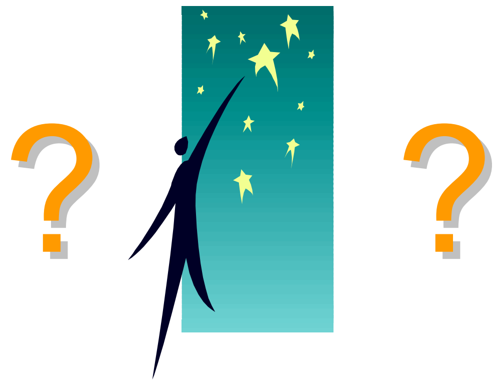
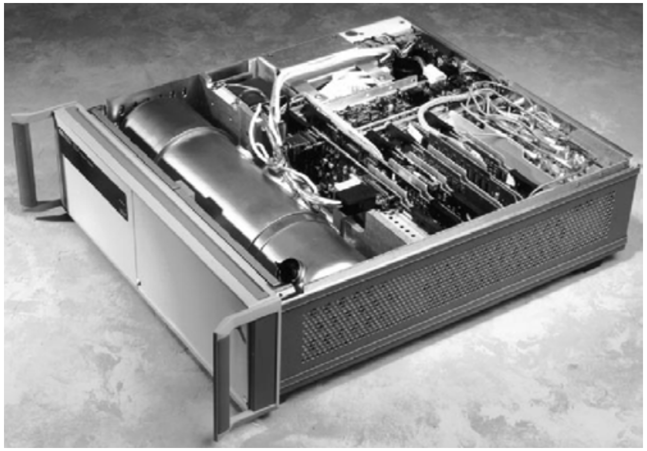




Proposal to increase the credibility of LIGO timing using atomic clocks and an optical fiber based time distribution system

LIGO-G030233-00-D

Commissioning Meeting

28 April 2003

Szabolcs Márka and Daniel Sigg

LIGO

Statement and a much valued outside opinion…

Prologue

I strongly believe that the concept I will present is sensible and it is vital for LIGO in the medium term.

Proposal to purchase, install and commission atomic standard based timing systems at the LIGO observatories to

- establish legally traceable and accurate LIGO timing
- ensure long term stability
- provide a single time standard for each observatory
- dramatically increase timing reliability, dependability and robustness via quality and redundancy
- set the standard for international GW collaboration timing systems
- make it better than the “absolutely necessary” for extra confidence and long lasting performance
- do it right the first time and avoid future “timing mitigation” efforts and expenses
- **give us the confidence we need for the first detection!**

Hello,

In general it would be a mistake to depend on a raw GPS receiver for timing control. There are just too many potential problems and reliability issues.

A standard commercial cesium has a time dispersion of a few ns per day once its rate offset has been calibrated. It could easily provide a primary time source for your facility. A rubidium standard would be much cheaper, but its free-running performance would not be good enough to support your requirements. A GPS-disciplined rubidium could do the job. It would be much cheaper than a cesium, but it would not provide the same level of independence from outside problems. There are a number of commercial devices that you could choose from -- you don't have to build this yourself.

It is a simple matter to synchronize two sites to much better than 1 us using GPS. It is not too hard to get synchronization at the level of tens of ns, and you could get down below 10 ns if you are willing to work at it. The time could be traceable to NIST or USNO without too much trouble. You could also use the NIST services to calibrate and certify your frequency standards if you wanted continuous real-time traceability.

The hardware provided by Timing Solutions will certainly do the job for you. It is probably quite a bit fancier than you need based on your requirements, but it will certainly do what you want. Generally speaking, it is hard to transmit 1 pps signals over any distance, and it is more common to use one of the other formats and to regenerate the 1 pps when it is needed.

Judah Levine
Time and Frequency Division
NIST Boulder

Background and questions

- Present LIGO timing is solely based on GPS…
  - » Large number of independent units and antennas
  - » Large distances between units and antennas
  - » None of the GPS units can fail during operation
  - » Most units are from a single small manufacturer
- Can we afford to have different time at different crates?
- Can we keep timing in case of GPS outage?
- How reliable and accepted is GPS based timing?
- How reliable are GPS receivers?
- Can we present credible timing to the world in case of detection?
- Can we make it more robust?
- For coincidence analysis accurate relative and absolute timing is a necessity
  - » Is it wise to solely rely only on the GPS system?
  - » Delays on the signal path?
  - » Are we synchronized to the world? (e.g. external triggers)
  - » Are we running in sync? How much in sync?
  - » Do boards from different manufacturers give us the same time?
  - » Do we ALWAYS get the right time from the GPS?
  - » GPS is complicated -> are there firmware bugs?

LIGO

Various levels of potential GPS failures

- **Core GPS system level**
  - » Selective availability, jamming, software bugs, …
- **Satellite level**
  - » On board clock failures, spacecraft to spacecraft inconsistencies, …
- **Geophysical / RF transmission level**
  - » Solar activity, ionosphere, troposphere, storms, multipaths, …
- **Antenna / cabling level**
  - » Satellite visibility, environmental issues, reflections, connectors, …
- **Board / firmware level**
  - » Limited firmware precision, board to board, time to time variations, built in bugs, …

