Adventures in Engineered Measurement: Answering Questions with Geomatics at the Sudbury Neutrino Observatory

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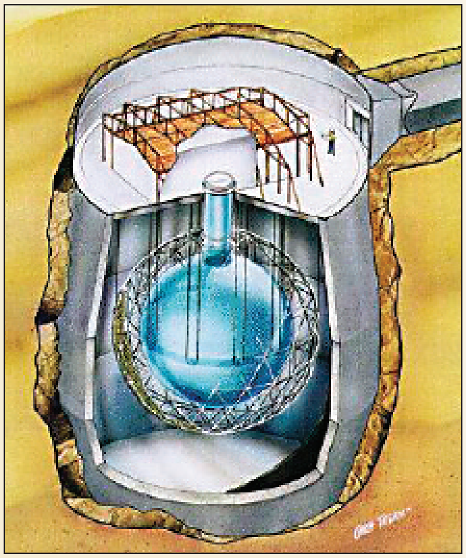

Figure 1: Artist's Impression of SNO (Picture Credit: Garth Tietjen on behalf of SNO)

Overview:

The Sudbury Neutrino Observatory needed to precisely determine the shape of a 12 metre diameter spherical acrylic vessel. D.S. Dorland Ltd was engaged to determine the extent of the vessel's deviations from that of a best-fit sphere, to within a specified tolerance of 3.2 mm or 1/8" at k = 2 or 95% confidence. Geomatics engineering methods were utilized for pre-analysis and measurement conformation.

Measurement Conditions:

The Sudbury Neutrino Observatory (SNO) is located in a barrel shaped underground cavern 22 metres in diameter and 30 metres high, approximately 2 kilometres underground at Vale Inco's Creighton Mine, near Sudbury, Ontario. Neutrinos were detected via their reaction with 1000 tonnes of heavy water housed in a clear acrylic spherical vessel suspended within the cavern as shown in Figure 1. The reaction produces minute traces of light which are detected and analysed by 9600 ultrasensitive phototubes that surround the acrylic vessel as shown in Figure 2. The area outside the vessel, including the phototubes, was filled with purified normal water which helped to support the weight of the vessel through buoyant forces generated on the vessel itself. The observatory is housed deep underground to allow the rock above to filter out cosmic rays emanating from space that would have otherwise interfered with the detection of neutrinos.

Access to the underground facility is provided via Creighton Mine. It is imperative that dust from the mine not enter the observatory area because it could interfere with the detector by becoming a source of background radiation, which would impede with the detection of neutrinos; this necessitates running the entire underground observatory as a cleanroom. D.S. Dorland Ltd twice wrapped all equipment brought into the observatory with plastic bags to prevent contamination while being transported through the mine. The bags were removed upon arrival at the underground facility and the equipment was then inspected and re-cleaned as required, before use within the observatory. Personnel entering the observatory were required to clean their boots before entering the first stage of cleaning. They were then required to remove their clothing, shower and dress themselves with specially cleaned suits, boots and hairnets made available specifically for use within the underground facility. Adhesive strips are placed at the entrance to passageways in order to remove any materials that have collected on the soles of a person's boots while in the observatory. As they near the detector itself they are required to take an air shower to further remove dust before entering the main cavern which holds the detector. The area directly above the vessel is maintained at a higher atmospheric pressure than the surrounding observatory, maintaining airflow away from vessel to reduce dust contamination. Persons wishing to enter the area above the vessel must once again change boots while the area is cleaned and before entrance to the vessel itself is permitted. A cylindrical tube which extends out of the top of the vessel, as can be seen in Figure 1, provides access to the vessel itself and persons and equipment are lowered via a tethered chair or mesh bag attached to a pulley system anchored to the supporting frame of the vessel. All told, the entire process of travelling from the surface to inside the acrylic vessel underground and setting up needed equipment for measurement required three to four hours for each visit.

