T2K Precise Time System Update

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This report describes major changes to the T2K Precise Time System made between 20 January, 2014, and the start of T2K Run 5 in May, 2014. Included is a measurement of the change in timing of the Official Time System used at Super-Kamiokande.

Work Overview

The primary objectives for this period of work were:

- Relocate the primary Official Time System equipment and all of the Precise Time System
- Measure cable delays after the move
- Perform GPS receiver firmware upgrades
- Perform auto-calibration of the Time Interval Counters

These tasks were completed, in addition to several other house-keeping and opportunistic tasks.

S-K Time System Relocation

Relocation of the Precise Time (PT) system from the Radon hut at the Atotsu entrance to the mine housing Super-Kamiokande was coordinated with the relocation of the Official Time (OT) system. A separate on changes to the OT system is provided here. The PT system installation at the Radon hut is detailed in several documents collected here:

- PT Installation at Rn hut Documentation[1]
- PT System Installation Photos, November 2012[2]
- Most recent PT System Connection Diagram[3] prior to move

Immediately prior to the move, the situation is

Figure 1: GPS equipment at the Radon Hut (until 31 January, 2014)

Figure 2: GPS antennas at the Radon Hut

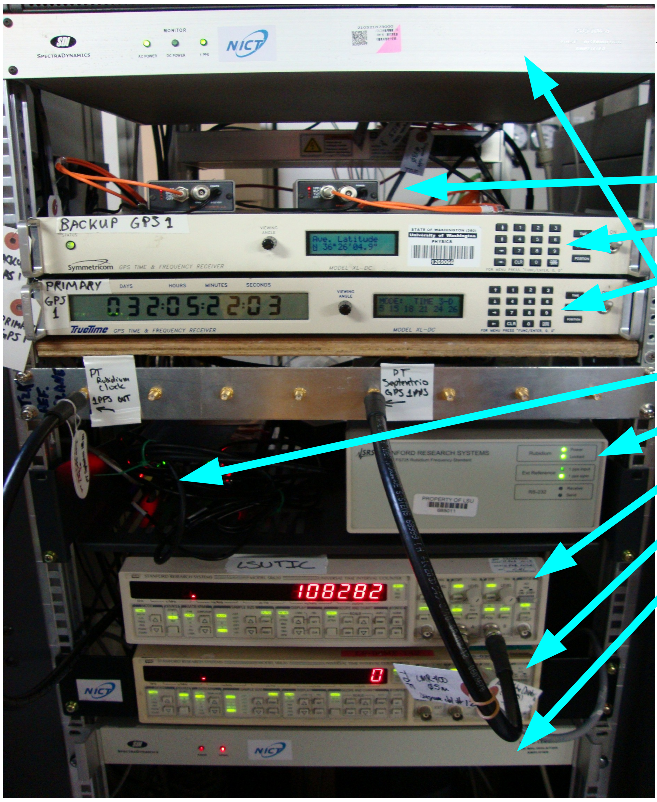


Figure 3: Timing system equipment in Kenkyu-tou computer room.

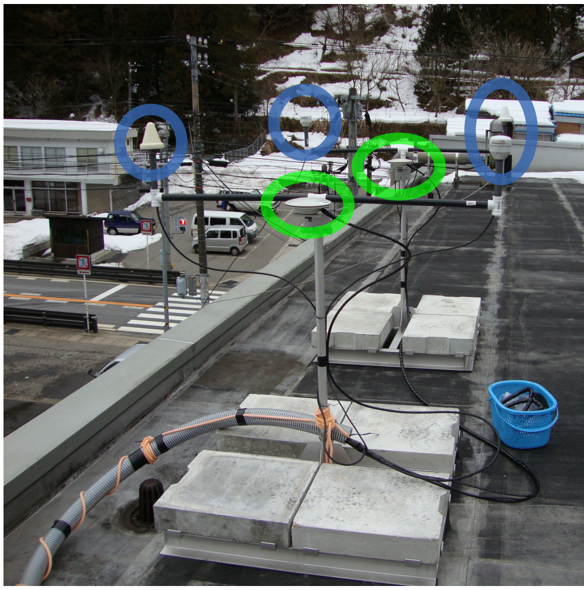


Figure 4: GPS Antennas atop Kenkyu-tou building

OT GPS Antennas (4)

Precise Time GPS Antennas

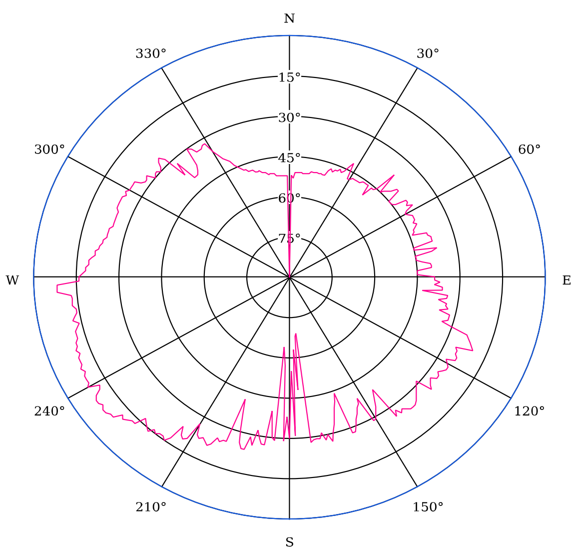


Figure 6: Local horizon at ***Radon Hut***

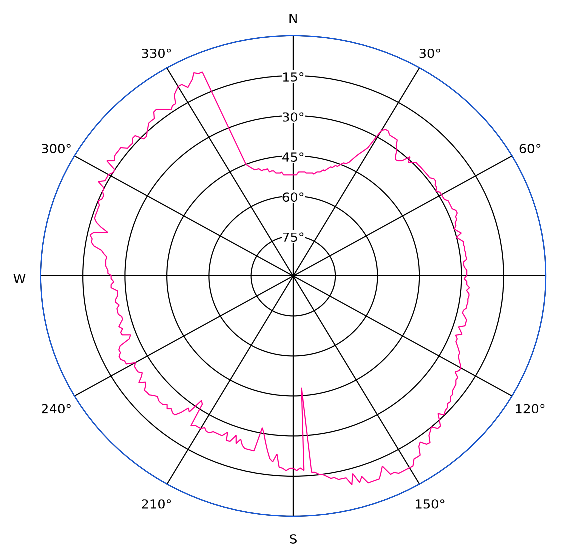


Figure 5: Local horizon at ***Kenkyu-tou***

as shown in Figure 1 and Figure 2. By this time, the secondary or backup Official Time System GPS equipment had already been moved moved to the Kenkyu-tou building. This was completed in August, 2013, to allow testing and confirmation of performance at the new location prior to relocating the primary components.

The new location of both timing systems is the Kenkyu-tou building of the Kamioka Observatory in Higashi-Mozumi, Kamioka-cho, Gifu. The equipment is now installed as depicted in Figure 3. The antennas are installed as shown in Figure 4. The documentation has been updated, accordingly. Please see Hardware Details (Current)[4].

Summary of the Super-Kamiokande Official GPS Timing Shift

T2K members may be familiar with the small timing shifts which are known to occur in the Official Time System after power outages. These are due to the relatively coarse resolution of the OT system, resulting in random placement of the initial 1PPS signal leading edge within a time window of width O(100 ns). Now that the Official Time System is being continuously compared to the Precise Time System, it is possible to measure these timing changes relative to the PT system. The PT system's greater precision means that restart timing jumps due to first-cycle ambiguities are restricted to O(10 ns). Such a shift was expected during the move since the OT GPS receivers had to be powered off. The direction and magnitude of the change was measured and the results are summarized in this section. For a complete description of the measurement, see Appendix B.

Analysis of the time differences between the GPS1 primary receiver and the Precise Time System shows, approximately, a 200 ns delay in the timing of GPS1 primary after the move. That is, relative to the PT system, the timing signal of the OT GPS1 primary receiver occurred 200 ns later, when relocated to the Kenkyu-tou building, than it did before, when located at the Radon hut. The same comparison can be made for the OT GPS2 primary receiver. Relative to the PT system, a 223 ns delay in GPS2 primary was observed after the move.

The data from which these results are concluded are shown in Figures 20, 21, 22, and 23. The data plotted has been adjusted as described later in the section titled Analysis. The equation expressing all adjustments is developed in this section and appears at the end of the subsection titled Official Time System GPS1 and GPS2 Adjustments. Figure 24 and Figure 25 show the original, raw data prior to all corrections. Figures 26, 27, 28, and 29 are simply more detailed plots of the fully adjusted measurements shown in Figures 20 and 21. The remaining plots show the progression of individual adjustments developed in the Analysis section.

Official Time System Timing Change Measurements		
	Timescale Change (After - Before)	Combined Uncertainty
GPS1 primary	200 ns	22.8 ns
GPS2 primary	223 ns	22.8 ns

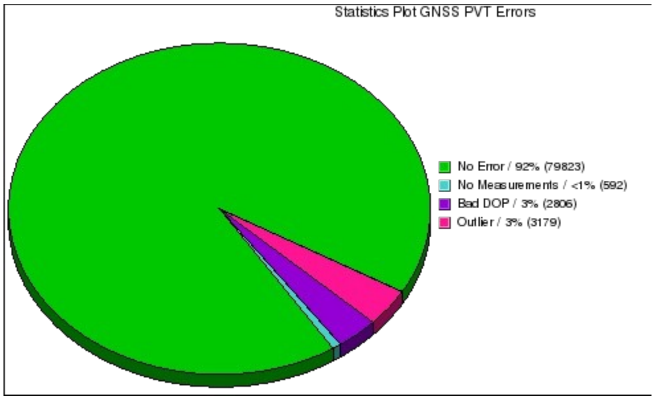


Figure 7: PVT error sources at ***Radon Hut***

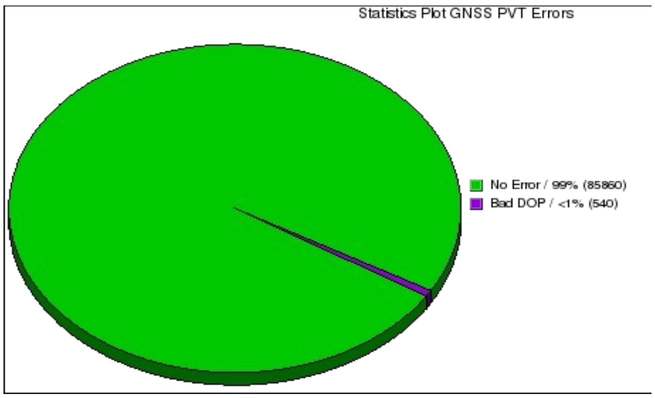


Figure 8: PVT Error sources at ***Kenkyu-tou***

GPS Performance: Local Horizon

The new location of GPS equipment was expected to improve performance because it has a better view of the sky. A comparison of local horizons as seen from the both locations is shown in Figure 6 and Figure 5. It is clear from these plots that the local horizon is generally improved after the move to Kenkyu-tou. The horizon is slightly worse, however, over an azimuthal range of approximately 70 degrees in the W-SW direction.

GPS Performance: SVs in PVT

The number of satellites available for use in the calculation of Position, Velocity, Time (PVT) is another factor that affects GPS performance. This quality is plotted over one day for both old and new locations in Figure 9 and Figure 10, respectively. The graphs show improvement at Kenkyu-tou during many periods of these sample days, but also a few periods of decreased satellite visibility.

One measure of the gain attributed to increased satellite availability is the increase in total PVT solutions obtained in the two sample days. At the Radon Hut, approximately 8% of PVT solutions were not calculated or usable due to a variety of a factors related to satellite visibility. A chart of the statistical composition of PVT solutions and errors at the Radon Hut for the sample day shown in the plot of available satellites is shown in Figure 7. The same chart for the location at Kenkyu-tou is shown in Figure 8. Using these particular samples from before and after the move, the PVT error rate was reduced from 8% to less than 1%.

GPS Performance: DOP

Even when the number of available satellites is sufficient, the receiver may fail to produce a proper PVT solution if the satellite positions are unfavorable. Dilution of Precision (DOP) is the measure of the increase in uncertainty due to the geometry of satellite positions used.

GPS Performance: C/No

Another performance metric is the GPS signal-to-noise ratio, C/No in GNSS terminology. This measure also improved slightly after moving equipment to the new location. Specifically, the fraction of time when C/No ratio is less than 40 dB is substantially reduced. This value is plotted in Figure 15 and Figure 16 for the old and new locations, respectively.