DIPLOMARBEIT

Fehlverhalten von GPS-Satellitenempfängern

im Hinblick auf ihren Einsatz

im Forschungsprojekt SynUTC

verfaßt
am Institut für Automation
der Technischen Universität Wien

a 270 page thesis …

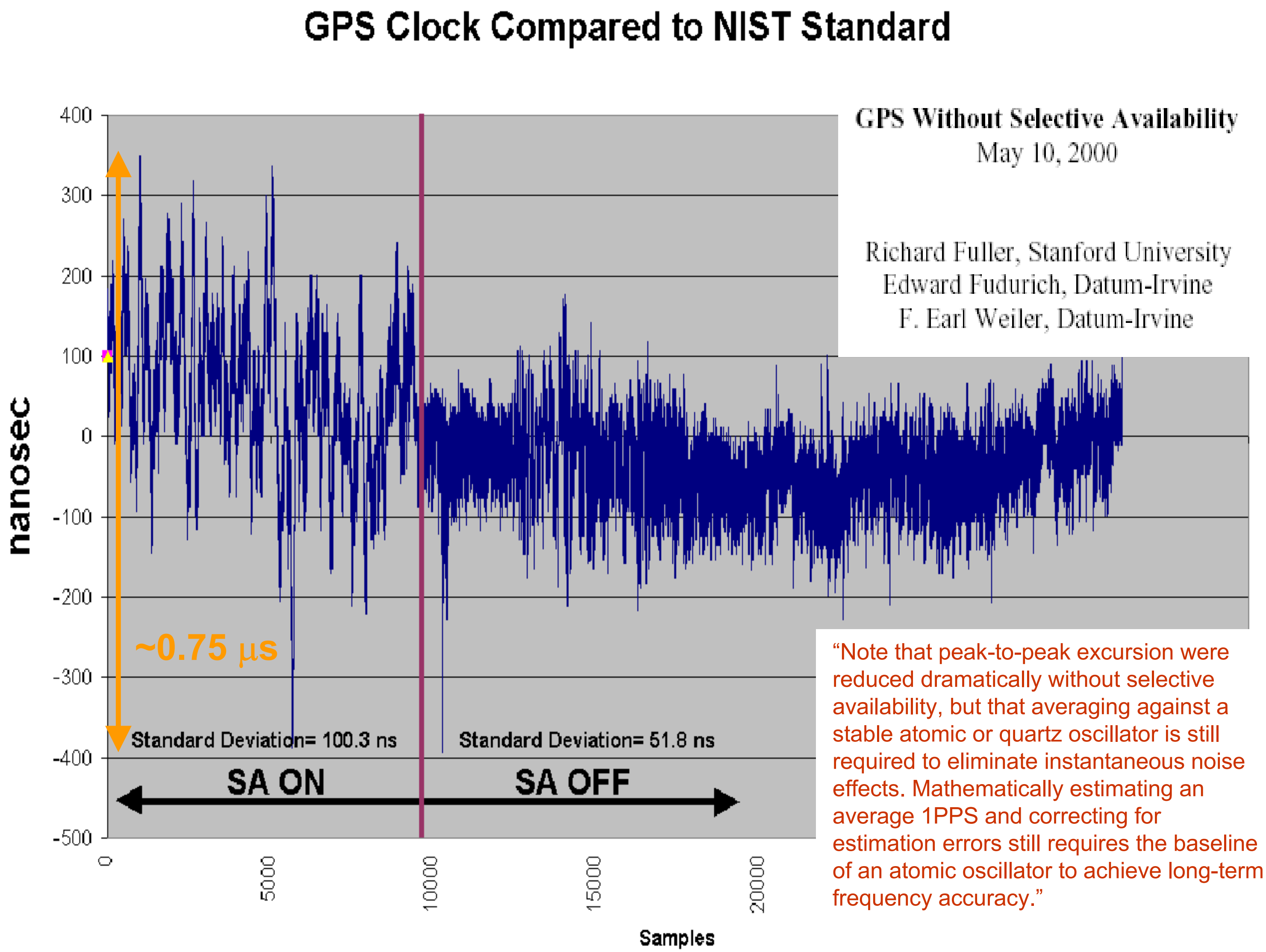
unter Anleitung von Univ. Doz. Dr. Ulrich Schmid
von
Dieter Höchtl

- Fundamental limitations
- Failure modes experienced
- Failure modes possible
- Avoidable but “unavoided” failures

Wide selection of scary examples in the literature !

Selective availability is off … is it for forever?

- Factor of ~2 in rms improvement only
- The military is still more accurate
- Ionosphereric uncertainty is significant
- Long term stability still requires a local atomic oscillator
- **Dynamic use of GPS timing information is dangerous**



"Note that peak-to-peak excursion were reduced dramatically without selective availability, but that averaging against a stable atomic or quartz oscillator is still required to eliminate instantaneous noise effects. Mathematically estimating an average 1PPS and correcting for estimation errors still requires the baseline of an atomic oscillator to achieve long-term frequency accuracy."

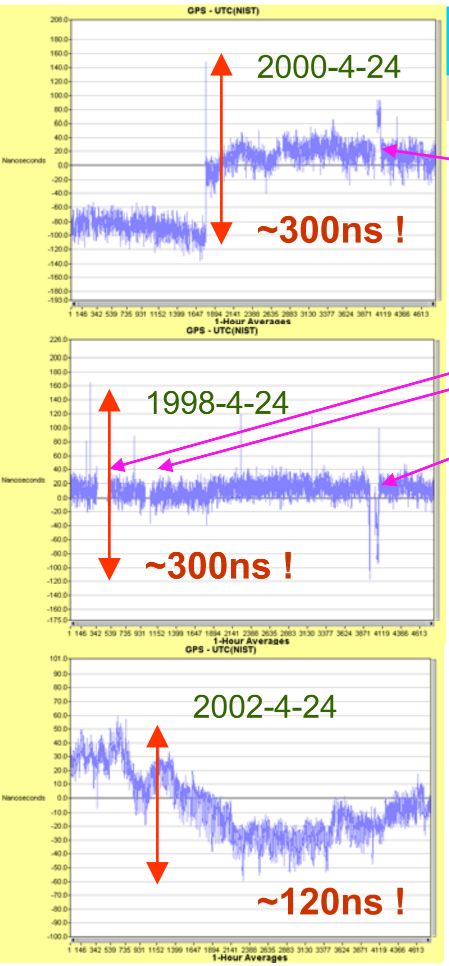
Figure 3. GPS 1 PPS accuracy before and after SA was set to 0.

