Synchronization between remote sites for the MINOS experiment

Main
Injector
Neutrino
Oscillation
Search

A collaboration

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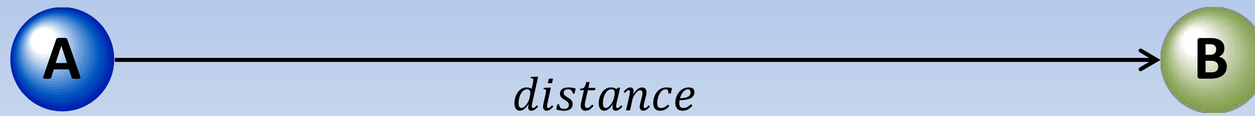
The experiment



$$v = \frac{distance}{t_{arrival} - t_{departure}}$$

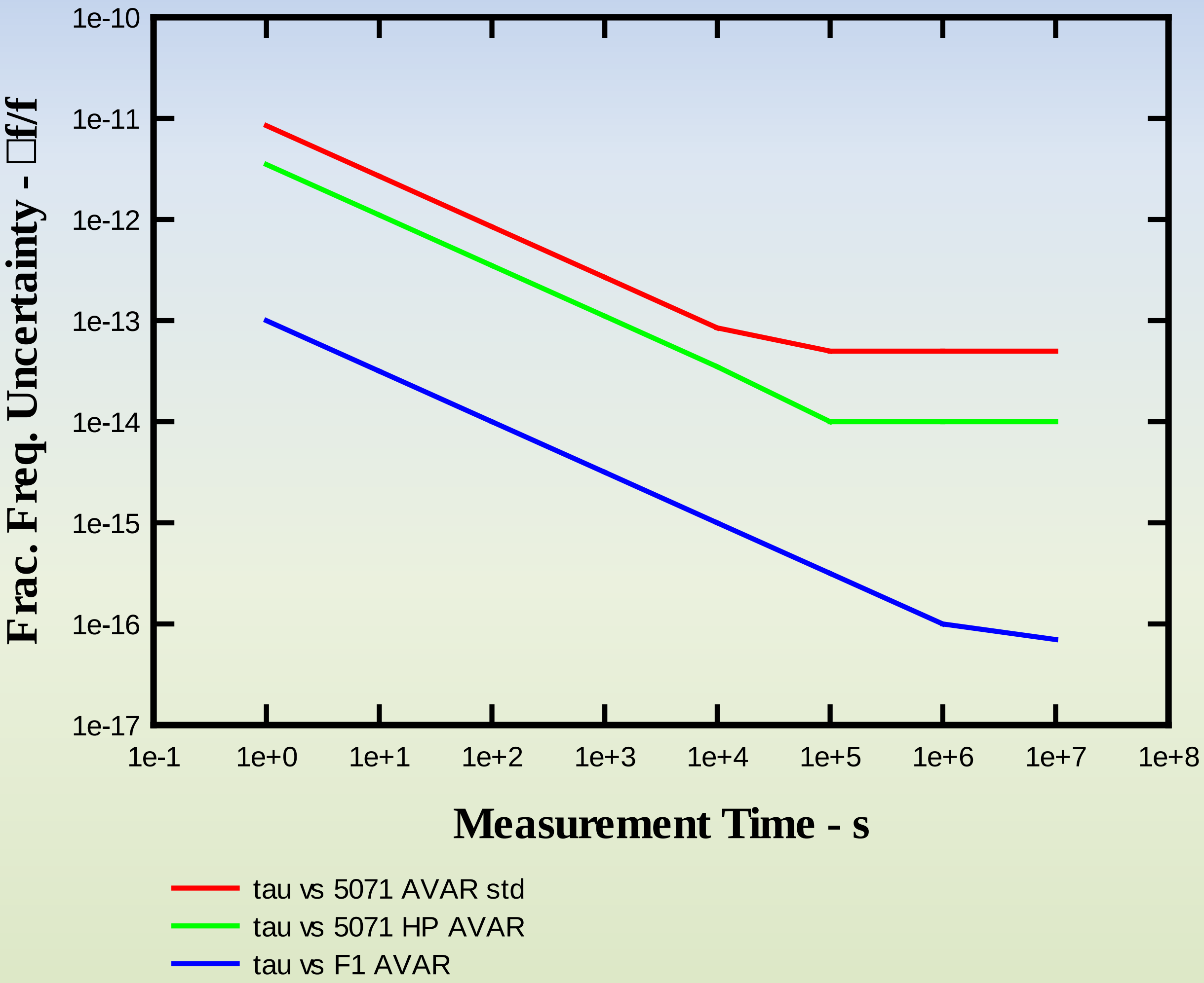
We need…….