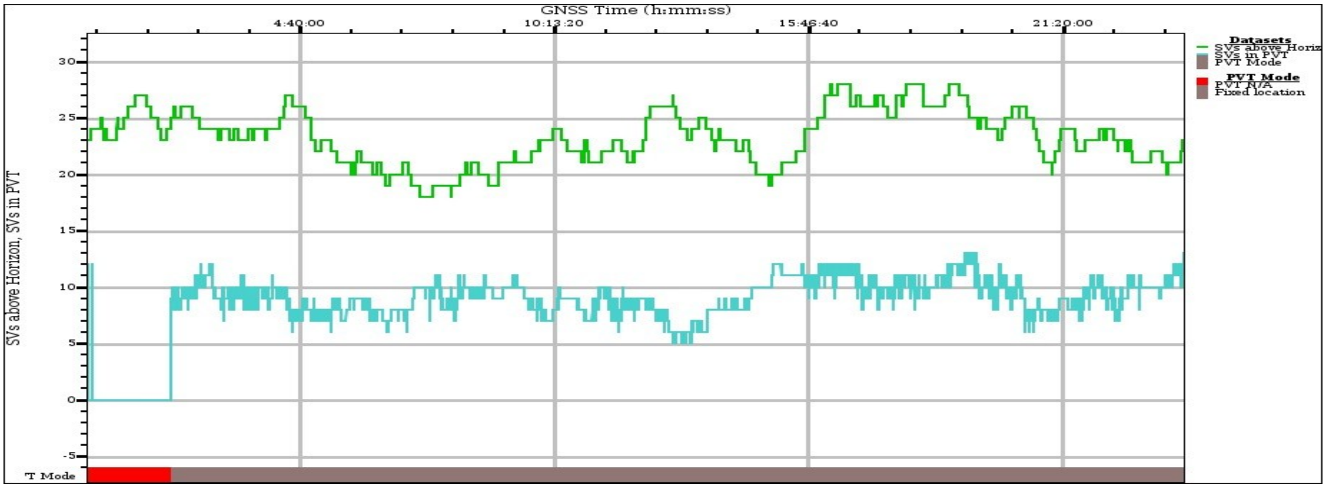


Figure 9: Satellites above horizon and in use at ***Radon Hut***

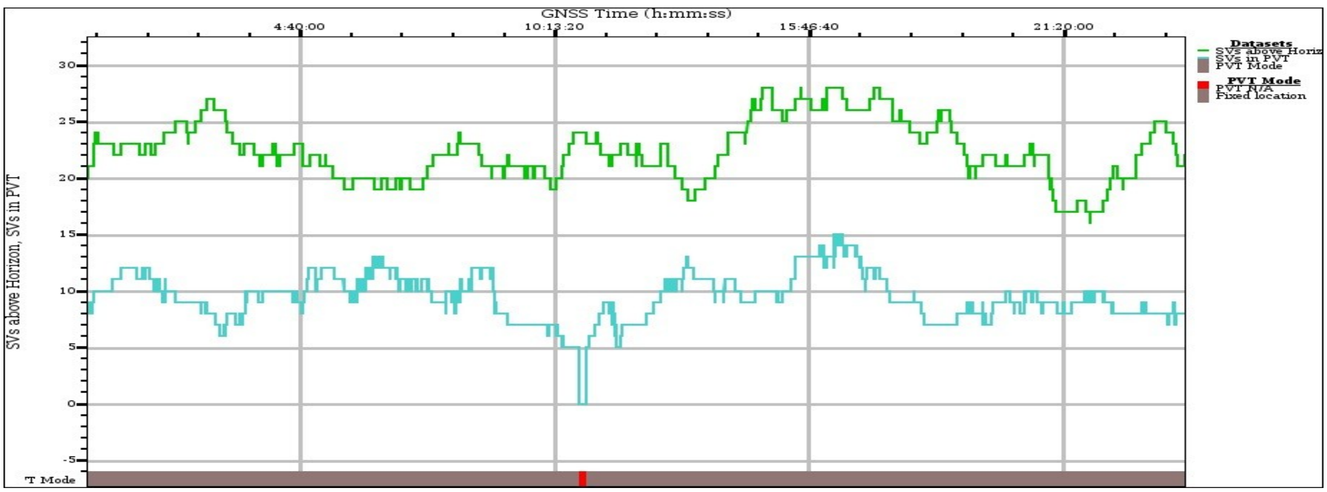


Figure 10: Satellites above horizon and in use at ***Kenkyu-tou***

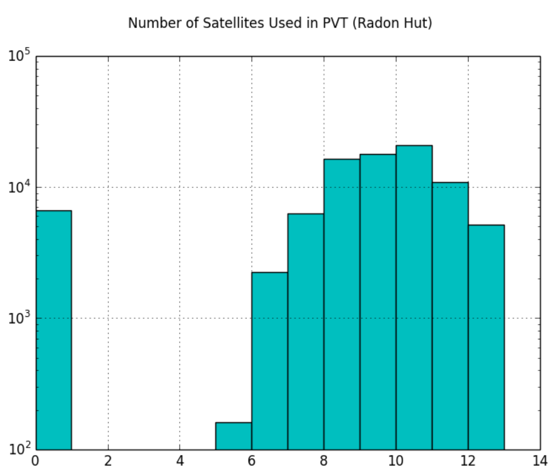


Figure 12: Histogram of SVs in PVT at ***Radon Hut***

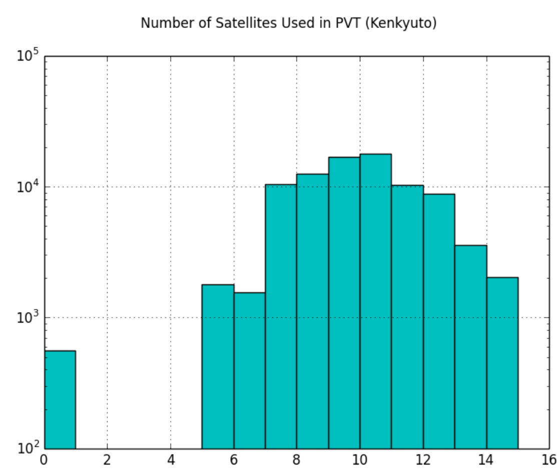
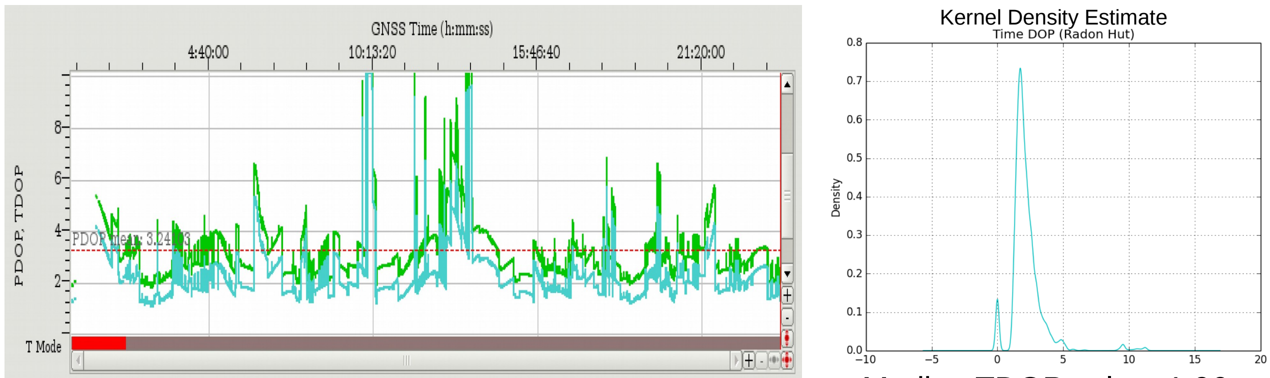
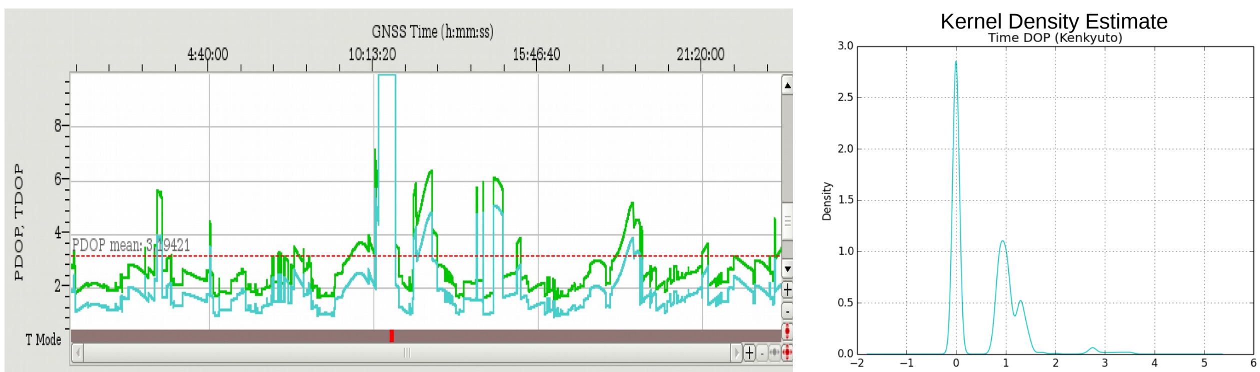


Figure 11: Histogram of SVs in PVT at ***Kenkyu-tou***



Median TDOP value: 1.96

Figure 13: Dilution of Precision at ***Radon Hut***



Median TDOP value: 0.78

Figure 14: Dilution of Precision at ***Kenkyu-tou***

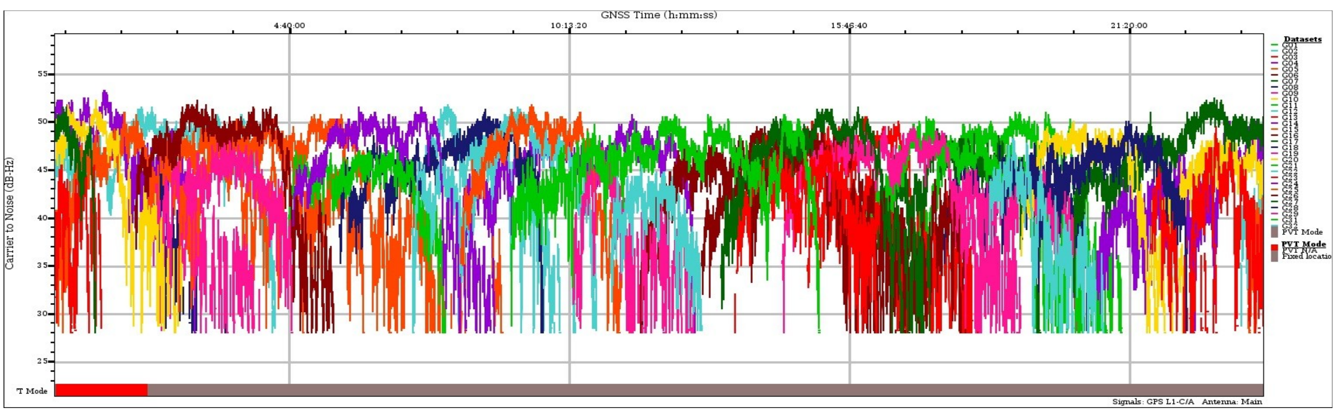


Figure 15: Signal-to-noise ratio (L1 carrier freq., Coarse/Acquisition code) at ***Radon Hut***

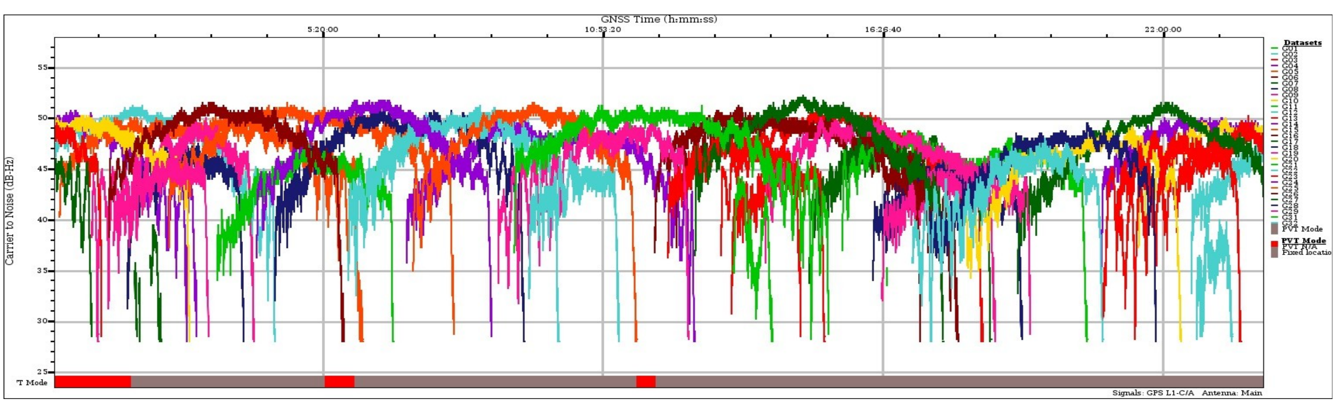


Figure 16: Signal-to-noise ratio (L1 carrier freq., Coarse/Acquisition code) at ***Kenkyu-tou***

Changes at Super-Kamiokande

Several changes in the equipment configuration should be noted:

1. OT 1PPS source change
2. OT 1PPS delay change
3. Rb 1PPS OUT cable change
4. Antenna cable split to NICT CV receiver
5. 10MHz provided by PT Rb clock

The first change of note directly affects the PT-OT measurements at Super-Kamiokande. Previously, when equipment was in the Radon Hut, the Official Time signal was taken from the GPS2 Primary receiver. After moving the equipment, the OT signal was taken from the GPS1 Primary receiver. Documentation has been updated, accordingly.

The second change also affects the PT-OT measurement. The cables connecting the OT signal source to the NICT pulse distribution amplifier was changed. The previous OT-to-TIC delay was 33.1ns and the current delay is 25.8ns. The new delay measurement was performed on site after installation was completed at the Kenkyu-tou location. Documentation has been updated, accordingly.

The third alteration is minor, affecting the PT Rubidium clock 1PPS output. The 2 meter LMR400 cable connecting the Rubidium 1PPS OUT to the PT reference plane was replaced with a 1 meter composite LMR400 cable and the new delay was measured. This was done so that the 2 meter cable could be taken to NU1 and used to achieve a symmetric delay in the cable path leading away from the PT 1PPS output port. (See Changes at J-PARC.)

A forth and final change to the configuration at Super-Kamiokande is that the 10MHz source was changed to the PT Rubidium clock. Previously, 10MHz was provided by the CV CODER receiver and delivered to the NICT TIC via the isolation amplifier. Now, the amplifier is fed by the Rubidium clock and both NICT and LSU TIC instruments are supplied with 10MHz reference signals. Documentation has been updated.

Temporary Antenna Change at Super-Kamiokande

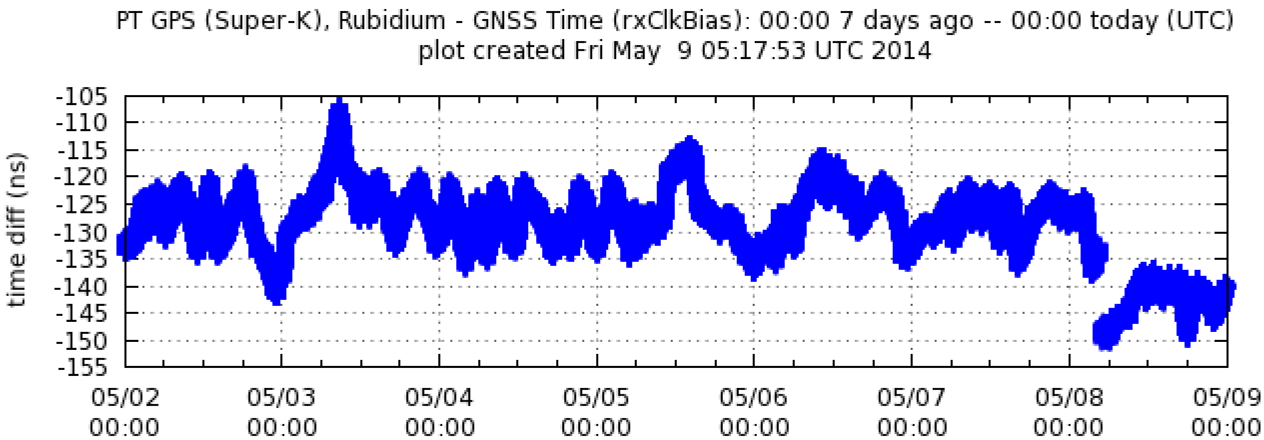


Figure 17

On 7 February, 2014, several days after the relocation of timing equipment, the GPS antenna cable for the Precise Time System at Super-Kamiokande, was split in order to permit the NICT Common View receiver to share the antenna. Consequently, an extra cable of approximately 15 ns (3 meters) was added to the antenna cable. No adjustment was made in the timing signal to account for this change. The sharing of the PT antenna was discontinued on 8 May, 2014. Therefore, the timing signals from the PT system where, during this period, delayed by approx. 15 ns. If the Precise Time System timing data from this period is used, it must be adjusted to account for this additional delay, among others.

This effect is clearly observed in the time difference, as measured by the PT System GPS receiver (Septentrio PolaRx4), between the PT Rubidium local clock and the calculated GNSS (GPS) time solution. This time difference is directly related to the antenna delay. A roughly 15 ns change is observed after this extra antenna cable was removed near 03:00 8 May, 2014 UTC. See the plot in Figure 17.

It should be noted that satellite signal quality was affected during this time. The C/No ratio ratio was degraded from what is shown above in Figure 16. The signal strength under the split antenna condition is plotted in Figure 18, for comparison.