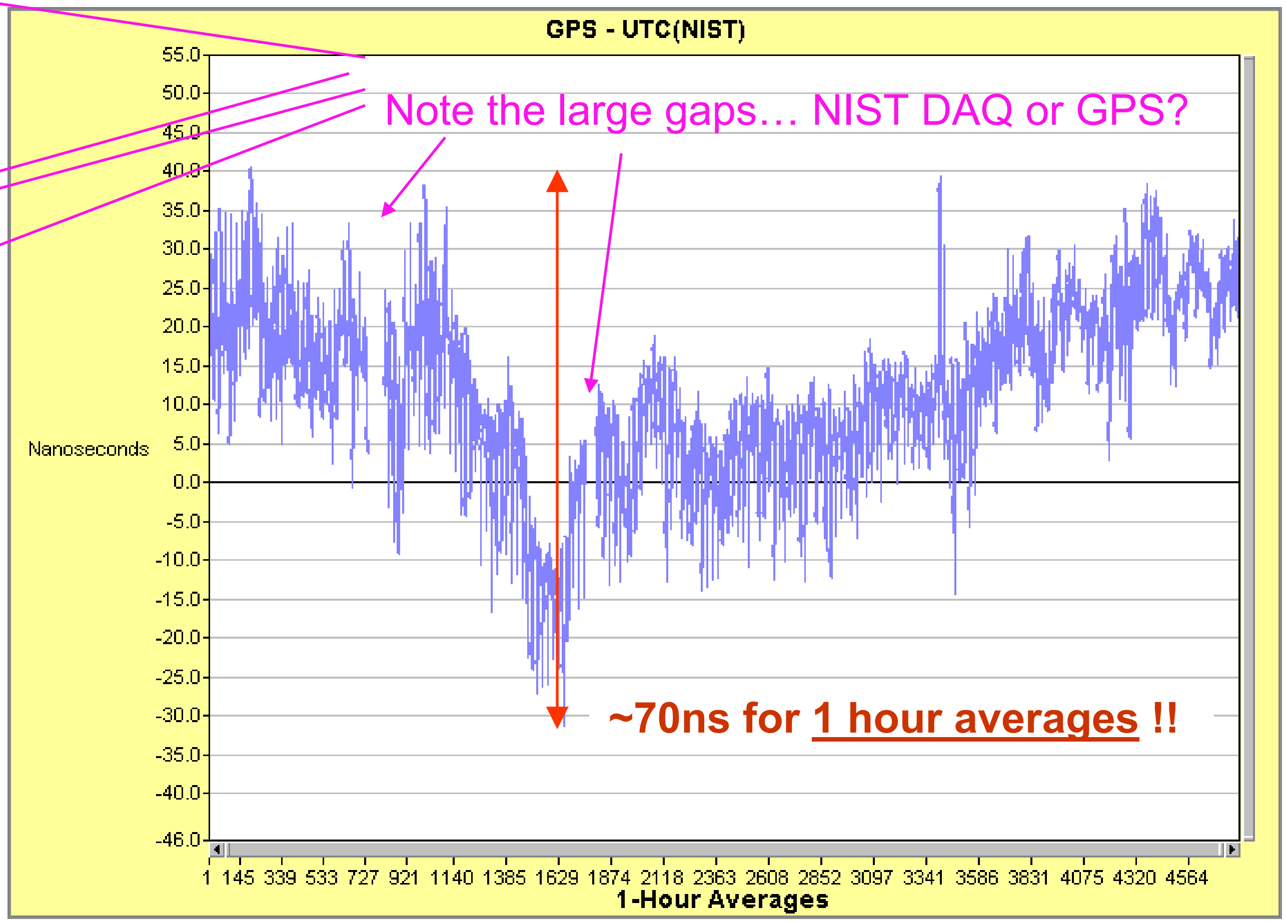
GPS monitoring data for the 200 day period ending 2003-04-24 (as received at NIST in Boulder, Colorado)

http://www.boulder.nist.gov/timefreq/service/gpstrace.htm

GPS - UTC(NIST)
(one-hour averages using all satellites in view)

Hours	Mean Time Offset (ns)	Range (ns)	Frequency Offset	Confidence (r)
4660	12.1	71.8	$<1.0 \times 10^{-15}$	+0.22





Not much good news from a long-term GPS evaluation project…

6 Conclusions and Future Work

Our results, as limited as they are due to their snapshot-like nature, reveal a number of interesting facts about the issues touched in Section 2. First of all, our findings confirm that trusting blindly in all timing data provided by a GPS receiver is definitly inappropriate for fault-tolerant applications. Moreover, since failures like systematic bias cannot be locally detected, redundant verification information is mandatory — and this is exactly the basic assumption underlying our interval-based clock validation scheme.