1) Distance …..This is the geodesist's job…..see talk at 10:15 this session

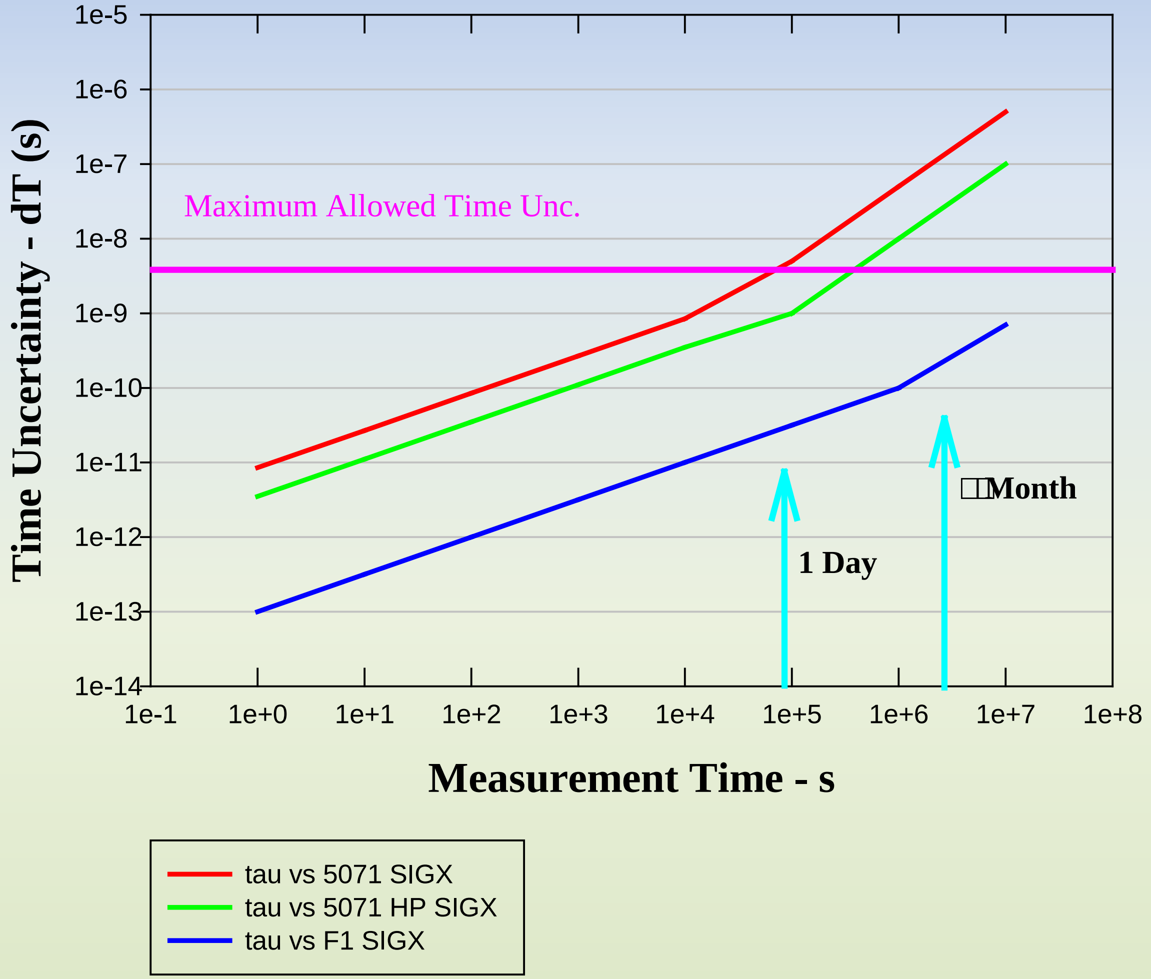
2) Something to measure …. A physical event…… OK, this is the neutrino beam

3) The time between departure and arrival….this involves 2 separate clocks in two different locations….which implies we must have synchronization between them….how hard can this be, ie. go ½ way between Fermi and Soudan with two clocks, set them to the same time and carry them slowly to their final destinations right…..(hint this doesn't work)……forget General & Special Relativistic effects, clocks have (at best) white frequency noise…time is $\int \omega dt$ so that the frequency noise averages down, but the <u>time</u> uncertainty grows like $\sqrt{\tau}$ ….. even very good Cs clocks are several ns/day

