Determination of True North for the Sudbury Neutrino Observatory Detector

Version 1

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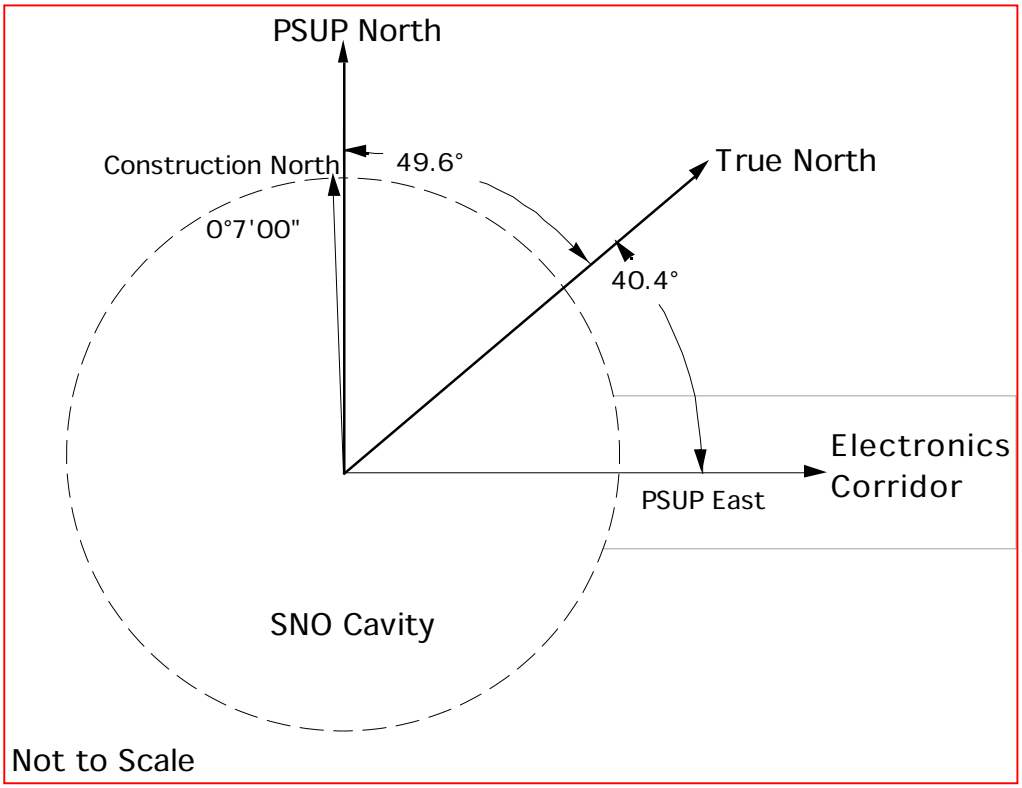
STR-2000-xxxx

6/20/00

Abstract: Using a commercial gyrocompass the orientation of the SNO detector with respect to True North was determined. A correction of 2.49 ± 0.22 ± 0.47 degrees with respect to the PSUP Construction North and INCO/Monenco survey data was determined. The implementation of the PSUP orientation in SNOMAN was confirmed. True North is determined to lie 49.58 degrees east of PSUP Construction North (and 40.42 North of the electronics corridor).



Introduction

The orientation of the SNO detector is a critical parameter to interpret the solar neutrino elastic scattering signal and other astrophysical signals. A rough estimate of the precision of this parameter is obtained from the size of the PMT/reflector combination used in SNO. The opening face of the reflector is 280mm and the distance from the front face of the reflector is approximately 840cm so the angular acceptance of a PMT across the full detector is ~ 0.46°.[1]. Studies of the angular response of the SNO detector similarly support that a determination of the PSUP orientation to approximately 1° should be adequate for essentially all of SNO's solar neutrino studies.