In addition, the following facts deserve attention:

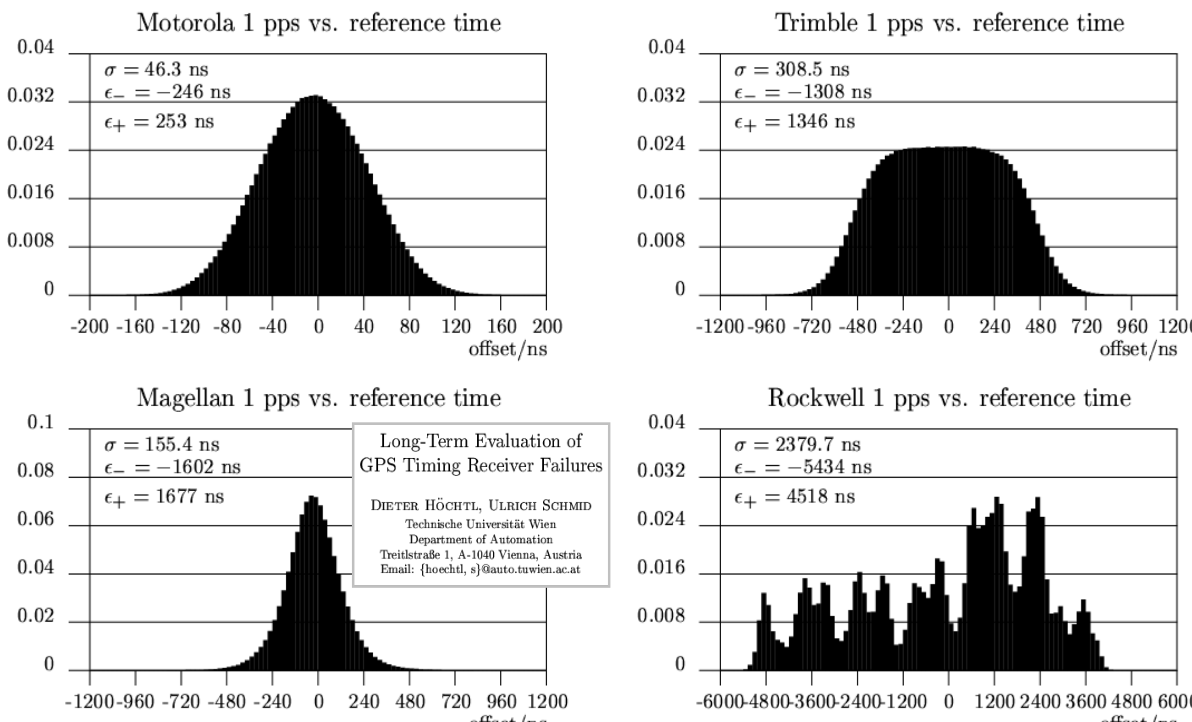
- Transient omissions of 1 pps pulses are relatively frequent.
- One cannot always rely upon the health status provided by a GPS receiver, in particular after a non-health situation.
- The time tag can be wrong, making some kind of agreement mandatory.

data reveal actually three different classes of transient failures, namely

- "obviously" erroneous (spurious) pulses,
- "step" pulses, characterized by a sudden deviation from the correct time,
- "ramp" pulses, which drift away from correct time gradually (and usually slowly).

Abstract

This paper provides an overview of the results of a continuous, 2 month experimental evaluation of all timing data provided by several GPS receivers. The primary purpose of this experiment was to provide measurement data facilitating fault modeling in our project SynUTC[1], which aims at external clock synchronization in fault-tolerant distributed real-time systems. As expected, the GPS receivers under test exhibited a wide variety of failures, ranging from transient omissions up to considerable deviations of the timing signals provided. Whereas those findings justify the appropriateness of our basic failure assumptions, it became nevertheless apparent that rerunning the experiment for a longer duration and with new brands/models of GPS receivers is advisible.



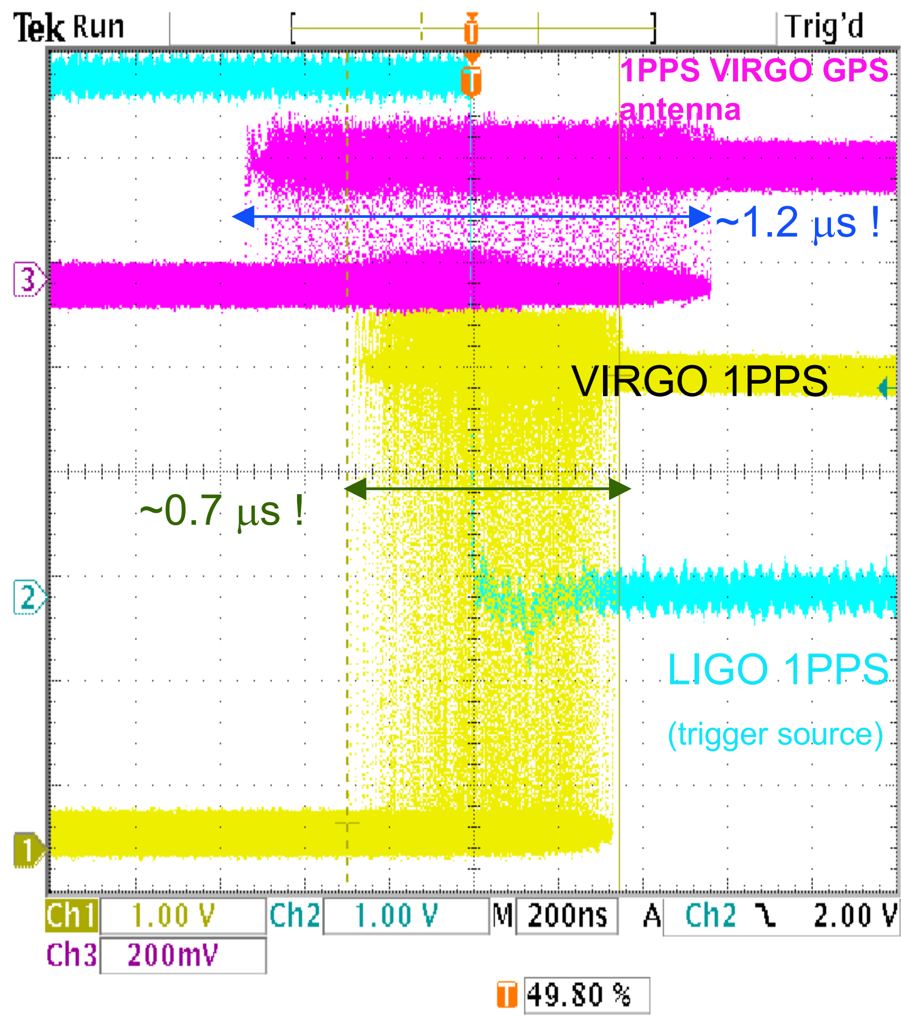
Long-Term Evaluation of GPS Timing Receiver Failures