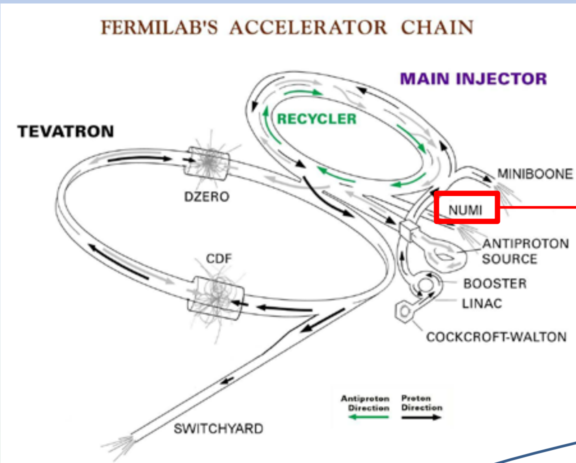
Clock Behavior 101

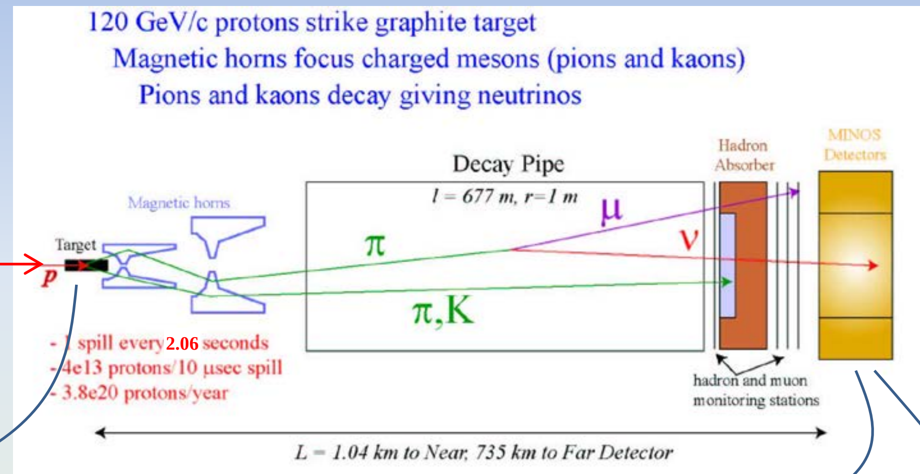


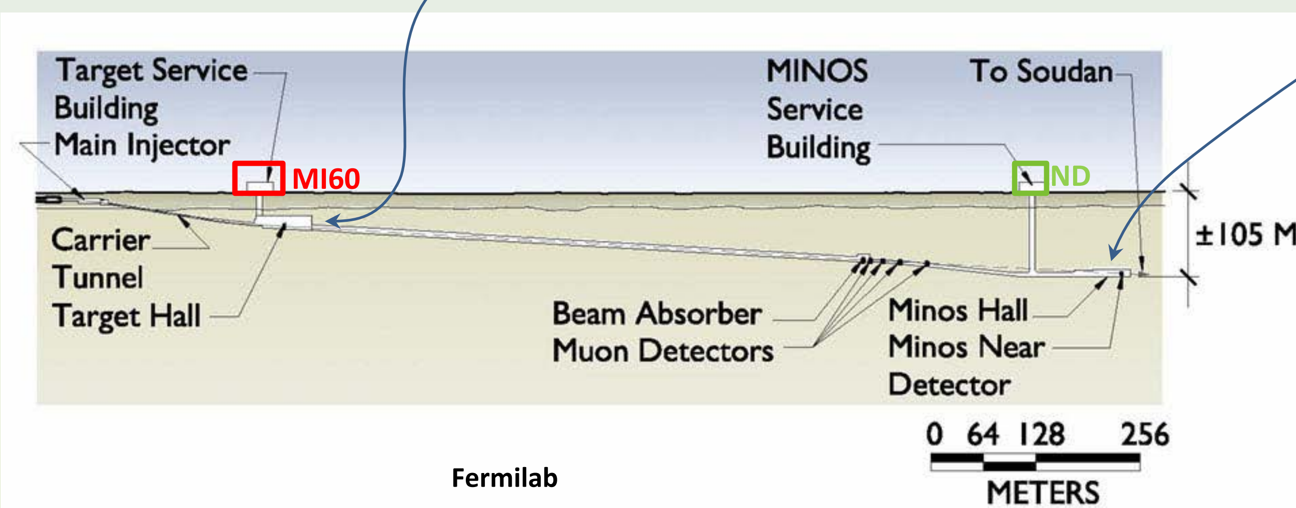
Clock Behavior 101 - cont

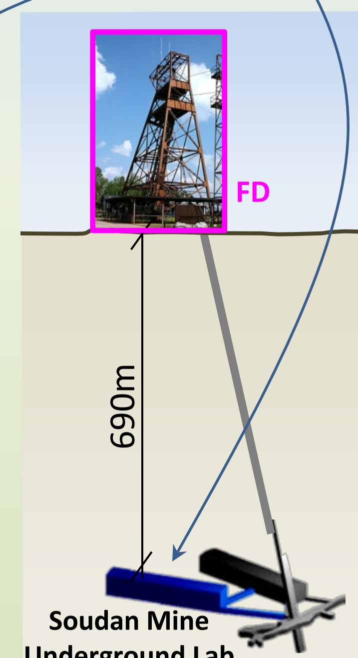