Previous attempts to determine the PMT Support Structure (PSUP) orientation and the orientation of the PSUP and PMT coordinates in SNOMAN are based on cavity deck and PSUP survey work performed during the PSUP installation and are linked to a True North survey through the INCO mining coordinate system and mine survey data [2]. The translation of the surface coordinate system into the SNO cavity relied on multiple surveys, benchmark placement, and traditional survey techniques. The opportunity for errors being generated in this process with a cumulated magnitude large enough to compromise the specification listed above as well as a desire to independently confirm the PSUP orientation led us to perform a survey of the PSUP and separately determine the orientation of the PSUP and the PMT coordinates.

The determination of True North (TN) in the SNO cavity can be adequately obtained with the use of a gyrocompass. These instruments are commonly used as navigational aids and there are suppliers of these units worldwide. These compasses utilize the measurement of the spin-spin interaction between the gyroscope and the Earth's rotation to determine the orientation of the gyroscope axis with respect to the Earth's rotation axis (TN). With the 0.5° specification in mind we selected a vendor, RentMAR, in Annapolis, Maryland to rent a gyrocompass SCAN2000 manufactured by Scan-steering Denmark. The unit was small and portable enough to permit its operation on the deck and to survey a significant number of PSUP support points with relative ease. The unit operates with 110VAC (or 24VDC) and requires input for only the latitude and speed of the unit during operation to return the heading of the compass head. Both digital and visual headings are obtained from the unit. We manufactured a mounting plate to ease in the handing of the unit and in obtaining better placement of the compass head during the survey.

The technical data on this unit are summarized below[3]:

Quantity	Unit specification	Application to SNO
Time of Settling	<45 minutes	o.k.
Tracking speed	>200°/sec	N/A
Accuracy at tracking speed of 6°/second	0.1°	N/A
Settle Point (SP) Error	±0.35°	±0.35°
Repeatability of SP Error	±0.25°	±0.25°
Heading error in straight and uniform sailing	0.25°	0.25°
Error due to Rapid Change of speed of 20 Knots	±0.6°	N/A
Error due to rapid change at 180°	0.6°	N/A
Maximum operation speed	90 Knots	Estimated <2 Knots
Maximum roll angle	45°	N/A
Maximum pitch angle	45°	N/A
Operational Latitude (south or north)	0 to 75°	46°28'30"N 81°12'04"W
GPS input for auto latitude and speed	NMEA 0183 RS232/422	N/A
System Outputs	NMEA 0183 RS 422(232) 24Vdc Step (6 steps/degree)	N/A
Error of heading data transmission the repeaters does not exceed	0.1° NMEA output 0.2° (STEP output)	0.1°
Power input	24VDC	Provided by converter
Power Consumption	<50W (start up) <30W (ready)	<50W (start up) <30W (ready)
Operating Temperature	-10 to 55°C	~20°C
Relative Humidity	Up to 98% at +40°C	~46%
Base Vibration Frequency with Acceleration up to 10 m/s^2	5-80 Hz	N/A
Horizontal Acceleration at Vessel Swinging	Up to 1 m/s^2	Up to 1 m/s^2
Weight Main unit Weight Electronic unit Weight Control unit	10 Kg 12 Kg 4.5 Kg	10 Kg 12 Kg 4.5 Kg

Table 1. Gyrocompass Technical Data

Operation of the Gyrocompass and PSUP Survey Procedures and Measurements

To determine the orientation of the PSUP with the cavity flooded and sealed, the only accessible reference point are the cable terminations for the PSUP suspension. The ends of the PSUP suspension cables penetrate the cavity deck and protrude above the top of the spherical bearing on the deck by ~28 cm. Removing the PSUP dust covers exposes the upper cable ends. These cable ends were swaged onto the PSUP cables during manufacturing of the cables and are assumed to be collinear with the cables and straight to ±0.125 inches. During the initial acceptance testing of these cables there were all noted to be straight to the eye when under load[4]. The cables do not hang vertically, but as required by the cavity profile there is a small canting of the cables between 0.873° for C hubs and 0.991° for BAC hubs[5]. (C and BAC suspension points differ in elevation and radius: C hub suspension points are at a radius of 873.216cm and 166.769cm above the

PSUP centerline; BAC hub suspension points are at a radius of 875.807cm and 152.588cm above PSUP centerline). The connection of the PSUP cables to the geodesic sphere involves precisely machined keyways (between the E-brackets and the PSUP hubs), precisely machined receptacles for the clevis pins in the E-brackets, and commercially supplied clevis pin hardware. The tolerances between these pieces are all much tighter than the placement of the of the PSUP Suspension hardware on the cavity deck. This placement was initially installed by the Project in 1994 and was subsequently corrected to meet LBNL specifications of ±0.25". The specified locations and the as-built locations are summarized in the table below.

