LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO –
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
&
VIRGO EXPERIMENT
CNRS-INFN

Technical Note	LIGO-T020036-00-D VIR-NOT-LAP-1390-198	March 30, 2002

Measurement of the time offset Between the LIGO and VIRGO Data Acquisition Systems

Sz. Márka, A. Masserot, B. Mours

VIRGO CNRS/INFN
Traversa H di Via Macerata
56021 S. Stefano a Macerata
Cascina (PI), Italy
Phone (39) 050 752 521
Fax (39) 050 752 550

California Institute of Technology
LIGO Laboratory - MS 18-34
Pasadena CA 91125
Phone (626) 395-212
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Laboratory - MS 16NW-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

www: http://www.ligo.caltech.edu/
www: http://www.virgo.infn.it

Table of Contents

1 INTRODUCTION 3

1.1 OVERVIEW 3

1.2 REQUIREMENTS 3

2 VALIDATION OF GPS BOARDS 5

2.1 PURPOSE 5

2.2 GPS CLOCK VENDORS 5

2.2.1 Inherent accuracy of LIGO's GPS clocks 5

2.2.2 Inherent resolution of VIRGO's GPS clocks 5

2.3 EXPERIMENTAL SETUP 6

2.4 RESULTS 7

3 GLOBAL DAQ TIMING VALIDATION 8

3.1 PRIMARY GOAL 8

3.2 PRINCIPLE OF NDAS TRANSFER BASED TIMING ACCURACY MEASUREMENTS 8

3.3 DESCRIPTION OF THE PROTOTYPE EVENT GENERATORS: 9

3.4 EVENT RESOLUTION 9

3.5 LOCAL CALIBRATION OF THE ARRIVAL TIME 10

3.6 COMPARISON OF LIGO AND VIRGO ARRIVAL TIMES 10

3.7 COMPARISON OF LIGO AND VIRGO ARRIVAL TIMES 13

3.8 NDAS CLOCK DEVELOPMENT PLANS 18

4 PROPOSAL FOR ATOMIC CLOCK BASED TIMING MONITORING 19

4.1 LOCAL ATOMIC CLOCK PROPOSAL 19

5 SUMMARY 24

6 ACKNOWLEDGEMENTS 24

7 REFERENCES: 25

7.1 GPS AND TIMING RELATED LIGO DOCUMENTS: 26

7.2 TIMING RELATED VIRGO DOCUMENTS: 26

.

1 Introduction

1.1 Overview

Multi Detector Network analysis requires an accurate timing of each participating detector. Systematic effects in the time tagging of the astrophysical events introduce a bias when identifying the event's sky location and polarization or in the worst case could lead to the loss of an event.

Both LIGO and Virgo data acquisition systems rely solely on reliable but extremely complex GPS system for their timing. Fortunately, the GPS hardware that translates the satellite information to DAQ signals is not the same for LIGO and Virgo. A systematic survey of absolute and relative timing accuracy is due at this time. This should include the characterization and validation of timing hardware, end-to-end timing accuracy, and inter-experiment timing accuracy. Serious consideration should be given to reliability, redundancy and parallel timing solutions with an eye on optimal risk management. This study is a first of a series to cover some of these topics systematically, while concentrating on inter-experiment timing and GPS hardware validation.

This document reports the result of joint measurements conducted between February 21 and 24, 2002 at the LIGO Livingston site. The first measurement compares the output of the two types of GPS boards (used at VIRGO and LIGO) when they are at the same location. The second part of the report describes the setup and the results from the preliminary testing of a simple, GPS independent prototype system, which is able to verify inter-experiment timing on the millisecond level and able to point out large GPS problems immediately. The third part is the overview of available local clocks and a recommendation to install one in every observatory.

Of course, there can be several additional problems that can introduce delays and uncertainties; Are the delays introduced by the ADC readout and their anti-aliasing filters properly calibrated for each detector? Are there any bugs in the DAQ system, like tagging the end of the frame instead of the beginning of the frame? How reliable is the GPS information provided by our boards placed at different location? To provide a global answer to this class of questions, we have to perform a series of end-to-end measurements.

1.2 Requirements

We considered two important orders of magnitude for this relative timing accuracy investigation:

- 30ms/1ms: 30ms is the largest time delay between the LIGO and Virgo detectors. If the timing accuracy does not meet this number, we are going to loose events when doing coincidences between detectors. If we are sure that we know the delay on the 1 ms level, we are already capable of making astrophysically relevant statements about source locations.
- 30-100us: The typical arrival time resolution for an astrophysical event search with dominant frequency f is 1/(pi*f*SNR) [Tinto, TR]. Figure 1. shows this resolution for a

dominant signal frequency of 200Hz. If we take the extreme case of a dominant frequency of 1kHz with a SNR of 10, the arrival time resolution could go down to 30us. For coalescing binaries. Monte Carlo studies [ref TR] have also shown that the time resolution is of the order of 0.1ms for a SNR of 10. This comes from the fact that the dominant frequency is a few hundred Hz and knowing that the SNR gives roughly the resolution within one period. If the signal stretches over many cycles, like for binaries, the search techniques are equivalent to the sum of all cycles into one single cycle.

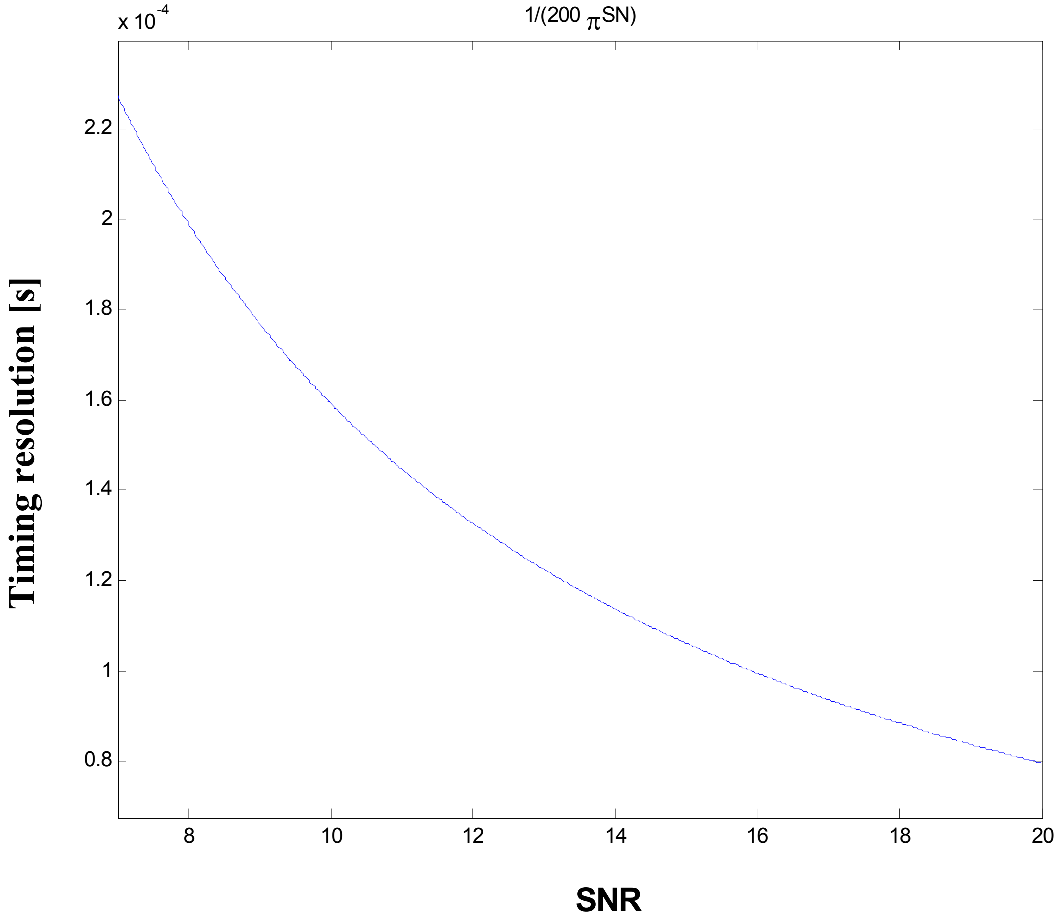

Figure 1 Timing resolution of astrophysical searches vs SNR

In order not to introduce bias in the event's sky location, we should get the absolute timing accuracy of each data acquisition system, well bellow the arrival time resolution. Therefore, for the first generation of GW detectors, 10 μs accuracy seems to be an adequate requirement. This number will have to be reduced when larger signals will be observed or if the frequency turns out to be above 1 kHz. Also, it is mandatory in our opinion that GPS independent proof exists to the individually achieved accuracy (of <10 us) and the inter-experiment timing is continually cross-checked for a meaningful level (of <1ms).

2 Validation of GPS boards

2.1 Purpose

LIGO and VIRGO use GPS antennas and boards from different vendors. The difference in the definition of the 1 Pulse Per Second (PPS) signal can directly introduce bias in the relative time stamps. The purpose of this measurement was to determine the time difference between the 1 PPS signals provided by the two types of boards, which are being used by the two collaborations.

2.2 GPS clock vendors

The LIGO GPS VME-SyncClock32 Synchronized Clock boards were purchased from Brandywine Communications, who obtains them from JXI2 Inc. JXI2 builds them using Motorola UT PLUS Oncore GPS Receivers. All customizations and all the upgrades for LIGO were done by JXI2 Inc.

VIRGO uses Datum Inc.'s bc637VME, originally made by BANCOM.

Board level information about the GPS timing boards used by VIRGO and LIGO is available from the manufacturers' web site (VIRGO [VGPS], LIGO [LGPS] and JXI2's board [JGPS] for the 104 bus, which is similar to LIGO's model).

