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Precision Positioning of SuperKamiokande with GPS for a Long-Baseline Neutrino Oscillation Experiment

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Abstract

A positioning of the neutrino detector SuperKamiokande (SK) was made for a long-baseline neutrino oscillation experiment planned at KEK. For positioning, Global Positioning System (GPS) was employed. It has been demonstrated that GPS is of practical use for measuring the positions of SK and KEK, being 250 km distance from each other, to a better resolution. The geodetic coordinates at the SK center were obtained to be Lat. $36^{\circ}25'32.5862''$ N., Long. $137^{\circ}18'37.1241''$ E., H. 371.839 m in the global ellipsoidal coordinate system, WGS-84. The obtained coordinates are based on the coordinates given at a triangulation point at the KEK site. The present work will be fed back for constructing the neutrino beam line.

Figure 1: Illustration of GPS positioning at Kamioka (SK) and Tsukuba (KEK-PS), which are 250 km from each other.

1 Introduction

Exploring neutrino oscillations is one of the most important subjects in particle physics, since it is a new physics phenomenon beyond the standard model. The existence of neutrino oscillations, if proved, directly indicates finite neutrino masses and flavor mixing in the lepton sector, which would have great impacts not only on particle physics, but also on astrophysics and cosmology. So far, a few indications of possible neutrino oscillations have been reported. Of those, an anomalous behavior of atmospheric ν_μ/ν_e found by the Kamiokande group and other underground experiments, if interpreted in terms of two-flavor $\nu_\mu \leftrightarrow \nu_e$ or $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, indicates $\Delta m^2 \sim 10^{-2} \text{ eV}^2$ and $\sin^2 2\theta \gtrsim 0.6$, where Δm^2 is the mass-squared difference and θ the mixing angle between two neutrino flavors. This region of Δm^2 can be explored in accelerator-based long-baseline neutrino oscillation experiments with a few GeV ν_μ beam and a baseline of several hundred kilometers.

Recently, a long-baseline neutrino oscillation experiment (KEK-PS E362) was proposed at the KEK 12-GeV Proton Synchrotron (KEK-PS) [2], and a facility for the experiment is under construction. In this experiment, muon neutrinos produced at KEK will be sent to SuperKamiokande (SK) located about 250 km west of KEK (Fig. 1). SK is a 50,000-ton water Cherenkov detector located 1,000 m underground in the Kamioka mine.

In constructing a neutrino beam line for this experiment, a hitherto unasked problem arises. Namely, a precise control of the neutrino beam direction better than 10^{-3} radian is required [2], though it is impossible to optically view SK. It would be impracticable to determine the beam center by scanning the neutrino beam direction to obtain the maximum of neutrino reaction

events at SK, since the event rate is too low to do so. A practical way to meet this requirement is to place a mark near to the KEK site on a line precisely from the neutrino production point to SK. Thus, a precision positioning of SK relative to KEK over 250 km must be made.

We recently carried out a series of surveys employing the Global Positioning System (GPS) [3] to measure the positions of SK and KEK. GPS (carrier phase differential GPS) is a kind of interferometry using artificial satellites revolving at a height of $\sim 20,000$ km around the earth. The nominal precision of GPS static positioning is $\sim 10^{-6}$. GPS is thus suitable for the precision positioning of SK and KEK, being 250 km distance from each other.

In the following we first introduce an outline of the beam line to be constructed for the neutrino experiment in section 2. We then report on details concerning surveys of SK and KEK in section 3. The precision of the measurements is discussed in section 4.

2 Layout of the Neutrino Beam Line

2.1 Primary Beam Line

The neutrino beam line will be extended from the existing primary beam line, EP1-A, in the North Counter-Experimental Hall of KEK-PS, as illustrated in Fig. 2. The EP1-A beam line has two target stations for secondary beam lines, K5 and K6, in cascade [4]. All of the beam-line elements of EP1-A are kept so that a fast-extracted beam (for neutrino) and a slow-extracted beam (for K5 and K6) can be used without any rearrangement. The neutrino beam line comprises three parts, (i) a straight section, (ii) an arc section, and (iii) an target station section.

The straight section is from the K6 target to the entrance of the arc section. A pair of symmetric quadrupole triplets are placed in the first 33 m subsection. The magnification of the beam is modified here so that the beam can pass through the straight section. After the first subsection, the beam line is bent down at a gradient of -5 m for 72 m. The beam image at the entrance of the slope is transferred at the exit by four pairs of quadrupole doublets with an optical transformation of $(-I)^2$, where $-I$ represents a transformation of point-to-point imaging with a magnification of minus unity (an inverse imaging) and of parallel-to-parallel imaging (infinite focal length), formed by two pairs of quadrupole doublets. Before the arc section, another pair of symmetric quadrupole triplets are placed. Here, the magnification of the beam is modified again so that the beam can pass through the arc section.