HUB Type	PSUP Node	SNO Label	Radius inch ±0.25"	Angle degree ±2.5°	Spec. X (inch)	Spec. Y. (inch)	As-built X (inch)	As-built Y (inch)	Elevation fax dated 28 Jan 94
BAC	32	15	336.46	348.18	-68.92	329.33	-68.97	329.56	99.25
C	43	14	336.46	324.00	-197.77	272.20	-197.76	272.49	99.25
BAC	41	13	336.46	299.82	-291.91	167.31	-291.89	167.44	N/A
BAC	48	12	336.10	276.18	-334.15	36.18	-334.06	36.17	N/A
C	52	11	336.10	252.00	-319.65	-103.86	-319.63	-103.98	99.27
BAC	50	10	336.46	227.82	-249.33	-225.92	-249.53	-225.94	99.27
BAC	57	9	336.46	204.18	-137.82	-306.94	-137.68	-307.07	99.26
C	61	8	336.46	180.00	0.00	-336.46	0.06	-336.48	99.26
BAC	59	7	336.46	155.82	137.82	-306.94	137.96	-306.97	99.29
BAC	66	6	336.46	132.18	249.33	-225.92	249.20	-225.88	99.27
C	70	5	336.10	108.00	319.65	-103.86	319.70	-103.81	99.27
BAC	68	4	336.10	83.82	334.15	36.18	333.96	36.40	99.27
BAC	74	3	336.46	60.18	291.91	167.31	291.83	167.47	99.28
C	76	2	336.46	36.00	197.77	272.20	197.83	272.09	99.29
BAC	39	1	336.46	11.82	68.92	329.33	68.88	329.41	99.24

Table 2. PSUP Suspension hardware specifications and ultimate as-built locations [6]

To survey the PSUP orientation with respect to TN, a total of nine PSUP suspension cable ends were exposed and survey lines stretched between PSUP suspension cable ends. Deck hardware, electronics crates, cavity clean room walls, water pipes and the like interfered with additional survey lines from being used. The PSUP suspension cable combinations listed in Table 3 were used to determine the orientation of the PSUP.

Hub 1		Hub2	Hub1		Hub2	Hub1		Hub2
52	to	48	43	to	32	74	to	68
48	to	41	32	to	39	68	to	70
52	to	41	43	to	39	74	to	70

Table 3. PSUP Suspension cable combinations used to survey TN.

On June 14, 2000 the compass was transported underground and the following surveys conducted. The gyrocompass was powered from a deck powerpoint and started

up in the control room. The speed setting for the compass was set at 0.0 Knots and the latitude was set to 46° N. Variation in the latitude by ±1° altered the heading of the stationary compass by <0.1°. Operation of the compass in the control room and on the deck was found to have no negative effects on the SNO electronics and resulted in no increase in counting rates, electronic pickup, or other negative effects on detector operation. Without interrupting AC power to the compass it was transported to the different locations on the deck and the surveys conducted. In general the surveys were conducted at mid-point between the PSUP suspension cables. The different deck elevations resulted in some surveys being indexed to the compass base while others were indexed to the compass card on top of the compass. We measured one location both with the compass card and with the base and discovered a small difference between these two references. In the analysis presented below, correcting for this small bias results in a minor correction to the average correction determined from the set of 18 surveys.

The survey measurements are presented in Table 4.