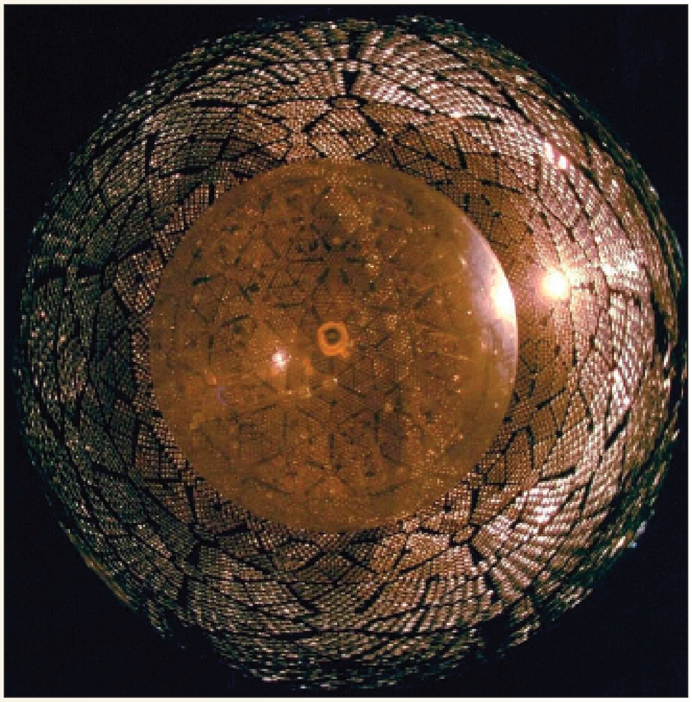

Figure 2: Acrylic Vessel and Phototubes (Photo Credit: Lawrence Berkely National Laboratory – Roy Kaltschmidt)

Project Outline:

SNO was in operation for a period of seven years since October 1999 and the experiment was deemed a success. During this period the acrylic vessel itself was acted upon by various forces which may have deformed the sphere from its original shape. The same or a similar vessel could be used by the successor experiment termed SNO+. In order to determine whether to rebuild or reuse the existing acrylic vessel, precise measurements of its inner surface were required to compare its current shape with the original constructed shape. To maintain the functionality of the existing sphere, it must be maintained in pristine condition and could not be marked, touched or scratched in any way. SNO personnel defined points of interest by adhering small (2-3 cm^2) pieces of paper onto the vessels' inner surface using a special adhesive tape. A cross was marked in ink onto each paper target which were then placed by personnel from within a small water craft, as the vessel was emptied of water. Figure 3 demonstrates how access is provided to the vessel and the white specks on the inner surface of the vessel are the paper targets. In total some 530 points of interest were defined in this way.

Figure 3: Vessel Access and Marking (Photo credit: Dr. Peter Skensved)

At this point D.S. Dorland Ltd was contacted to determine the shape of the vessel. Through discussion with SNO personnel it was determined that the radii from the centre of a best-fit sphere to each point of interest must be known to within 3.2 mm or 1/8" at k = 2 or 95% confidence to ensure valid decisions were made using the results provided.

Given the project constraints and the need for measurement verification, it was decided that a conventional total station utilizing reflectorless EDM would be used as the measurement instrument. It was also decided that all targets would be measured from a minimum of two separate setups, to both confirm and ensure the repeatability of each measurement through statistical analysis. This conforms to the same logic as that of a level loop or closed traverse; perform a measurement twice and if the difference between the two results is less than expected it is reasonable to conclude that the measurements are consistent and to the precision expected.

A pre-analysis was performed using a Type B (ISO, 2008) estimate of measurement uncertainty, and relied on uncertainties as described by the manufacturer. The instrument used in the pre-analysis and final survey was a Leica TCR 802. Using estimated positions and measurements, the utilitarianism of a weighted least-squares adjustment allowed for rigorous error propagation. In the case of this project, the steps illustrated below were required to propagate errors of the measurements into the propagated errors of the derived radii:

$$[l, C_l] \overset{1}{\Rightarrow} [X, C_X] \overset{2}{\Rightarrow} [K, C_k] \overset{3}{\Rightarrow} [r, C_r]$$

where,

l	vector of measurements (Direction, Zenith Distance and Slope Distance)
C_l	covariance matrix describing the uncertainty of the measurements
$\overset{1}{\Rightarrow}$	process of a weighted non-linear parametric least-squares adjustment
X	vector of parameters estimated by the parametric adjustment. These parameters being the spatial rectangular coordinates of the points of interest (Y, X, Z)
C_X	covariance matrix describing the uncertainty of the parameters Y, X and Z for each point
$\overset{2}{\Rightarrow}$	process of a weighted non-linear combined least-squares adjustment
K	vector of parameters estimated by the combined adjustment. These parameters being the spatial rectangular coordinates of the centre of a best-fit sphere and a best-fit radius, these being denoted by H, K, L and R respectively
C_k	covariance matrix describing the uncertainty of the parameters H, K, L and R.
$\overset{3}{\Rightarrow}$	process of calculating differences between the best-fit radius and the distance from the best-fit centre to each point of interest. And in conjunction, the process of error propagation through the use of the same functional model and its' associated Jacobian matrix.
r	vector of calculated differences from best-fit sphere
C_r	covariance matrix describing the uncertainty of each of the calculated differences.