Dieter Höchtl, Ulrich Schmid
Technische Universität Wien
Department of Automation
Treitlstraße 1, A-1040 Vienna, Austria
Email: {hoechtl, s}@auto.tuwien.ac.at

Figure 7: *Distribution functions for 1 pps pulses of all 6 receivers against the reference time (the means were eliminated)*

LIGO – Virgo GPS board comparison results

- LIGO and VIRGO use different GPS boards
  - » Is there a difference?
  - » Measure the board to board jitter 1 PPS signals …



Conclusion

- Significant difference exist
- The software correction on the Datum (Virgo) card helps but not too much
- When confronted, the Datum executives were
  - » Not at all surprised
  - » Stated that such difference is
    - – **normal**
    - – **will exist between even identical boards**
  - » Attributed to the board and not to the GPS system
  - » Kindly offered regular and costly calibration services
- LIGO has its own history of GPS related glitches
  - » Firmware bug
  - » Cable and antenna problems
- Ergo, presently the timing dynamically varies
  - » from site to site
  - » from building to building
  - » potentially from rack to rack
  - » from board to board
  - » from time to time

Establishing legal traceability for our timing is impossible now

Can timing compromise our credibility in the future?

Proposed Timing System Extension

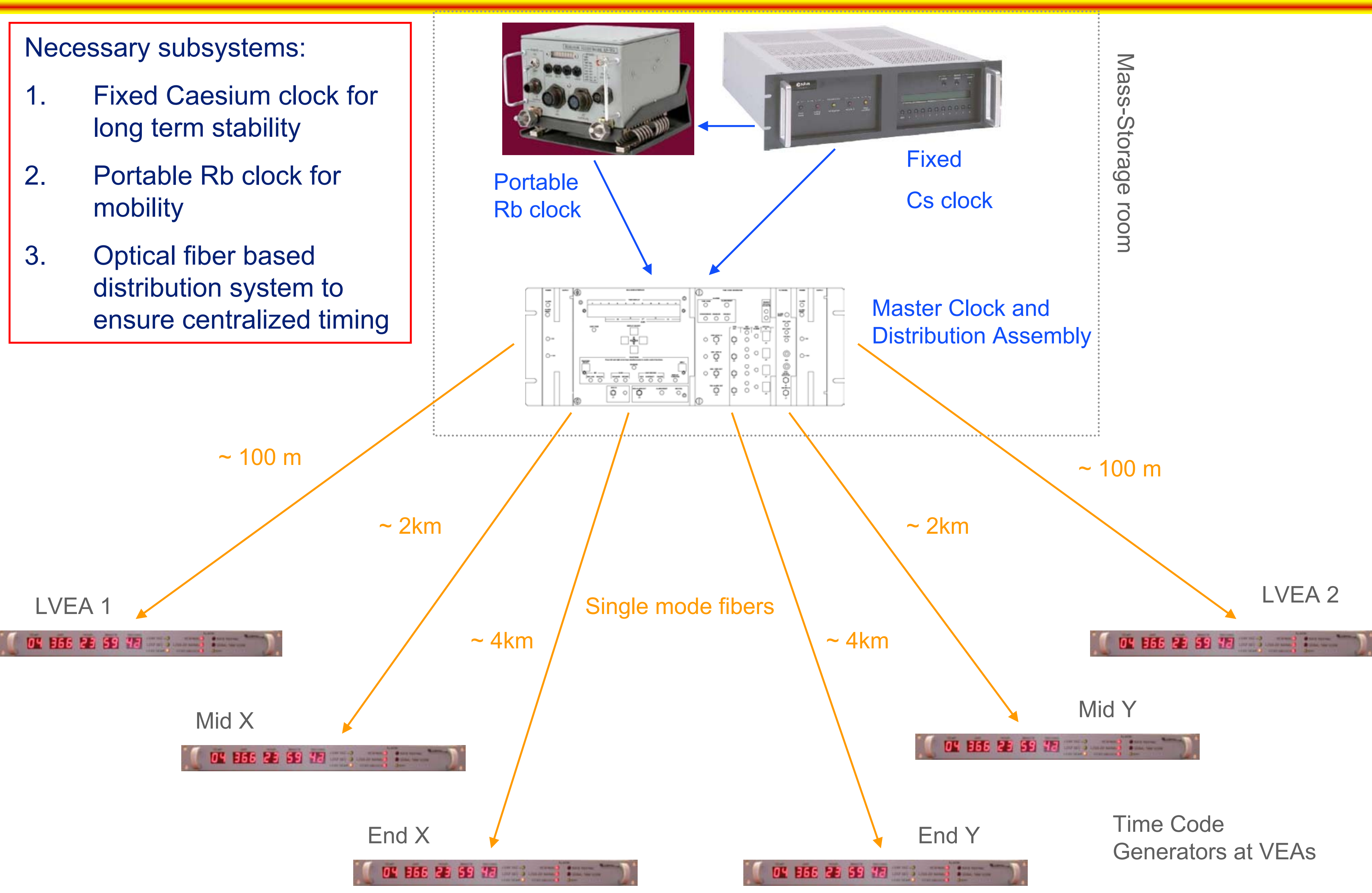
- Centralized atomic clock with time distribution over fiber to the corner/mid/end stations.
- Serves as an independent means to verify current GPS based timing system.
- Periodic calibrations to NIST standard.
- Long term: may use it as the primary clock.
- Use it to synchronize the photon calibrator.
  Yields accurate timing calibration of ETM displacements.
- Some might think it is an “overkill” but it should eliminate any doubts in the current (rather complicated) system.