Since the EP1-A beam line is directed to the north, the extended line must bend almost 90 degrees to the west. The arc section is thus necessary. Eighteen bending magnets (pole length=5.86 m each) and eighteen quadrupoles (pole length=0.914 m each) are placed in the arc, where a unit-cell FODO comprising two quadrupoles (F and D) and two dipole magnets are arranged periodically. An achromatic transformation is realized by 8 cells, where a $-I$ transformation is formed by two cells.

The target station section is placed after the arc section. The proton beam is finally focused on the neutrino-production target. Before the final focus, the beam is focused once at the point

Figure 2: Plan view of the beam line for the long-baseline neutrino oscillation experiment. The neutrino beam line will be extended from the K6 target (K6 TGT) of the EP1-A beam line. See text for details.

Figure 3: Beam envelope calculated with TRANSPORT.

15 m upstream of the production target, so as to stabilize the beam profile and direction. Since the direction of SK is about 1 degree downward at the level of the production target, a steering magnet is placed just before the target.

2.2 Beam Transport

The beam envelope was calculated with the computer code TRANSPORT [5], as shown in Fig. 3. The total length of the neutrino beam line (from the extraction point of KEK-PS to the final focus point) is about 400 m. The beam profile at the final focus point was estimated with the computer code DECAY TURTLE [6]. Phase-space distributions of rays (position versus divergence) at the production target in the horizontal and vertical directions are shown in Fig. 4. The distribution calculation was based on the calculated beam profile [7] at the extraction point of KEK-PS, corresponding to twiss parameters of $(\alpha, \beta)=(0.772, 4.962)$ and $(-1.797, 17.212)$ in the horizontal and vertical directions, respectively. The horizontal and vertical emittances were assumed to be $13.0\pi\text{mm}\cdot\text{mrad}$ and $8.4\pi\text{mm}\cdot\text{mrad}$, respectively. A momentum spread of $\Delta p/p=\pm 0.3\%$ (full width) was taken into account.

2.3 Target Horn

After the production target, two magnetic horns [8, 9] are placed in tandem. The horns are focusing elements for secondary positive pions (and a small fraction of kaons), which decay in

Figure 4: Beam phase-space distributions at the production target in (a) the horizontal and (b) vertical directions calculated with DECAY TURTLE.

flight into a muon and a muon neutrino. The first horn has dimensions of 2.37 m in length and 0.70 m in diameter. The production target, 66 cm long and 2 cm diameter, is integrated into the first horn as a part of an internal conductor. The second horn has dimensions of 2.76 m in length and 1.65 m in diameter, located 8 m downstream of the first horn. Since the momentum distribution of the secondary pions and kaons is wide (from 0 upto ~ 10 GeV/c), the second horn is necessary to efficiently increase the neutrino flux at zero degree.

The horns are driven every 2.2 seconds with a 2 msec long 250 kA pulsed current (half a cycle of a sine wave) in coincidence with the fast-extracted beam (~ 1 μ s bunch width) to generate toroidal magnetic fields with respect to the beam axis. The field strength (B in Tesla) is a function of the radial distance (r in meter) from the beam axis, written as $B = 0.05/r$ at 250 kA. The horn system is expected to strengthen the neutrino flux at SK by about a factor of 14 [9].

2.4 Decay Section

The secondary pions and kaons are lead to a decay tunnel [10] where they decay into a muon and a muon neutrino. The decay tunnel is a tube of 200 m in total length. The entrance is located 20 m downstream from the production target point. The tube gradually widens; the first 10 m is a tube of 1.5 m in diameter, and the second 90 m and the last 100 m are tubes of 2 m and 3 m in diameter. The decay tunnel will be filled with He gas in order to reduce losses of pions and kaons due to interactions with gases as well as to keep the radiation level small in the surrounding soil. At the end of the tunnel, an iron dump is placed so as to absorb unwanted hadrons. Behind the dump, muon chambers [11] are installed to monitor the muon profile, which gives the neutrino profile.

In the present experiment, it is required that the production target, the magnetic horns, the decay tunnel, and SK be aligned with precision. In particular, misalignment of the horns would significantly affect the neutrino beam direction. The position and direction of the horns are adjustable. However, an adjustment must be kept small because the volume of the decay tunnel may not be so large as to allow a large correction of the direction. The direction of SK seen at the production target must be precisely marked on the muon chambers in order to adjust the neutrino-beam direction to SK.