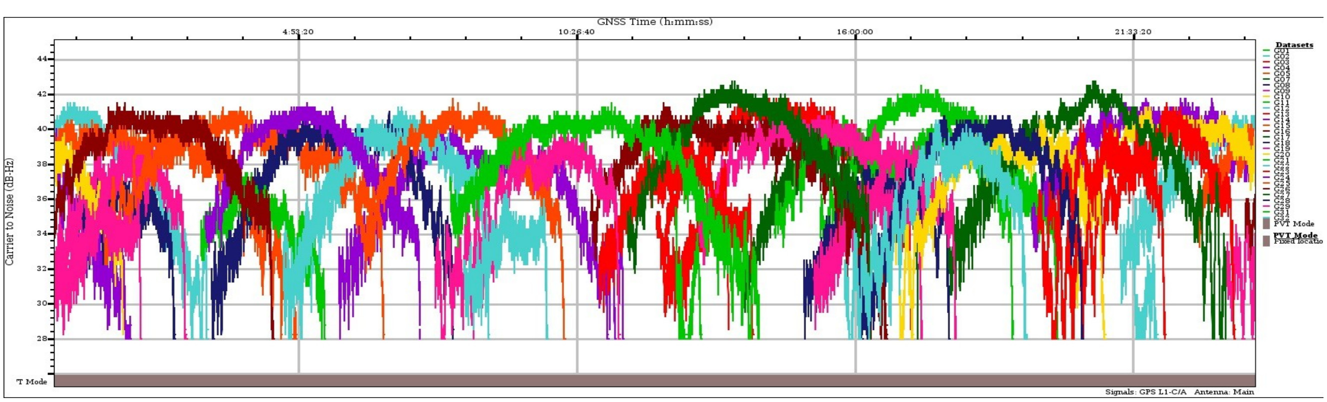
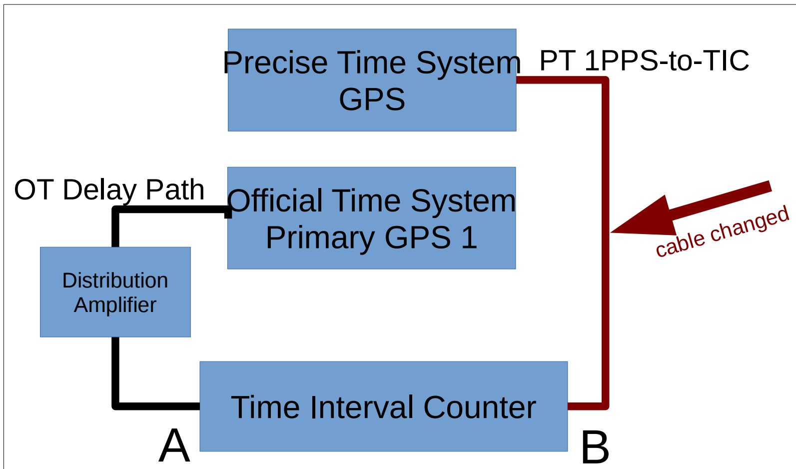


*Figure 18: Signal-to-noise ratio (L1 carrier freq., Coarse/Acquisition code) at **Kenkyu-tou** while antenna shared with NICT Common-View CODER receiver*

Changes at J-PARC

The only change at J-PARC is the replacement of a cable in the path of the PT 1PPS timing signal. This change makes the delay between the PT GPS receiver's 1PPS output port and the reference plane the identical at both NU1 and Super-Kamiokande. This reduces the uncertainty of time-transfer measurements, since now the whole-path delays for the PT signal is same at both sites. The previous cable, used since installation, had a delay of 10ns (nominal); the replacement has a delay of 8.2ns.



Drawing 1: Diagram of cable changed at J-PARC NU1 building.

In addition, the reference plane was moved from the rear of the rack to the front. Consequently, the cables on either side of the reference plane were swapped, but this does not affect cable delays, of course. Documentation has been updated. (See Figure 19, Drawing 1, and Appendix A.)

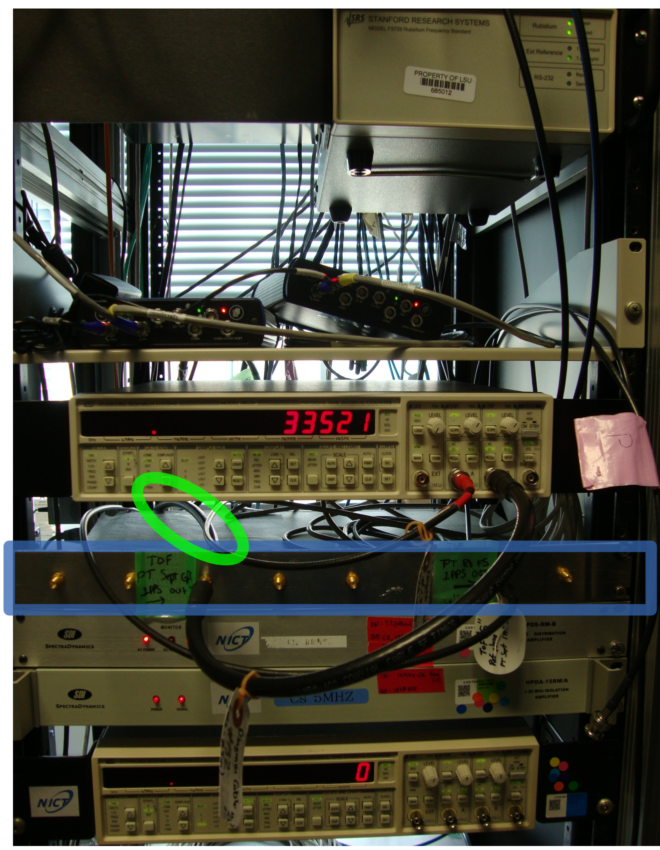


Figure 19: NU1 Precise Time System

Miscellaneous Tasks

Several other tasks were completed:

1. Auto-calibration of TICs
   1. SK LSU TIC: 1 February
   2. SK NIC TTIC: 1 February
   3. NU1 LSU TIC: 3 February
   4. NU1 NICT TIC: 3 February
   5. TravTIC: 6 February
2. Measured and calibrated some TIC internal clocks
   1. NU1 LSUTIC: 6 February
   2. TravTIC: 6 February
3. Added 10MHz reference to TICs at Kenkyu-tou from PT Rb Clock (via isolation amplifier).
4. Added 10MHz signal to TICs at NU1 from NICT CODER receiver (via isolation amplifier).
5. Measured some whole-path delays
6. Moved reference plane at NU1 (See Figure 19.)
7. Upgraded all PolaRx4 receiver firmware to version 2.5.2
8. Upgraded PT PC monitoring software to RxTools Package version 1.10.0
   1. library version 2.1.11
   2. RxControl version 4.11

The duty cycle of the SRS SR620 Time Interval Counter instruments is 1000 hours. After using the TICs for this amount of time, it is necessary to perform a calibration. The instrument is capable of self-calibrating most adjustable parameters, however, so this auto-calibration was completed for all five TICs deployed at Super-Kamiokande, J-PARC, including the Traveler TIC. Auto-calibration was performed before any other measurements made during this trip. The “LSU” TIC instruments were purchased by Louisiana State University and are the primary measurement devices used at both sites to measure the time difference between the OT & PT timing signals. The “NICT” TIC instruments were purchased by NICT and have been used for various secondary measurements and calibrations. In the past, it had also been used to measure the time difference between the PT Rubidium clock and the OT timing signals. That measurement has been abandoned because the OT Rubidium clock is steered by the OT signal and it is, therefore, of little interest.

One of the TIC internal parameters that must be manually calibrated is the internal oscillator frequency adjustment. The internal oscillator frequencies were measured using the PT Rubidium clock at Kenkyu-tou and NU1. The oscillator in the traveler TIC was compared to the Cesium clock frequency in the Traveler Box. Here are the results:

TIC	Freq Before Calibration (Hz)	Jitter (μHz)	#Meas
NU1 LSUTIC	10000001.15165	255	200
NU1 NICTTIC	9999998.819589	315	200
SK LSUTIC	9999999.99853		
SK NICTTIC	9999993.00975		
Traveler TIC	9999999.998390	174	100

The frequency adjustment parameter of the NU1 LSUTIC and the Traveler TIC were adjusted until the 50 measurement mean was within 100 microhertz of 10MHz. The internal oscillator calibration was performed after other measurements, such as whole path delays, made during this trip. Due to time constraints, the NICT TICs were not able to be calibrated.

The measured departure from 10MHz is larger among the TICs without Option 1, the ovenized oscillator, which is expected. It is preferable to use an external frequency reference for these TICs and the NICT TICs were installed in such a configuration. Since the TOF DAQ software selects the internal frequency source, however, these measurements are noteworthy.

In addition to these calibrations, several whole-

path delays were measured. These delay measurements have been added to the cable list spreadsheet. (See Hardware Details (Current)[5].)

The remaining listed miscellaneous tasks are not discussed.

Additional Changes Accommodating Long-Term Sustainability of the Precise Time System

In the time between the relocation of the Super-Kamiokande timing equipment and the restart of the T2K neutrino beam, several other changes were made to the Precise Time System. Some of these changes addressed unanticipated problems that arose after the move. All of them, however, were necessary to improve the robustness and, thus, the long-term usefulness of the Precise Time System.

These changes were:

- Adding a 300 ns delay to the PT system 1PPS timing signal
- Automating the recovery of the PT-OT measurement data acquisition (DAQ) system
- Implementing periodic, automated calibration of the Time Interval Counter (TIC)
- Adjusting the TIC measurement settings
- Miscellaneous DAQ software fixes

Self-Imposed 300 ns Delay

After relocating the time systems to Kenkyu-tou, it was discovered that the PT-OT measurements are very large, nearly 1 second. (See Figure 25.) This is undesirable as it increases the measurement uncertainty and, in this condition, every other measurement is lost. Consequently, this increases the complexity of applying the measurements as corrections to the OT event time-stamps and, worse, some information is permanently lost.

To eliminate this condition, the PT 1PPS signal was deliberately delayed by a specific known value, 300 ns. This was implemented in the PT system at both Super-K and the NU1 building at J-PARC so the impact is symmetric. This solves the problem by shifting the 1PPS timing signal so that it will always be measured later than the OT 1PPS timing signal, but only very slightly later so that the measurements are on the order of 100 ns. That is to say, the measurements are certain to be not too large and not too small.

For accurate absolute timing, of course, this self-imposed delay must be taken into account. For site-to-site comparisons, however, such as time-of-flight studies, for example, it can be safely neglected.

DAQ Automatic Recovery

All of the data produced by the Precise Time System is automatically transferred from the T2K network to two systems, one at the University of Washington and one at Louisiana State University. The key data acquisition program, however, was not automated. This is the program that measures the PT-OT time differences.

This program was automated on 04 May, 2014. Since then, the program automatically starts when either of the PT system monitoring computers at Super-Kamiokande or at the J-PARC NU1 building are restarted. Should the PT-OT measurements cease for any reason, the PT PC need only be rebooted to restart the DAQ program. This component was automated in this way to reduce the complexity and increase the sustainability of PT system.

Periodic Auto-Calibration

It is recommended by the manufacturer that the Time Interval Counters be calibrated at least once every 1000 hours of operation. Calibrations have two distinct components: self- calibrations and calibrations of the internal oscillator. Both the LSU TIC at NU1 and the Traveler TIC were fully

calibrated in January, 2014. (See Miscellaneous Tasks.)

The auto-calibration updates all adjustable parameters of the TIC instrument, except for the frequency of internal oscillator. Instructions to initiate TIC auto-calibrations at regular intervals was incorporated into the PT-OT measurement DAQ program and deployed. This also occurred in May, 2014, and ensures the instrument will continue to produce reliable measurements in the future.

The internal oscillator is an option installed in only some of our TIC instruments. Calibrating the oscillator is prohibitively complicated to automate, however, and no such work is planned for the future. Instead, the PT Rubidium clock provides a timebase or reference frequency to both TIC instruments at Super-Kamiokande and the J-PARC NU1 building. The new DAQ program also instructs the TIC to use the external reference instead of the internal oscillator. This also ensures the reliability of the PT-OT measurements in the future.

DAQ Measurement Settings

One other change was also made to the DAQ program in May, 2014. TIC measurements are now made using the +TIME trigger arming mode. The previous trigger arming mode, ±TIME, has some ambiguity as to the order of the measurement. The +TIME mode always measures time values between the Start trigger and the Stop trigger, which are set by the DAQ program. This change gives more control to the DAQ program and ensures that the TIC measurements are always the intended measurement.

Use of Galileo Constellation Discontinued

In April, 2014, it was discovered that satellites from the Galileo constellation were significantly affecting the time solution of the PT system GPS receivers. Since other constellations provided more than enough satellites to perform the necessary time solutions, Galileo satellites are excluded in the receiver configurations of all three installations: J-PARC NU1 building, J-PARC ND280, and Super-Kamiokande.

Use of GLONASS Constellation Discontinued at J-PARC

Also in April, 2014, the GLONASS constellation experienced two global service outages which also affected the PT system GPS receivers. While investigating the impact on the PT system, it was discovered that the use of multiple GNSS constellations presents significant challenges for precision timekeeping. Consequently, it was decided that GLONASS should also be excluded, if possible. At J-PARC, where the sky-view is excellent, GLONASS is no longer used by the PT GPS receivers. This was implemented on 2 May, 2014, for the receiver at NU1 and, later in May, for the receiver at ND280.

Though the sky-view is improved at Kenkyu-tou, there are still too few GPS constellation satellites visible at all times to remove GLONASS from the PT receiver configuration at Super-Kamiokande.

Precise Time System Monitoring Web-Site

The GPS-based Official Time System is easily monitored by responsible parties and any interested T2K member using a simple web-site hosted at the University of Washington:

- J-PARC OT System Monitor[6]
- Super-Kamiokande OT System Monitor[7]

A similar web-based monitoring system was created to assist T2K members in monitoring the Precise Time System performance and results.

- Precise Time System Monitor[8]

Recommendations

In anticipation of the restart of T2K beam, there is one further change that may prove valuable for future users of the Precise Time System: a final cable change at Super-Kamiokande. It is recommended that two 2 meter EnviroFlex 400 SMA-to-BNC cables, identical to those connecting the Official Time 1PPS signal to the Time Interval Counter at NU1, be sent to Kenkyu-tou to replace the symmetric cable path at Super-K. This last cable change would render the PT-OT measurements identical at both sites, reducing the uncertainty in any future site-to-site difference measurement.