Hub 1	Hub2	Measurement Index	Angle from PSUP Construction North	Angle from INCO True North	Measured Angle from True North	Average Angle from True N	Correction to INCO Survey
52	48	Base	354.12	302.05	**304.6**	124.5	-2.45
48	52	Base	174.12	122.05	**124.4**		
52	41	Base	5.84	313.77	**316.2**	136.2	-2.43
41	52	Base	185.84	133.77	**136.2**		
41	48	Base	197.81	145.74	**148.4**	148.5	-2.76
48	41	Base	17.81	325.74	**328.6**		
43	32	Card	66.1	14.03	**16.1**	16.1	-2.07
32	43	Card	246.1	194.03	**196.1**		
43	39	Card	77.95	25.88	**27.9**	28	-2.12
39	43	Card	257.95	205.88	**208.1**		
32	39	Card	90.06	37.99	**40.0**	40	-2.01
39	32	Card	270.06	217.99	**220.0**		
74	68	Base	162.10	110.11	**112.5**	112.55	-2.44
68	74	Base	342.18	290.11	**292.6**		
74	70	Base	174.14	122.07	**124.3**	124.3	-2.23
70	74	Base	354.14	302.07	**304.3**		
68	70	Base	185.81	133.74	**135.9**	135.85	-2.11
70	68	Base	5.81	313.74	**315.8**		
						Average	-2.29
						SD	0.24
74	68	Card	162.10	110.11	**111.8**	111.95	-1.84
68	74	Card	342.18	290.11	**292.1**		
					Corrected	Average	-2.49
						Corrected SD	0.22

Table 4. Survey measurements on PSUP suspension cables on June 14, 2000. The average of the two orientations for the compass between PSUP suspension ropes is used to calculate the correction to the INCO surveys. When the apparent bias between measurements made to the compass base or to the compass card is corrected the corrected average is also shown. Units are in degrees.

Discussion of Errors Associated with True North (TN) Determination

There are a number of errors and limitations to our accuracy and precision in determining TN. These items include errors in aligning the compass to the survey lines, placement of the survey lines, use of the top of the PSUP suspension cables as survey benchmarks, alignment of the cables to the PSUP, and finally reproducibility, accuracy, and precision of the gyrocompass itself. In Table 5 we present the errors estimates for these factors and a final assessment of the survey errors.

Experimental Errors

Item	Δ-dimension	Resultant Δθ of Survey on Deck (degrees)
Angular misalignment due to cable end hardware	±0.25"	±0.002°
Angular misalignments due to BAC and C Hub elevation/radii differences	C R=343.786" H=461.167" BAC R=344.806" H=466.764	±0.036°
Angular misalignment due to deck hardware placement	±0.025"	±0.147°
Angular misalignment due to bent cable ends	±0.10"	±0.041°
Angular misalignment due to survey line placements	±2mm	±0.064°
RMS of these measurements		0.169°
Compared to		
Standard Deviation of measurements listed in Table 4		0.22°

Systematic Errors

Base alignment		0.3°
Compass accuracy		0.1°
Settle-Point Error		0.35°
RMS of these		0.472°

Final Estimated Correction to SNO's TN and INCO Surveys

Correction	Experimental Error	Systematic Error
2.49°	±0.22°	±0.47°

Table 5. Experimental and Systematic Errors Associated with the True North Determination

Confirmation of SNOMAN Geometry

A comparison of measured values with SNOMAN geometry has been carried out. As a first step in this comparison, the surveyed locations of the tops of the PSUP support ropes were compared with the positions as described in the SNOMAN geometry routines (version 4.0081). In SNOMAN, one fifth of the PSUP is modeled in detail and the remaining components reproduced with a rotation about the z-axis.

PSUP hub	SNO Node	As built x (inches)	As built y (inches)	SNOMAN x (inches)	SNOMAN y (inches)
39	1	68.88	329.41	68.87	329.63
76	2	197.83	272.09	197.63	272.31
74	3	291.83	167.47	292.02	167.31
68	4	333.96	36.40	334.77	36.37
70	5	319.70	-103.81	319.86	-103.87
66	6	249.20	-225.88	249.36	-226.02
59	7	137.96	-306.97	138.04	-307.15
61	8	0.06	-336.48	0.06	-336.55
57	9	-137.68	-307.07	-137.91	-307.00
50	10	-249.53	-225.94	-249.46	-226.20
52	11	-319.63	-103.98	-319.83	-104.05
48	12	-334.06	36.17	-334.59	36.29
41	13	-291.89	167.44	-292.21	167.36
43	14	-197.76	272.49	-197.72	272.24
32	15	-68.97	329.56	-68.88	329.43

Table 6. Comparison of PSUP as-built coordinates and those in SNOMAN.

