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Accurate GPS orientation of a long baseline for neutrino oscillation experiments at Fermilab

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Abstract. Recent research in elementary particle physics is concentrating a great amount of effort on neutrino oscillation experiments. These studies require the accurate pointing of neutrino beams between two distant points. The Fermi National Accelerator Laboratory (Fermilab) intends to build a new particle beamline to direct a beam of muon neutrinos from its Main Injector toward a far-off (735 km away) underground detector capable of searching for non-zero neutrino mass by looking for neutrino oscillations. This paper describes the GPS work carried out to accurately position the reference ground marks at the two sites from which the spatial orientation of the baseline can be accurately determined. The effect of plate rotations on the absolute orientation of the baseline was also investigated.

Introduction

Under a project named Neutrinos at the Main Injector (NuMI), the Fermi National Accelerator Laboratory (Fermilab), Batavia, Illinois, required the accurate three-dimensional positioning of two points defining the ends of a spatial baseline. These points are separated by about 735 km, one located on the Fermilab grounds and the other at Soudan, Minnesota. The main scientific purpose of the project is to send a high-intensity beam of muon neutrinos produced by the collision products of a 120-GeV proton beam from the underground Main Injector at Fermilab towards a remote, abandoned iron mine in northern Minnesota where, 713 m below surface, a massive 5.4-kiloton detector will be built (for background information see *Schwarzschild*, [1996]). The neutrino beam will travel beneath the earth crust reaching the depth of the mine shaft where, for the neutrino energy spectrum physics test to work properly, the primary proton beam must be within ±12 m from its ideal position at the far detector. A maximum transversal error of 12 m at a distance of 735 km is equivalent to a beam direction error of 3.36 arc sec (i.e., 3".36). Thus, it is imperative to obtain the correct spatial orientation of the baseline defined by its two end ground marks in order to assure the accurate pointing of the neutrino beam between the two distant laboratory targets. This task would have been extremely difficult without the development of new Global Positioning System (GPS) technology, the high accuracy of current three-dimensional geocentric terrestrial reference frames, and the recent establishment by the National Geodetic Survey (NGS), NOS, NOAA, of the Continuously Operating Reference Stations (CORS) network [*Snay and Weston*, 1999]. The National CORS network is becoming not only the logical tool for accurate 3D geodetic positioning in the United States but its GPS data holdings are used by a plethora of investigators interested in ionospheric research, crustal motions, water vapor studies, etc.

Physicists expect that future neutrino oscillation experiments may help to discern fundamental questions in the field of particle physics and that new findings could also be extrapolated to other scientific disciplines such as astrophysics and cosmology. Consequently, GPS surveys designed to accurately determine the orientation of long baselines committed to neutrino experiments have been carried out by other international high-energy research organizations. Previous surveys at the Super-Kamiokande lab in Japan [*Noumi et al.*, 1997] and the Gran Sasso laboratory in Europe