Appendix A

Table of Changes at Super-Kamiokande

Item	Prior State	Current State	Who?	Date Changed
All PT Components	Radon Hut	Kenkyu-tou building	P. DeStefano	2014.01.31
OT 1PPS source	GPS2 Primary	GPS1 Primary	P. DeStefano	2014.01.31
OT-to-TIC delay	33.1 ns	25.8 ns	P. DeStefano	2014.01.31
Rubidium 1PPS IN cable	2 meter LMR400	1 meter LMR400	P. DeStefano	2014.01.31
10MHz Ext Ref for LSUTIC	None	OT Steered PT Rubidium	P. DeStefano	2014.01.31
S-K PT Antenna	Direct, single cable	Split w/ NICT CODER Receiver	P. DeStefano	2014.02.07
DAQ Software	June 2013 version	May, 2014 version	P. DeStefano	2014.05.04
S-K PT Antenna	Split W/ NICT CODER Receiver	Direct, single cable	P. DeStefano	2014.05.08
Galileo excluded	All satellite constellations included	GPS & GLONASS constellations only	P. DeStefano	2014.05.02

Table of Changes at J-PARC

Item	Prior State	Current State	Who?	Date Changed
PT-to-TIC delay	12.7 ns	10.2 ns	P. DeStefano	2014.02.03
10MHz Ext Ref for LSUTIC	None	NICT CV CODER Receiver	P. DeStefano	2014.02.03
DAQ Software	June 2013 version	May, 2014 version	P. DeStefano	2014.05.04
Galileo & GLONASS excluded	All satellite constellations included	GPS constellation only	P. DeStefano	2014.05.02

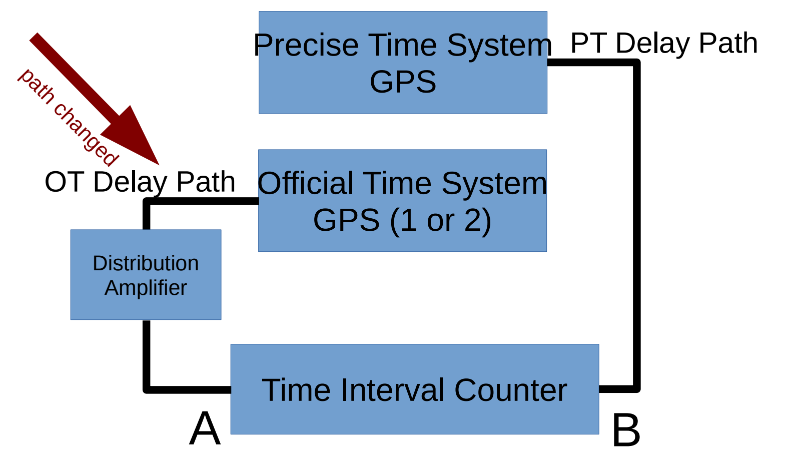
Appendix B

Measurement of the Shift in the Super-K Official Time System

Measurement

The aforementioned measurements of the shift in the Official Time System are the result of analysis that combines four independent measurements:

1. Time differences between the Official Time System and the Precise Time System.
2. Cable delays in the instrumentation.
3. Internal GPS receiver measurements of 1PPS signal "offsets" (which are the differences between PT 1PPS and GPS timescales).
4. Time differences between the two primary GPS receivers that compose the Official Time System.



Drawing 2: PT vs OT Measurement Diagram

The time difference between the Official Time System and the Precise Time System is measured every second using an Time Interval Counter (TIC). These direct measurements form the basis for the analysis described in this document. The complete configuration is described in documents linked to the [Precise Time System Hardware documentation page](#).[9] There is no reason to suspect the PT system timescale shifted relative to the OT system as a result of the move, since it does not use optical fiber links. Also, the accuracy of the PT system relative to GPS time is documented to be +/- 10 nanoseconds (before xPPS offset corrections). Furthermore, experience of the PT GPS receiver as deployed has shown that power resets do not have a noticeable effect on timing solutions. Thus, the PT system serves as a reference timescale for the OT system before and after the relocation of equipment.

In addition, relevant changes to the cable between the OT system and the TIC are described earlier in this document and summarized in Appendix A. When the cable was installed that carries the 1PPS signal from the OT system to the TIC, the delay path was measured to be 33.1 ns. This cable was not changed until both OT and PT systems were relocated to Kenkyu-tou. After this relocation, a new cable was installed between the OT and PT systems and the delay path was measured to be 25.8 ns. Since the delay was altered during the period in question, the measured time difference at the TIC device cannot be used to determine the change in timescales between the two timing systems without adjusting for TIC channel delays.

The last measurement of relevance is the difference between the timescales of the two GPS receivers within the OT system, namely, GPS1 primary and GPS2 primary. The time difference between these two timescales is measured by the Local Time Counter (LTC), which is part of the OT system. This data is used to refer GPS1 to GPS2 and vice-versa, since the PT system 1PPS is compared to only one of the two primary GPS 1PPS timing signals using the TIC. In order to calculate the the shift for the OT GPS receiver that was not measured by the TIC, it is necessary to combine the TIC and LTC measurements to make an indirect comparison. It should be noted that the LTC uses a 60MHz reference frequency and, therefore, has a native resolution of 16.6 ns.

Analysis

The measurements described above were used in the following procedure. The first adjustment was a correction for the physical cable delays between the two time systems. Then, the internal measurement of the PT GPS receiver 1PPS offset was applied. Next, a special adjustment was applied to a portion of the data in which the TIC measurements were nearly 1.0 seconds. These measurements required special treatment. Finally, the LTC measurements of GPS1-GPS2 were applied to yield two separate sets comparison data, one for each of primary OT GPS receivers.

The raw measurement data from the TIC is shown without any adjustments in Figure 24 and Figure 25. Figure 24 shows the TIC measurements taken at the Radon hut location where the values are the time differences between the arrivals of PT system 1PPS and the OT GPS2 primary 1PPS timing signals: $PT - OT_{GPS2}$. Figure 25 shows the TIC measurements taken at Kenkyu-tou where the values are the time differences between the PT system 1PPS and the OT GPS1 primary 1PPS timing signals: $PT - OT_{GPS1}$.

Cable Delays

The following formula was used to correct for cable delays in the instrumentation.

$$TIC\ \ Measurement = (PT + delay_{PT}) - (OT + delay_{OT})$$
$$TIC\ \ Measurement = PT - OT + delay_{PT} - delay_{OT}$$
$$PT - OT = TIC\ \ Measurement - delay_{PT} + delay_{OT}$$

where the values of cable delays are shown in the table from Appendix A.

Precise Time System GPS Receiver xPPS Offsets

As described elsewhere in documentation for the Precise Time System, the GPS receiver produces a timing signal that is accurate to 20 ns. It also provides, however, aninternal measure of the time difference between the generated one pulse per second signal and the calculated GPS 1-second rollover time. This difference is referred to as the xPPS “offset”. It is extracted from the receiver logs and used according to the following definition.

$$xPPSoffset = PT\ xPPS\ Time - GPS\ Time$$

where we call the 1 PPS signal “PT xPPS” for generality. Combined with the preceding result, this gives

$$(TIC - delay_{PT} + delay_{OT}) - xPPSOffset = (PT - OT) - (xPPS\ \ Time - GPS\ \ Time)$$
$$TIC - delay_{PT} + delay_{OT} - xPPSOffset = GPS\ \ Time - OT$$

since the PT signal time is the PT xPPS signal time.

1-second Adjustment of Kenkyu-tou Measurements

Using the two adjustments described thus far, what is achieved is a comparison of the OT timescale and GPS time. There is a complication, however, that must be addressed before further corrections are considered. Before the move, the OT timing signal preceded the PT timing signal and instrumentation was configured to measure this value as simply as possible. The equation was $TIC_{RadonHut}\,Measurement = PT - OT$ such that positive values would indicate the amount of time the PT system lagged the OT system.

After the move, however, the TIC measurements were changed. The OT signal now lagged the PT signal. Under this condition, the TIC was unable to give a comparable measurement, which would have been negative values. Instead, a different measurement was performed: the time difference between *adjacent* 1 second rollover signals. This is the reason the measured values shown in Figure 25 are so large. These are valid measurements, but they correspond to a different measurement than before.

The correct equation for these measurements is

$$TIC_{Kenkyuto}\,Measurement = (PT + delay_{PT}) - (OT_{previous} + delay_{OT})$$

where

$$OT_{previous} = OT - 1\,second$$

Substituting yields

$$TIC_{Kenkyuto}\ Measurement = (PT + delay_{PT}) - (OT - 1\ second + delay_{OT})$$
$$TIC_{Kenkyuto}\ Measurement = PT - OT + 1\ second + delay_{PT} - delay_{OT}$$
$$PT - OT = TIC_{Kenkyuto}\ Measurement - delay_{PT} + delay_{OT} - 1\ second$$

This equation gives the difference between PT and OT timescales, which is directly comparable to the measurements made previously at the Radon hut.

It is critical to note that the xPPS offset measurement from the PT GPS receiver matches the time recorded for the measurement on the DAQ computer, while the OT GPS1 primary receiver signal was from the *previous* 1 second rollover. This has two implications in addition to the formula change. The first is that the xPPS offset adjustments must be matched to the TIC measurements using the recorded time of the TIC measurement. This is because the measured PT signal is the later of the two signals and this causes the TIC measurement to be recorded with the later time stamp. The second implication is that the opposite is true for the OT signal. It was produced the previous second and, therefore, any further adjustments to the OT signal must be applied using the *previous* second's adjustment.

Official Time System GPS1 and GPS2 Adjustments

As previously mentioned, the Time Internal Counter measurement only compares 1PPS timing signals from one of the *two* primary OT GPS receivers. A comparison of the PT system verses the other OT GPS receiver can be accomplished using the time difference between GPS1 and GPS2 as measured by the LTC.

$$LTC\,Measurement = OT_{GPS1} - OT_{GPS2}$$

Combining this equation with the previous formula for comparing GPS2 against GPS Time at the Radon hut yields a comparison of GPS1 and GPS Time at the Radon hut:

$$TIC_{RnHut} - delay_{PT} + delay_{OT} - xPPSOffset = GPS\ Time - OT_{GPS\,2}$$
$$TIC_{RnHut} - delay_{PT} + delay_{OT} - xPPSOffset = GPS\ Time - (OT_{GPS\,1} - LTC\ Measurement)$$
$$TIC_{RnHut} - delay_{PT} + delay_{OT} - xPPSOffset - LTC\ Measurement = GPS\ Time - OT_{GPS\,1}$$

Also, the LTC measurement can be combined with the formula for GPS1 vs GPS Time at Kenkyu-tou, which yields a new comparison of GPS2 and GPS Time at Kenkyu-tou:

$$TIC_{Kenkyuto} - delay_{PT} + delay_{OT} - xPPSoffset - 1\ second = GPS\ Time - OT_{GPS\ 1}$$
$$TIC_{Kenkyuto} - delay_{PT} + delay_{OT} - xPPSoffset - 1\ second = GPS\ Time - (LTC\ Measurement + OT_{GPS\ 2})$$
$$TIC_{Kenkyuto} - delay_{PT} + delay_{OT} - xPPSoffset - 1\ second + LTC\ Measurement = GPS\ Time - OT_{GPS\ 2}$$

Again, it is emphasized that the value of $delay_{OT}$ is also different at the Radon hut than it is at Kenkyu-tou.

Calculation of the Change in the Official Time System

Thus far, four equations have been derived. This set of formulae compare both of the OT system GPS receivers to a common reference, GPS Time as resolved by the PT system's GPS receiver. All that remains is to combine corresponding equations for each OT GPS receiver to find the net change in each OT GPS receiver's 1PPS time signals. Symbolically, all four quantities have the form

$$GPS\,Time - OT_{before} \quad \text{and} \quad GPS\,Time - OT_{after}$$

Therefore

$$GPS\,Time - OT_{before} - (GPS\,Time - OT_{after}) = OT_{after} - OT_{before}$$

where the GPS Time of the PT system cancels because it is the standard against which the OT system is being compared. It is reasonably assumed that the time solutions of the PT system GPS receiver before and after the move are consistent to within the uncertainty of the system.

Final results can now be directly calculated from the mean values of the fully adjusted measurements before and after the relocation to Kenkyu-tou. The following table contains the calculated mean values and the resulting net change for both GPS1 and GPS2 primary OT receivers:

Mean Values (Fully Adjusted)	
GPS Time – OT GPS1 Before	87.3 ns
GPS Time – OT GPS1 After	-112.0 ns
OT GPS1 After – OT GPS1 Before	-199.3 ns
GPS Time – OT GPS2 Before	90.7 ns
GPS Time – OT GPS2 After	-132.3 ns
OT GPS2 After – OT GPS2 Before	-223.0 ns

Uncertainty

The combined uncertainty of the measured change in the Official Time System is estimated as the sum of the estimated standard uncertainties for each of the component quantities in the calculation just derived. The following table lists each of these component measureands and the estimated uncertainty or uncertainties associated with its estimation. The methodology used to determine each estimated uncertainty is discussed after, although a short note is provided in the table. Type A uncertainties are estimated using statistical analysis of a series of observations, while Type B uncertainties are estimated by other means.

Uncertainty: Sources and Estimation in Final (After-Before) Calculation			
Measurement Component	Type A (ns)	Type B (ns)	Methodology
OT cable delay before move		0.5	Dominant TIC uncertainty factor from documentation
OT cable delay after move		0.5	Dominant TIC uncertainty, different TIC
PT cable delay		0.0	Same measurement cancels itself in final calculation
$TIC_{Kenkyuto} - TIC_{RadonHut}$		< 0.1	In a difference of difference measurements using the same TIC, systematic uncertainty cancels
Absolute GSP Time After – Absolute GPS Time Before	9.1		Unbiased standard deviation of Precise Point Positioning (a.k.a. post-processing) residuals
PT 1PPS w/ xPPS correction		3.0	Estimate given by manufacturer
OT GPS1 vs OT GPS2		9.6	$\frac{1}{\sqrt{3}}\delta x$ where δx is the LTC resolution, 16.6 ns
Combined Uncertainty	22.8		Sum

Cable delay measurements were made using the TIC and have uncertainties recorded with their measurement. The documented uncertainty calculations for the TIC are complex. For small measurements on the order of 100 ns or smaller, however, they are dominated by an additional, fixed, 0.5 ns uncertainty component that cannot be reduced by repeated measurements. Thus, the uncertainty for the delays are estimated at 0.5 ns. The uncertainty of the cable delay between the PT system and the primary measurement trigger is eliminated, however, as it is the same before and after the move and the quantity is canceled by itself in the final calculation (after move - before move).

The TIC is also used for primary measurements and, therefore, also incurs a 0.5 ns minimum uncertainty. The manufacturer, however, suggests that systematic uncertainties, like this dominant term, are canceled in the difference calculation of measurements made by the same TIC. Consequently, the uncertainty is estimated for the for the overall after-before calculation at less than 0.1 ns, which accounts for the remaining terms such as a 25ps resolution, for instance.

The uncertainty of the absolute GPS Time solutions provided by the Precise Time System's GPS receivers is estimated as the unbiased standard deviation of the GPS Time corrections calculated in post-processing by Precise Point Positioning software. The uncertainty is 4.6 ns (see Figure 36), but occurs twice in the after-before calculation, so it must be doubled. The uncertainty of the 1PPS signal with respect to the GPS Time calculated by the PT GPS receiver is estimated by the manufacturer to be +/- 3 ns *after* xPPS corrections. Finally, the time difference between GSP1 and GPS2 primary 1PPS signals is assumed to lie somewhere in the interval $X-\delta x$ and $X+\delta x$ where X is the value indicated by the LTC and δx is the resolution of the LTC (16.6ns). The probability distribution over this interval is assumed to be rectangular, meaning the value indicated is equally likely for any time difference measureand in the interval. The standard uncertainty for such a distribution is $\frac{1}{\sqrt{3}}\delta x$.

