the start of an antenna|    60X     |
 |                    | section                                  |            |
 +--------------------+------------------------------------------+------------+
 |TYPE / SERIAL NO    | Receiver antenna:                        |            |
 |                    |  - Antenna type: strict IGS              |    A20,    |
 |                    |    rcvr_ant.tab antenna and radome codes |            |
 |                    |  - Serial number (blank: all representa- |  A20,20X   |
 |                    |    tives of the specified antenna type)  |            |
```

```
 |                    | Satellite antenna:                       |            |
 |                    |  - Antenna type: name of the satellite   |            |
 |                    |    block                                 |            |
 |                    |    Example: ’BLOCK IIR’                  |            |
 |                    |  - Serial number (blank: all satellites  |            |
 |                    |    of the specified block)               |            |
 |                    |    For the selection of a single         |            |
 |                    |    satellite the PRN together with the   |            |
 |                    |    satellite system flag (blank,’G’,’R’, |            |
 |                    |    ’E’) has to be specified.             |            |
 |                    |    Example: ’G05’                        |            |
 +--------------------+------------------------------------------+------------+
 |METH / BY / # / DATE| - Calibration method:                    |     A20,   |
 |                    |     ’CHAMBER’,’FIELD’ or blank           |            |
 |                    | - Name of agency                         |     A20,   |
 |                    | - Number of single calibrations          |    I6,4X,  |
 |                    | - Date                                   |     A10    |
 +--------------------+------------------------------------------+------------+
 |DAZI                | Increment of the azimuth:                |  2X,F6.1,  |
 |                    |   0 to 360 with increment ’DAZI’         |     52X    |
 |                    |   (in degrees).                          |            |
 |                    |   360 degrees have to be divisible by    |            |
 |                    |   ’DAZI’.                                |            |
 |                    |   Common value for ’DAZI’: 5.0           |            |
 |                    | For non-azimuth-dependent phase center   |            |
 |                    | variations ’0.0’ has to be specified.    |            |
 +--------------------+------------------------------------------+------------+
 |ZEN1 / ZEN2 / DZEN  | Receiver antenna:                        |  2X,3F6.1, |
 |                    |   Definition of the grid in zenith:      |     40X    |
 |                    |   ’ZEN1’ to ’ZEN2’ with increment ’DZEN’ |            |
 |                    |   (in degrees).                          |            |
 |                    |   ’ZEN1’ and ’ZEN2’ always have to be    |            |
 |                    |   multiples of ’DZEN’.                   |            |
 |                    |   ’ZEN2’ always has to be greater than   |            |
 |                    |   ’ZEN1’.                                |            |
 |                    |   Common value for ’DZEN’: 5.0           |            |
 |                    |   Example: ’     0.0  90.0   5.0’        |            |
 |                    | Satellite antenna:                       |            |
 |                    |   Definition of the grid in nadir:       |            |
 |                    |   ’ZEN1’ to ’ZEN2’ with increment ’DZEN’ |            |
 |                    |   (in degrees).                          |            |
 |                    |   ’ZEN1’ and ’ZEN2’ always have to be    |            |
 |                    |   multiples of ’DZEN’.                   |            |
 |                    |   ’ZEN2’ always has to be greater than   |            |
 |                    |   ’ZEN1’.                                |            |
 |                    |   Common value for ’DZEN’: 1.0           |            |
 |                    |   Example: ’     0.0  14.0   1.0’        |            |
 +--------------------+------------------------------------------+------------+
 |# OF FREQUENCIES    | Number of frequencies, for which phase   |   I6,54X   |
 |                    | patterns are stored for the current      |            |
 |                    | antenna.                                 |            |