The experiment

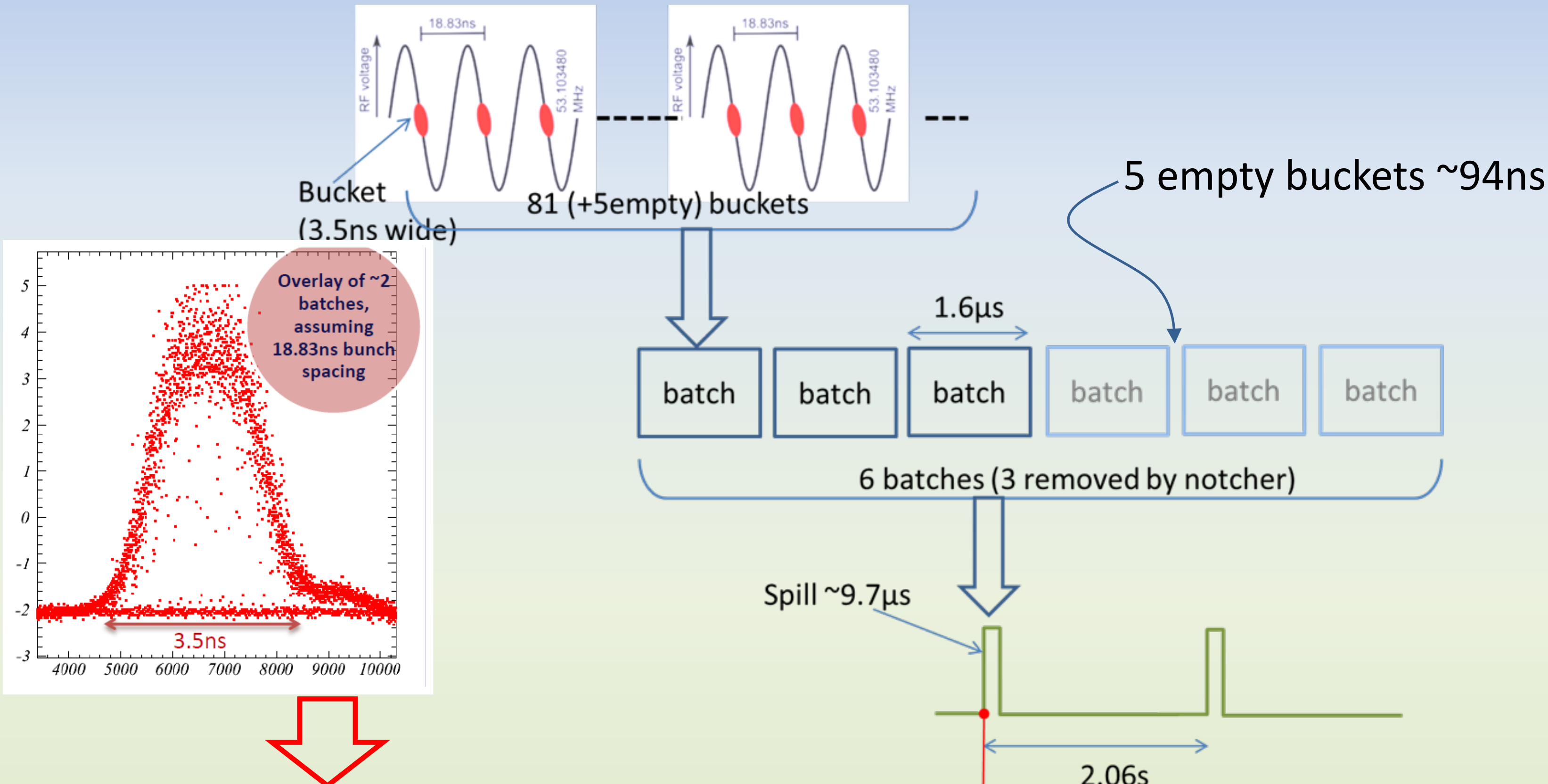








Beam structure



synchronization accuracy and stability
~ ns

First-time ns-requirement outside the T&F community!