2.2.1 Inherent accuracy of LIGO's GPS clocks

The absolute accuracy of the GPS signal, as it is received, is specified by Motorola to be +/- 200nsec. This can be reduced to +/- 45nsec via a Position Hold upgrade (The better we know the position of the antennas the better we can calculate the time corrections). Position Hold averages over 10,000 seconds (about 3 hours) after turn on and will save a precise position from which the unit can make more accurate time correction calculations. +/- 50nsec quantization error is introduced by the 10MHz clock in the Motorola receiver. JXI2 Inc. built a 2^{23} Hz clock into the board for LIGO, which adds a +/- 60nsec quantization error. (LIGO needs a binary clock so that it would not get glitches or missing pulses in the clocks for the ADCs and DACs.) Thus the absolute error can be as large as (+/- 200nsec) + (+/- 50nsec) + (+/-60nsec) = +/- 310nsec.

Good introductory talks about GPS systems provided by H. Fruehauf of Zyfer Inc. are available at [GPSBA], [GPSENC], [GPSTF]. A collection of LIGO documents related to the GPS and timing system is listed in [L1] [L8].

2.2.2 Inherent resolution of VIRGO's GPS clocks

Trimble Navigation Ltd manufactures the VIRGO GPS receiver module (active antenna). The 1PPS absolute accuracy of the GPS receiver is 1 μs. The signal provided by the GPS receiver module drives the oscillator of the bc635VME time and frequency module. This module gives a GPS time encoded with a resolution of 100ns.

2.3 Experimental Setup

For our measurement, a VIRGO GPS antenna was installed outside the building and connected to a VIRGO GPS board installed in a standalone VME crate. We utilized the 1PPS signal of the LIGO GPS board in the mass storage room and connected it to an oscilloscope via an ~18m long cable. The 1PPS clock signal from the VIRGO board was sent to the same oscilloscope via a short cable, as well as the 1PPS coming from the VIRGO antenna (see Figure 2.). The Virgo antenna was connected to the VME boards via a ~15m long BNC cable.

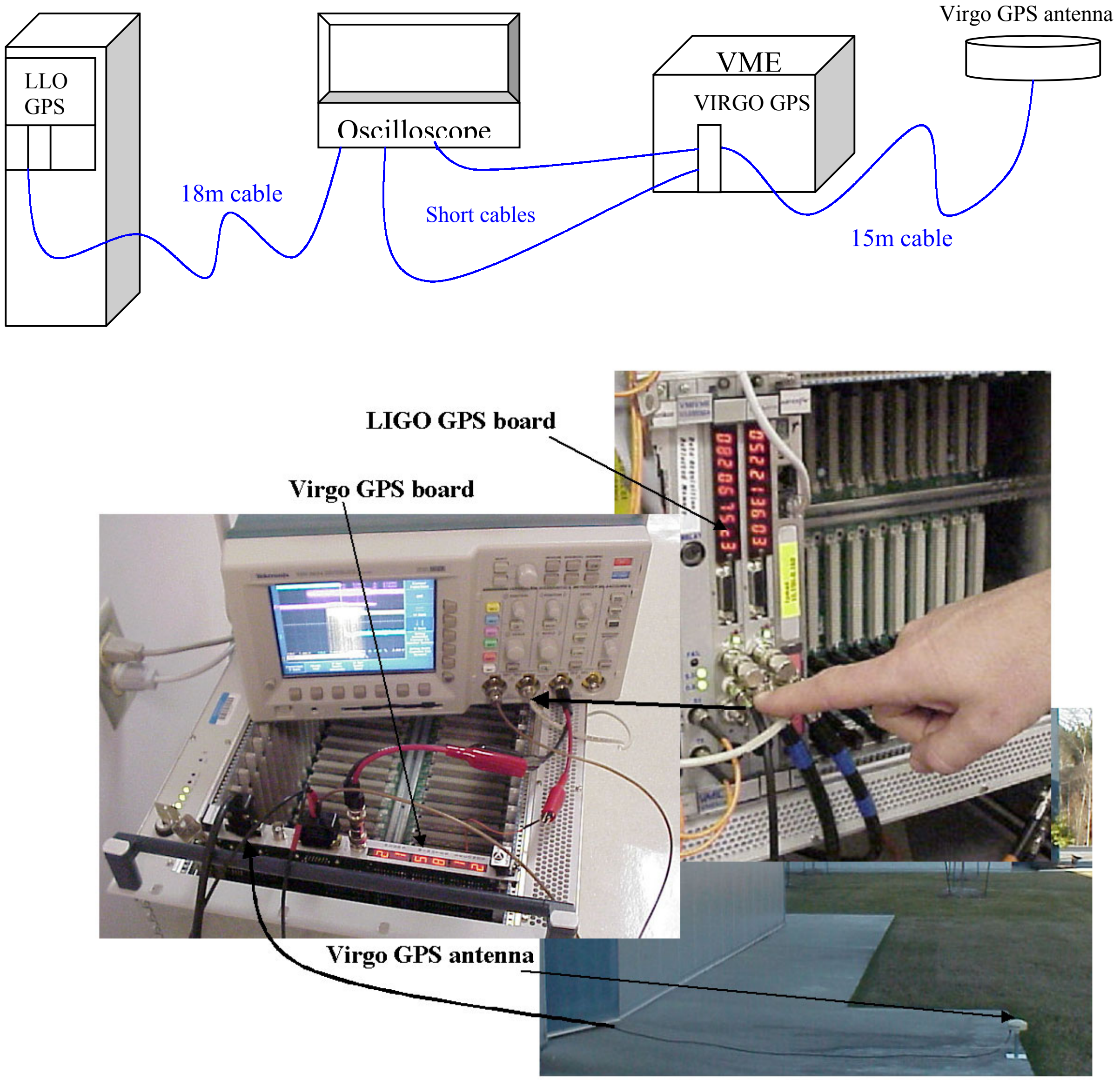

Figure 2 : Experimental setup for the 1 PPS measurement.

2.4 Results

Figure 3. shows the traces as observed by the oscilloscope. We triggered on the significant edge of the 1 PPS of the LIGO GPS board (blue trace on Figure 3.) and observed the relative jitter of the signals from the VIRGO GPS board and active antenna (receiver). The yellow trace (starting bottom left) is the signal from the VIRGO GPS board. The edge arrives within a +/- 300ns interval around the trigger. A slight offset between the trigger and the center of the yellow region can be observed, but it is definitely less than 100ns. We do not expect systematic effects coming from the distance between antennas (which was less than 50m) because the GPS receivers claim that the time provided is independent of the antenna location. This claim is not verified and it requires further study. Also, we did not have a chance to verify the effects of multiple reflections from the building, but it should be negligible when considering a timescale of hundreds of nanoseconds. The pink trace is the 1 PPS signal coming directly from the VIRGO GPS antenna. It arrives within +/-600 ns of the trigger with no observable offset.

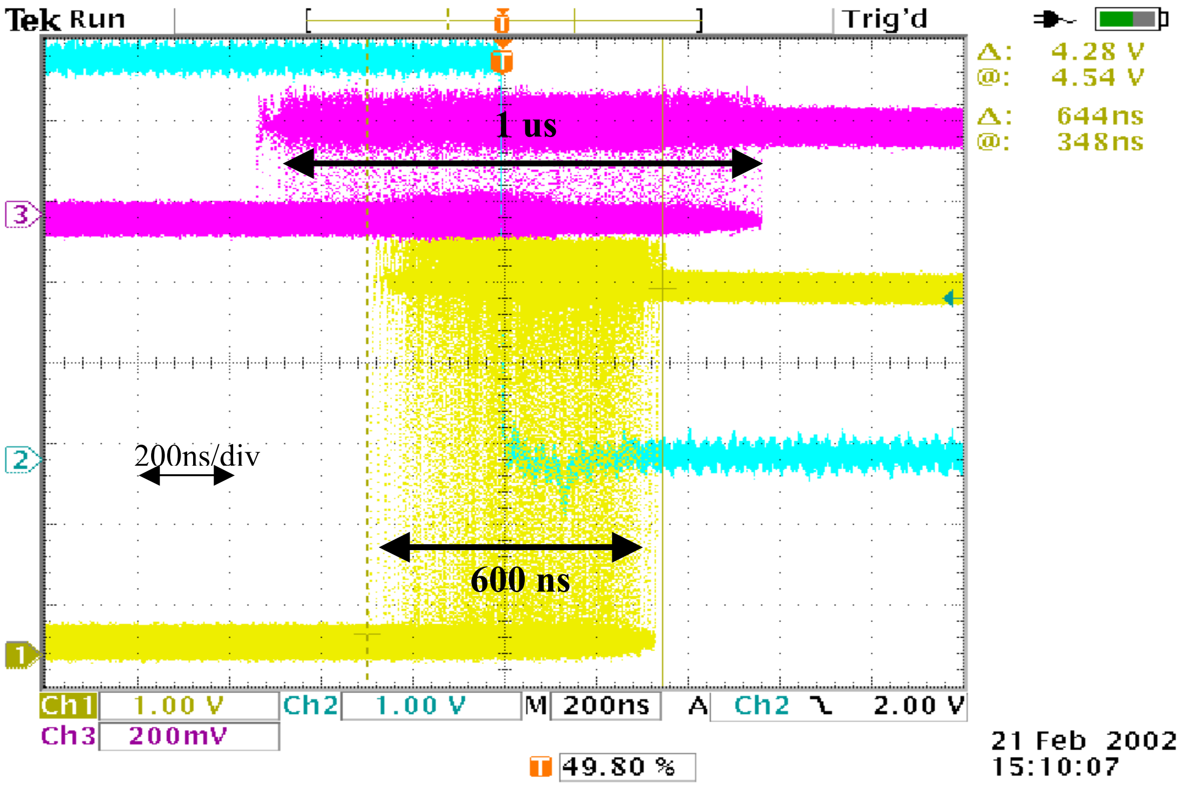

Figure 3: Traces for the 1PPS signals. See text for trace description.