 +--------------------+------------------------------------------+------------+
*|COMMENT             | Comment line(s)                          |     A60    |*
 +--------------------+------------------------------------------+------------+
 |START OF FREQUENCY  | Record indicating the start of a new     |3X,A1,I2,54X|
 |                    | frequency section. The satellite system  |            |
 |                    | flag (blank,’G’,’R’,’E’) has to be       |            |
 |                    | specified together with the number of the|            |
 |                    | frequency.                               |            |
```

```
 +--------------------+------------------------------------------+------------+
 |NORTH /EAST / UP    | Receiver antenna:                        | 3F10.2,30X |
 |                    |  Eccentricities of the antenna phase    |            |
 |                    |  center relative to the antenna reference|            |
 |                    |  point (ARP). North, east and height     |            |
 |                    |  component (millimeters).                |            |
 |                    | Satellite antenna:                       |            |
 |                    |  Eccentricities of the antenna phase    |            |
 |                    |  center relative to the center of mass of|            |
 |                    |  the satellite in X-, Y- and Z-direction |            |
 |                    |  (millimeters).                          |            |
 +--------------------+------------------------------------------+------------+
 |AZI/ZEN1/ZEN2/DZEN  | Record initializing a new phase pattern  |  2X,4F6.1, |
 |                    | data block for azimuth 'AZI', from 'ZEN1'|    34X     |
 |                    | to 'ZEN2' (with increment 'DZEN').       |            |
 |                    | Neither other types of records nor       |            |
 |                    | comment lines are allowed after this     |            |
 |                    | record and within the subsequent data    |            |
 |                    | block!                                   |            |
 +--------------------+------------------------------------------+------------+
 |(Pattern values)    | Phase pattern values in 0.01 mm.         |   mF8.2    |
 |                    | After 10 values (per azimuth) continue   |            |
 |                    | values in next data record.              |            |
 +--------------------+------------------------------------------+------------+
 |END OF FREQUENCY    | Record indicating the end of a frequency |3X,A1,I2,54X|
 |                    | section (see also 'START OF FREQUENCY'). |            |
 +--------------------+------------------------------------------+------------+
*|START OF FREQ RMS   | Record indicating the start of an rms    |3X,A1,I2,54X|*
 |                    | value block related to the specified     |            |
 |                    | frequency.                               |            |
 +--------------------+------------------------------------------+------------+
*|NORTH /EAST / UP    | Rms of the eccentricities (millimeters). | 3F10.2,30X |*
 +--------------------+------------------------------------------+------------+
*|AZI/ZEN1/ZEN2/DZEN  | Record initializing a new phase pattern  |  2X,4F6.1, |*
 |                    | rms data block for azimuth 'AZI', from   |    34X     |
 |                    | 'ZEN1' to 'ZEN2' (with increment 'DZEN').|            |
 |                    | Neither other types of records nor       |            |
 |                    | comment lines are allowed after this     |            |
 |                    | record and within the subsequent data    |            |
 |                    | block!                                   |            |
 +--------------------+------------------------------------------+------------+
*|(Pattern rms values)| Phase pattern rms values in 0.01 mm.     |   mF8.2    |*
 |                    | After 10 values (per azimuth) continue   |            |
 |                    | values in next data record.              |            |
 +--------------------+------------------------------------------+------------+
*|END OF FREQ RMS     | Record indicating the end of an rms value|3X,A1,I2,54X|*
 |                    | block (see also 'START OF FREQ RMS').    |            |
 +--------------------+------------------------------------------+------------+
 |END OF ANTENNA      | Record indicating the end of an antenna  |    60X     |
 |                    | section                                  |            |