3 Positioning of SK and KEK

It should be noted that GPS refers to the global ellipsoidal coordinate system, WGS-84 (see Appendix A). Strictly speaking, the geodetic coordinate system usually seen in Japan is not identical to the ellipsoidal coordinate system. For historical and practical reasons in technology of surveying, the usual geodetic coordinate system consists of two independent frames: one is latitude and longitude, and the other is altitude, where the altitude is given as a height above the mean sea level (or geoid). The geoid plane cannot be expressed in a simple analytic function; this fact makes analytic treatments of the measured coordinates complicated. The ellipsoidal coordinate system is more convenient for the present purpose, where the ellipsoidal height is introduced instead of altitude. Therefore, in principle, we express the geodetic coordinate in WGS-84 in the present article. A transformation between WGS-84 and the TOKYO Datum (the geodetic coordinate Japan standard) was made numerically using the computer code TKY2WGS [15] when necessary.

3.1 Survey at KEK

This subsection describes a survey made at KEK. Fig. 5 shows a map of the KEK site, where the locations of the measured points are indicated. Point “7” has geodetic coordinates in the 4th grade Japan standard given by the Geographical Survey Institute (GSI). Positioning of the relevant points was based on the coordinate at “7” in the present series of surveys. Point “T” corresponds to a point about 5 m above the position where the production target will be placed. The other points (“2”, “6”, “33”, and “IP”) are placed so as to be used for constructing the beam line. Actually, although marker “T” will be lost due to construction, it can be reconstructed from the other points, and the direction to SK can be determined.

The geodetic coordinates at “1”, “T”, and “7” in WGS-84 are listed in Table 1. See Appendix B for the other points.

3.2 Survey between KEK and Kamioka

We made a long-baseline GPS survey between KEK and Kamioka, since the purpose of the present survey is to determine the positions of SK and KEK (the production target) in the same coordinate system, as mentioned in section 1.

Figure 5: Map of the KEK site. The measured points are indicated by closed circles. A triangulation mark is placed at point “7”.

point	WGS-84
1	Lat. 36°09'12.2039" N.
	Long. 140°04'02.5892" E.
	H. 69.410 m
T	Lat. 36°09'14.9531" N.
	Long. 140°04'16.3303" E.
	H. 70.218 m
7	Lat. 36°08'38.1716" N.
	Long. 140°04'20.4853" E.
	H. 69.008 m

Table 1: Results of the GPS survey at the KEK site. The geodetic coordinates at point “7” are given in the 4th grade Japan standard by GSI. All of the coordinates are given in WGS-84.

session	KH(WGS-84/GPPS)		K0(WGS-84/GPPS)	
	Latitude Longitude Height	L RMS	Latitude Longitude Height	L RMS
LB-A	36°18'20.2656" N. 137°18'28.6846" E. 604.942 m	248640.352 m 0.035 m	36°18'22.6467" N. 137°18'22.9072" E. 605.296 m	248788.217 m 0.035 m
LB-B	36°18'20.2639" N. 137°18'28.6854" E. 605.125 m	248640.334 m 0.032 m	36°18'22.6451" N. 137°18'22.9062" E. 605.423 m	248788.244 m 0.029 m
A-B	0.0017" -0.0008" -0.183 m	0.018 m	0.0016" 0.0010" -0.127 m	-0.027 m

Table 2: Geodetic coordinates at the “KH” and “K0” at Kamioka obtained by the long-baseline GPS survey between KEK and Kamioka are listed for the two sessions in WGS-84. Data analyses were made with GPPS (CASE 1). Here, L and RMS represent respectively the length of the vector from point “1” to each point and its deviation determined in the data analysis.

Fig. 6 shows a map of the Kamioka area, where the positions of the GPS receivers are indicated. Points “KH” and “K0” are involved together with points “7” and “1” at the KEK site in the present long-baseline survey. Near to “KH”, a triangulation point (“Kokaya”) is placed, where the geodetic coordinates are given in the 4th grade Japan standard by GSI. The Kokaya triangulation point is located about 15 km south of SK, and is the nearest point from SK which we can easily reach. The “KH” point was used as a reference point when we carried out a GPS survey around SK. The survey around SK will be described in section 3.3. The Kokaya point is useful to check consistency of the positioning made by the present survey, as mentioned in section 3.2.3. Two sessions (LB-A and LB-B) were successively made in the present survey; it took 6 hours for each session.