Therefore, we conclude that the 1 PPS signals delivered by the LIGO and VIRGO units do not show statistical difference larger than 200 ns. The comparison also proves that it is fair to assume that the corresponding edges of 1PPS signals from the two boards are never farther away from each other than 1us. More in depth tests, with multiple boards of each kind, with co-located antennas seem like a good idea since they can provide us with a more accurate picture of the board to board accuracy and a possible cross calibration.

3 Global DAQ timing validation

3.1 Primary goal

Now that we have ensured that the GPS time is provided within a μs for all three observatories, we have to make sure that the DAQ timestamps on each data series are sufficiently accurate and do agree to the required level.

- A series of tests to check the accuracy of the LIGO DAQ time stamps, relative to the 1PPS signal provided by the local GPS clocks, were conducted [L4-L6] in the past. The results led to the discovery of a hardware bug, which limited the timing accuracy to ~60us. The bug was fixed and LIGO should now have a sub μs level accuracy after the extra software corrections at the LIGO observatories, as long as we trust the local GPS clocks.
- Experience shows that due to the complex nature of GPS based systems and the variety of different product levels, GPS based timing can have significant glitches. Thus, to fully trust the GPS based timestamps it is mandatory in our opinion to have a local set of sufficiently stable local (atomic) clocks, which can also be used to verify in-site timing. They can be synchronized to each other via portable atomic clocks or by using the GPS system at times when its accuracy is ensured and verified. A comparison and a proposed set of clocks is given in the next chapter.
- Besides trusting the accuracy of the local timing to determine inter-site timing accuracy, it is a good idea to implement a third system, specifically made to verify the agreement in timing among remote sites. This must be a fully redundant system not relying on either GPS system or the local atomic clock. It should also produce a logged and documented output, which can be referenced later. We did set up such a system and it proved to be capable of ensuring inter-site timing accuracy on the ms level, which is the minimum requirement for a meaningful pointing. The first version of this system has been installed and is running in LLO and VIRGO.

3.2 Principle of NDAS transfer based timing accuracy measurements

We measured end-to-end timing variations between sites based on simultaneously recorded 1PPS events called “NDAS Clock Events” at the LIGO (Livingston) and VIRGO sites.

The synchronization of the events is done using the Network Time Protocol (NTP) over the Internet. This protocol measures the travel times of data on Internet and uses this information to determine a correction that removes the propagation time offset. A comprehensive overview of the common time codes are provided in Ref.[DTC] and detailed information of the Network Time Protocol (NTP) is given by D. L. Mills in Ref. [NTP]. It is worth noting that this event synchronization is completely independent of the GPS and local atomic clocks. The absolute timie is based on trustworthy national time standards.

These events are recorded with each DAQ system, written to frames and transferred by the Network Data Analysis Server (NDAS) [NDAS]. An offline analysis compares their times of arrival. This difference gives the systematic error when doing the common analysis.

3.3 Description of the prototype event generators:

The diagram of the system used to produce the "NDAS Clock Events" is shown in Figure 4. It is based on two identical PCs (HP VL 400MTS), called "NDAS clocks", located at each site. The PCs are running the Linux operating system (Red Hat v6r2). The internal clocks of both PC's are slaved to a common clock (usually atomic clock) using the Network Time Protocol (NTP) over Internet. Both PCs use the same NTP server at any given time, therefore their clocks are always synchronous, to within the (~ms) limitations of NTP.

Several widely separated NTP servers have been used to study systematic effects on the accuracy of the Internet travel time cancellation. Each PC generates periodic pulses on its parallel port, which is connected to one ADC channel. The DAQ records these pulses as it records any other channel. In order to check for large errors (one second for instance), the NTP time of the event is encoded in the pulse length.

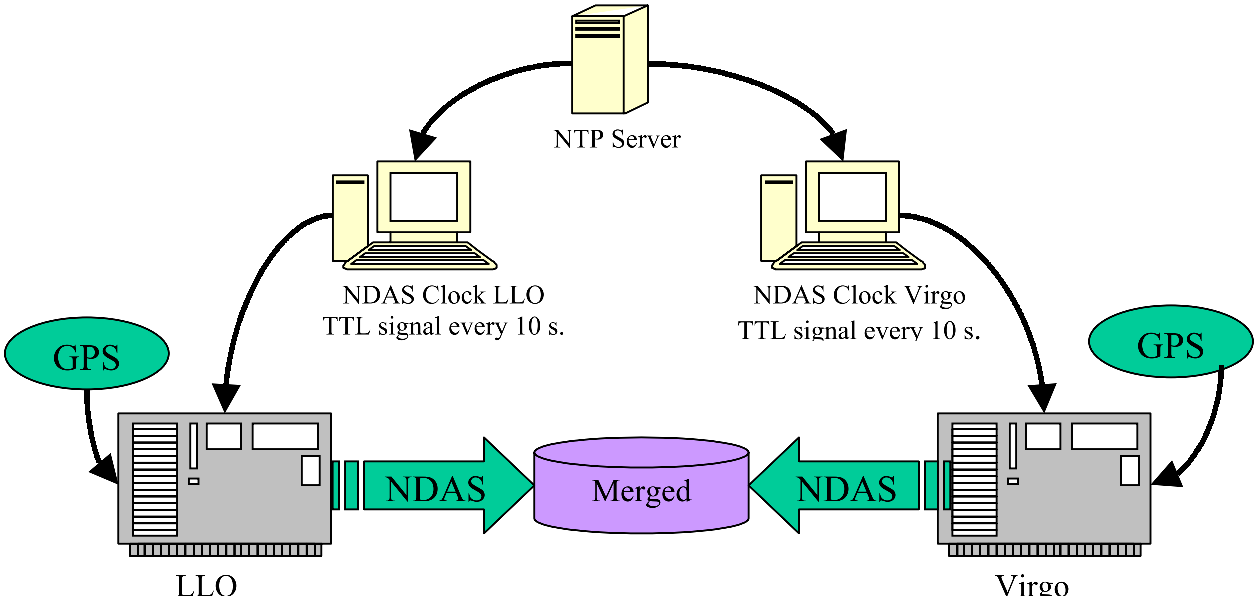

Figure 4 Set up for the global timing measurement

3.4 Event resolution

Since the signal being fed to the ADC is generated by software (without a real time system) and since the event detection is done by applying a threshold on an analog signal, there is some jitter on the event arrival time. To measure this overall event arrival time resolution, including event generation and event detection, the relative arrival times of consecutive NDAS clock events measured at the same site were histogramed. In this case, the PC clocks were not readjusted during the course of the measurements.

Figure 5 presents the distribution of arrival times. The expected (10 s) time offset was subtracted. The observed RMS is small (26µs or 50µs), much smaller than the effects we will measure in the following sections. In fact, this RMS could not have been much smaller since a simple threshold algorithm was used to define the event arrival time and therefore we are limited by the sampling rate of the data acquisition systems (16kHz for LIGO and 20kHz for Virgo). The observed difference between the two sites is not significant and could be due to binning effect for instance.

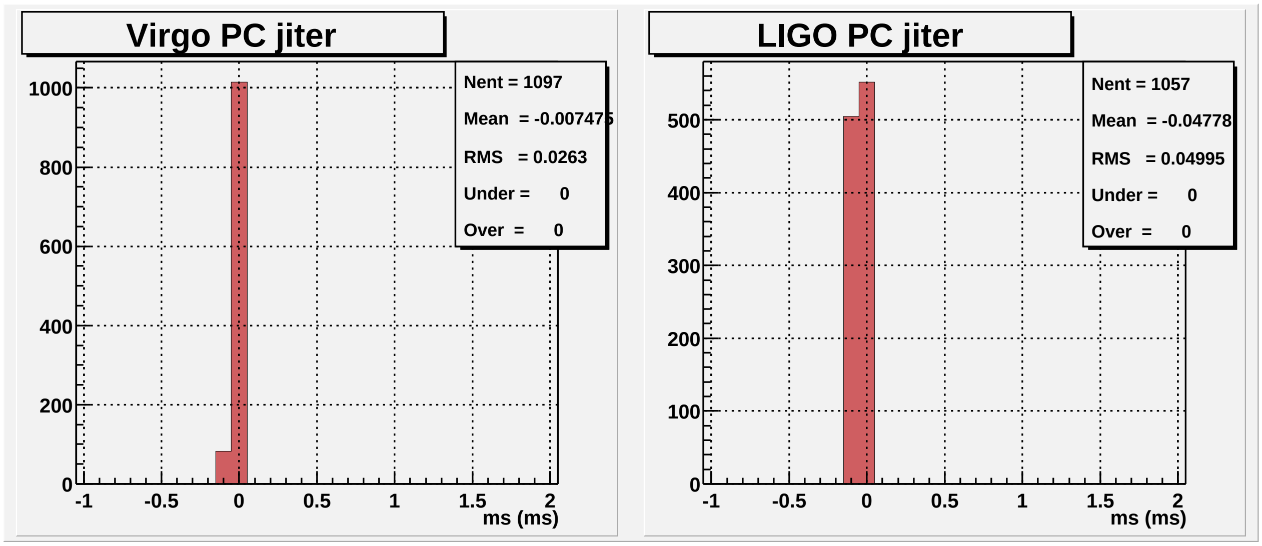

Figure 5 Event arrival time resolution: arrival time relative to the previous pulse measurement without updating the PC clock. The two measures are separated by 10 seconds.