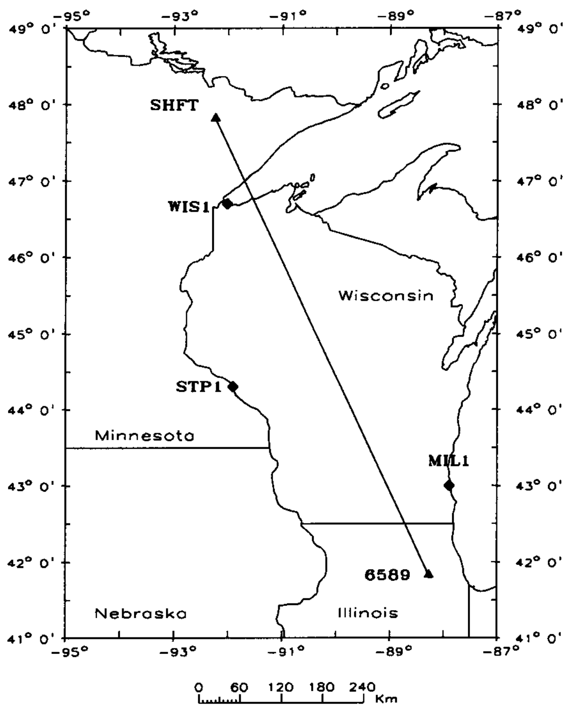

Figure 1. Fermilab's NuMi project GPS long baseline

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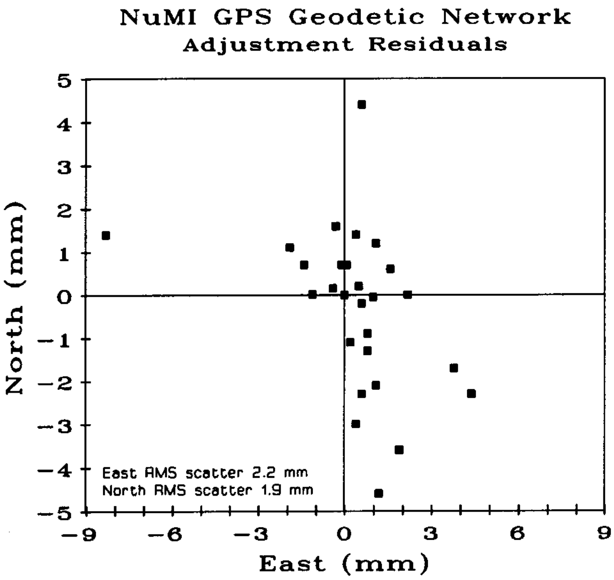

Figure 2. Adjustment residuals plotted on the geodetic horizon plane

[*Crespi et al.*, 1999] have referred their positioning results to the WGS84 coordinate frame. In contrast, this investigation is exclusively based on the International Terrestrial Reference Frame of year 1996.0 (ITRF96) [*Sillard et al.*, 1998], which in North America is rigorously defined through the coordinates of the National CORS network, the fundamental framework defining the National Spatial Reference System (NSRS). There are other notable differences (e.g., antenna phase pattern corrections and plate motion updating considerations) between the GPS reduction methodology advocated here and earlier work.

Data Collection and Processing

The NuMi GPS survey comprised a total of 3 days of observations collected using six Trimble 4000SSE geodetic receivers during April 18-20, 1999 (day-of-year: 108, 109, 110). Co-participants on this survey were Fermilab's Survey, Alignment, and Geodesy Group and the Minnesota Department of Transportation (MnDot). Fig. 1 depicts the geographical location of the long baseline measured with GPS for the NuMI project. The two ground marks at the ends of the baseline are named 6589 (at Fermilab) and SHFT (at the mine in Soudan). In addition to these two primary points, four more points near Soudan were surveyed; two of them (JERRY and MYER) form part of Minnesota's High Accuracy Reference Network (HARN). Similarly, at Fermilab, two additional pre-existing monumented points (6563 and 6591) that are part of the Fermilab local geodetic control network were positioned by GPS in order to tie them to the more accurate ITRF96 reference frame. GPS data were collected for a minimum of an 8^h observation window each day, staggering the starting times in order to observe the complete satellite orbital period of 12 hours. Although raw data were collected at 15-second intervals, the selected sampling rate to process the observations of this project was set at 30 seconds, a restriction imposed by the data collection interval at the CORS stations. A minimum elevation angle of 15° was chosen as the cut-off angle for all carrier-phase observables used during the processing stage.

GPS observations were reduced following a two-step process. First, three CORS stations (WIS1, MIL1, and STP1) were selected as fiducial stations to compute the coordinates of the two baseline end-points. The term "fiducial station" is loosely applied to describe continuously operating GPS sites whose data are electronically made available to the geodetic/geophysical community. Single vectors were determined from the two closest CORS stations: WIS1 (Wisconsin Point, WI) to SHFT; and MIL1 (Milwaukee, WI) to 6589. In addition, two longer vectors radiating from STP1 (St. Paul, WI), which is located about midway between SHFT and 6589 were computed. To complete the GPS survey, once the coordinates of the two primary stations defining the baseline were known, they were fixed as references to process the short vectors to the other points at each local area.

The GPS data were processed at NGS headquarters in Silver Spring, MD, using NGS software PAGES adapted for Windows NT. PAGES applies solid Earth tides according to IERS conventions [*McCarthy*, 1996] and antenna/elevation-dependant phase corrections, which is a must when an observing session involves stations that have different antenna types. There were a total of three distinct type of antennas used in this project, two Trimble antennas (part numbers 22020-00 and 14532-00) and three Ashtech antennas (all part number 700829.A1) permanently deployed at the CORS sites. Their required antenna parameters were determined using standard NGS calibration procedures [*Mader*, 1999].