The proton wall detector (MI60)

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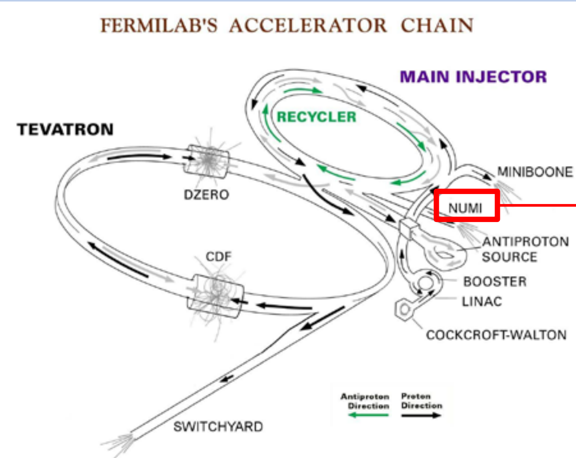
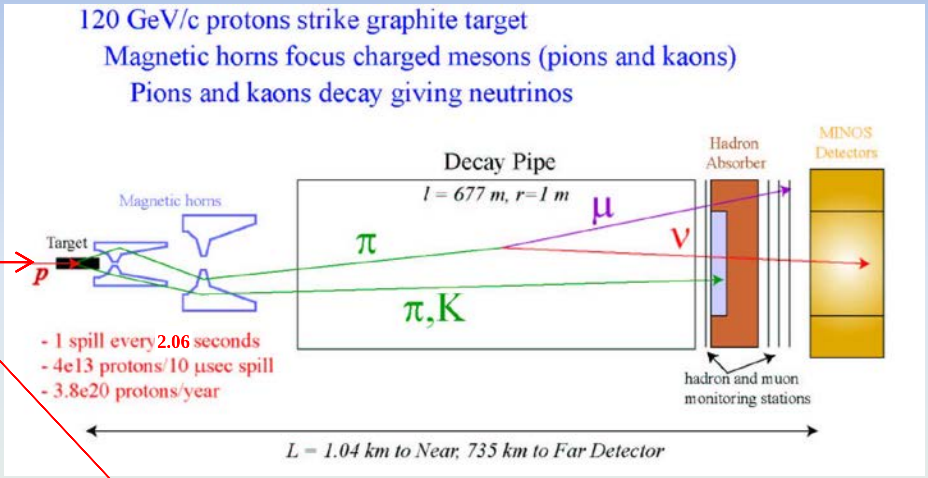
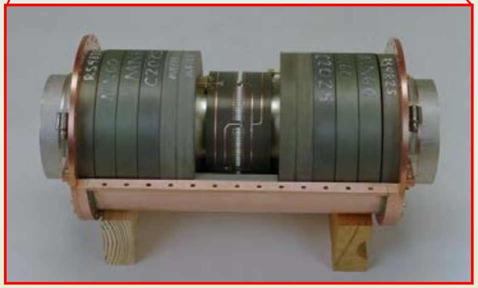
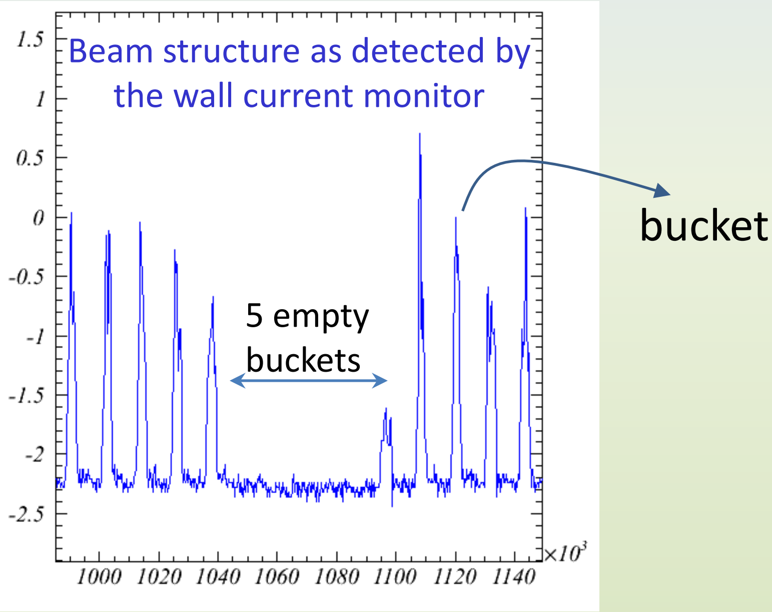
ed to
Far
I)