3.2.1 Analysis with GPPS

Data analyses were made with the computer code GPPS [12] (CASE 1). GPPS is commercially available for public surveying. The obtained coordinates at “KH” and “K0” are listed for each session in Table 2. They were obtained by analyzing three points, “KH”, “K0”, and “1”, where the coordinates at “1” were determined from “7” prior to the long-baseline analysis. The lengths of the vectors from “1” to “KH” and “K0” were determined within a deviation of ~ 3 cm r.m.s. in the data analysis. The lengths of the vectors in session LB-A seem to be identical to those in session LB-B within the deviation. The discrepancies of the ellipsoidal heights obtained between the two sessions are ~ 18 cm and ~ 13 cm for “KH” and “K0”, respectively.

3.2.2 Analysis with GAMIT-GLOBK

GPS supports a precise ephemeris for additional precision analyses of long baselines, where the positioning resolution can be potentially improved by 2 orders of magnitude better than

Figure 6: Map of the Kamioka area. The measured points are indicated by the closed circles. The triangulation points at “Kokaya”, “Nishi-sho”, “Sekitori”, and “Tsubono” were referred in the GPS survey for a comparison.

Figure 7: Locations of the continuous GPS observation points employed in the analysis.

that typically obtained in public GPS surveying. We could apply the precision analysis to the present surveys in collaboration with GSI.

The computer codes GAMIT [13] and GLOBK [14] were employed for precision analyses of the long baselines and to adjust the geodetic coordinates, respectively (CASE 2). In this analysis, 6 points, “0042”, “0043”, “0046”, “0052”, “0058”, and “TSKB”, were newly involved in addition to points “1” and “KH”. These new points belong to the GPS Regional Array for Precise Surveying (GRAPES) equipped by GSI, and are continuously observing GPS. Fig. 7 shows the locations of the 6 points.

The geodetic coordinates of “KH” were obtained by a precision analysis, as listed in Table 3. The length of the vector from “1” to “KH” was determined within a deviation of ~ 3 mm r.m.s. The deviation obtained in the precision analysis is almost one order of magnitude better than that in the analysis with GPPS. The lengths of the vectors derived from sessions LB-A and LB-B are slightly different, However, the discrepancy is smaller than that obtained in the analysis with GPPS. Also, the discrepancies in the ellipsoidal heights obtained between the two sessions are considerably reduced.

3.2.3 Analysis of a local GPS survey

For a comparison, the geodetic coordinates at “KH” are derived from a different approach, which is based on a local GPS survey (CASE 3) referring to 3 triangulation points (“Nishi-sho”, “Sekitori”, and “Tsubono”) and a leveling from the Kokaya point. The referred triangulation points are located near to Kamioka town, as indicated in Fig. 6. All the points have the geodetic

KH(WGS-84/GAMIT-GLOBK)		
session	Latitude Longitude Height	L RMS
LB-A	36°18'20.2618" N. 137°18'28.6838" E. 604.911 m	248640.403 m 0.002 m
LB-B	36°18'20.2618" N. 137°18'28.6842" E. 604.936m	248640.395 m 0.003 m
A-B	0.0000" -0.0003" -0.025 m	0.008 m

Table 3: Geodetic coordinates at point “KH” obtained by precision analyses with GAMIT and GLOBK are listed in WGS-84 (CASE 2). Here, L and RMS represent respectively the length of the vector from point “1” to “KH” and its deviation determined in the data analysis.

KH(TOKYO Datum)	KH(WGS-84)
Latitude Longitude Altitude	Latitude Longitude Height
36°18'09.0798" N. 137°18'39.5430" E. 564.145 m	36°18'20.2596" N. 137°18'28.6719" E. 604.023m

Table 4: Geodetic coordinates at “KH” obtained from the local GPS survey (CASE 3). The results are given in TOKYO Datum and WGS-84. The transformation of coordinates was made with the computer code TKY2WGS.

coordinates in the 4th grade Japan standard (TOKYO Datum) given by GSI. In this survey, the altitude at “KH” was determined by leveling from the Kokaya point. The latitude and longitude at “KH” were determined by the local GPS survey. This operation was necessary in order that a vertical line difference of WGS-84 from the TOKYO Datum would not affect the estimation of the altitude at “KH”. The results are listed in both the TOKYO Datum and WGS-84 in Table 4. The transformation of WGS-84 to the TOKYO Datum was made using the computer code TKY2WGS. TKY2WGS corrects integrated errors due to a distortion in the geodetic network of the TOKYO Datum, different definition of the height, and different reference ellipsoid [16].