At the time the GPS observations were collected, the International GPS Service (IGS) precise ephemerides [*Kouba et al.*, 1998] were expressed in the ITRF96. The adopted coordinates for the CORS stations used in the reductions described herein are also referred to the same coordinate frame. However, because observations were taken during April 1999, before processing the carrier-phase observables, program PAGES applies the ITRF velocity field to update the

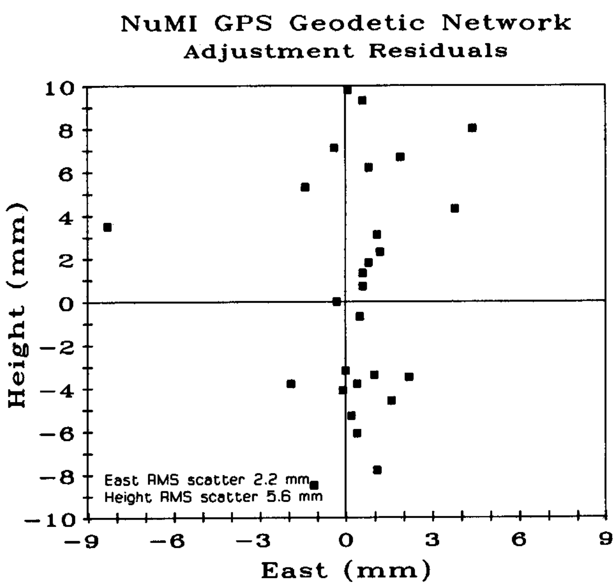

Figure 3. Adjustment residuals plotted on the prime vertical plane

Table 1. Cartesian and curvilinear coordinates of the NuMI project long baseline end-points

Cartesian (ITRF96, epoch 1999.2968)	Curvilinear (GRS80)
Point 6589 (Fermilab, Batavia, Illinois)	
x = 143932.515 ± 0.002 m;	λ = 88° 16' 01".48198W (± 1.4 mm)
y = - 4757405.360 ± 0.003 m;	φ = 41° 49' 56".59464N (± 1.2 mm)
z = 4231881.398 ± 0.004 m;	h = 196.262 m (± 5.1 mm)
Point SHFT (Mine Shaft, Soudan, Minnesota)	
x = - 167841.470 ± 0.001 m;	λ = 92° 14' 30".28538W (± 1.5 mm)
y = - 4287595.689 ± 0.002 m;	φ = 47° 49' 11".82975N (± 2.5 mm)
z = 4703794.871 ± 0.006 m;	h = 455.245 m (± 5.7 mm)

coordinates of the CORS stations (available at epoch 1997.0) to the average epoch of each individual observing session. As a result of this precaution, the components of all determined vectors are, in a sense, "instantaneous" and refer to the ITRF96 (the ephemeris frame) and a variable epoch which is determined by the time at which the observations were actually taken (e.g., April 19, 1999, 13:24 UTC = 1999.2980). The proper identification of the ITRF frame and its appended epoch tag become crucial in case the processed vectors are used in future scientific applications.

Only static, multi-station, relative GPS procedures between selected "base" and "remote" stations were implemented. Final solutions were determined using double-difference carrier-phase measurements, and the ionosphere-free linear combination of the L1 and L2 frequencies [*Leick* 1995, p. 306]. Single L1 frequency reductions were used when the length of the vectors was shorter than 2 km. A zenith tropospheric scale factor was estimated for every 3 hours. Ambiguity biases were fixed whenever possible.

Results and Discussion

Following NGS standard procedures, a GPS session file was created for each observing day in the NuMI project. This file contains all linearly independent vector components of each session referred to a topocentric frame parallel to ITRF96 located at the origin of the vectors. The selected session epoch is the average of the total observation span. General matrix equations to rigorously transform vector components and their covariances at different epochs are given in *Soler* [2000].

A minimally constrained three-dimensional least-squares network adjustment using NGS program ADJUST with station STP1 held fixed to the ITRF96, epoch 1999.2968, was performed.