3.5 Local calibration of the arrival time

The measured arrival times of events were corrected for the time delay introduced by the DAQ readout. This was done by recording the DAQ frame signal in an ADC channel and removing any observed offset. In the LIGO case, no significant offset was observed. In the VIRGO case, 1.75ms were removed that corresponds to the time delay introduced by the ADC conversion and readout (this large delay exists only for the environment monitoring channels due to the type of ADC used for these channels). Future measurements should use one of the ADC channels used for the dark fringe readout.

3.6 Comparison of LIGO and Virgo arrival times

Data was recorded during the nights of Saturday February 23 to Sunday February 24 (6 hours starting at GPS time = 698568002). The NDAS clocks were set to produce pulses every 10 seconds. The repetition rate could not be much faster due to the time needed by the "ntpdate" command. On every other pulse (i.e. every 2x10 = 20 seconds) the PC clocks were simultaneously reset using one of the following NTP servers:

- "ntp.univ-lyon1.fr" referred as 'Lyon' (a GPS based stratum 1).
- "time-A.timefreq.bldrdoc.gov" referred as 'NIST' (an atomic clock based stratum 1).
- "london.ligo-la.caltech.edu" referred as 'london' (a local stratum 2).
- "time.ien.it" referred as 'Torino' (an atomic based stratum 1). This NTP server is on the Italian backbone.

Several NTP servers were used to get an idea of the systematics involved in the measurement. The two first one are stratum 1 sites while the two last NTP servers are at or close to one of the sites. The following table gives the site distance (round trip time) measured using the Unix ping command.

Round trip time for the four NTP servers.

	From LIGO	From Virgo
To Lyon	160 ms	52 ms
To NIST	48 ms	143 ms
To London	0.5 ms	161 ms
To Torino	152 ms	26 ms

Figure 6 displays, as function of time, the arrival times of the NdasClock events relative to the frame starting time. Data was recorded at the LIGO site using the four NTP servers. Only the first event after a clock reset, using one of the four NTP servers, is plotted. Several observations can be made:

- The arrival times are close to zero because there is not even a fraction of second difference between the definition of the atomic and GPS time. The delay introduced by the pulse generation is small and therefore, the time of the events is aligned to the 1PPS signal, to within a few milliseconds.
- The local NTP server ('london') has slow drift. This comes probably from the fact that this server was not synchronized to a master NTP server during our measurement.
- For a given NTP server (except for 'london') one can see different discrete levels. This is not understood. They may arise from the different network routes used during the NTP synchronization, especially if the in and out route are not the same. The fact that the 'london' plot is continuous, gives an idea of how well the NTP set up can perform when the server is close and when the network route is predictable.
- The dispersion of the measured values suggest that in order to reduce bias in the measurement, we might use NTP servers located at each interferometer site, and then, we should average the results.

Figure 7 is the same plot as Figure 6 but for the data collected at the Virgo site. The main difference is the reduction of the correlation between one measurement and the next one. A possible source of this effect is the firewall used at Virgo. However, this was not checked and it requires further study.

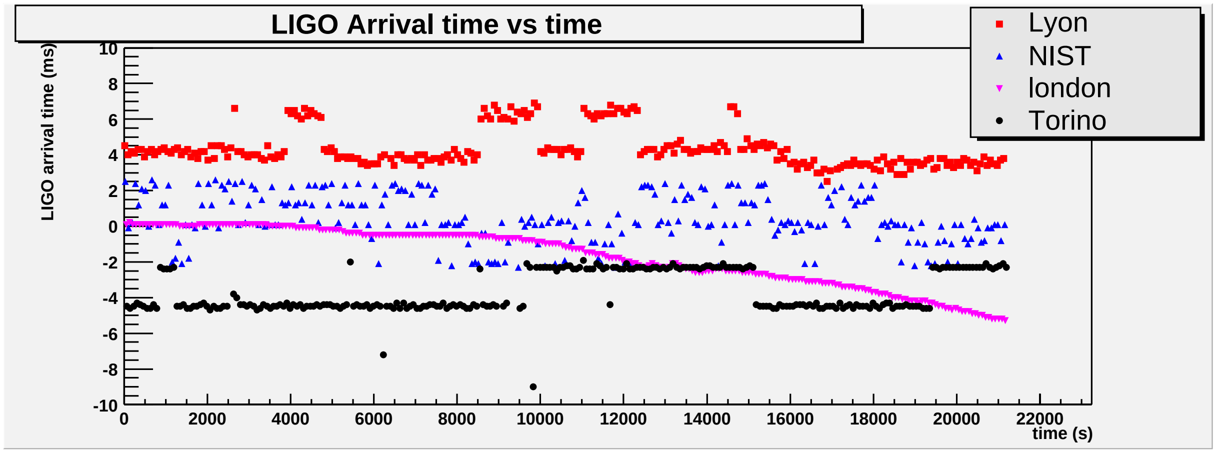

Figure 6: Arrival time at the LIGO site. The drift of the LIGO NTP server (london) is visible.

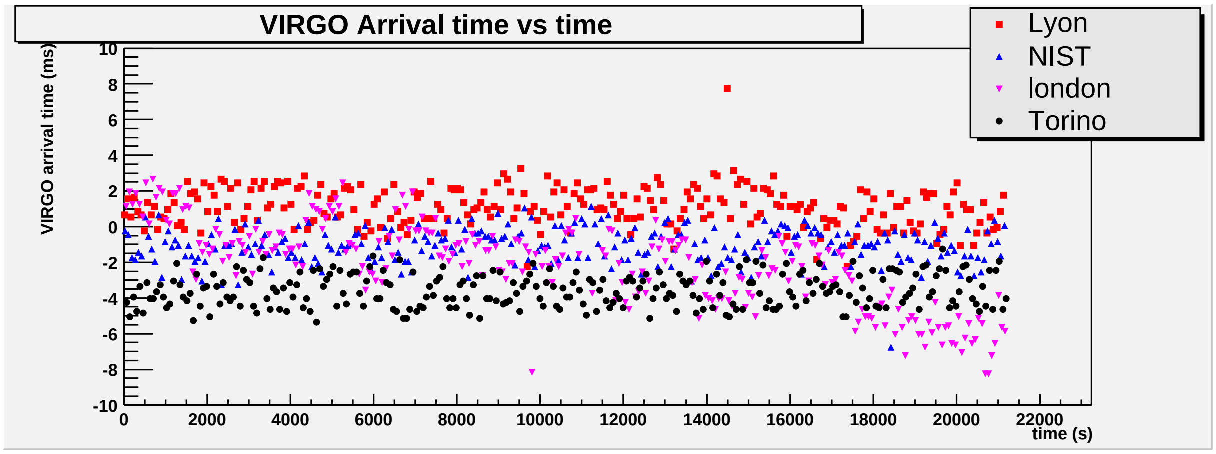

Figure 7: Arrival time at the VIRGO site.

3.7 Comparison of LIGO and Virgo arrival times

To remove the instability from the NTP server clock like in the ‘london’ case, the arrival time at LIGO and Virgo were compared, event per event. Figure 8 to Figure 11 present these results. The mean values of the time differences for the six hours are (values from an empirical Gaussian fit to remove the effects of the tails):

dt(Lyon) = -3.17 ms
dt(NIST) = -1.56 ms
dt (London) = -0.59 ms
dt (Torino) = 0.03 ms

The statistical error given by the Gaussian fit is of the order of 0.10 to 0.15 ms. This error is probably somehow underestimated because the χ^2/ndf value is larger than 1.

The systematic error is likely larger and difficult to estimate. The dispersion of the results gives an idea of this systematic error. The dominant contribution in this error is the uncertainty during the PC clocks synchronization (the ntpdate command) as already discussed.

As a first upper limit, we can state that the time difference between the LIGO and VIRGO timestamps is less than 3 ms.

To get a more precise result, additional data with more clever NTP server geometry is needed. For instance, one can use the PCs themselves as NTP servers for the other site. Such configuration will be investigated in the future. We will also investigate the effect of firewalls and varying network routes on the systematic error.