Confidence is extremely important—both inside and outside of the collaboration!

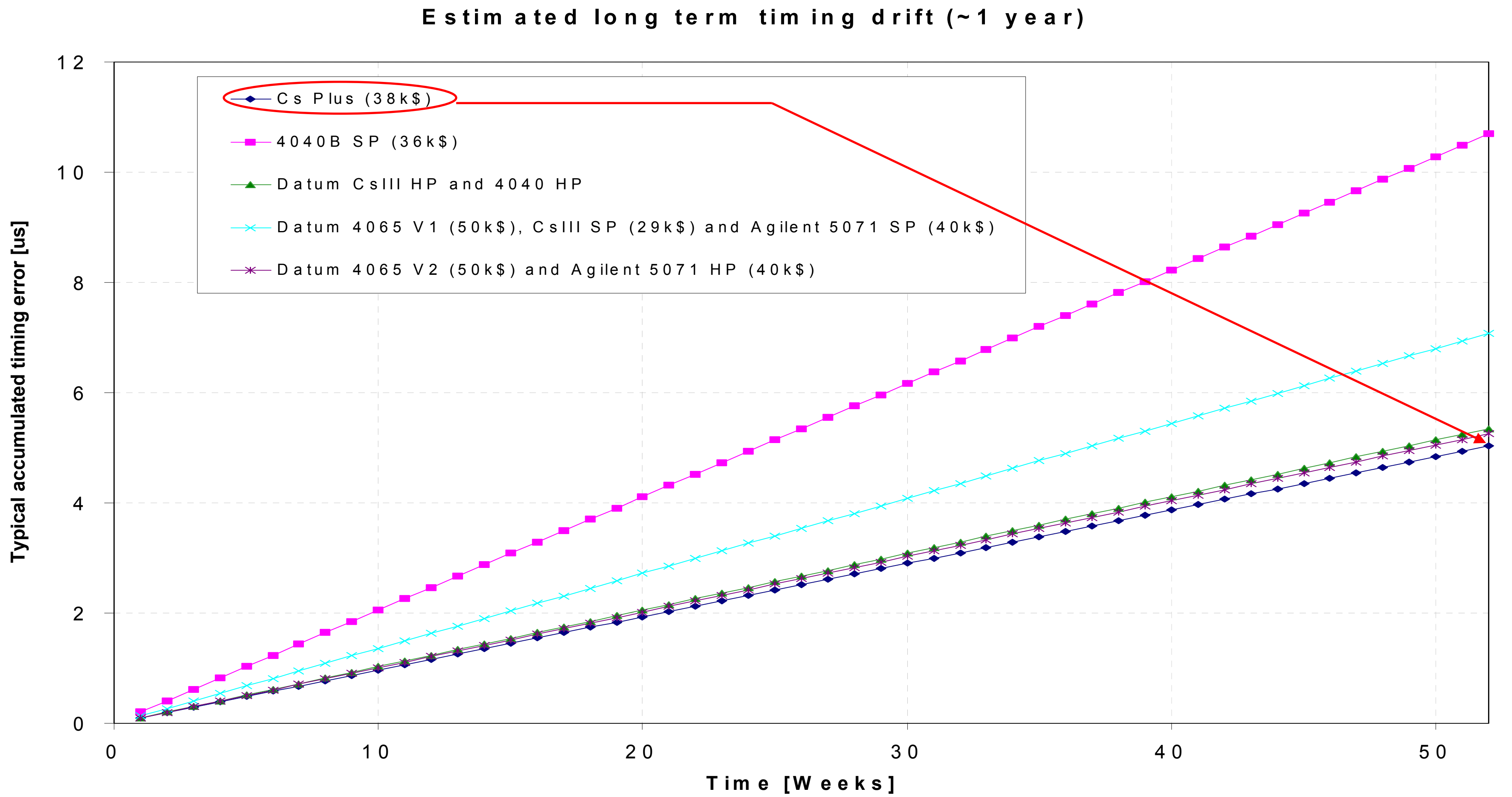
Proposed timing system geometry

Necessary subsystems:

1. Fixed Caesium clock for long term stability
2. Portable Rb clock for mobility
3. Optical fiber based distribution system to ensure centralized timing



Manufacturer Model	Price USD ($)	Expected drift [us/year]	Rack mount	Portable	Battery/DC	RF out [MHz]	1 PPS	IRIG-B	GPS	Cs tube Wrnt. [years]	Comment
Datum Cs Plus	38,090.00	5	yes	no	no	1,5,10	yes	yes	yes	12	
Datum CsIII SP	28,710.00	7	yes	yes	no	5,10	yes	no	no	6	Portability kit: +$570
Datum CsIII HP	??	5	yes	yes	no	5,10	yes	no	no	??	
Datum 4065 V1	49,980.00	7	yes	no	no	0.1,1,5,10	yes	no	no	12	Rack slides: +425
Datum 4065 V2	49,980.00	5	yes	no	no	0.1,1,5,10	yes	no	no	3	Rack slides: +425
Datum 4040B SP	36,200.00	11	yes	no	no	0.1,1,5,10	yes	no	no	12	
Datum 4040B HP	??	5	yes	no	no	0.1,1,5,10	yes	no	no	??	
Agilent 5071 SP	40,312.00	7	yes	yes	yes	0.1,1,5,10	yes	no	no	1	Rack mount flange: +36.9
Agilent 5071 HP	40,312.00	5	yes	yes	yes	0.1,1,5,10	yes	no	no	1	