Figures 2 and 3 depict all adjustment residuals projected on the planes of the geodetic horizon (east versus north) and prime vertical (east versus ellipsoid height ≡ up). The GRS80 ellipsoid was used for these calculations. The plots in the figures present each observation residual obtained from the least-squares NuMI network adjustment. Notice, for example, that the horizontal displacement does not exceed ±9 mm and ±5 mm in longitude and latitude, respectively. However, the RMS of the scatter is only 2.2 mm in longitude and 1.9 mm in latitude. Higher vertical uncertainties (RMS of scatter = 5.6 mm) are consistent with the difficulty in modeling the atmospheric refraction (ionosphere and troposphere).

The final coordinates of the two primary stations defining the NuMI baseline are given in Table 1. Formal errors of geodetic (curvilinear) coordinates were transformed to linear units referred to a local geodetic coordinate frame which are more intuitive and easier to visualize. However, small undetected systematic biases may still be present in the reductions and the values of the formal errors should not be taken in an absolute sense. These plots primarily show that the internal consistency of the network, that is, the precision of the measurements, is excellent. To measure external consistency –accuracy– we need to compare the results to known absolute standards. In this particular case the only available external information was the coordinates of the CORS stations which were assumed errorless and fixed when the GPS data was processed. However, the computed coordinates of the two CORS stations (MIL1 and WIS1) resulting from the least-squares adjustment fixing STP1 could be compared to their official published values once the effect of plate rotation is taken into consideration. The differences encountered given in the sense "published" minus adjusted were: MIL1 (Δe = 0.1 mm; Δn = -0.1 mm; Δh = 8 mm) and WIS1 (Δe = 0.3 mm; Δn = 6 mm; Δh = 16 mm). These results clearly

Table 2. NuMI baseline orientation components

Distance: d = 735,273.058 m (± 0.3 mm)

Geodetic Azimuth (positive clockwise from north):

6589 to SHFT: α_1 = 336° 05' 52".36530 (± 0".00004)
SHFT to 6589: α_2 = 153° 17' 29".42787 (± 0".00003)

Geodetic Altitude (positive above geodetic horizon)

6589 to SHFT: υ_1 = - 3° 17' 17".82068 (± 0".00031)
SHFT to 6589: υ_2 = - 3° 19' 38".70671 (± 0".00030)

show that the processed GPS vectors fit well the absolute reference frame defined by the CORS stations, essentially, the ITRF96 frame. A larger than expected difference in the vertical component of WIS1, although not critical, may indicate a weakness in the published height of the station. The orientation of the baseline, the main objective of this investigation, can be readily computed from the values given in Table 1. Pertinent parameters are presented in Table 2.

As a corroboratory check, an independent direct determination of the baseline orientation was computed. The coordinates of 6589 at Fermilab given in Table 1 were fixed and the three days of GPS data were re-processed using the single baseline technique to determine the coordinates of SHFT. Notice that in this simplified reduction scheme, which requires good knowledge of the absolute position of the base station, no data from the fiducial CORS sites are included. The differences from the results tabulated in Table 1 were only 1 mm, 4 mm, and 3 mm, respectively in longitude, latitude, and ellipsoid height. These differences are insignificant and will not change the orientation parameters given in Table 2. This remarkable agreement shows, as expected, that the two approaches (network versus single baseline) are equivalent once accurate coordinates of the fixed station are known a priori. Unfortunately, this is not the typical situation, thus, for rigorous geodetic or geophysical investigations, use of GPS data from the known CORS network becomes imperative.

Finally, assuming that the present orientation of the baseline was accurately determined, the possible effects of plate tectonics on the calculated orientation was investigated. Recall that although both points are on the North American plate, their velocities are not exactly the same. Moreover, because both points are moving in space, it is important to know if the future absolute orientation of the baseline may significantly change from the GPS results determined in 1999. Positional changes at the two main stations during a 100-year span were computed using the interactive program HTDP (Horizontal Time-Dependent Position). This software is freely available from NGS web site under the hypertext «Geodetic Tool Kit». Only changes of 0".11 in geodetic azimuth and 0".01 in geodetic altitude were detected in the orientation of the baseline after assuming 100 years of plate rotations. These changes in azimuth with respect to an assumed fixed North Pole are negligible and validate that the orientation of the baseline should be stable, consequently, the determined neutrino beam direction should not change for many years to come.

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