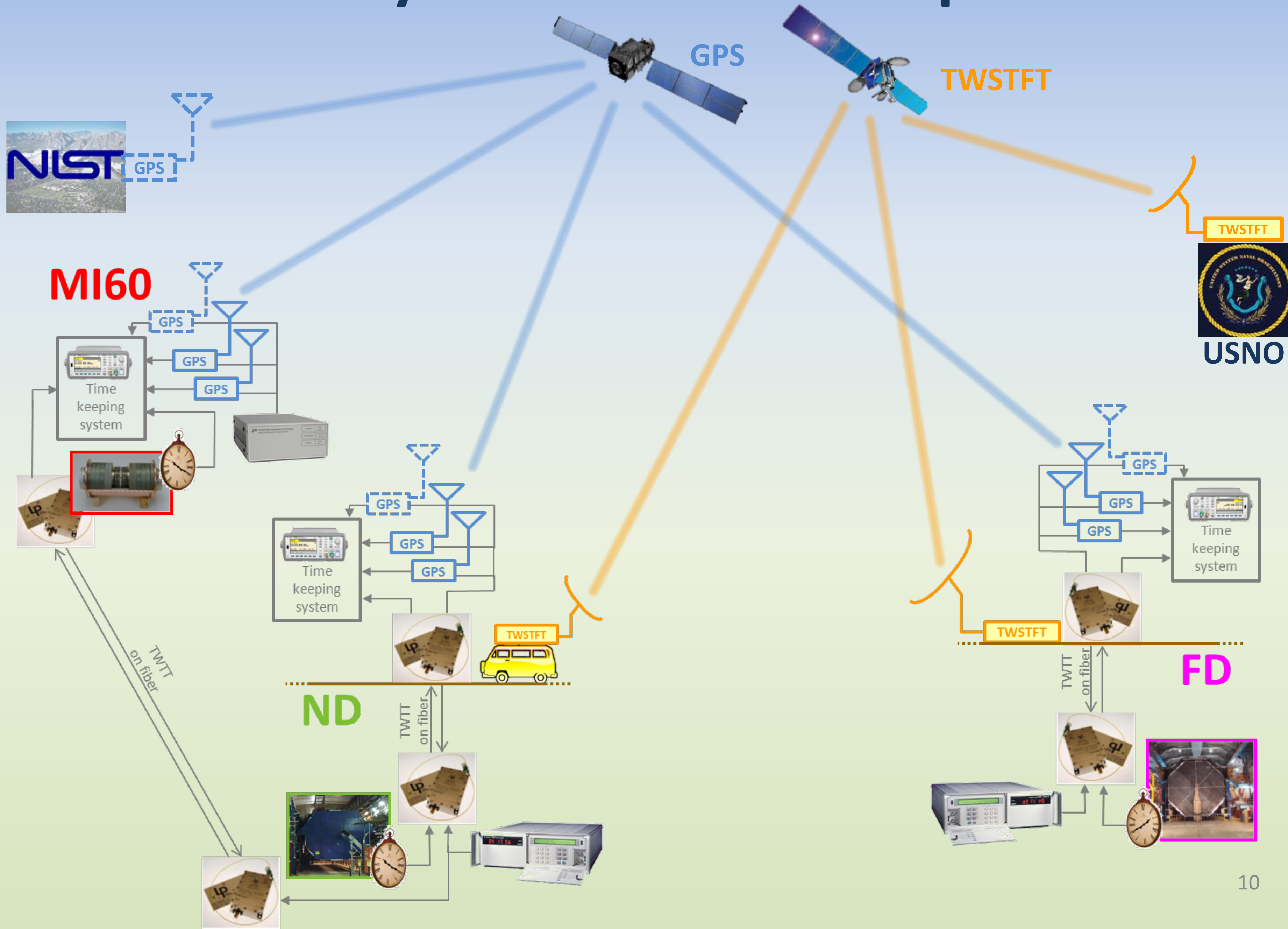




Resistive
wall current monitor



Synchronization setup

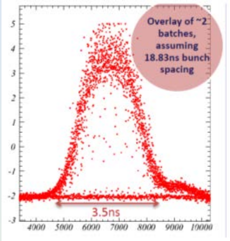


Synchronization: how well should we do?

- Given the scrutiny that a possible superluminal result would trigger, it is important to consider the confidence of each calibration, not only its accuracy/stability

- We should then think 3-σ error bars (99.5% confidence)

- From the graph of a "bucket" shown previously, we understand the need for accuracies (and stabilities) on the order of few ns



- Three ways to provide synchronization between clocks at remote locations:
  - GPS link (C/A, carrier phase)
  - Two-Way Satellite Time and Frequency Transfer (TWSTFT)
  - Clock trip