Datum Caesium Plus

Short Term Stability	<1E-11
Long Term Stability	<2E-14
Holdover Stability	<5E-14
RF Outputs	1, 5, 10 MHz
Low Harmonic Distortion	<-40dB
Non-Harmonic Distortion	<-80dB
1 PPS Output ref. To GPS	20ns
Time Code Outputs IRIG B	AC
Monitor and Control Interface	RS232

CONNECTOR CHART

CONN	CONN TYPE		SIGNAL DESCRIPTION
J104	BNC		1PPS
J105	BNC		10 MHz
J106	BNC		5 MHz
J107	BNC		1 MHz
J108	BNC		IRIG
J110	BULKHEAD JACK		ANTENNA
J100 AC INPUT	PIN 1	3EP7	AC POWER
	PIN 2		NEUTRAL
	PIN 3		SAFTEY GND
J102 RS232	PIN 1	9 PIN "D" CONN	DCD
	PIN 2		RXD
	PIN 3		TXD
	PIN 4		DTR
	PIN 5		GROUND
	PIN 6		DCR
	PIN 7		RTS
	PIN 8		CTS
	PIN 9		NC
J103 ALARM	PIN 1	9 PIN "D" CONN	(F=CL) MAJ
	PIN 2		(COM) MAJ
	PIN 3		(COM) MIN
	PIN 4		(F=CL) MIN
	PIN 5		GROUND
	PIN 6		NC
	PIN 7		(F=OP) MIN
	PIN 8		(F=OP) MAJ
	PIN 9		NC

Item No.	Model Number & Description	Part Number	Qty	Unit Price	Value
1	Cesium Plus Frequency Standard with Internal GPS Receiver Standard Performance, 2 yr electronic, 12 year tube warranty		1	37,800.00	$37,800.00
option	Certified shipping container, cardboard		1	290.00	$290.00

Multiple uses for a portable Rb clock

A PORTABLE RUBIDIUM CLOCK FOR PRECISION TIME TRANSPORT

Helmut Hellwig and A. E. Wainwright
National Bureau of Standards
Frequency & Time Standards Section
Boulder, Colorado 80302

ABSTRACT

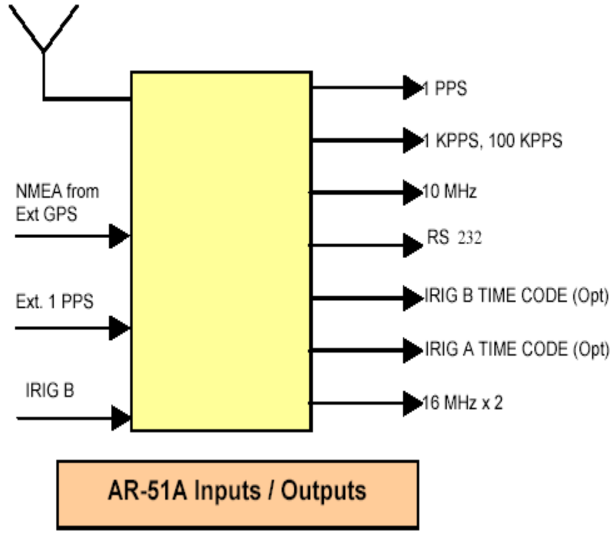
Based on a commercially available rubidium standard the National Bureau of Standards (NBS) developed a portable rubidium clock. Technical modifications which reduce the sensitivity against temperature, magnetic environment, and barometric changes allow stabilities in the 10^{-12} range under typical clock transport conditions. Under laboratory conditions the clock shows a best stability of 3 parts in 10^{14}. Clock packages based on sealed lead-acid batteries featuring a total weight of 21 kg and 18 hours battery operation were tested; an improved clock package was realized using silver-zinc batteries with 11 kg weight and 28 hours battery operation. Reports of several clock trips to the U.S. Naval Observatory and of one clock trip each to the Bureau International de l'Heure in Paris and to the Hewlett-Packard Company in Santa Clara, California are reported. Time transport precisions of .02 μs have been obtained. Special aspects of the clock modifications and the operating characteristics are discussed, as well as an optimal use of the data of a clock round-trip.

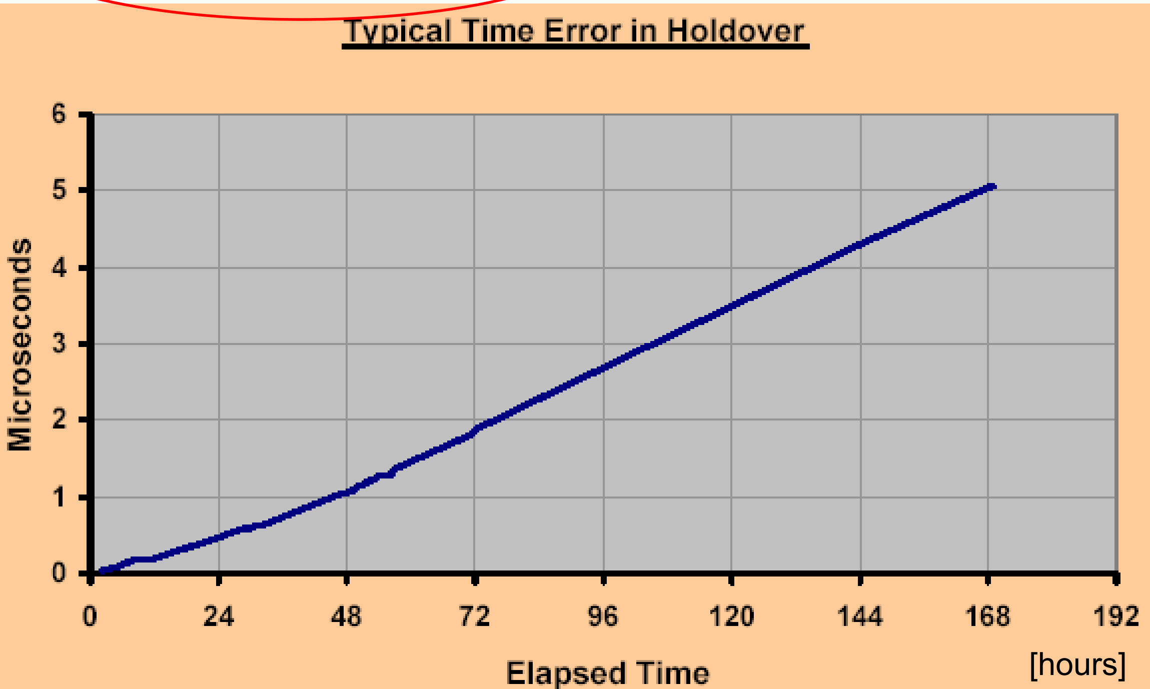
- GPS independent time transfer between primary clocks
- Mobile base to investigate intra-site, inter-site and international timing issues
- Instant backup for Caesium or local clocks