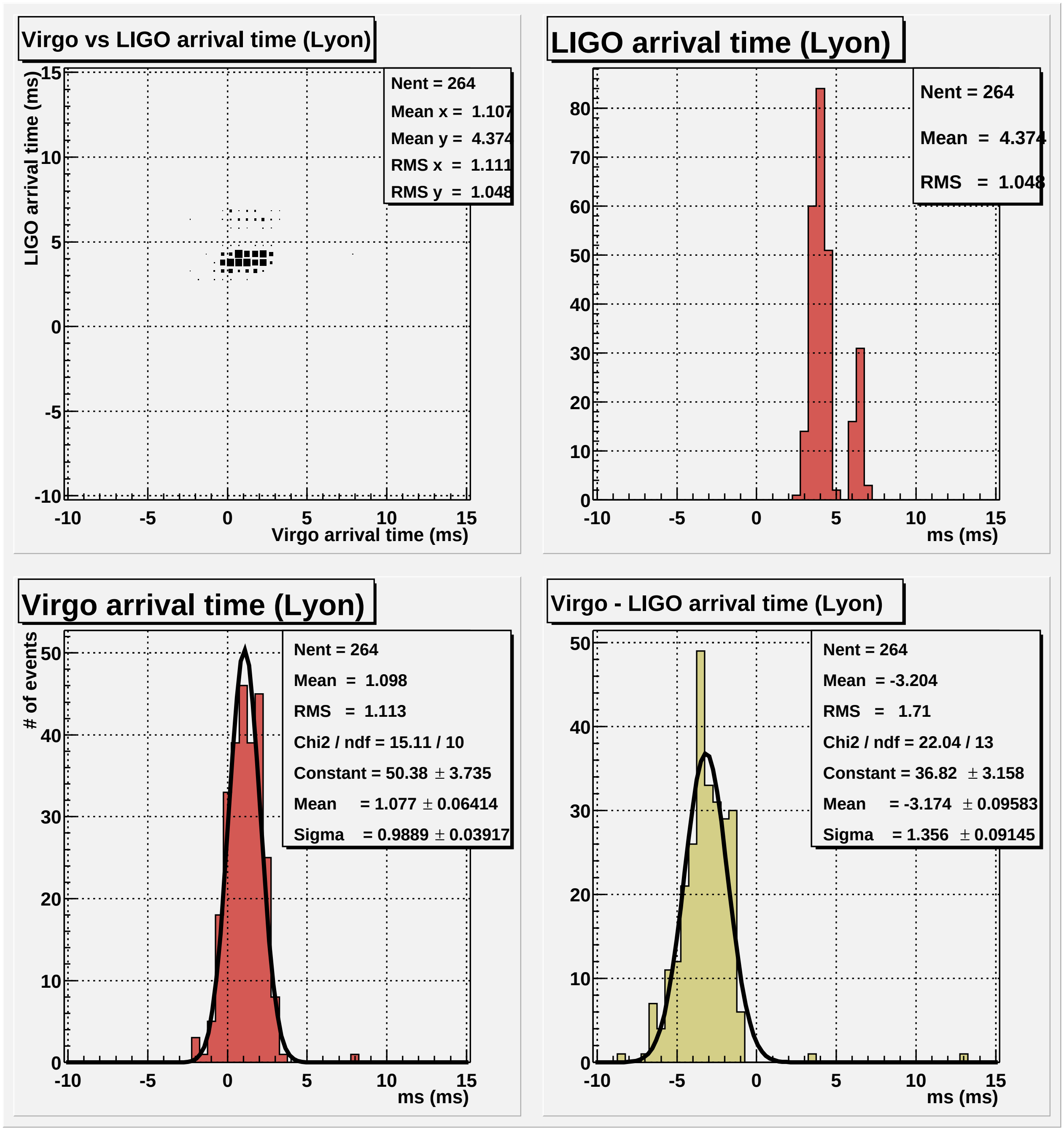

Figure 8: Arrival times when the PC clocks are set using the Lyon NTP server. The binning size used for the scatter plot is 0.5 ms.

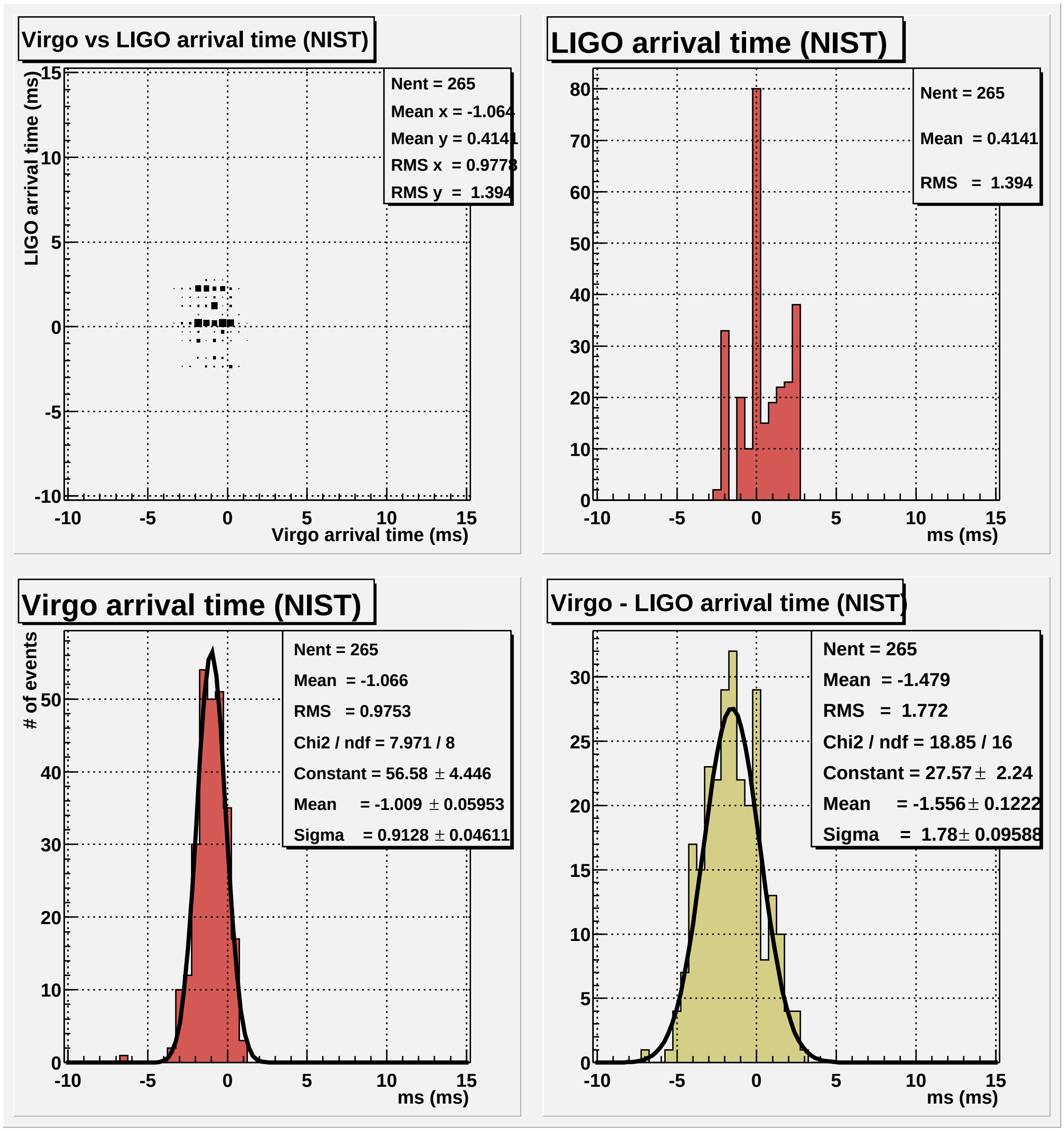

Figure 9: Arrival times when the PC clocks are set using the NIST NTP server.

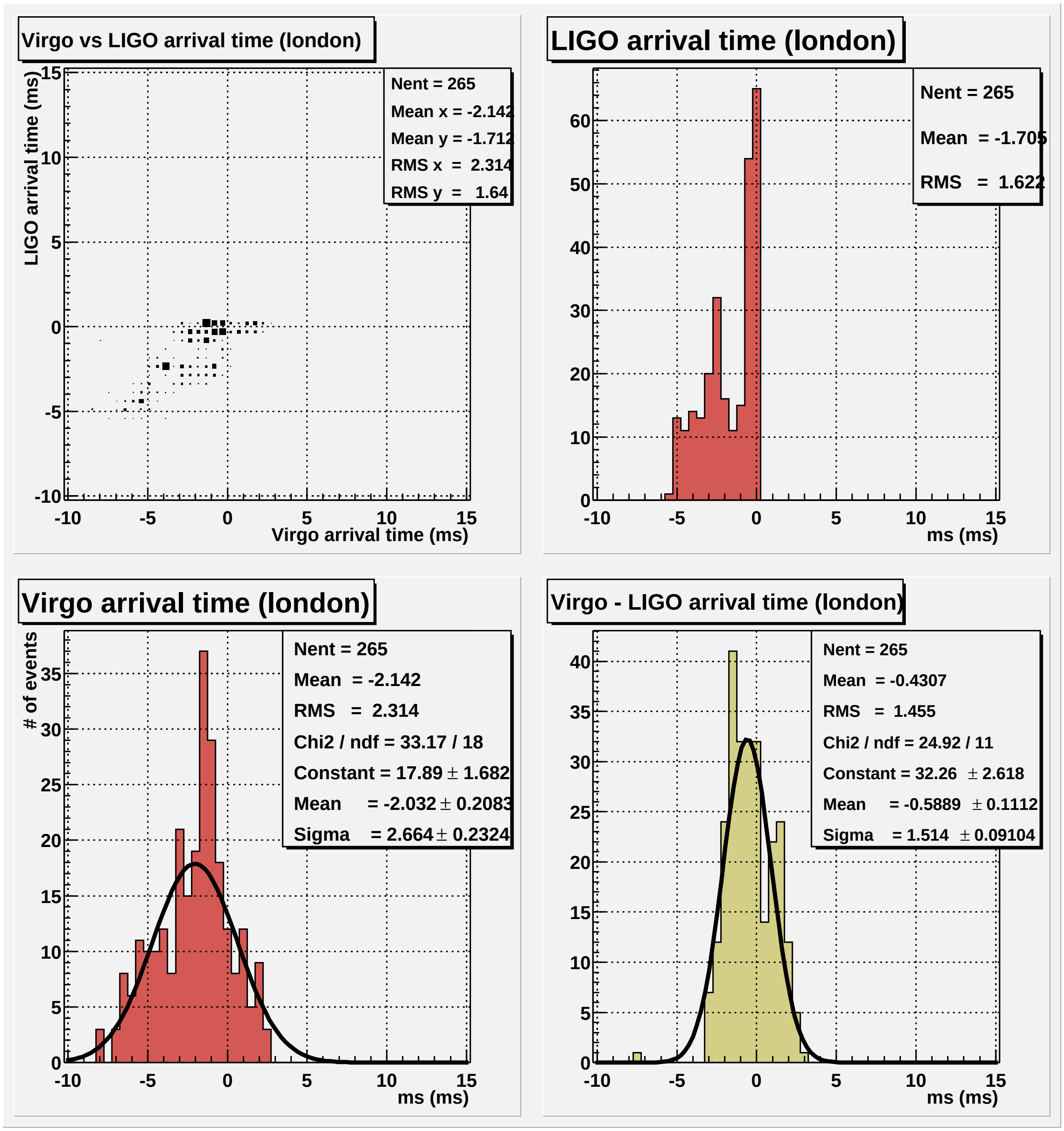

Figure 10: Arrival time when the PC clocks are set using the 'london' NTP server.