 +--------------------+------------------------------------------+------------+


Example of an ANTEX file:
-----------------------

================================================================================
     1.0            G                                       ANTEX VERSION / SYST
```

```
A                                                           PCV TYPE / REFANT
                                                            COMMENT
                                                            COMMENT
                                                            END OF HEADER
                                                            START OF ANTENNA
TRM33429-20+GP      1220226043                              TYPE / SERIAL NO
FIELD               FESG                     3    03-APR-02 METH / BY / # / DATE
     0.0                                                    DAZI
     0.0  90.0   5.0                                        ZEN1 / ZEN2 / DZEN
     2                                                      # OF FREQUENCIES
                                                            COMMENT
                                                            COMMENT
   G01                                                      START OF FREQUENCY
      0.20     -0.75     72.86                              NORTH / EAST / UP
     0.0   0.0  90.0   5.0                                  AZI/ZEN1/ZEN2/DZEN
   -6.19   -1.03    2.02    3.25    3.31    2.76    1.90    0.74   -0.80   -2.72
   -4.78   -6.55   -7.56   -7.48   -6.30   -4.35   -2.23   -0.61    0.00
   G01                                                      END OF FREQUENCY
   G02                                                      START OF FREQUENCY
     -0.19     -0.23     65.76                              NORTH / EAST / UP
     0.0   0.0  90.0   5.0                                  AZI/ZEN1/ZEN2/DZEN
   -6.75   -3.68   -1.52   -0.08    0.97    1.85    2.61    3.19    3.46    3.35
    2.89    2.20    1.45    0.80    0.34    0.09    0.00   -0.01    0.00
   G02                                                      END OF FREQUENCY
                                                            END OF ANTENNA
================================================================================
```

References

Aparicio, M., P. Brodie, L. Doyle, J. Rajan, and P. Torrione, GPS Satellite and Payload, in *Global Positioning System: Theory and Applications*, vol. 1, edited by B.W. Parkinson and J.J. Spilker, pp. 209–244, Progress in Astronautics and Aeronautics, Volume 163, 1996.

Böder, V., F. Menge, G. Seeber, G. Wübbena, and M. Schmitz, How to Deal With Station Dependent Errors - New Developments of the Absolute Calibration of PCV and Phase-Multipath With a Precise Robot, in *Proceedings of the ION GPS-01, Salt Lake City, Utah*, 2001.

Jaldehag, R.T.K., An Experimental and Theoretical Study of Antenna Related Error Sources, *Technical Report 276*, Chalmers University of Technology, Göteborg, Sweden, 1995.

Mader, G., GPS Antenna Calibration at the National Geodetic Survey, *GPS Solutions*, *3*(1), 50–58, 1999.

Mader, G., A Comparison of Absolute and Relative GPS Antenna Calibrations, *GPS Solutions*, *4*(4), 37–40, 2001.

Rocken, C., C. Meertens, B. Stephens, J. Braun, T. VanHove, S. Perry, O. Ruud, M. McCallum, and J. Richardson, Receiver and Antenna Test Report, UNAVCO Academic Research Infrastructure (ARI), 1996.

Rothacher, M., Comparison of Absolute and Relative Antenna Phase Center Variations, *GPS Solutions*, *4*(4), 55–60, 2001.

Rothacher, M., W. Gurtner, S. Schaer, R. Weber, W. Schlüter, and H. O. Hase, Azimuth- and Elevation-Dependent Phase Center Corrections for Geodetic GPS Antennas Estimated From GPS Calibration Campaigns, in *International Association of Geodesy Symposia, Symposium No. 115: GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications*, edited by G. Beutler et al., Springer, Boulder, CO, USA, 1995.

Rothacher, M., W. Gurtner, S. Schaer, R. Weber, and H. O. Hase, Azimuth- and Elevation-Dependent Phase Center Corrections for Geodetic GPS Antennas Estimated from GPS Calibration Campaigns, in *IAG Symposium No. 115*, edited by W. Torge, pp. 335–339, Springer-Verlag, 1996.

Schmid, R., and M. Rothacher, Estimation of Elevation-Dependent Satellite Antenna Phase Center Variations of GPS Satellites, in preparation, 2002.

Schupler, B.R., T.A. Clark, and R.L. Allshouse, Characterizations of GPS User Antennas: Reanalysis and New Results, in *International Association of Geodesy Symposia, Symposium No. 115: GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications*, edited by G. Beutler et al., Springer, Boulder, CO, USA, 1995.