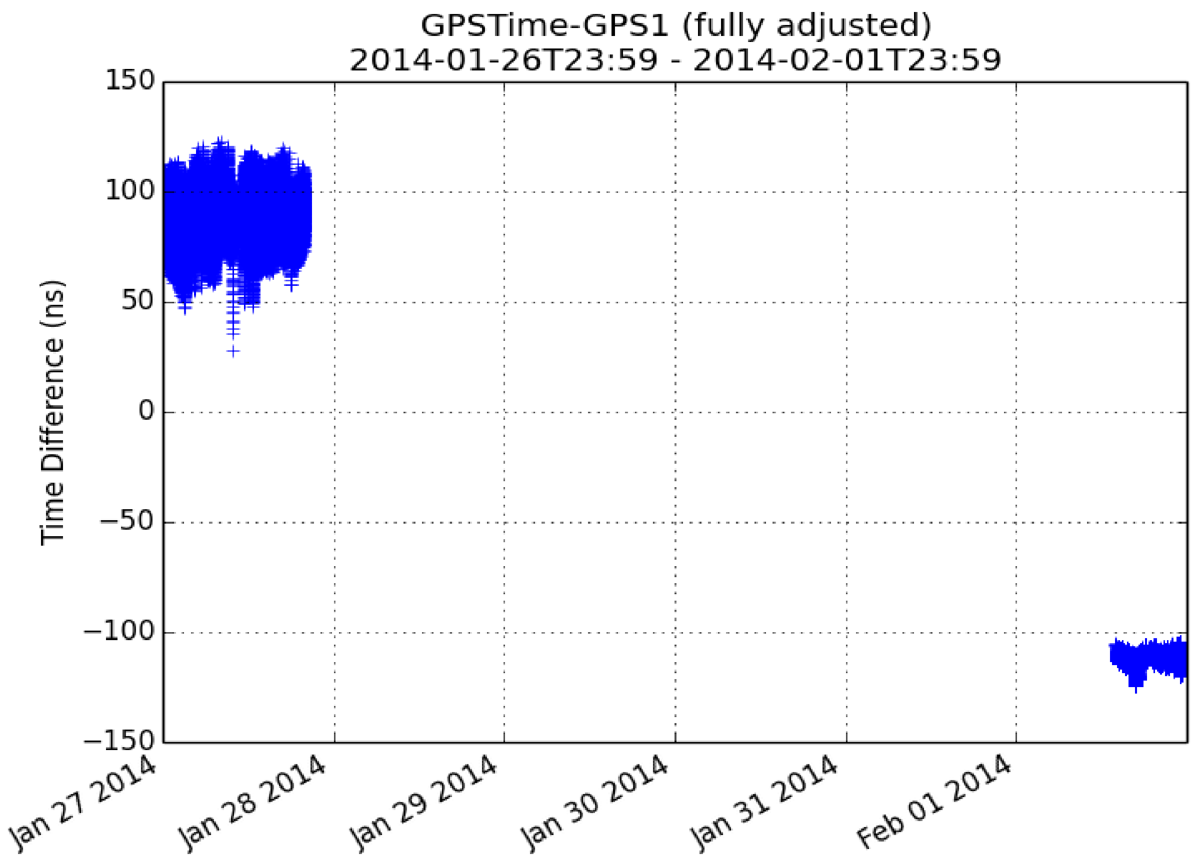


Figure 20

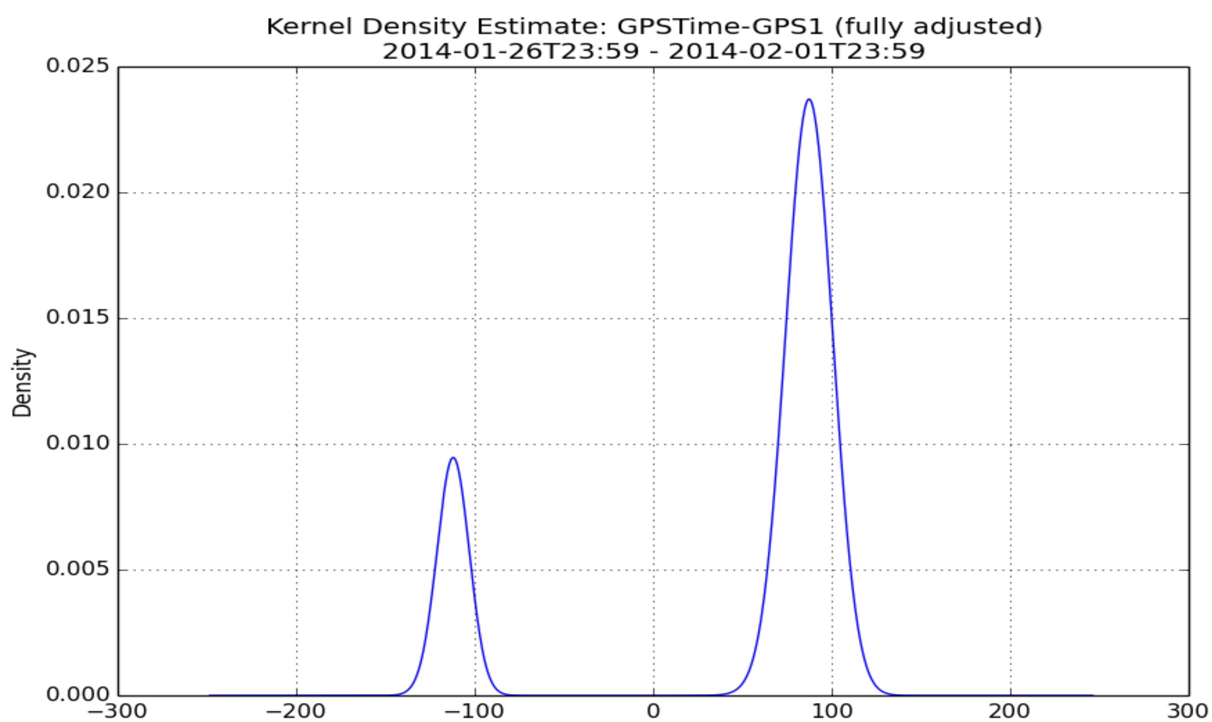
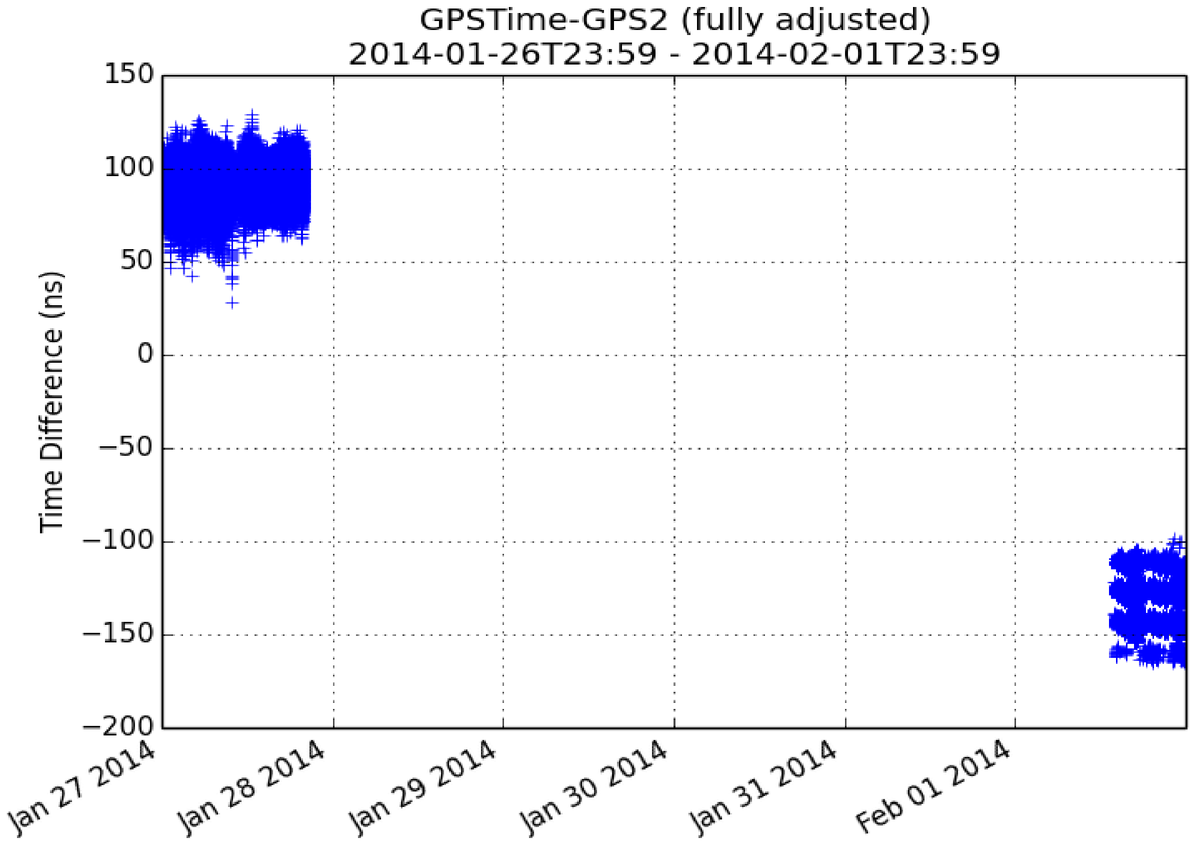


Figure 21


GPSTime-GPS2 (fully adjusted)
2014-01-26T23:59 - 2014-02-01T23:59
Time Difference (ns)
150
100
50
0
−50
−100
−150
−200
Jan 27 2014
Jan 28 2014
Jan 29 2014
Jan 30 2014
Jan 31 2014
Feb 01 2014

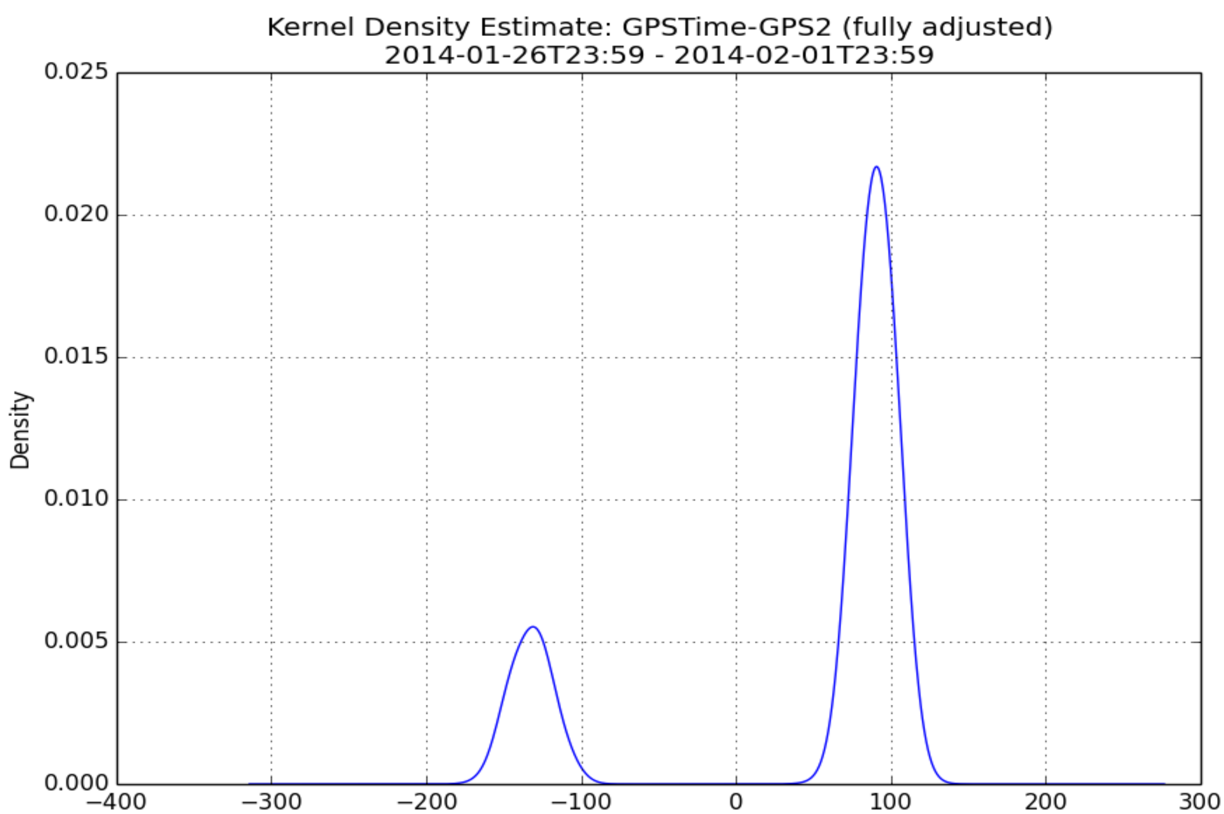

Kernel Density Estimate: GPSTime-GPS2 (fully adjusted)
2014-01-26T23:59 - 2014-02-01T23:59
Density
0.025
0.020
0.015
0.010
0.005
0.000
−400
−300
−200
−100
0
100
200
300

