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Time synchronization improvements in the T2K long-baseline neutrino experiment

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For the T2K Collaboration *

* A list of all members of the T2K Collaboration may be found in Reference [1].

We describe the upgraded hardware and methods now implemented to bring T2K GPS time synchronization accuracy down to the O(1 ns) scale. These improvements form the basis for a neutrino time-of-flight (TOF) analysis within the T2K experiment.

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1. Introduction

T2K (Tokai to Kamioka) [1] (Fig. 1) is a second-generation neutrino long baseline experiment whose primary goal is to measure the mixing properties of neutrinos ("neutrino oscillations"). A neutrino beam line at the J-PARC synchrotron is aimed towards the Super-Kamiokande (SK) underground water Cherenkov detector [2], 295 km away, with an intentional angular offset of 2.5^o, in order to select a narrow band of neutrino energies around 600 MeV.

At a distance of 280m from the target, neutrinos pass through a set of detectors, both on the beam axis (INGRID), and a fine-grained magnetized off-axis detector (Near Detectors at 280m, or ND280). The proton beam has a bunch structure of 6 or 8 bunches, with bunch width about 20 ns (FWHM) and bunch spacing about 580ns, and is carefully monitored by a variety of proton beam intensity and position monitors. Fig. 2 shows the beam bunch structure (from beam monitor CT1) reproduced by time distribution of neutrino interactions in one of the ND280 detectors. Detailed descriptions of the T2K beam line, beam monitors, and near detectors can be found in references [1, 2] and references therein. The Super-Kamiokande detector is described in reference [3].

While the primary physics goal of T2K is the measurement of neutrino oscillation parameters, its physics program is broader, and includes neutrino cross section measurements using the ND280 detectors, and neutrino TOF studies. In general, the latter goal is motivated by non-standard theories, which (for example) predict the speed of neutrinos may deviate from the speed of light at the level of 10^{-4} , or neutrino beams may include light dark matter [4].

2. "Official time" system

The original T2K GPS time synchronization system design provides O(30 ns) precision for time synchronization between neutrino event trigger timestamps at SK, and beam spill timestamps logged at J-PARC. In practice, absolute accuracy, estimated from the distribution of deviations between independent GPS receivers at the same site, is typically 50 ns RMS. This system is adequate for the primary goals of T2K, and continues to be used to log "official timestamps" for beam spills and far detector event triggers; the "Official Time" (OT) synch system is described in detail elsewhere [1]. At each site, complete duplicate OT GPS receiver sets were prepared, to avoid any loss of timing data during T2K beam operation.

At both sites, the OT primary GPS receiver is a Synergy Systems SynPaQIII receiver, and the secondary receiver is a TrueTime (Symmetricom) rack-mounted time receiver. These C/A code, single-frequency GPS receivers are connected to antennae located on the roof of the NU1 building at J-PARC, the location of neutrino beamline controls and monitor systems, which has a clear sky view with large solid-angle acceptance. At Super-Kamiokande, GPS antennae are on the roof of the "Radon Hut" building, which houses air pump equipment for the SK Rn-free air system, just outside the mine entrance. Due to the narrow river valley in which the mine entrance is located, the sky view is restricted. Plans are in place to move all SK GPS receivers to a location with better sky view, as will be described below.

Time stamps are generated by a custom electronics board, the Local Time Clock (LTC), which uses a time base derived from a commercial rubidium atomic clock (Stanford Research

Systems FS725), steered to GPS time using input from the two independent commercial GPS receivers. The LTC operational firmware was coded to interface efficiently with the SK and J-PARC data acquisition systems, and the trigger signals they produce.

At J-PARC, the LTC is located in the same rack as the GPS receivers, in the NU1 building, and an optical fiber link sends 1 PPS signals directly to the ND280 data acquisition system. At SK, the LTC and Rb clock are located inside the mine, in the "Central Hut" which houses trigger electronics, atop the SK water tank. The LTC receives data from the GPS receivers over a 2km long multimode fiber link, with measured delay times incorporated into the analysis software.

In addition to the OT system GPS receivers, independent GPS receivers with Common View capability, Coder Model CD9955, were installed at both sites in 2009. In December, 2011, the Coder receivers were significantly upgraded, providing dual frequency reception, and new firmware for improved time resolution. The Coder Common View receivers are used only to monitor the performance of the OT time synchronization system receivers, not to generate timestamps themselves.

3. Precise Time System

The GPS equipment at both sites was upgraded by supplementing the existing OT system with a new "Precise Time" (PT) system (Fig. 3), comprising a Septentrio Polar4X GPS receiver and a rubidium atomic clock (SRS FS725), with a Linux PC host for control and data logging. In addition, a Time Interval Counter (TIC, SRS Model FS620) is used to relate the OT system time to the PT system time at each site. An active fan-out (SpectraDynamics PD-RM-B pulse divider) is used to send a precise copy of the OT primary receiver 1 PPS output to the TIC where its delay is measured relative to the 1 PPS output of the Septentrio Polar4X. An isolation amplifier (SpectraDynamics HPDA-15RM/A) forwards the 10 MHz output from the Codec CV receiver to serve as the TIC reference frequency.