This entire calculation algorithm and related statistical analysis was computer coded in-house, specifically for this project, due to its unique requirements. Pre-analysis concluded that project requirements could be met with the TCR 802 and also highlighted potential observation weaknesses which were eliminated through proper positioning of the total station. This process was made possible by the completeness of information provided by Leica regarding their instruments, allowing observation uncertainties to be properly modelled and weighted. In order to meet these requirements it was determined that the paper targets themselves would define the mapping datum so that none of the errors associated with instrument setup would propagate into the measurements. This method requires that for each position of the instrument, the spatial rectangular coordinate and rotation about the Z-axis relative to the paper targets be included as parameters of interest in the least-squares adjustment. This essentially means that the instrument positions' were determined by a 530 point resection.

Measurement and Results:

Measurements were completed in four days, comprising of two campaigns of two days duration each. Due to the time required in gaining access to the vessel, practices were devised so that the process of taking measurements in both faces, storing and coding the data took no more than 1 to 1 _ min for each target. Special apparatuses were fabricated by on-site engineers to allow the instrument to be securely mounted on the vessel without damaging or marking its inner surface in any way.

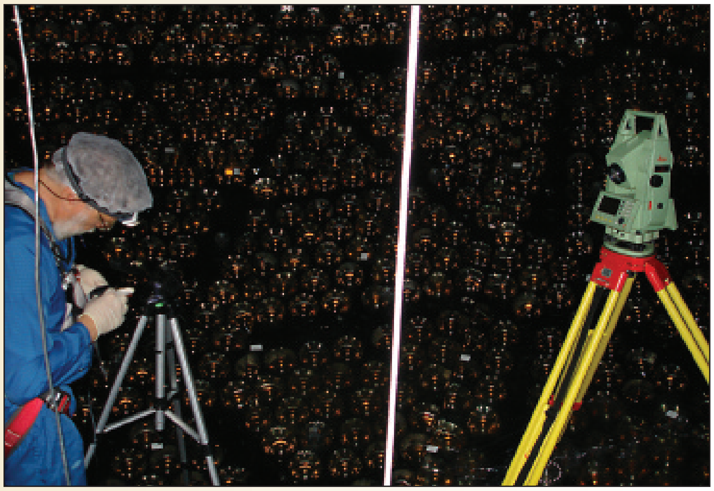

Figure 4: Typical Measurement Situation (Photo credit: James Dorland)

Once all the measurements were completed, the observed information was fed into the computer algorithm. This allowed for statistical analysis and the determination of a radius from the center of a best-fit sphere to each point of interest. Measurement outliers were removed and a report describing the observed shape of the acrylic vessel was prepared. Instrument and human pointing errors needed to be empirically derived from observation data due to the less than "ideal" design of the stick-on targets. Beyond this, the measurement repeatability exceeded expectation. It is important to note that not only were the results verified, but the quality of these results was also verified through statistical analysis and was fully described in the report. It is also important to note that proper engineering practices were followed; giving consideration to all systematic and random errors, a *design* process was followed to ensure effective utilization of the instrument. This allowed for determination of the expected uncertainty of the requested information *before* measurement, ensuring project requirements would be met.

References

ISO, International Organization for Standardization (2008). "Guide 98-3: Uncertainty of measurement" Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), first edition 2008. 120 pp.

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More Notes on Historical Context – The Islands of Georgian Bay - *cont'd from page 16*

administered by the federal Department of Indian Affairs, "in trust for the Indians", pursuant to the 1876 Pardee-Laird agreement. This arrangement was considered and approved by the Privy Council as set out in Order in Council OCPC 3059, dated 10 December 1914, attached to which is a list of the islands in the vicinity of the Great Manitoulin already sold and granted by the federal government. The agreement was ratified by the Ontario government by Order in Council dated 23 December 1914.

Part 2 of these notes will look at some practical applications involving the effect of the jurisdictional history reviewed above, with important considerations for surveyors (including water levels) when conducting surveys of islands and the adjacent shores of Georgian Bay.

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[1] The authority for dealing with Indian Affairs from the conquest of 1759 to confederation in 1867 was a confused matter (not the subject of study for this article). After confederation, Indian Affairs continued to be administered by an autonomous entity in Ottawa apparently known simply as "Indian Affairs", which was run by a Superintendant. In 1873, Indian Affairs was officially formalized as a responsibility of the newly-created Department of the Interior, until the creation of the Department of Indian Affairs in 1880.