Springer, T.A., *Modeling and Validating Orbits and Clocks Using the Global Positioning System*, Ph.D. dissertation, Astronomical Institute, University of Berne, Berne, Switzerland, 1999.

Wübbena, G., M. Schmitz, F. Menge, V. B öder, and G. Seeber, Automated Absolute Field Calibration of GPS Antennas in Real-Time, in *Proceedings of the ION Meeting 2000*, Salt Lake City, 2000.

Absolute Receiver Antenna Calibrations with a Robot

~~Martin Schmitz~~, Gerhard Wübbena, Gerald Boettcher

Geo++®
Gesellschaft für satellitengestützte geodätische und navigatorische Technologien mbH
D-30827 Garbsen, Germany
~~www.geopp.de~~

Günter Seeber, Volker Böder, Falko Menge

Institut für Erdmessung (*IfE*),
Universität Hannover
D-30167 Hannover, Germany
www.ife.uni-hannover.de

Phase variations (PCV) of GPS receiving antennas are a significant error component in precise GPS applications. A calibration procedure has been developed by Geo++® and IfE, which directly determines absolute PCV in a field procedure without any multipath influence. The precision and resolution of the procedure allows the determination of reliable elevation and azimuth dependent variations.

There exists several problems with existing relative field calibration procedures and with absolute chamber calibration results. However, PCV are urgently needed for mixed antenna type applications (e.g. RTK networks, engineering tasks). The goal of the developments is the separation of multipath and phase variations to get absolute PCV independent from a reference antenna and independent from site or location. Since 1995 the absolute PCV field calibration has been developed, which resulted into the Automated Absolute PCV Field Calibration in Realtime in the beginning of 2000.

The MP is eliminated through short-term differences, as MP is the same for subsequent epochs. The PCV information is reintroduced by orientation changes (rotations and tilts) of the antenna, which are performed by a robot. The robot itself is calibrated and gives a precise, fixed and stable rotation point for an antenna, fast orientation changes, a high level of automation and robot guidance in realtime.

The automated procedure serves for a homogeneous coverage of the antenna hemisphere by 6000 to 8000 different positions. Certain optimizations concerning satellite constellation, observation time, dynamic elevation mask are use in the operational calibration. The absolute field calibration has been verified intensively and has been compared to absolute chamber and relative calibration results. Also the major concern of the global scale associated with the use of absolute PCV has been experimentally proven to be due to the relative PCV. Over large baseline satellites are viewed under different elevations and hence different relative PCV.

The repeatability of the Absolute PCV Field Calibration is at the 1 mm level, which corresponds to the standard deviation in the 0.2 to 0.4 mm (1 sigma) range. A calibration gives absolute 3D offsets, absolute elevation and azimuth dependent PCV in a simultaneous adjustment of L1, L2 GPS and GLONASS signal within a few hours.

Two findings from the numerous calibrations already performed are the effect of dome construction on PCV and outliers in high quality geodetic antennas. The effect of domes may be small at the few millimeter level, but can also amount to PCV changes of 10 mm close to the zenith (~75 deg), or 12 mm at ~30 deg elevation for the ionospheric free linear combination L0. Within the "Dorne Margolin Type" choke ring antennas of two manufacturers outliers have been detected. Basically the offset was differing compared to a type mean, which transfers to 15 mm effects in L0 PCV.

Depending on the applications, PCV affects long term static GPS differently than real-time GPS. At the same time different antenna types are involved, which requires the knowledge of absolute PCV. The use of type means is appropriate for antennas not accesible, but uncertainties on the correctness remain. For precise applications an individual calibration is recommended. The PCV determination is also a first step to separate PCV and MP and to calibrate absolute station dependent carrier phase MP. Less investigations have been done on absolute PCV of rover antennas, which, however, becomes more important due to the mixed antenna situation in GPS reference networks and RTK networks.