3.2.4 Comparison of the results

The geodetic coordinates at “KH” derived from three different approaches are summarized in Table 5. The results of session LB-A in CASE 1 and 2 are listed here. One can see that the geodetic coordinates in CASE 1 and 2 show similar values. The difference between CASE 1 and 2 is of less significance, since it is almost the same as the difference at point “1”. (See Tables 7 and 9 in Appendix B.) This does not imply that the precision of the analysis with GPPS is

	KH(WGS-84)		
approach	Latitude Longitude Height	$\Delta(x-2)$	$\Delta(x-3)$
CASE 1 (GPPS)	36°18'20.2656" N. 137°18'28.6846" E. 604.942 m	0.0038" 0.0008" 0.031 m	0.0060" 0.0127" 0.919 m
CASE 2 (GAMIT-GLOBK)	36°18'20.2618" N. 137°18'28.6838" E. 604.911 m		0.0022" 0.0119" 0.888 m
CASE 3 (Local)	36°18'20.2596" N. 137°18'28.6719" E. 604.023 m		

Table 5: Geodetic coordinates at the point “KH” derived from the three different approaches are listed. Those in CASE 1 and 2 were obtained in analyses with GPPS and GAMIT-GLOBK, respectively. Those in CASE 3 were obtained by a local GPS survey and leveling. All of the coordinates are given in WGS-84. Here, $\Delta(x-2)$ and $\Delta(x-3)$ represent the discrepancies of the geodetic coordinates in CASE x ($x=1,2$) from those in CASE 2 and 3, respectively.

almost the same as that with GAMIT-GLOBK, because the systematic error on the surveying could not be estimated from only the present surveys. Surveys between “1” and “KH” must be made many times to estimate the systematic error. The discrepancies of the latitude and longitude in CASE 1 or 2 from those in CASE 3 are consistent within the expected positioning resolution of the order of 1 ppm. The discrepancies in the height between CASE 3 and the others seem to be slightly larger than expected. However, considering the precision provided by TKY2WGS, it is not clear if the discrepancies are significant or not.

3.3 Survey at Kamioka

Since SK is located in a tunnel of the Kamioka mine, a positioning of SK cannot be made directly with GPS. SK is located about 3 km south-east of the Mozumi entrance, and about 2 km north of the Atotsu entrance. As reference points for a survey in the tunnel, two pairs of points (“M1”/“M2” and “AP”/“A2”) are placed at the Mozumi and Atotsu entrances of the Kamioka mine, respectively, as shown in Fig. 6. The geodetic coordinates of these points were measured by a GPS survey with points “KH”, “K0”, and “K1”. Then, in order to obtain the position of SK, a traverse surveying and a leveling were made from one pair of entrance points to the other and from an intermediate point (“M19” in Fig. 6) to SK.

The derived geodetic coordinates at “SK” are listed in Table 6, which are based on the coordinates at “KH” given in 3 cases. Here, “SK” stands for the center of the SK water tank. The center was taken at the point 21.5 m below the center of the tank ceiling, since the ceiling center could be positioned by the present survey. Since traverse surveying is based on the azimuth from “M1” to “M2”, a tiny discrepancy of the coordinates at “M1” and “M2” was widened at “SK”. Thus, the discrepancies Δs in Table 6 are slightly different from those in

	SK(WGS-84)		
approach	Latitude Longitude Height	$\Delta(x-2)$	$\Delta(x-3)$
CASE 1 (GPPS)	36°25'32.5862" N. 137°18'37.1214" E. 371.839 m	0.0038" 0.0007" 0.032 m	0.0082" 0.0111" 0.919 m
CASE 2 (GAMIT-GLOBK)	36°25'32.5824" N. 137°18'37.1207" E. 371.807 m		0.0044" 0.0104" 0.887 m
CASE 3 (Local)	36°25'32.5780" N. 137°18'37.1103" E. 370.920 m		

Table 6: Geodetic coordinates at SK derived from the three different approaches. All of the coordinates are given in WGS-84. The quantities Δ s have the same meanings as those in Table 5.

Table 5.

4 Discussion

4.1 Precision of the positioning

It might be necessary to make surveys many times in order to confirm the uncertainty of the positioning. In the present surveys, however, the uncertainty must be estimated with the nominal precision of surveying.