In addition to 1 PPS and C/A code functionality, as provided by the OT receivers, the Polar4X dual-frequency receivers also supply P3 code, carrier phase measurement, and common-view capabilities. Data files are in industry-standard data formats, allowing comparison of calculated satellite ranges with each other and with the Coder receivers, which can then be differenced to cancel out common systematic errors and provide substantially improved "common view" precision.

A third independent PT system has been installed in the NM hall, location of the near detectors (ND280) at J-PARC. Optical fibers transport 1PPS signals from the OT system at NU1 to the NM building, where they are compared to 1PPS signals from the new PT receiver using a CAEN Time-to-Digital Converter (TDC). Data from the TDC are logged by the near detector data acquisition system.

In addition to regular direct atomic-clock cross-calibrations, achieving O(1 ns) accuracy from GPS time data requires offline post-processing to integrate manufacturer-supplied corrections and supplementary data from international GPS/GLONASS user-community (IGS) databases [5]. Since identification of beam-induced event at SK is performed offline, late in the data analysis procedure, PT post-processing does not delay T2K data flow. PT data generates corrections to the physics database timestamps recorded by the OT system. Corrections need

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only be applied to the relatively small number (hundreds) of beam-induced SK events, which are identified after applying T2K event filters to the raw SK trigger sample.

4. "Traveler" system for cross-calibration

Time synchronization to the 1 ns accuracy level, making full use of high precision GPS measurements, requires a significant level of calibration effort. Actual timing accuracy is directly measured periodically by a time transfer (TT) operation, transporting a GPS receiver and Cs oscillator (the "traveler system", Fig. 4) from Tokai to Super-Kamiokande and back again, synchronizing at each site with the stationary systems, and thus directly determining the deviations between identical systems. In addition, very short TT trips are made between the NU1 building and the ND280 experimental hall, 280m apart; these are primarily for checking the TT process. The new PT GPS instrumentation set thus includes another, identical Polar4X GPS receiver, a cesium atomic oscillator time base with high-precision Cs tube (Symmetricom 5071A), and a Time Interval Counter (SRS FS620 TIC). The TIC is used to compare the traveling with the stationary components. A Linux laptop serves for control and TIC data logging. Vehicle position versus time is recorded using a commercial GPS vehicle-tracking logger, providing data for general relativity corrections due to altitude changes. The Cs atomic clock must run continuously throughout, so we provide a thermally-insulated transportation box, with ventilation and auxiliary battery power supply, designed to permit reliable continuous operation of the Cs clock for >24 hr. The Cs clock can provide 1 ns accuracy for comparisons over a 24 hr time period, so a TT round trip must be completed within approximately one day.

The traveler system calibration procedure has two distinct components: cross-comparison 1) of the atomic clocks, and 2) of the 1 PPS outputs of GPS receivers

First, the traveler Cs clock is compared to the Rb clock at the NU1 site, and it is then transported by car to Super-K (or the ND280 hall), where its offset relative to the local Rb clock is measured with the TIC, collecting data over several hours. The Cs clock is then driven back to NU1, to measure the offset between traveler and local atomic clocks, closing the loop after a round trip. TT trips to and from ND280 take only a few hours. Each round trip to Super-K requires about 24 hr. (The drive between near and far sites – much longer than the route neutrinos follow! – takes about 7 hr each way.) Over a 24 hr period, the Cs clock drift is O(1ns).

The second part of the calibration is comparison of the GPS receivers. The traveler system Polar4X receiver and its antenna are transported along with the Cs clock and TIC. Comparison of two identical receivers, with identical antennae mounted side-by-side, provides an estimate for the systematic error contribution due to the GPS receiver hardware and firmware design, and receiver construction fluctuations.

5. Status and plans

In order to maximize the fraction of time when common view data will be available, we plan to relocate the GPS antennae and receivers, from the mine entrance to the roof of the Kamioka Observatory Office/Laboratory ("Kenkyuto") building in the village of Higashi-Mozumi, about 5km from the mine entrance. This site, in a much wider valley, provides a substantially improved sky view solid angle. The move will require transporting fast trigger signals from the SK detector in the mine, to the Kenkyuto. Spare single-mode optical fibers to

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transport the signals between the mine and Kenkyuto are in place, and will be used for this purpose. To avoid disruption of T2K data-taking, we plan to install the necessary optical fiber adapter equipment and move the receivers during a shutdown period, when the T2K beam is off.