Preferred portable Rubidium clock

Main Features:

- GPS with Rubidium clock
- Outputs of 10MHz, 1PPS, IRIG B, RS232
- Inputs of 1 PPS, IRIG-B, 10MHz
- Time Accuracy: 1μs relative to UTC (std.)
  50ns relative to UTC (option)
- Frequency Accuracy: 2E-12
- Display of Time, Date, Status & BIT
- 1-hour Rechargeable Battery Back-up
- Built In Test - Up to 97%
- Operating Temperature: -20°C to +65°C (71°C for 30 min)
- Holdover (no GPS): 1μs/24hours, 5E-11/month
- Full MIL-STD Qualification for Mil. Applications.





Optical timing distribution system cost

TIMING SOLUTIONS CORPORATION

	TSC Part Number	Price each
TCT Chassis, Single Mode	4300S	$ 2,800.00
Quad Pulse Rate Output Module	4306	$ 400.00
5/10 MHz Module	4308	$ 800.00
Blank	4307	$ 15.00
IRIG-B Module	4303	$ 650.00
MCA - Full		$ 8,120.00
DA - Complete, 5 Single Mode Output Modules		$ 8,400.00

Hanford: (for 6 TCT nodes)

~39k$

+5k$ if 10MHz output is needed

Livingston: (for 3 TCT nodes)

~25k$

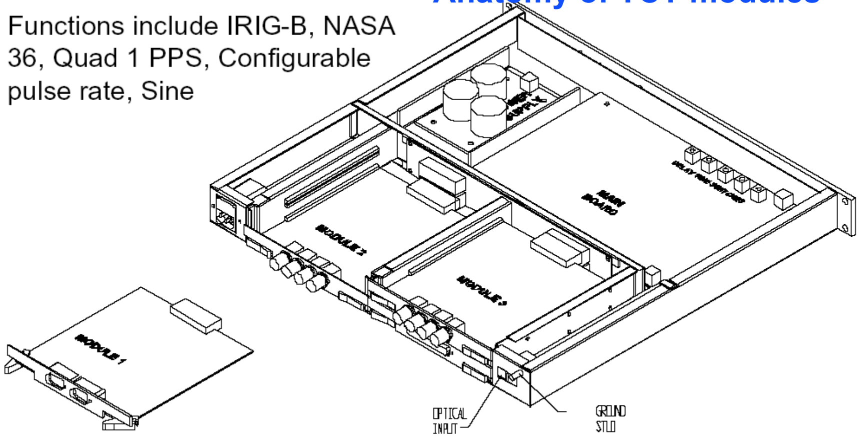
+2.5k$ if 10MHz output is needed

Total: (for 3 + 6 TCT nodes)

~64k$ ++ if extra outputs are needed

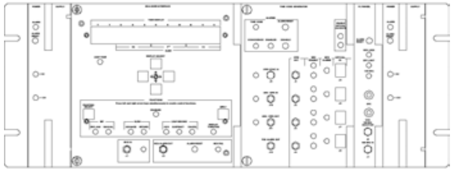
- 0-4 output modules can be inserted into the chassis
- Functions include IRIG-B, NASA 36, Quad 1 PPS, Configurable pulse rate, Sine

Anatomy of TCT modules



Major hardware cost

- **Caesium clocks**
  - » **~ 2 x 38k$**
- **Portable Rb clocks**
  - » **~ 2 x 15 k$**
- **Optical distribution system**
  - » **~ 25 + 39 k$**
- **Estimated total**
  - » **~ 200 k$**
    - – assumes an additional 30 k$ for initial calibration, installation, UPSs, epics alarms, etc.
  - » **The exact spare policy must be addressed as it depends on the method of use**
- **Delivery prospects:**
  - » **Clocks**
    - – ~4-6 wks ARO
  - » **Distribution system**
    - – 01 October 2003



Summary

- **It is sensible to complement our timing systems with**
  - **legally traceable highly accurate Caesium clocks**
  - **Portable Rb clocks which are**
    - very rugged
    - highly accurate on the short term (days)
  - **installing an optical fiber based timing distribution system**
    - go for high precision, let the atomic clock set the error
    - put the full observatory on a single time base
    - centralize backup power environmental requirements
    - Avoid RFI, ground loop and acoustic noise problems
- **If there is an intent to rely on this system, it is fairly straightforward to address**
  - **replacement part issues – the system is highly modular**
  - **redundancy issues – two atomic clocks at each site**
  - **Specific CDS signal requirements – TS will work with us**

It costs money, but this is the right way to do it.

Please visit http://www.ligo.caltech.edu/~smarka/Caesium/ for additional documents.