As already described, we took 4 surveying steps to obtain the SK position: surveys (1) at the KEK site, (2) between KEK and Kamioka, (3) at Kamioka, and (4) at the Kamioka mine. All of the steps, except (4), were made with GPS. The precision in public GPS surveying can be expressed by the formula

$$\pm(a + b \times d). \quad (1)$$

The first term (a) represents the error coming mainly from the GPS receiver, itself; the second term stands for the precision proportional to the distance between the measured points. The constant a takes nominal values of ~ 5 mm and ~ 20 mm in the horizontal and vertical directions, respectively. The coefficient b is nominally $\sim 10^{-6}$. In the present case, the precision of the GPS surveys is dominated by the contribution from the second term, and is estimated to be about ± 0.3 m in both the horizontal and vertical directions.

For step (4), traverse surveying was employed. In traverse surveying, the error integrated over the measurement (offset) was corrected so as to reproduce the geodetic coordinates at “M1”, “M2” and “A2” given by the GPS surveying. The offset of the coordinate at intermediate point “M19” was corrected by assuming that it is proportional to the path length from “M1”. The correction at “SK” is expected to be almost the same, since the distance from “M19” to “SK” is only 0.1 km, which is negligibly small compared with the total path length of about 5.1

km. The offsets at “A2” were 1.5 m and 0.6 m in the horizontal and vertical directions, which correspond to precisions of 1/3,400 and 1/8,500, respectively. Thus, the corrections at “SK” in the horizontal and vertical directions were evaluated to be 0.9 m and 0.4 m, respectively, since the path length from “M1” to SK is 3.4 km.

The values given above should be taken as the precision of the surveying. In the worst case, the errors are integrated over all the steps. As a consequence, the uncertainty in the SK position could be ± 1.2 m and ± 0.7 m in the horizontal and vertical directions, respectively.

4.2 Feedback to the construction

It is found that the EP1-A beam line must turn $88^{\circ}44'25''$ to the left (west). The proton beam must be bent $1^{\circ}04'30''$ downward with respect to the horizontal plane, just before the production target.

The direction of SK is determined in the frame of WGS-84. In general, the vertical line in WGS-84 is not parallel to gravity. This is due to the inclination of the geoid plane with respect to the surface of the reference ellipsoid. Since the construction work will refer to the geoid plane, the vertical line difference needs to be taken into account when one wishes to align the decay tunnel to SK. According to a precise geoid model determined by GSI, the inclination in Tsukuba is almost $20''$ [17].

In principle, this inclination can be measured at the target point and the vertical line difference can be corrected in the construction work. In order to measure the inclination precisely, expert knowledge, technique, and instruments on the astronomical surveying are required, which are of no practical use. In recent years, GPS surveying and leveling have been employed for the inclination measurements. This method seems to be more practical and convenient. However, one must be very much careful concerning the precision of the instruments even if one expects a precision of a few seconds in inclination measurements. Also, the correction of the vertical line difference would be limited mainly by the precision of the instruments used in the construction work.

Fine tuning of the neutrino-beam direction will be made using a muon monitor. A mark will be placed on the muon monitor so as to sight the neutrino beam right at SK. The positions of the production target and mark must be occasionally calibrated with GPS after completing the construction work. Since the distance between the target and the mark is about 250 m, the mark position is expected to be aligned toward SK at best with an accuracy of about $\pm 4''$ and $\pm 17''$ in the horizontal and vertical directions, according to eq.(1).

5 Concluding Remarks

1. We carried out positioning of SK relative to KEK for the long-baseline neutrino oscillation experiment, KEK-PS E362. It has been demonstrated that GPS is of practical use to precisely measure the positions of SK and KEK, being 250 km distance from each other.

2. We obtained the position of the SK center as Lat. $36^{\circ}25'32.5862''$ N., Long. $137^{\circ}18'37.1214''$ E., H. 371.839 m in WGS-84. These coordinates were obtained based on the geodetic coordinates given at triangulation point “7” at the KEK site. We obtained geodetic coordinates with different analyses for a comparison. The derived coordinates are consistent with each other within the expected precision.
3. We estimated the uncertainty of the SK positioning with nominal precision of the surveying. At most, it could be ± 1.2 m and ± 0.7 m in the horizontal and vertical directions, respectively.
4. The mark will be placed at the muon monitor so as to sight the neutrino beam at SK. The mark position will occasionally be measured with GPS. It has been estimated that the mark position can be determined at best about $\pm 4''$ and $\pm 17''$ in the horizontal and vertical directions, respectively.