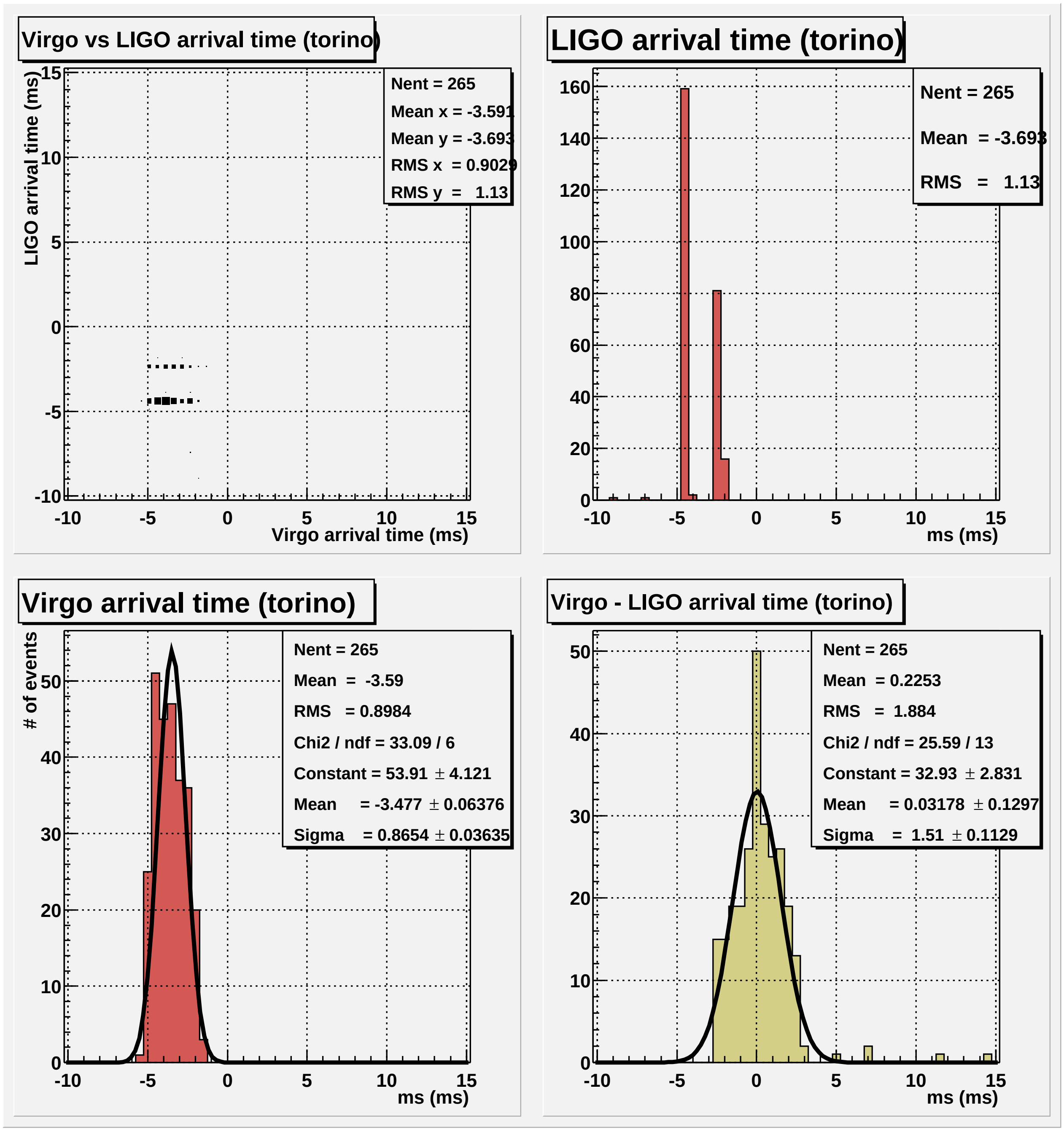

Figure 11: Arrival times when the PC clocks are set using the Torino server.

3.8 NDAS Clock development plans

As it is already useful we propose to convert the NDAS clock to a permanent system running at all the sites, which will provide us with a continuous monitoring of the relative time difference between sites. It requires the installation of a set of identical PCs at each participating GW observatory. We can also improve the understanding of the NDAS clock systematic errors. New data is needed with a better choice of NTP servers and a more careful check of the network route.

The error achieved already allows us to not miss coincidence and to reach the minimum requirement for rudimentary pointing. Such a system would catch errors introduced due to large drift of the local timing system or due to bugs introduced in new release of the GPS and DAQ software. It will also give us a continuous monitoring of the DAQ systems synchronization.

4 Proposal for atomic clock based timing monitoring

Timing of the DAQ is critical for the coincidence analysis between detectors or for long-term studies like periodic sources search. In the light of widespread problems caused by the 2002 rollover anomaly' [TT] of some TrueTime GPS receivers (caused by a very simple software bug), it is even more important to review and fortify our timing strategy. We propose to continuously monitor the stability of the GPS system against a sufficiently reliable atomic clock, which will give us a more accurate measurement of absolute timing, the GPS clock stability at one site and an accurate cross check between sites.

4.1 Local atomic clock proposal

As we have shown during the GPS board validation in Section 2, our GPS boards from different manufacturers are sufficiently close (~us) to each other when they are at the same geological location receiving signals from the same satellites and their firmware also operates bug free. However, in the light of the recent problems with GPS based units we cannot take the purely GPS based timing for granted, especially when requiring extremely high up time and extremely high reliability from a network of detectors. There are several conceivable failure modes that can cause the loss of timing accuracy or the loss of our confidence in our timing accuracy. It is advisable to develop solutions to make our timing system redundant, while relying on more than one independent time source. The straightforward solution to complement our existing GPS based system would be a very stable, synchronized but locally installed system of atomic clocks. These clocks will let us detect, in quasi real time, any glitches or shifts in the GPS timing systems. They can be disciplined to the same highly accurate source regularly but rarely and installed at each observatory. It might also be a good idea to purchase or develop a portable atomic clock that can be used in at-site timing tests as well as in inter-site synchronization. In the following paragraphs we survey the possible solutions and propose a feasible one to implement and test.

When comparing the long term timing accuracy and price of the three major types of commercially available frequency standards, we can see that the only feasible solution for network timing on the short term is a rubidium or cesium oscillator based devices (A comparative overview of commercially available oscillators is available from Ref.[OSCOV], and the graphical comparison of available technologies is shown on Figure 12.).

For the following “back of the envelope” calculation we assume that the clocks can be disciplined to a master source a few times a year. We estimate the errors after a couple of days (accurate measurement of the time difference by two DAQ systems) and after 90 days to give an idea of the achievable long-term stability. We also assume that it is sufficient to maintain the relative accuracy between any two sites below the expected accuracy of the matched filtering (~20us) for the free running periods (~90 days). This means that we need a device, which can produce accumulated time error of less than 10us over a 90 day period. This device should not be portable. For portable clocks we require that they do not drift more than ~1us a day, while they are durable, cost effective and light enough to carry.

Courtesy of http://www.zyfer.com/research/briefings/pdf/oscillator%20overview%2012-01.pdf