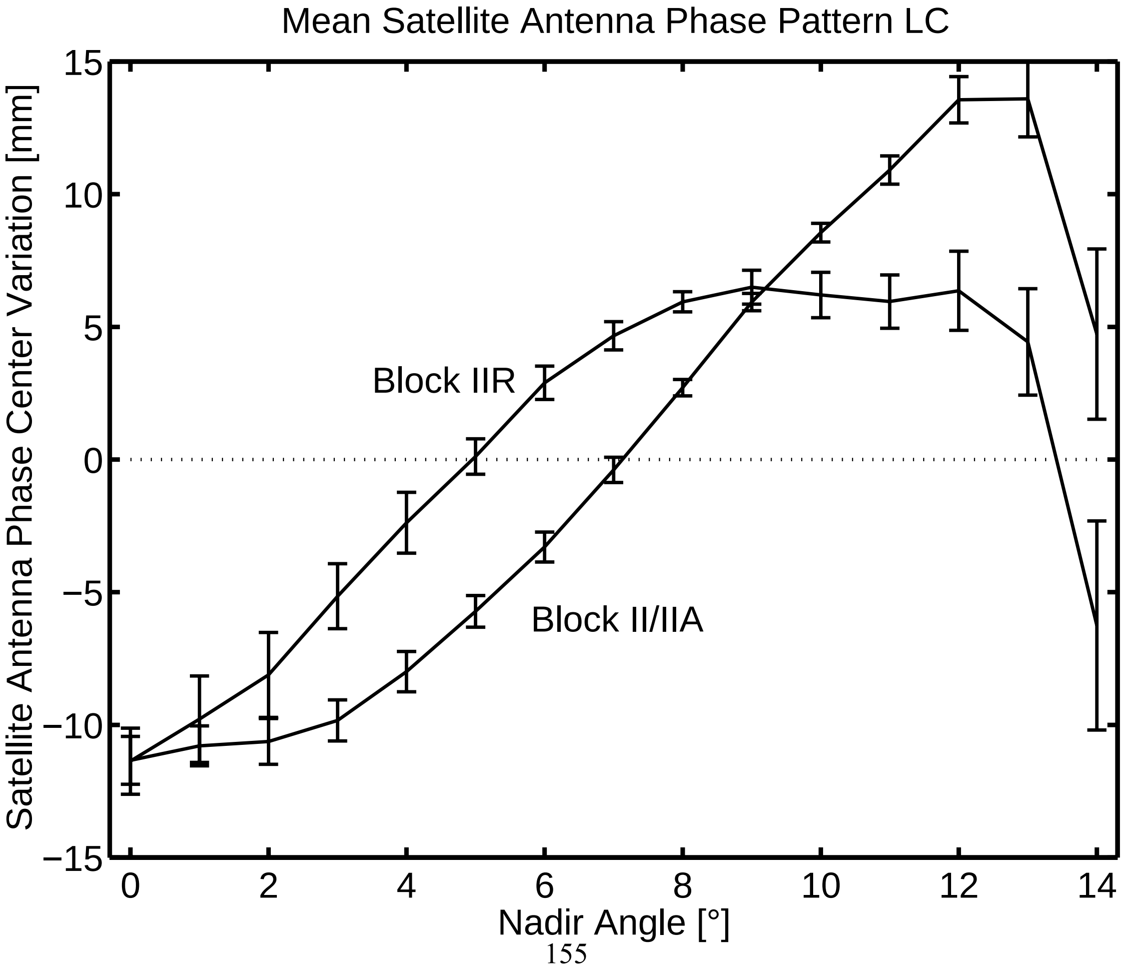
Estimation of Elevation-Dependent GPS Satellite Antenna Phase Center Variations

R. Schmid and M. Rothacher
Institut für Astronomische und Physikalische Geodäsie, TU München
schmid@bv.tum.de

At present absolute receiver antenna phase center patterns of reasonable quality are available (e.g. from robot measurements), but not in use, due to a large terrestrial scale of about 15 ppb that results in global GPS solutions. This effect is most probably caused by the GPS satellite antenna phase centers whose position varies with the emitting direction. Using relative receiver antenna phase center patterns these variations partially vanished in the past, because there is a one-to-one correspondence between receiver and satellite antenna patterns.