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Appendix

A. Brief Description of GPS

GPS is a kind of interferometry using artificial satellites, as mentioned in section 1. The orbits of these satellites are given in the global ellipsoidal coordinate system. See Fig. 8. In this system, the 3-dimensional coordinates (X, Y, Z) of a point are given by the latitude (ϕ), longitude (λ), and ellipsoidal height (H) as:

$$X = (N + H) \cos \phi \cos \lambda, \quad (2)$$

$$Y = (N + H) \cos \phi \sin \lambda, \quad (3)$$

$$Z = (N(1 - e^2) + H) \sin \phi. \quad (4)$$

Figure 8: Global ellipsoidal coordinate system.

Here, $N = a/\sqrt{1 - e^2 \sin^2 \phi}$ and $e^2 = f(2 - f)$ with a and f representing the equator radius and eccentricity of the ellipsoid, respectively. GPS refers to the global ellipsoidal coordinate system WGS-84 (World Geodetic System - 1984). WGS-84 takes $a=6378137.145$ m and $1/f=298.257223$ [18]. One measures path (phase) differences from satellites to a measured point receiving radio waves. In principle, one needs at least 3 satellites and a given position of a base point to determine a relative position of the measured point to the base point (base-line vector) in the given coordinate system. Practically, precision positioning, i.e., static positioning, involves at least 4 satellites to keep the resolution better.

B. Summary of the Geodetic Coordinates at Measured Points

The geodetic coordinates of relevant points obtained in the present surveys are summarized in Tables 7–10. The coordinates in the TOKYO Datum are listed together along with those in WGS-84. The transformation between the two system was made with TKY2WGS.

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point	WGS-84	TOKYO
1	Lat. 36°09'12.2039" N. Long. 140°04'02.5892" E. H. 69.410 m	Lat. 36°09'00.7224" N. Long. 140°04'14.3611" E. Alt. 29.463 m
2	Lat. 36°09'12.9247" N. Long. 140°04'14.6524" E. H. 70.070 m	Lat. 36°09'01.4430" N. Long. 140°04'26.4254" E. Alt. 30.130 m
33	Lat. 36°09'13.1319" N. Long. 140°04'17.7331" E. H. 70.143 m	Lat. 36°09'01.6502" N. Long. 140°04'29.5064" E. Alt. 30.204 m
6	Lat. 36°08'55.3797" N. Long. 140°04'16.4671" E. H. 70.029 m	Lat. 36°08'43.8959" N. Long. 140°04'28.2397" E. Alt. 30.129 m
IP	Lat. 36°09'14.4080" N. Long. 140°04'21.7560" E. H. 70.088 m	Lat. 36°09'02.9262" N. Long. 140°04'33.5296" E. Alt. 30.149 m
T	Lat. 36°09'14.9531" N. Long. 140°04'16.3303" E. H. 70.219 m	Lat. 36°09'03.4716" N. Long. 140°04'28.1035" E. Alt. 30.275 m
7	Lat. 36°08'38.1716" N. Long. 140°04'20.4853" E. H. 69.008 m	Lat. 36°08'26.6856" N. Long. 140°04'32.2576" E. Alt. 29.150 m

Table 7: Geodetic coordinates of the measured points at the KEK site. The coordinates at “7” are given in the TOKYO Datum.

point	CASE 1	
	WGS-84	TOKYO
KH	Lat. 36°18'20.2656" N. Long. 137°18'28.6846" E. H. 604.942 m	Lat. 36°18'09.0858" N. Long. 137°18'39.5557" E. Alt. 565.064 m
K0	Lat. 36°18'22.6468" N. Long. 137°18'22.9069" E. H. 605.256 m	Lat. 36°18'11.4674" N. Long. 137°18'33.7775" E. Alt. 565.382 m
K1	Lat. 36°19'42.6620" N. Long. 137°17'48.3953" E. H. 488.116 m	Lat. 36°19'31.4934" N. Long. 137°17'59.2632" E. Alt. 448.282 m
AP	Lat. 36°24'30.5977" N. Long. 137°18'26.9275" E. H. 381.632 m	Lat. 36°24'19.4644" N. Long. 137°18'37.8018" E. Alt. 341.842 m
A2	Lat. 36°24'31.1429" N. Long. 137°18'29.8710" E. H. 384.087 m	Lat. 36°24'20.0096" N. Long. 137°18'40.7456" E. Alt. 344.295 m
M1	Lat. 36°26'19.6398" N. Long. 137°16'42.8778" E. H. 380.312 m	Lat. 36°26'08.5219" N. Long. 137°16'53.7418" E. Alt. 340.656 m
M2	Lat. 36°26'18.8928" N. Long. 137°16'42.0306" E. H. 380.428 m	Lat. 36°26'07.7748" N. Long. 137°16'52.8945" E. Alt. 340.772 m
SK	Lat. 36°25'32.5862" N. Long. 137°18'37.1214" E. H. 371.839 m	Lat. 36°25'21.4605" N. Long. 137°18'47.9976" E. Alt. 332.071 m