Figure 23

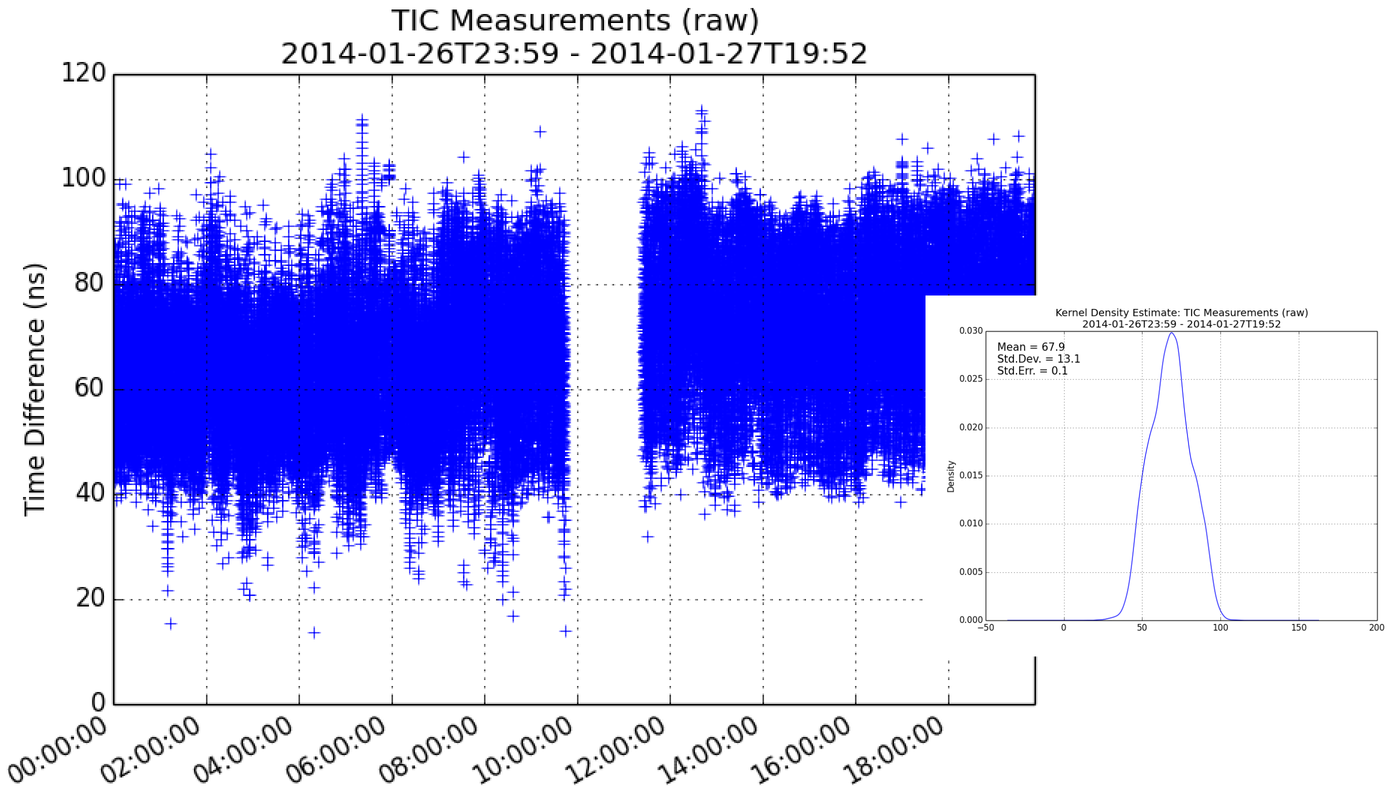


Figure 24

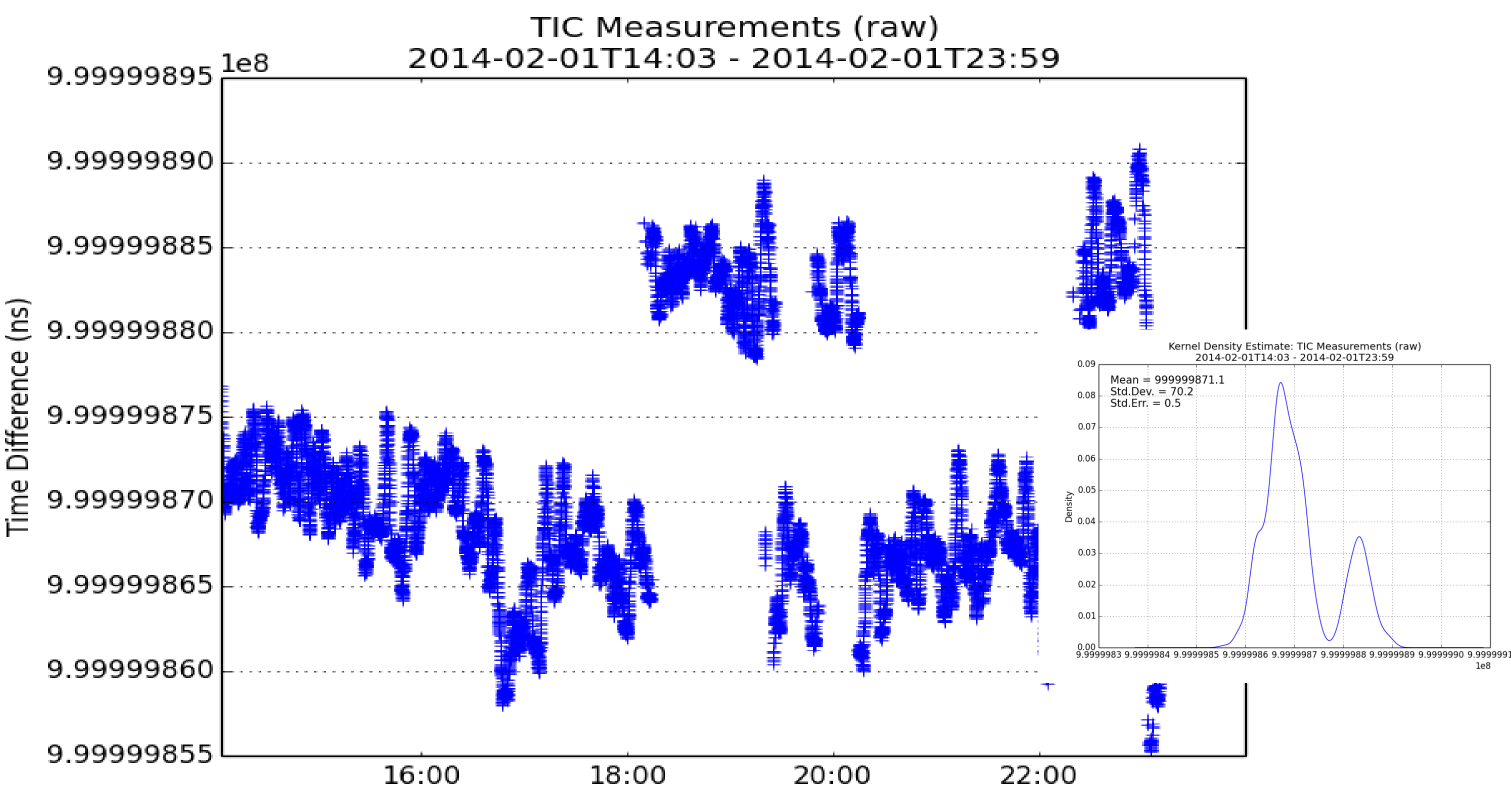


Figure 25

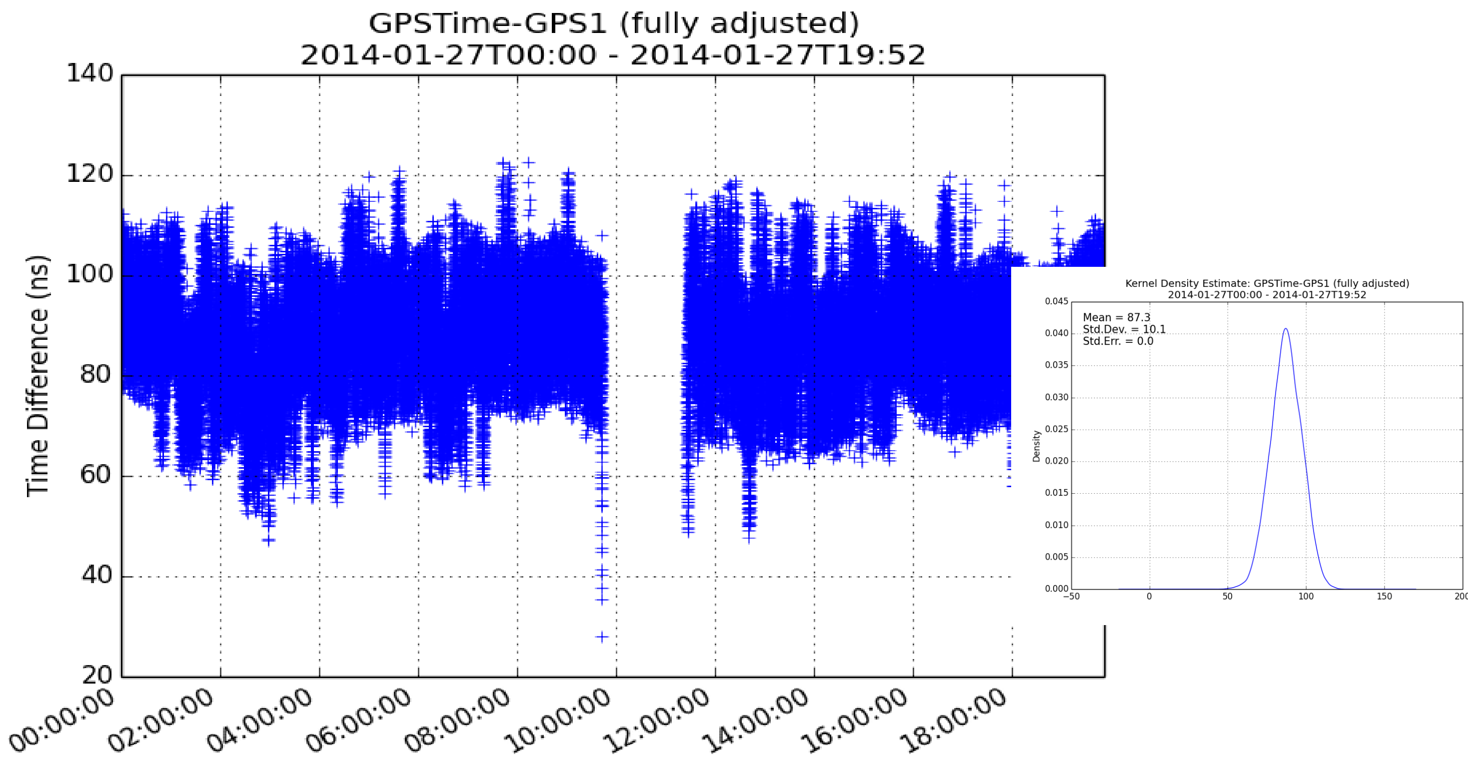


Figure 26

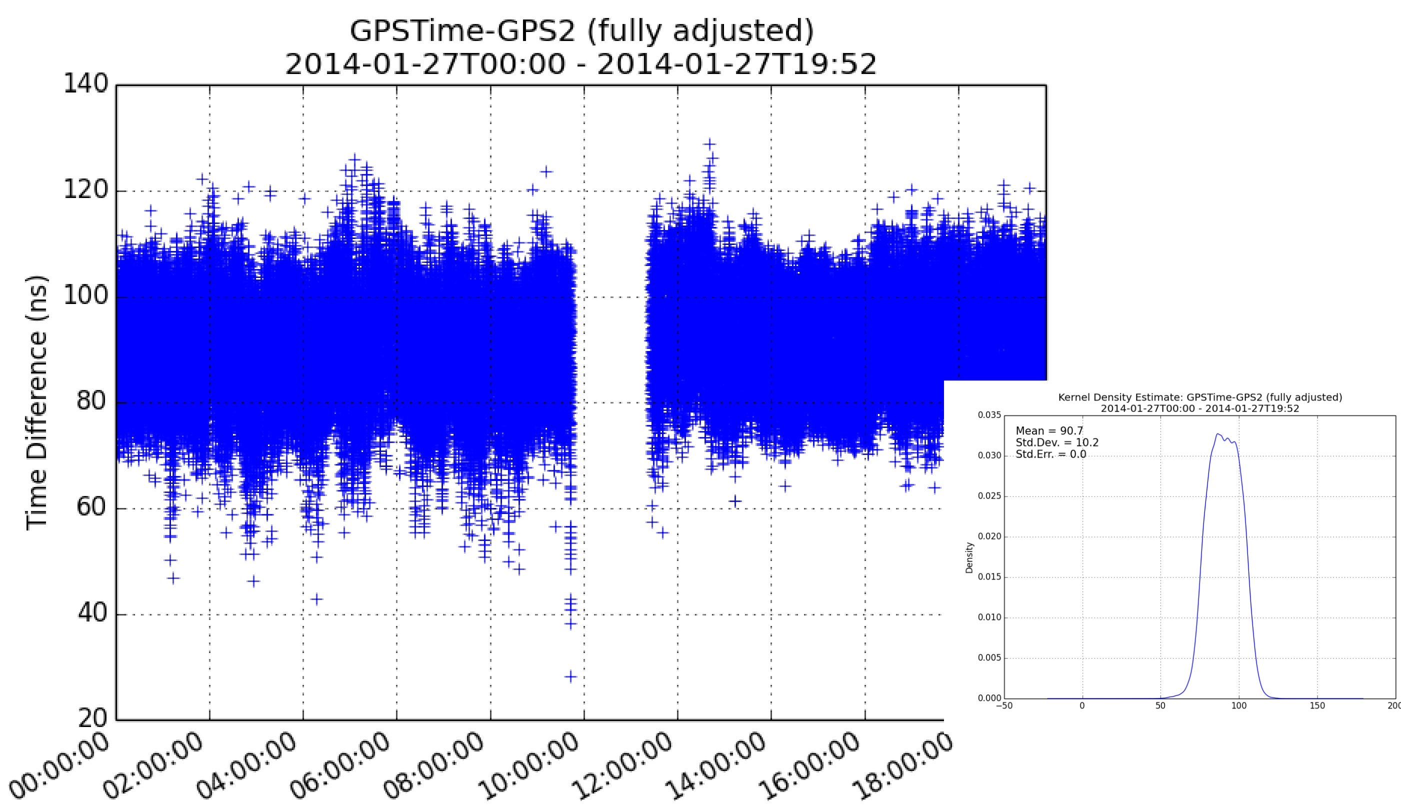


Figure 27

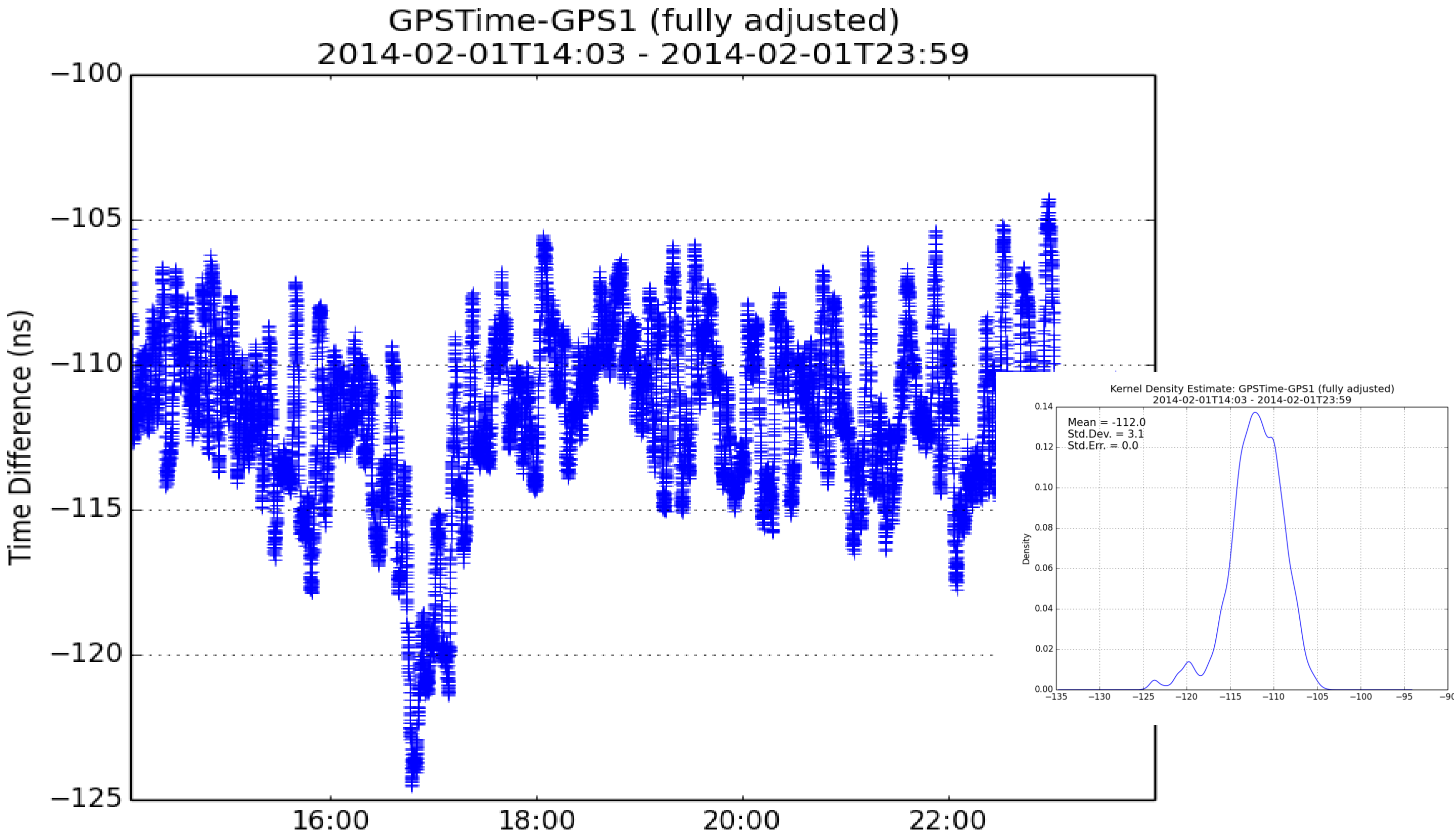


Figure 28

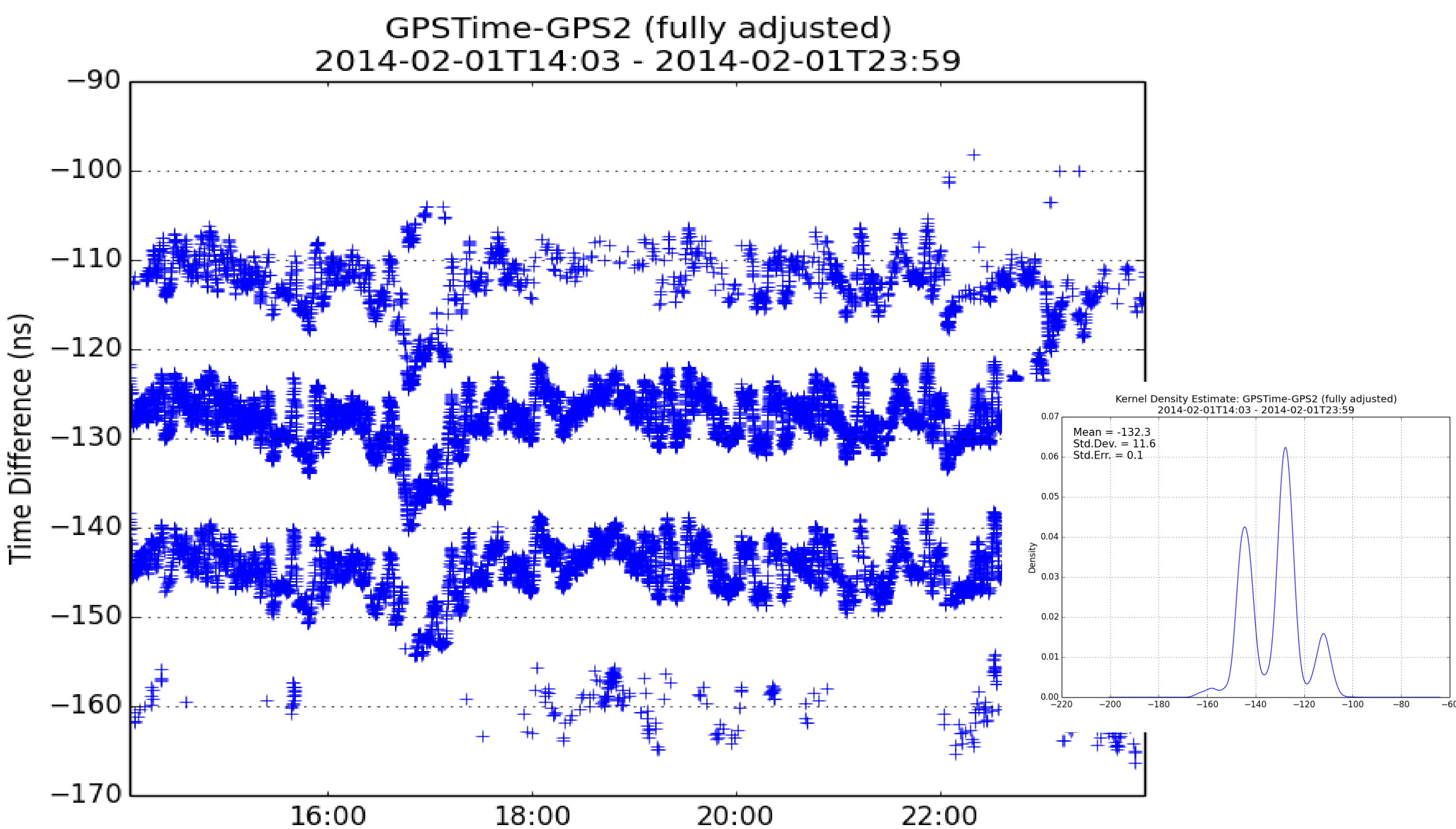


Figure 29

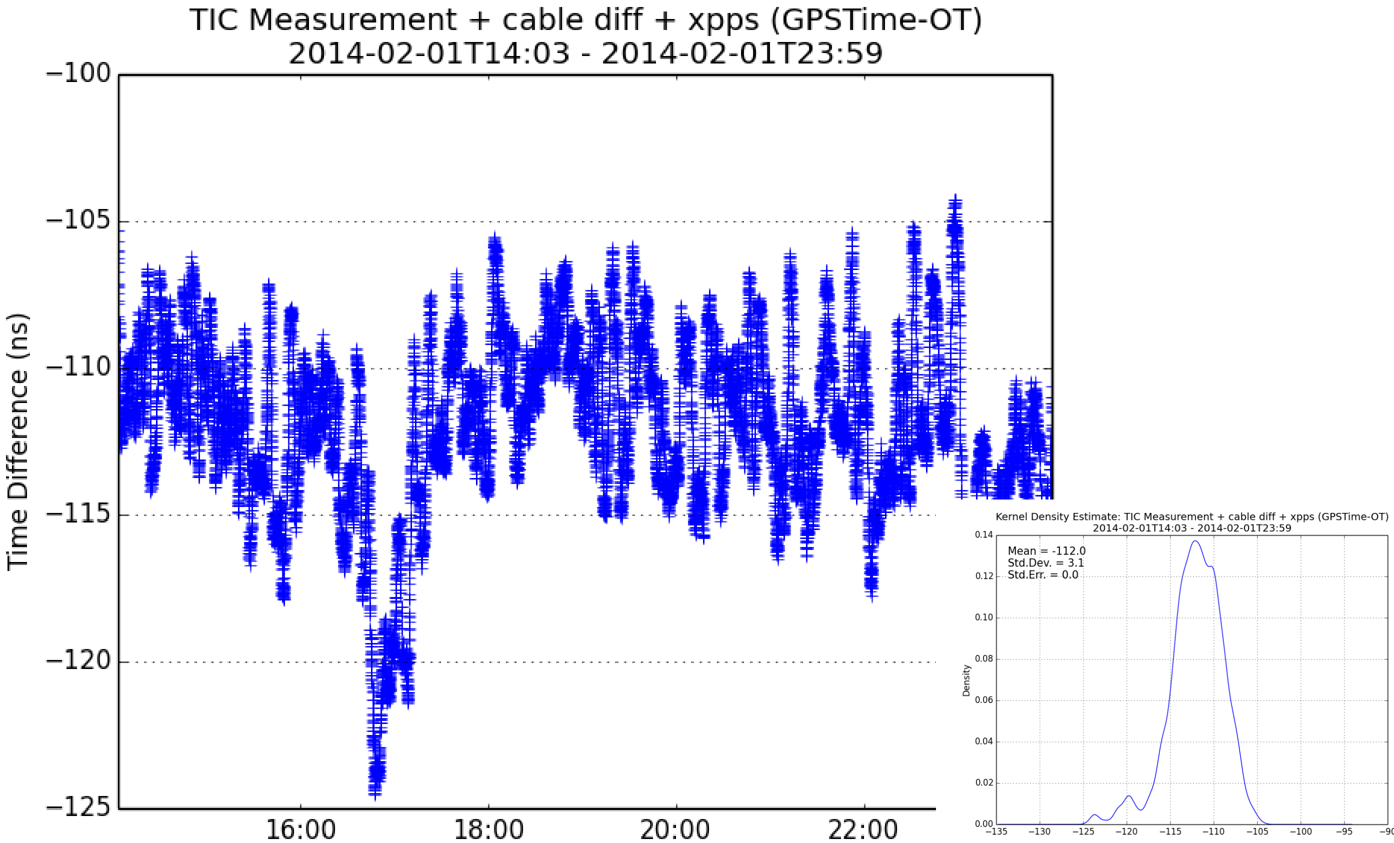


Figure 30

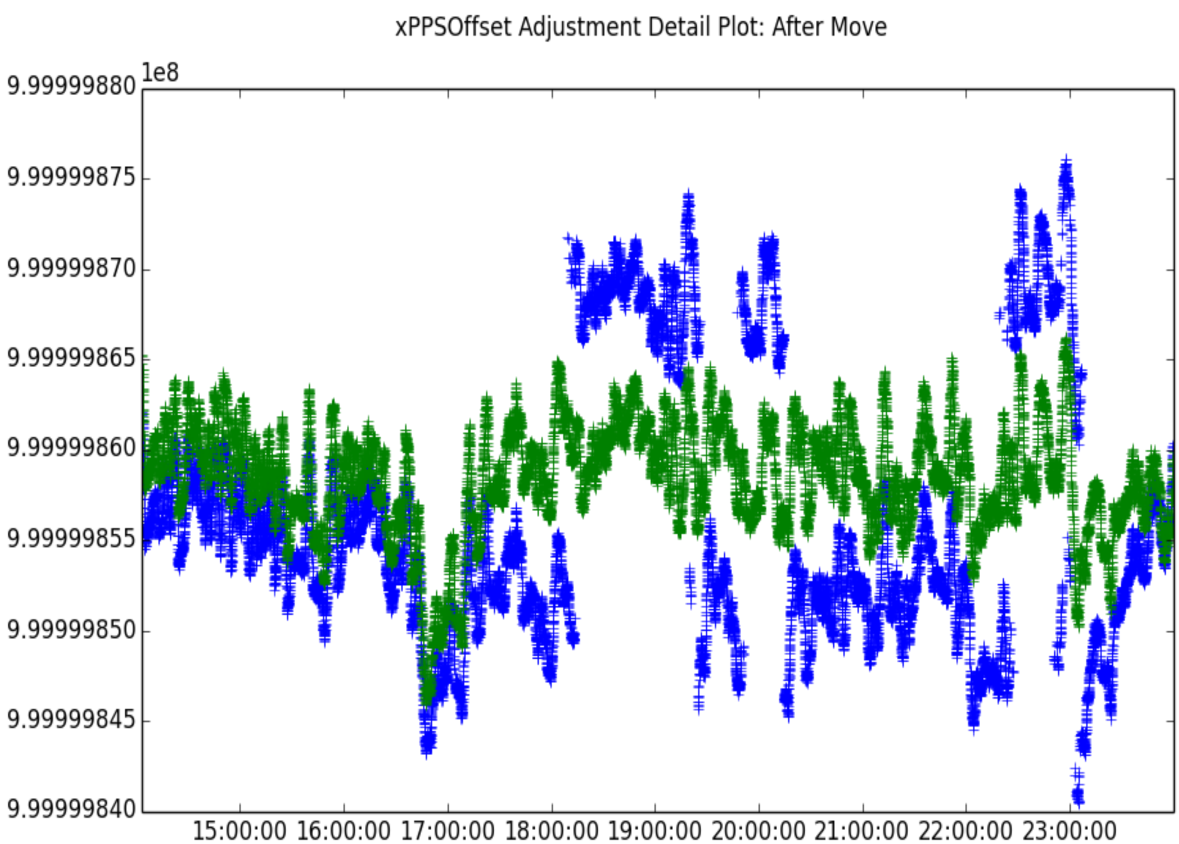


Figure 31

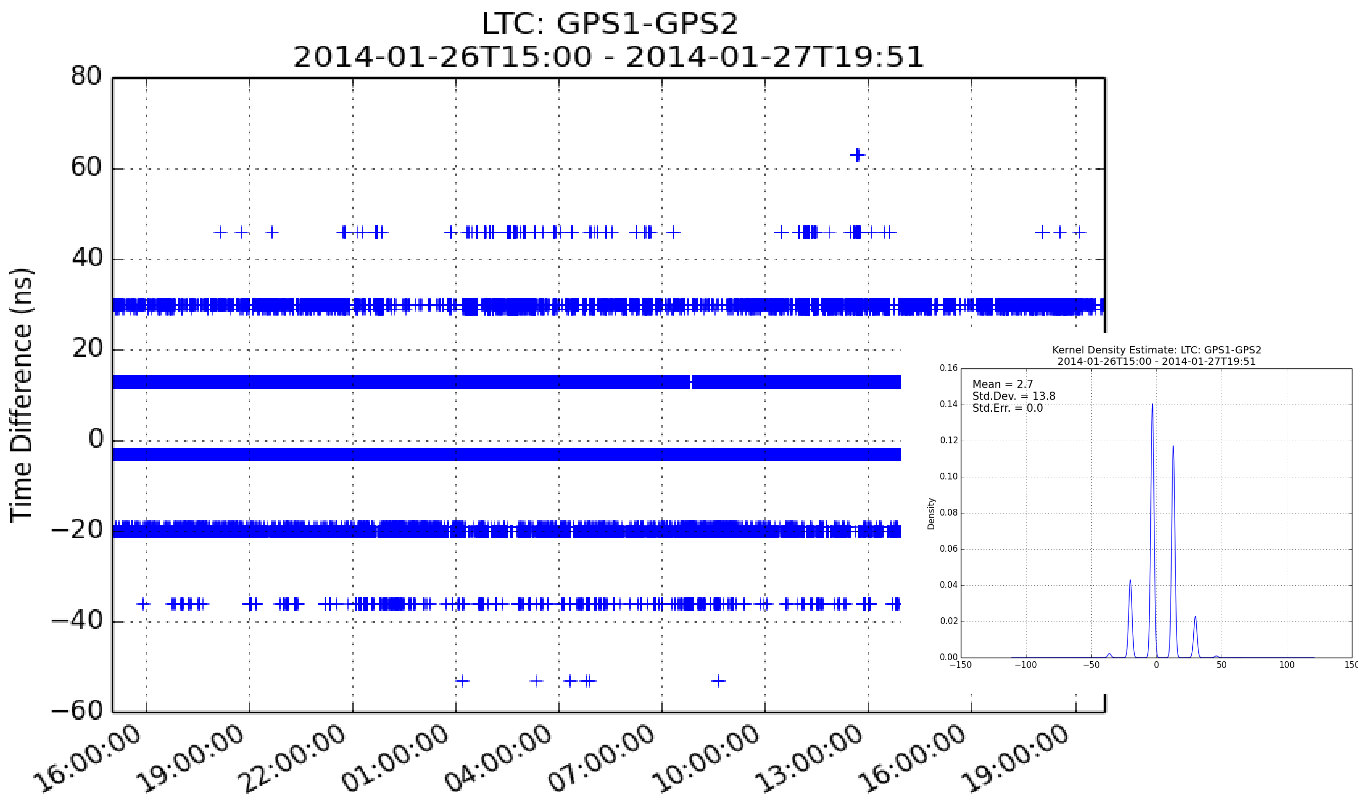


Figure 32

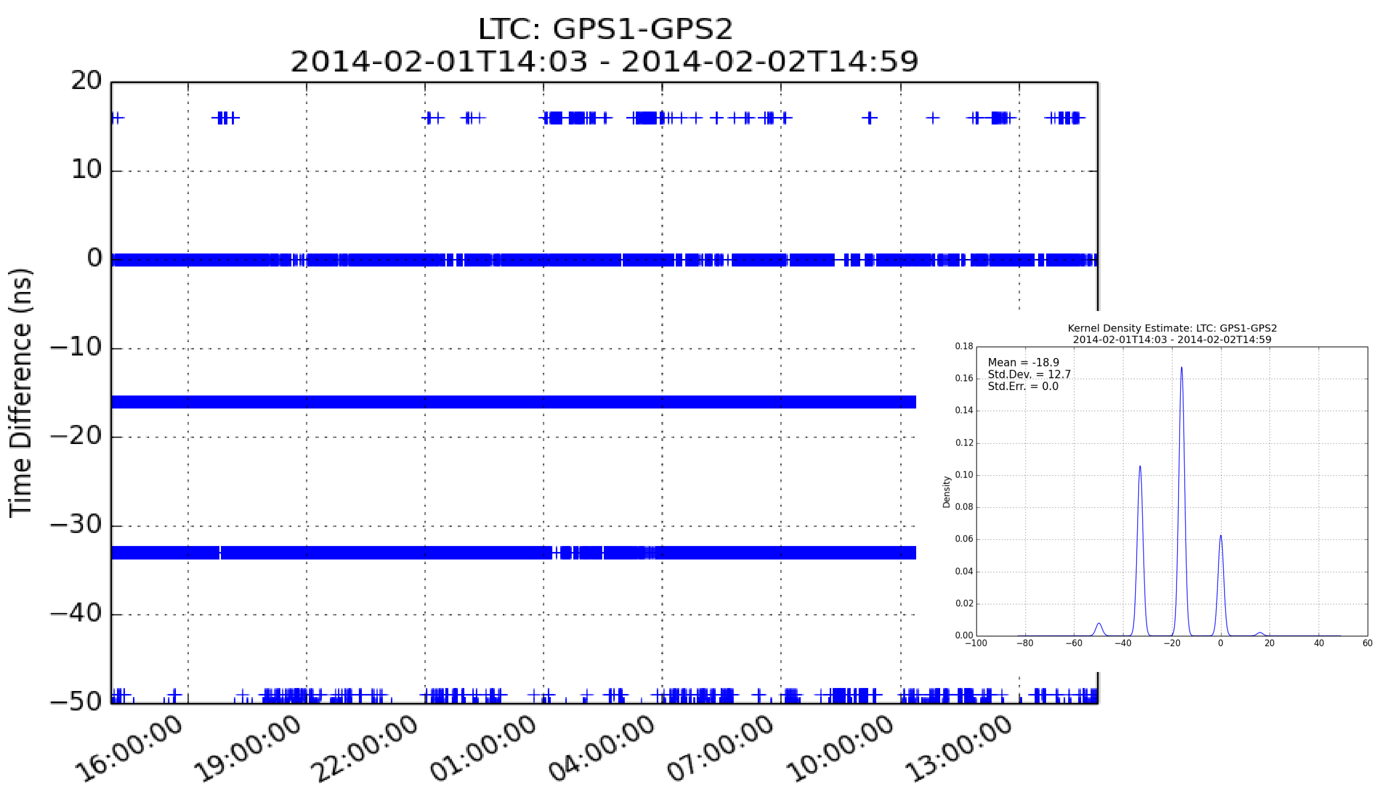


Figure 33

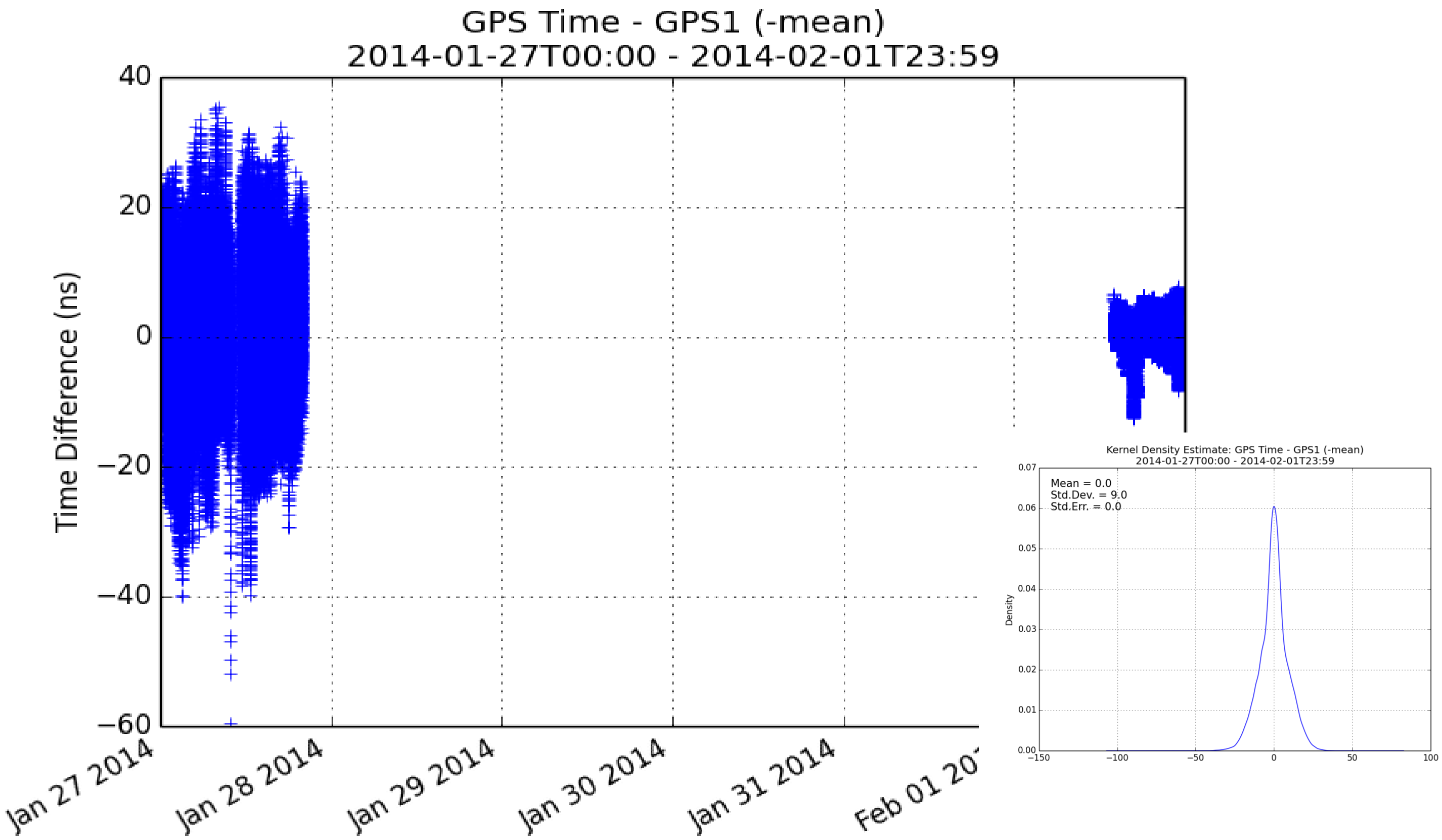