As a consistency check on the geometry, the locations of the PMTs at the centers of the panels corresponding to the support nodes were compared to the locations of the tops of the support ropes.

PSUP node	x node (cm)	y node (cm)	z node (cm)	ϕ node (radians)	PSUP rope	ϕ(node)–ϕ(rope) (degrees)
32	-171.269	808.52	140.719	1.780	15	0.150
43	-480.592	661.451	156.143	2.199	14	-0.009
41	-716.031	412.724	140.712	2.619	13	-0.159
48	-821.873	86.961	140.719	3.036	12	0.150
52	-777.588	-252.67	156.143	-2.827	11	-0.009
50	-613.789	-553.447	140.712	-2.408	10	-0.159
57	-336.678	-754.776	140.719	-1.990	9	0.150
61	0.015	-817.609	156.143	-1.571	8	-0.009
59	336.689	-754.772	140.712	-1.151	7	-0.159
66	613.796	-553.439	140.719	-0.734	6	0.150
70	777.597	-252.642	156.143	-0.314	5	-0.009
68	821.873	86.971	140.712	0.105	4	-0.159
74	716.024	412.731	140.719	0.523	3	0.150
76	480.568	661.469	156.143	0.942	2	-0.009
39	171.257	808.524	140.712	1.362	1	-0.159

Table 7 PSUP Hub locations in SNOMAN and Comparison between Hub Centers and Rope Centers.

The method for determining the correct proper orientation for the detector was to calculate the angle (in PSUP coordinates, counterclockwise with respect to the x-axis) of

the vector between two PSUP rope locations (β). This is combined with the measured value of the angle for this direction with respect to True North (α, degrees East with respect to True North) to give the direction of the x-axis in degrees east of True North.

$$\gamma=\alpha+\beta$$

PSUP rope pairs	PSUP angle (radians)	Measured degrees East of True North	x-axis degrees East of True North
3 to 4	-1.255	112.5	40.58
4 to 5	-1.677	135.9	39.83
11 to 12	1.676	304.6	40.60
12 to 13	1.258	328.6	40.68
14 to 15	0.418	16.7	40.63
15 to 1	0.001	40.6	40.68
3 to 5	-1.468	124.3	40.16
11 to 13	1.469	316.2	40.39
14 to 1	0.212	28.5	40.65
4 to 3	-1.255	292.6	40.68
5 to 4	-1.677	315.8	39.73
12 to 11	1.676	124.4	40.40
13 to 12	1.258	148.4	40.48
15 to 14	0.418	196.7	40.63
1 to 15	0.001	220.6	40.68
5 to 3	-1.468	304.3	40.16
13 to 11	1.469	136.2	40.39
1 to 14	0.212	208.7	40.85
		Average ± SD	40.46±0.30

Conclusions

Based on the gyrocompass survey we conclude that the PSUP and PMT coordinates need to be corrected by 2.5 degrees. We have compared the locations of the PMT coordinates in SNOMAN to the PSUP HUB locations and to the deck penetration locations for the PSUP suspension cables and find that the implementation of the PSUP coordinates in SNOMAN is correctly performed, but that SNOMAN will also require the correction for the new determination of True North. The $\cos(\Theta_{sun})$ plots generated to-date and displayed at several conferences are incorrect, but this error would be difficult to discern with the current statistics and the detector resolution.

[1] LBNL Drawings 23H8606, 23H8636, 23H8646 and University of Oxford Drawing NO-93-70
[2] See SNO-STR99-004 Poon, Koehler, Okada, and Lesko and references within.
[3] SCAN2000 Operation and installation Manual, Ver. 11 March 1998
[4] LBL Engineering Note SNO200 M7460 by David N. Beck
[5] See LBL drawings 23H3204, 23H3214 and 23H3476
[6] See LBL drawings 23H3466 and Peltomaki surveys