Independent calibration accuracies

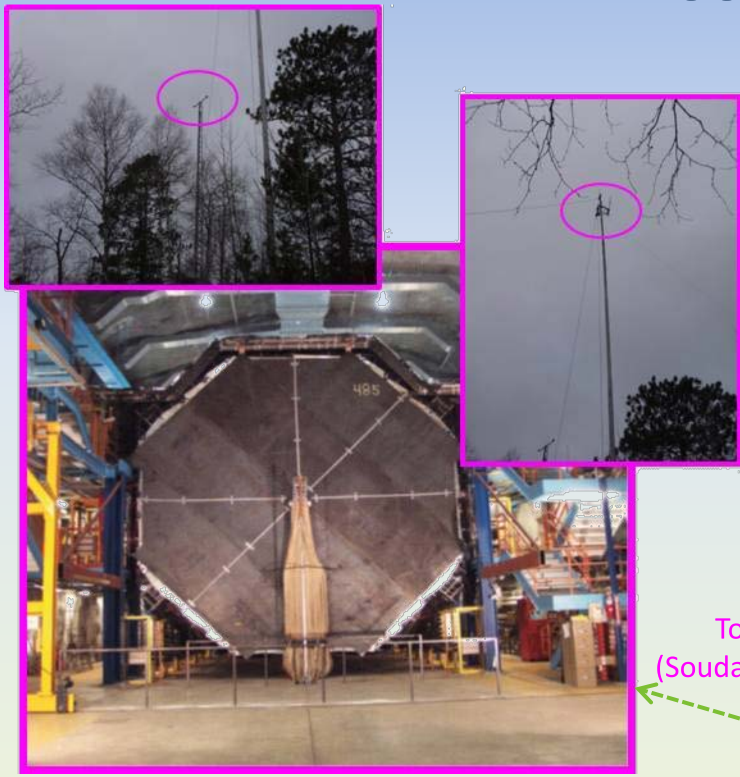
__GPS__ : ~ns/year
__TWSTFT__ : ~ns/year
__Clock Trip__ ~ ns or so

(68% confidence)

few ns/year (99.5% confidence)

The noise types aren't Gaussian so sigma isn't a good measure

The locations



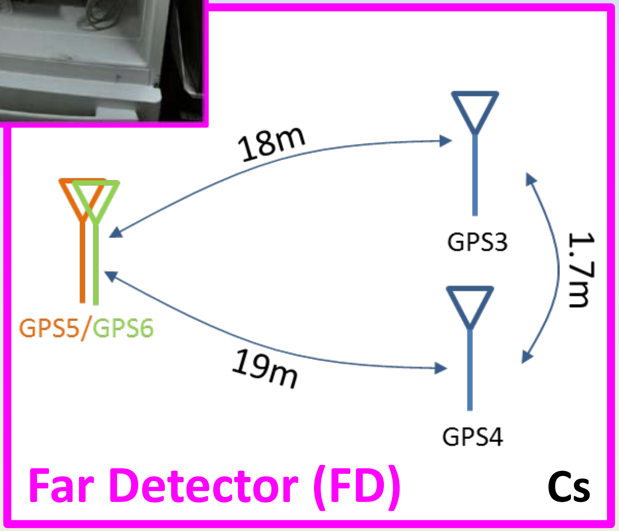
Far Detector (FD)
Soudan Mine

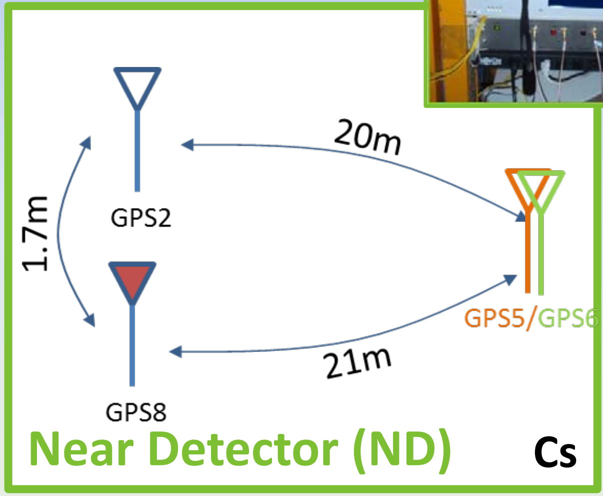
To FD
(Soudan Mine)

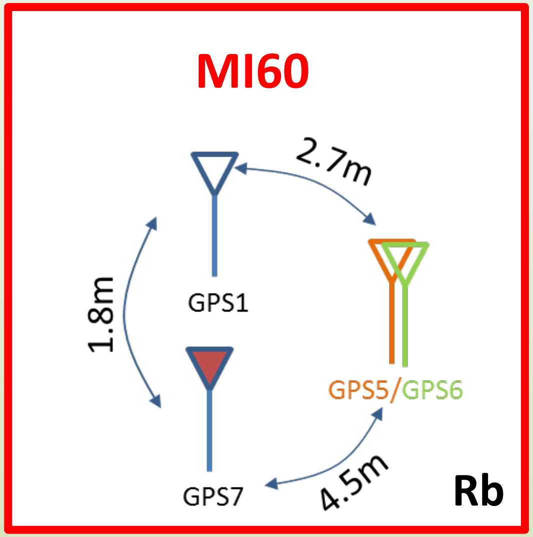
Near Detector (ND)