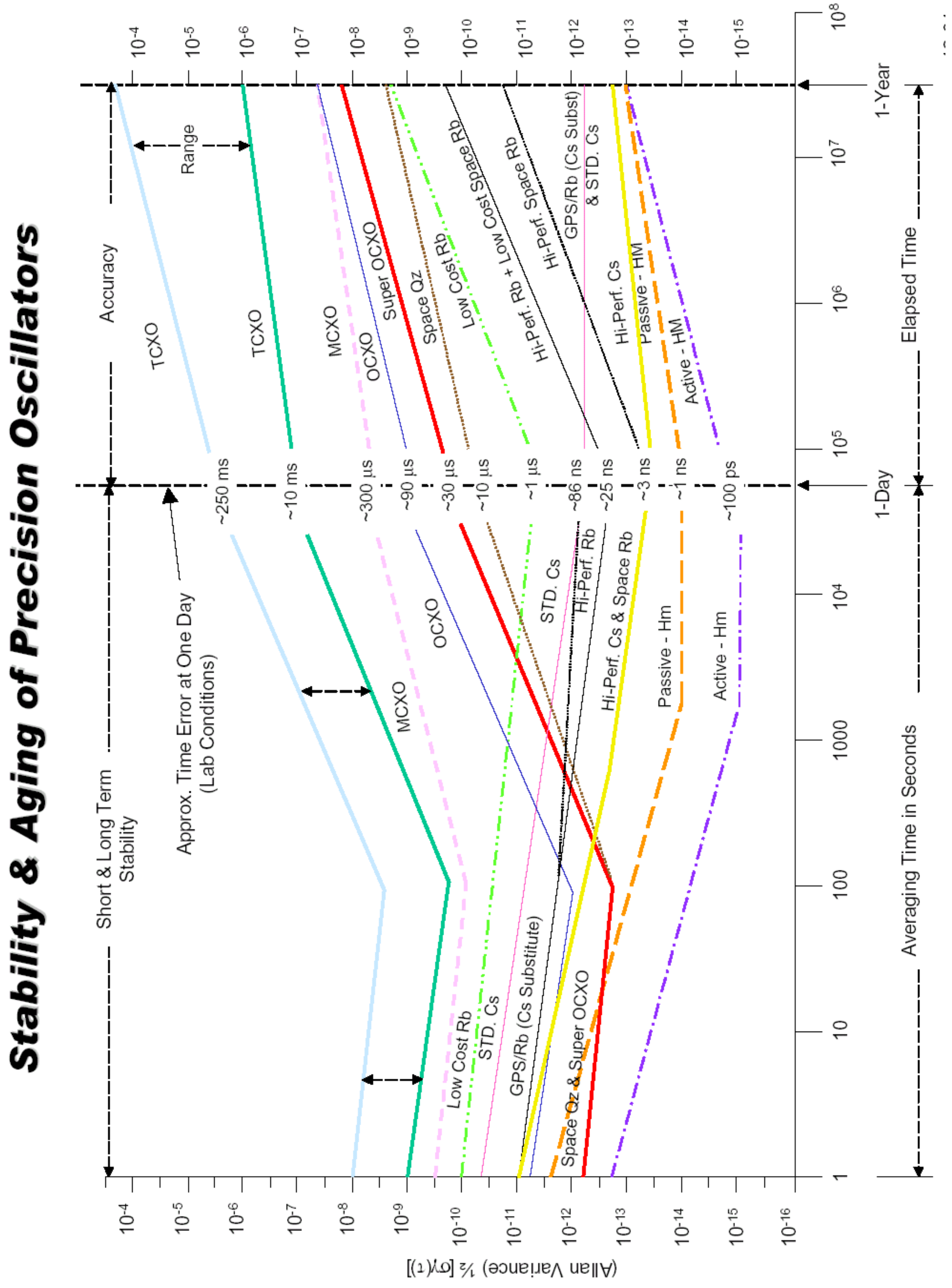

Figure 12 Comparison plot of achievable accuracy with present oscilator technology. For details please consult http://www.zyfer.com/research/briefings/pdf/oscillator%20overview%2012-01.pdf

Baked precision crystals will give us ~150 ms for the 90 day interval and ~400us for a day. We expect that software corrections cannot improve this substantially; therefore we should not consider these devices.

Commercially available cesium clocks will provide us with free running accuracy better than ~20us for the 90 day period and ~200ns for a day (Figure 14). This can be improved with software corrections to satisfy any of our requirements. However, the price (25K$/unit) is very high and in general Cesium based units are not portable. They are best utilized as stationary units at each observatory.

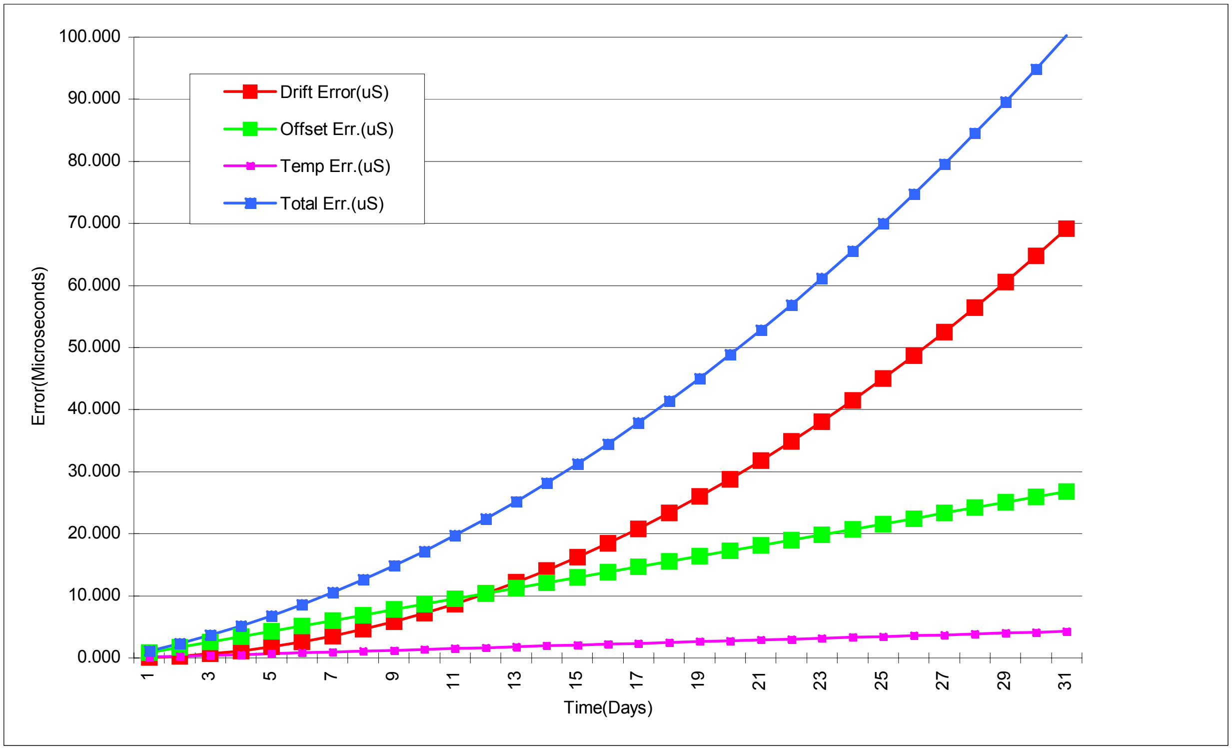

Figure 13 Contributions to the accumulated time shift for typical Rubidium (Rb) clocks. Note that the two major contributors are due to aging (frequency drift) and the original offset of frequency relative to the nominal value. The offset can be accurately measured at the time when the Rb clock is disciplined to the maser clock. The aging of individual units can be measured and modelled. It is conceivable to correct for the freqency offset and drift effects for the degree that long term accumulated timing error will become comparable to the error due to temperature effects. (This graph is the curtesy of Richard Bailey of Datum Inc. For this graph we assumed that the drift is 5.0E-11 per month, the offset is 1.0E-11 and the temperature offset is 8.00E-13 per Degree C, while allowing 2 degrees shift in temperature.)

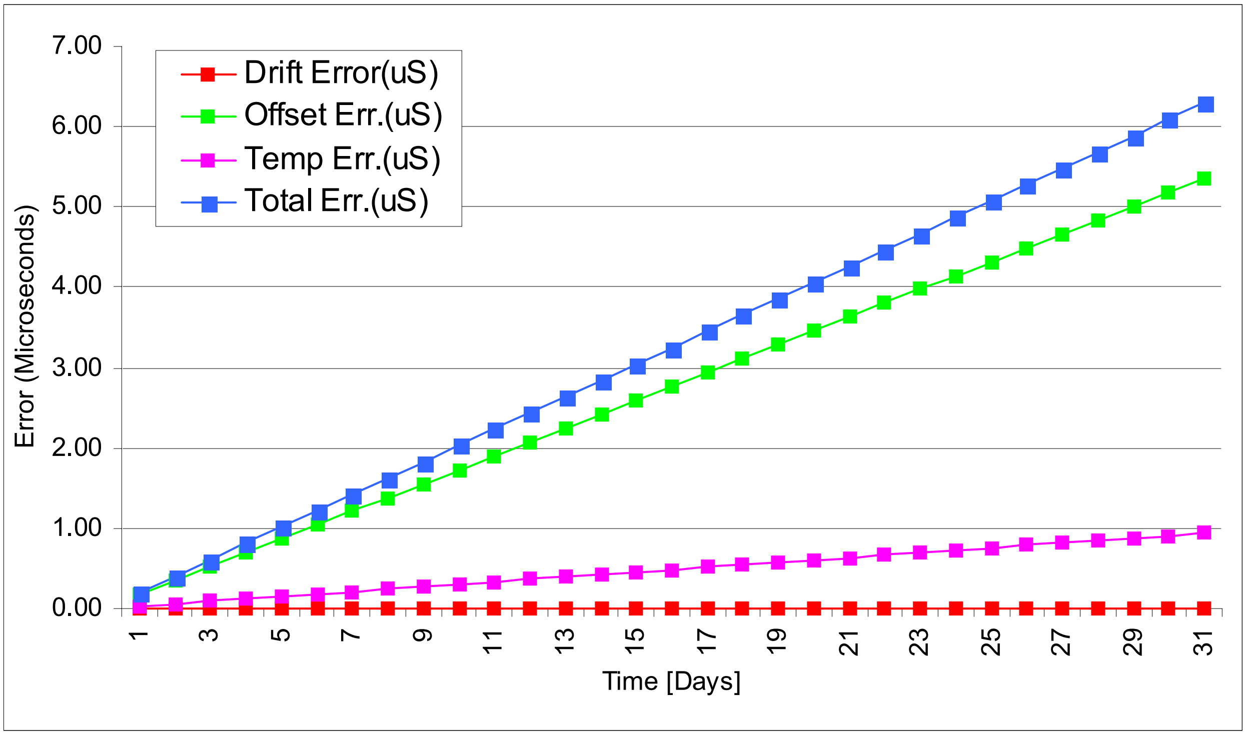

Figure 14 Contributions to the accumulated time shift for typical Cesium clocks. Note that the only major contributor is the the original offset of frequency relative to the nominal value. The offset can be accurately measured at the time when the Rb clock is disciplined to the master clock. It is conceivable to correct for the freqency offset for the degree that long term accumulated timing error will become comparable to the error due to temperature effects. (This graph is the curtesy of Richard Bailey of Datum Inc. For this graph we assumed that, the offset is 2.0E-12 and the temperature offset is 7.00E-14 per Degree C, while allowing 5 degrees shift in temperature.)