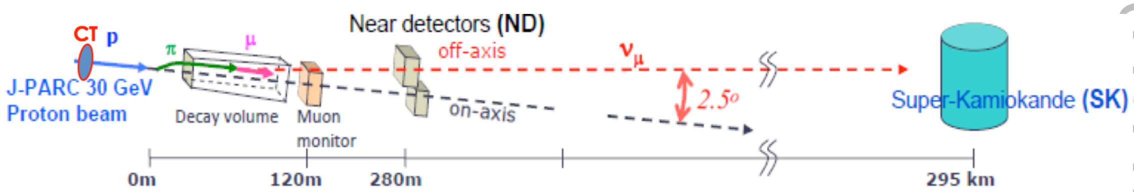
The T2K PT system is now in operation, with new equipment at J-PARC (stations at both NU1 and NM building) and SK. The traveler system is also operational and several TT expeditions have been completed. We will not have the capability of directly timing SK trigger signals until the optical fiber link upgrade and move of GPS receivers is completed. Meanwhile, we are logging data at both near and sites (as well as at the ND280 location), and also logging TIC data comparing OT 1PPS and PT 1PPS signals at both sites.

In addition to the GPS related equipment described here, colleagues at NICT in Japan will provide equipment and expertise required for two-way satellite time and frequency transfer (TWSTF) between J-PARC and SK. These calibrations will be infrequent, but provide a critical independent check on the continuous GPS time transfer system.

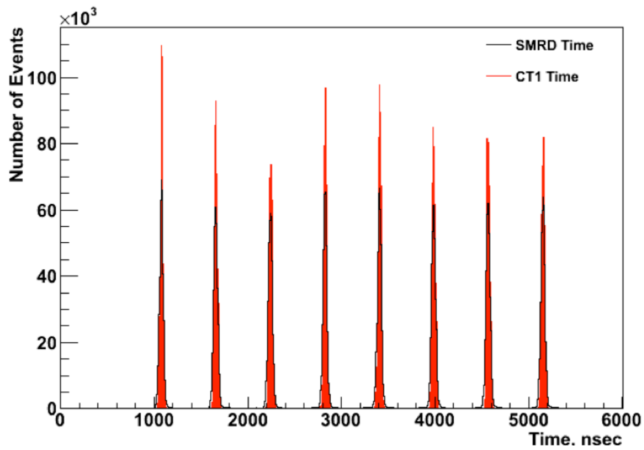
6. Acknowledgements

Reference [1] contains a list of members of the T2K Collaboration, as well as a complete list of acknowledgements for the T2K project. Thanks are due to Victor Zhang at NIST/Boulder, who provided essential advice and explanations. JW offers personal thanks to all members of the T2K-TOF group, and also to the Aspen Center for Physics (NSF-supported) for providing an environment for writing this paper.

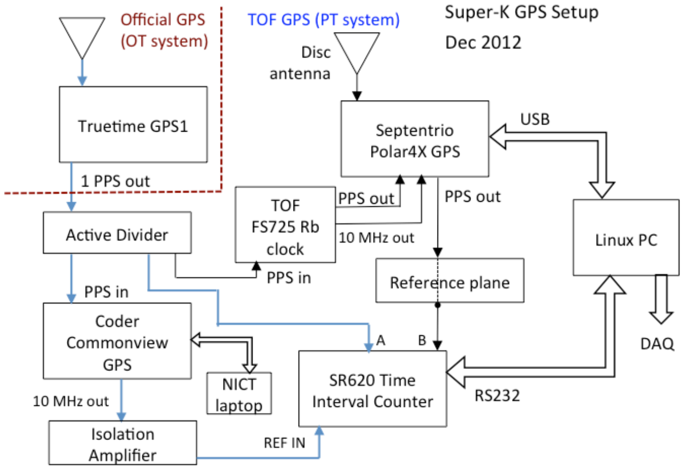
7. Figures



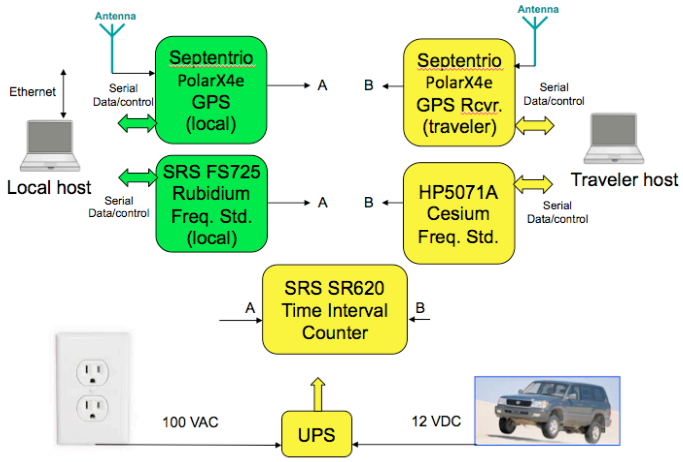
1. Overview of the T2K (Tokai to Kamioka) long baseline neutrino project. (CT=beam monitors)



2. Beam bunch structure displayed by neutrino interactions in proton beam monitor (CT1) and the SMRD (side muon range detector), part of the ND280 near detector.



3. Block diagram of the new Precision Time (PT) system installed at Super-Kamiokande. The system at J-PARC is identical except for minor details. The new equipment supplements the previously existing OT timestamp system.



4. Block diagram of the "traveler system" for time-transfer cross calibration. Local station equipment is shown in green, traveler system components in yellow.

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