Figure 34

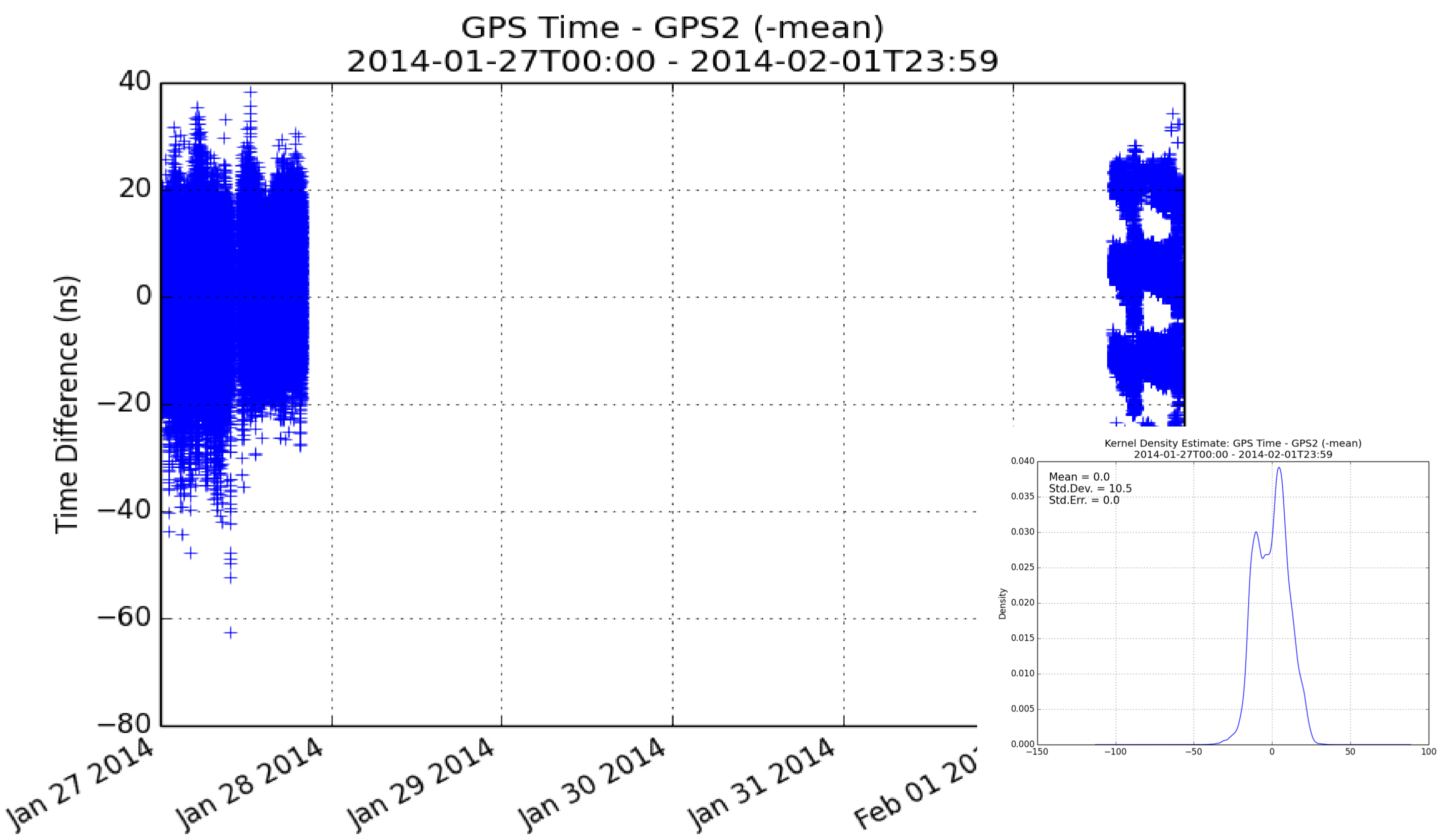


Figure 35

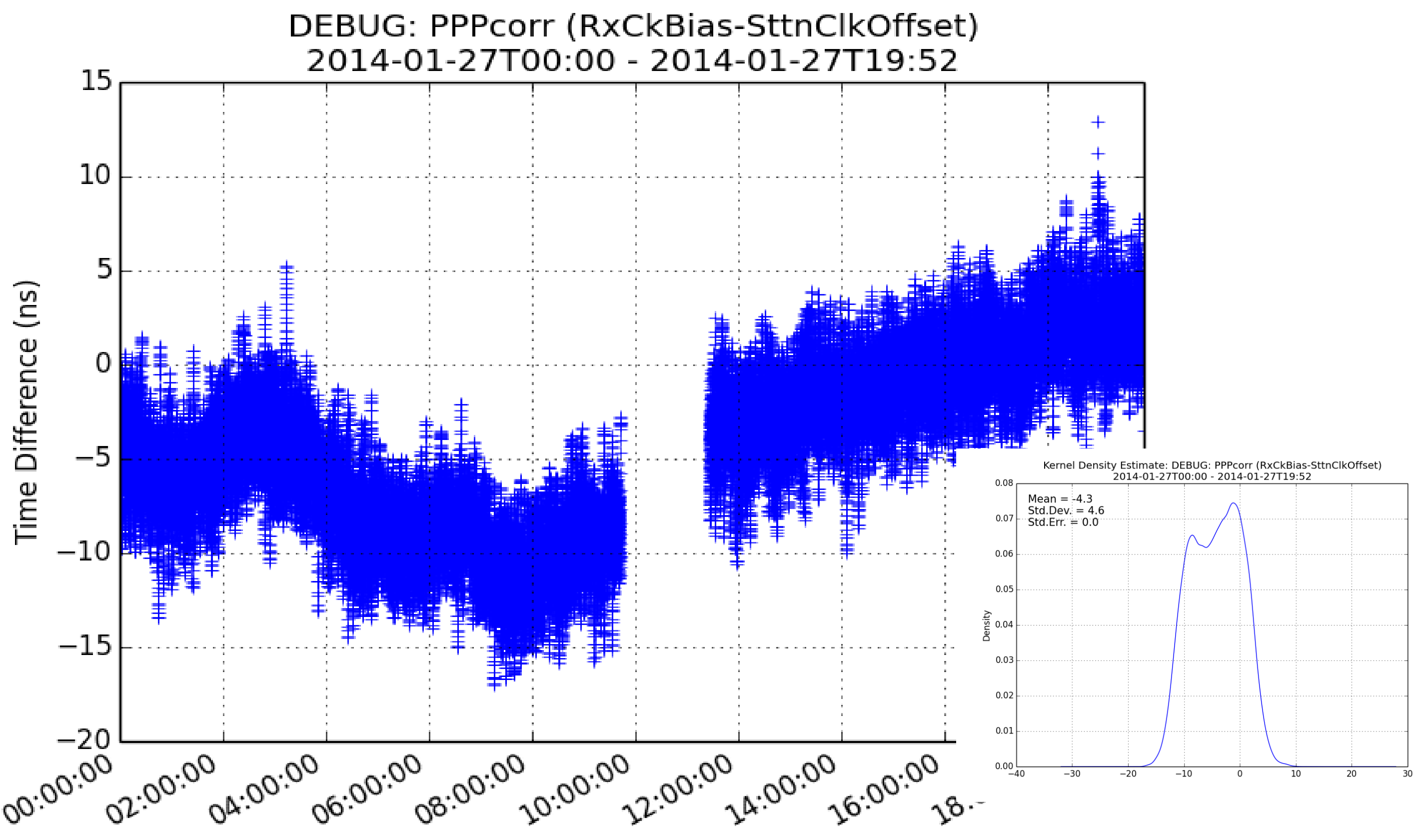

DEBUG: PPPcorr (RxCkBias-SttnClkOffset)
2014-01-27T00:00 - 2014-01-27T19:52
Time Difference (ns)
15
10
5
0
−5
−10
−15
−20
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
10:00:00
12:00:00
14:00:00
16:00:00
Kernel Density Estimate: DEBUG: PPPcorr (RxCkBias-SttnClkOffset)
2014-01-27T00:00 - 2014-01-27T19:52
Mean = -4.3
Std.Dev. = 4.6
Std.Err. = 0.0
Density

Figure 36

1 http://www.t2k.org/asg/nuTOF/TOF-documentation/PT/ptsys_hardware/superk-2012gpsblockdiagram121118
2 http://neutrino.phys.washington.edu/~t2k/post/gpsgroup/photos/japan-nov12/album/
3 http://www.t2k.org/asg/nuTOF/TOF-documentation/PT/ptsys_hardware/hwdiagram/pre-2014
4 http://www.t2k.org/asg/nuTOF/TOF-documentation/PT/ptsys_hardware/hwdiagram
5 http://www.t2k.org/asg/nuTOF/TOF-documentation/PT/ptsys_hardware/hwdiagram
6 http://neutrino.phys.washington.edu/~berns/T2K/GPS/plots_nu1gps/
7 http://neutrino.phys.washington.edu/~superk/onsite/wwwus/gps/
8 http://neutrino.phys.washington.edu/~t2k/post/gpsgroup/ptgps_monitor/
9 http://www.t2k.org/asg/nuTOF/TOF-documentation/PT/ptsys_hardware