We implemented elevation- (resp. nadir-) dependent satellite antenna phase center variations into the Bernese GPS Software and estimated daily patterns for eight consecutive days with real GPS data from more than 100 permanent IGS stations. Thereby absolute receiver antenna pattern values from the group in Hannover (IfE/Geo++) were introduced and the global scale was fixed.

We could show that there are two different satellite antenna phase patterns, one for the Block II/IIA satellites and a different one for the Block IIR satellites (see fig.). The patterns could be estimated with a repeatability of 1-3 mm between different days and between individual satellites within one block. In several global parameters systematic effects showed up: e.g. the geocenter of the Block II/IIA orbits was shifted by about -2 cm in y-direction and the tropospheric delays increased by about 3 mm.



Multipath characteristics of GPS signals as determined from the Antenna and Multipath Calibration System (AMCS): Preliminary results

Park, Kwan-Dong, Pedro Elosegui, James Davis, James Normandeau
(Harvard-Smithsonian Center for Astrophysics)
Per Jarlemark (SP Swedish National Testing and Research Institute)
Brian Corey, Arthur Niell (MIT/Haystack Observatory)
Chuck Meertens, and Victoria Andreatta (UNAVCO/UCAR Facility)

ABSTRACT

Geophysical applications of the Global Positioning System (GPS) for studies such as global sea level change and glacial isostatic adjustment require very high accuracy (1 mm/year) determinations of site velocity, especially of its vertical component. Despite the many efforts devoted by investigators to the calibration of site-specific errors, signal scattering and multipath remain an unsolved problem. We have developed an Antenna and Multipath Calibration System (AMCS) for characterizing site-specific GPS phase measurement errors. The system consists of a high-gain, multipath-free, 3-m diameter parabolic antenna, two test antennas, and two Trimble GPS receivers. The parabolic antenna can track GPS satellites in the azimuth angle range of 7-357 degrees and the elevation angle range of 5-87 degrees with pointing precision of better than 0.5 degree.

There are two modes of operating the AMCS: Zero-baseline (ZBL) and AMCS modes. In ZBL-mode, the two receivers simultaneously record the signal from the test GPS antenna. In this operating mode, one can determine the receiver clock offsets and the phase biases for each satellite. Typical RMS accuracies of ZBL-mode phase residuals are sub-millimeter level, ranging from 0.4 to 0.7 millimeter. In the AMCS-mode, one GPS receiver records the signal received at the test antenna, and the other records the signal from the parabola. Thus, one can compare the phases from the two receivers, and determine the antenna and multipath calibration errors of the test antenna.

To assess the antenna and multipath calibration errors in AMCS-mode we have tested several experimental configurations. For example, we can park the parabolic antenna pointing towards a fixed sky position (static-parabola), and let a satellite drift in and out of the antenna beam. The resulting RMS of the phase differences (or residuals) from these tests is usually two or three times larger than the RMS of the ZBL-mode. However, we find that by modeling the azimuth and elevation angle dependence of the phase residuals the RMS reduces to 1.2 mm. We can also program the system so that the parabolic antenna tracks a GPS satellite. The phase residuals obtained by tracking the same satellite over several days shows large amplitude variations over small elevation angle ranges with highly repeatable patterns. Modeling and subtracting the

repeating patters from the phase residuals results in RMS of about 1.2 mm.

We have recently installed a second GPS antenna at a nearby location where the multipath effects are presumably less significant than at the location of the first GPS antenna. The second antenna is equipped with all-weather microwave absorber to further reduce multipath effects. The amplitude of the phase residuals obtained for the second antenna location are significantly smaller than for the first antenna, implying that the second antenna is less affected by multipath. These independent results also served to confirm that the origin of the phase patterns measured is multipath.