Recent technological advances lead to very small Rb oscillator units that are available off the shelf for acceptable prices (~1.5K$/unit). The accumulated time error estimate for a typical device is shown on Figure 13. From the graph we can deduce that the accumulated time delay (@ (0.072 days^2 + 1.0022 days) us) at the end of the 2 day period should be less than ~4us (or ~700us for 90 day). The original frequency offset of the device can be measured at the time of disciplining and corrected for during the free running period. Assuming that the local GPS clocks work fine most of the time, the slow aging effects can be tracked and modeled. It is conceivable that the software corrections based on these models can improve the performance of the devices to the level of the thermally induced drift (~12us for 90 days and 200 ns a day). This means that a rubidium based clock might be able to satisfy the accuracy requirement, but to achieve this requires large amount of work hours. It is likely that our short-term requirement can be satisfied with relatively small extra investment though. However, the practical problem of portable power and the necessary investment in work hours is to be considered. Due to the oven built into the unit the power consumption is quite high and it seems that it is impossible to provide power for 24 hour using hi-tech rechargeable batteries and keeping the weight under practical 20-pound limit. A possible solution is to rely on a bank of readily available zinc-air batteries, which have very good power/weight ratio. These batteries are not user rechargeable but the price is quite low for refill cartridges (~10$). The conceptual layout for the portable units is shown on Figure 15.

As a conclusion we propose to equip each observatory with atomic clocks (Cesium at least at one site) and build (portable) test units based on Rb oscillators. This would be enough for feasibility and performance study between the LIGO and VIRGO sites. The estimated cost of the pilot project is ~50K(clocks) + ~6K$ (portable hardware) + work hours + travel, some of which would be shared between LIGO and VIRGO.

The choice of atomic clock to be installed at each site depends on the frequency of the timing checks and clock disciplining performed at each site. If this comparison can be done using either an upgraded NDAS timing system, a more frequent cross calibration via portable rubidium clocks or low rate crosschecks via the GPS system or by external institutions, then it might be enough to have only Rubidium clocks at most of the sites. If these solutions will not prove satisfactory then we will have to go to Cesium clocks everywhere.

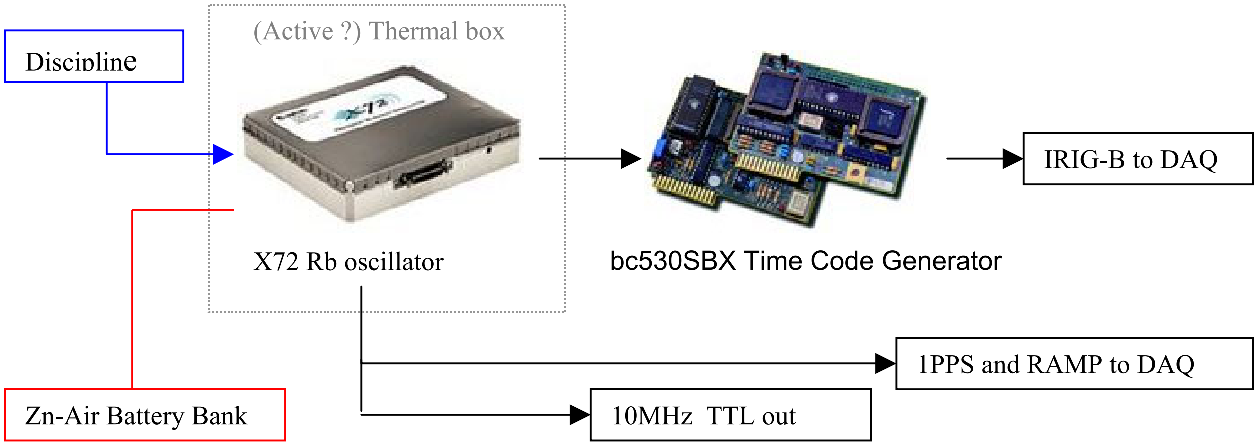

Figure 15 Conceptual box diagram of a simple rubidium oscillator based timing unit. The bc530SBX Time Code Generator and bc330SBX Time Code Translator (~500$) can be used as a CPU independent, standalone unit to produce accurate IRIG-B output. Detailed information about the Datum X72 precision rubidium oscillator is available from Ref. [DX72], while the Datum bc530SBX Time Code Generator is described in Ref. [530sbx].

5 Summary

Our first timing comparison between LIGO and Virgo gives the following results:

- The 1 PPS produced by the LIGO and VIRGO GPS vendors do not show an average offset larger than 200ns on average with a jitter less than 300ns.
- The full Data Acquisition system of LIGO and VIRGO tag their data with a relative accuracy better than a few milliseconds. Systematic effects dominate the measured time difference. We plan to continue the investigation in the coming months to reduce this error.

We propose to add an atomic clock at each site to check the local timing stability and to turn the NDAS clock system to a permanent system monitoring installed all GW detectors involved in Network Data analysis.

6 Acknowledgements

We are grateful to the Virgo DAQ group and the LIGO Livingston Observatory for their support, wich made this study possible. We would like to thank Dale Ouimette for his help with the LIGO GPS system and Richard Bailey of Datum Inc. for his expert advice regarding the timing errors and equipment. We would like to thank Albert Lazzarini for his useful and numerous comments, which helped us prepare this document. We are grateful to Hareem Tariq for her comments.
LIGO is funded by the National Science Foundation under the Cooperative Agreement PHY-9210038.

This work is a collaborative effort of Laser Interferometer Gravitational-wave Observatory and the Virgo Collaboration.

7 References:

[Tinto] “Near optimal solution to the inverse problem for gravitational-wave bursts”, M. Tinto, Y. Guersel, Phys. Rev. D 40, 3884-3938, 1989

[TR] "Estimation of the Needed Accuracy for the Calibration of the VIRGO Interferometer in Relation to the Detection of Coalescing Binaries" by D.Buskulic et al., Astroparticle Physics Vol 15/4, pp 383-389, 2001

[TT] "2002 rollover anomaly", TrueTime Inc., Cure: http://www.truetime.com/DOCSn/service_bulletins/F68info.pdf, Cure validation: http://www.truetime.com/DOCSn/service_bulletins/2002rolloverSB10.pdf

[VGPS] VIRGO GPS; "Datum bc635/637VME and bc350/357VXI Time and Frequency Processor modules", Datum Inc., Datasheet: http://www.datum.com/pdfs-ttm/bc635-637vme_bc350-357vxi.pdf, Manual: http://www.datum.com/manuals/ttm/bc635VME-bc350VXId.pdf

[LGPS] LIGO GPS; "JXI2 / Brandywine VME-SyncClock32 Synchronized Clock with VME Interface", Brandywine Communications, Datasheet: http://www.brandywinecomm.com/literature/bwc_bds_vme32_a.pdf

[JGPS] "JXI2 for 104 bus", JXI2 Inc., Datasheet: http://www.tri-m.com/products/jxi2/specs/timeprocessor.jpg

[DX72] "Datum X72 precision rubidium oscillator", Datum Inc., Datasheet: http://www.datum.com/pdfs-telcom/x72ds.pdf, Manual, http://www.datum.com/manuals/irvine/x72_mnl.pdf

[530sbx] "Datum bc530SBX Time Code Generator", Datum Inc., Datasheet: http://www.datum.com/pdfs-ttm/bc330-530_sbx.pdf

[DTC] "Timing & Time Code Reference", Datum Inc., http://www.datum.com/TTM/pdf/timeref.pdf

[NTP] "Internet Time Synchronization: The Network Time Protocol", D. L. Mills, IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 39, NO. 10, OCTOBER 1991, http://www.datum.com/TTM/pdf/itsapnt.pdf

[OSCOV] "Oscillator Overview", H. Fruehauf, Zyfer Inc., http://www.zyfer.com/research/briefings/pdf/oscillator%20overview%2012-01.pdf

[GPSBA] "GPS Basics", H. Fruehauf, Zyfer Inc., http://www.zyfer.com/research/briefings/pdf/gps_basics_2-02.PDF

[GPSENC] "Encryption Fundamentals", H. Fruehauf, Zyfer Inc., http://www.zyfer.com/research/briefings/pdf/Encryption-Fund'tls_9-01.pdf

[GPSTF] "GPS Time and Frequency Transfer", H. Fruehauf, Zyfer Inc., http://www.zyfer.com/research/briefings/pdf/gps_time_and_freq_transf_2-02.PDF

[NDAS] “Network Data Analysis Server (NDAS) prototype development” Sz. Marka, B. Mours, R. Williams, Class. Quantum Grav. 19 (2002) 1-4

7.1 GPS and Timing related LIGO documents:

[L1] "LIGO Data Acquisition System Final Design Review", LIGO-G980077-00-C
[L2] "GPS Clock Driver, Rev. 11", D. Ouimette, LIGO-D980369-11-C
[L3] "GPS Level One Clock Fan Out, Rev. 01", D. Ouimette, LIGO-D980362-01-C
[L4] "Timing Precision", D. Sigg, Sz. Marka, LSC Meeting August 13 -16, Hanford WA, LIGO-G010323-00-D
[L5] "Engineering Run 2. LHO, Detector Timing", Sz. Marka, D. Sigg, A. Takamori, LSC Meeting March 14 -17 2001 Livingston, LA, LIGO-G010129-00-D
[L6] "Timing System Test at the Second Engineering Run (E2) at LHO", Sz. Marka, D. Sigg, A. Takamori, LIGO-T010034-00-D
[L7] "Livingston Timing System Cable Diagram Corner Station Antenna/IRIG-B Connections", R. Bork, LIGO-D990083-A-C
[L8] "Hanford Timing System Cable Diagram", D. Barker, LIGO-D980354-00-C

7.2 Timing related VIRGO documents:

[V1] “The VIRGO Timing System”, D. Boget, F. Bellachia, A. Masserot, B. Mours, D. Verkindt VIR-TRE-LAP-5200-103