Table 8: Geodetic coordinates of the measured points at Kamioka. These are based on the coordinates at “KH” derived from the analysis with GPPS (CASE 1).

point	CASE 2	
	WGS-84	TOKYO
1	Lat. 36°09'12.2008" N. Long. 140°04'02.5902" E. H. 69.360 m	Lat. 36°09'00.7193" N. Long. 140°04'14.3621" E. Alt. 29.413 m
KH	Lat. 36°18'20.2618" N. Long. 137°18'28.6838" E. H. 604.911 m	Lat. 36°18'09.0820" N. Long. 137°18'39.5549" E. Alt. 565.033 m
K0	Lat. 36°18'22.6430" N. Long. 137°18'22.9061" E. H. 605.225 m	Lat. 36°18'11.4636" N. Long. 137°18'33.7767" E. Alt. 565.351 m
K1	Lat. 36°19'42.6582" N. Long. 137°17'48.3945" E. H. 488.085 m	Lat. 36°19'31.4896" N. Long. 137°17'59.2624" E. Alt. 448.251 m
AP	Lat. 36°24'30.5939" N. Long. 137°18'26.9267" E. H. 381.601 m	Lat. 36°24'19.4606" N. Long. 137°18'37.8010" E. Alt. 341.810 m
A2	Lat. 36°24'31.1391" N. Long. 137°18'29.8702" E. H. 384.056 m	Lat. 36°24'20.0058" N. Long. 137°18'40.7448" E. Alt. 344.263 m
M1	Lat. 36°26'19.6360" N. Long. 137°16'42.8770" E. H. 380.280 m	Lat. 36°26'08.5181" N. Long. 137°16'53.7410" E. Alt. 340.624
M2	Lat. 36°26'18.8890" N. Long. 137°16'42.0298" E. H. 380.397 m	Lat. 36°26'07.7710" N. Long. 137°16'52.8937" E. Alt. 340.741 m
SK	Lat. 36°25'32.5824" N. Long. 137°18'37.1207" E. H. 371.806 m	Lat. 36°25'21.4566" N. Long. 137°18'47.9968" E. Alt. 332.039 m

Table 9: Geodetic coordinates of the measured points at Kamioka. These are based on the coordinates at “KH” derived from the analysis with GAMIT-GLOBK (CASE 2). The geodetic coordinates at “1” obtained in the analysis with GAMIT-GLOBK are listed here.

point	CASE 3	
	WGS-84	TOKYO
KH	Lat. 36°18'20.2596" N. Long. 137°18'28.6719" E. H. 604.023 m	Lat. 36°18'09.0789" N. Long. 137°18'39.5430" E. Alt. 564.145 m
K0	Lat. 36°18'22.6408" N. Long. 137°18'22.8942" E. H. 604.337 m	Lat. 36°18'11.4614" N. Long. 137°18'33.7648" E. Alt. 564.463 m
K1	Lat. 36°19'42.6560" N. Long. 137°17'48.3825" E. H. 487.198 m	Lat. 36°19'31.4874" N. Long. 137°17'59.2504" E. Alt. 447.363 m
AP	Lat. 36°24'30.5917" N. Long. 137°18'26.9147" E. H. 380.713 m	Lat. 36°24'19.4584" N. Long. 137°18'37.7980" E. Alt. 340.922 m
A2	Lat. 36°24'31.1370" N. Long. 137°18'29.8583" E. H. 383.168 m	Lat. 36°24'20.0037" N. Long. 137°18'40.7329" E. Alt. 343.375 m
M1	Lat. 36°26'19.6338" N. Long. 137°16'42.8651" E. H. 380.393 m	Lat. 36°26'08.5195" N. Long. 137°16'53.7291" E. Alt. 339.737 m
M2	Lat. 36°26'18.8869" N. Long. 137°16'42.0179" E. H. 380.428 m	Lat. 36°26'07.7689" N. Long. 137°16'52.8818" E. Alt. 339.853 m
SK	Lat. 36°25'32.5780" N. Long. 137°18'37.1103" E. H. 370.920 m	Lat. 36°25'21.4522" N. Long. 137°18'47.9865" E. Alt. 331.152 m

Table 10: Geodetic coordinates of the measured points at Kamioka. These are based on the coordinates at "KH" derived from the analysis of the local GPS in the Kamioka area (CASE 3).