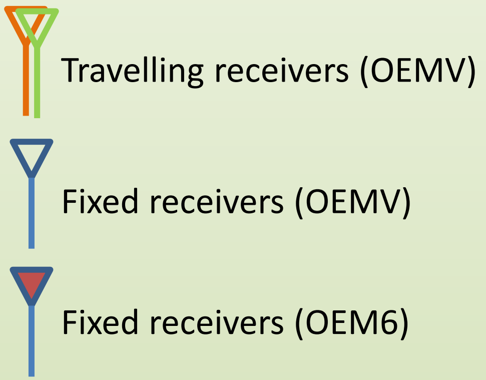
Fermilab

The receivers

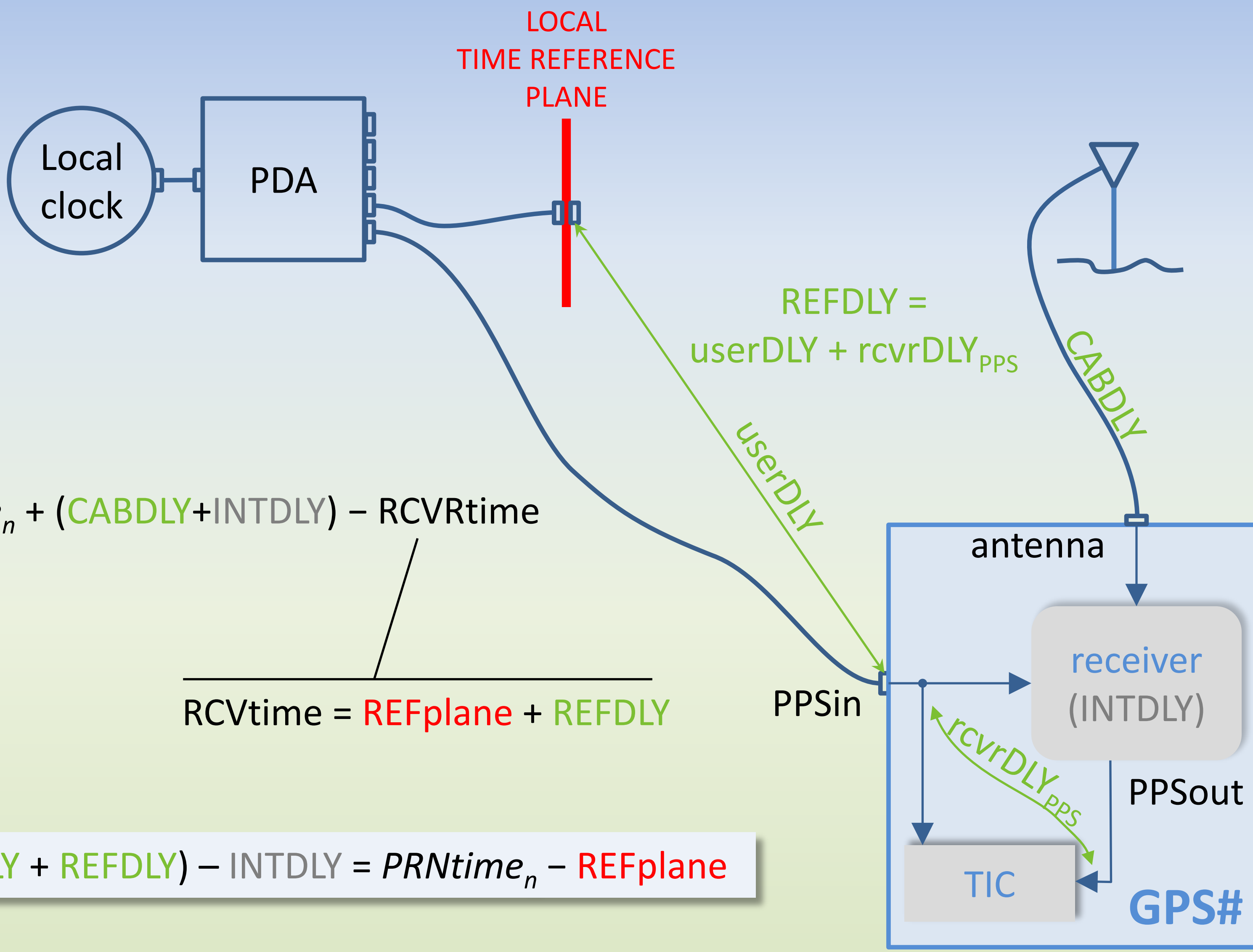








C/A: for each receiver



$$\text{data} = PRNtime_n + (\text{CABDLY}+\text{INTDLY}) - \text{RCVRtime}$$

$$\text{RCVtime} = \text{REFplane} + \text{REFDLY}$$

$$(\text{data} - \text{CABDLY} + \text{REFDLY}) - \text{INTDLY} = PRNtime_n - \text{REFplane}$$

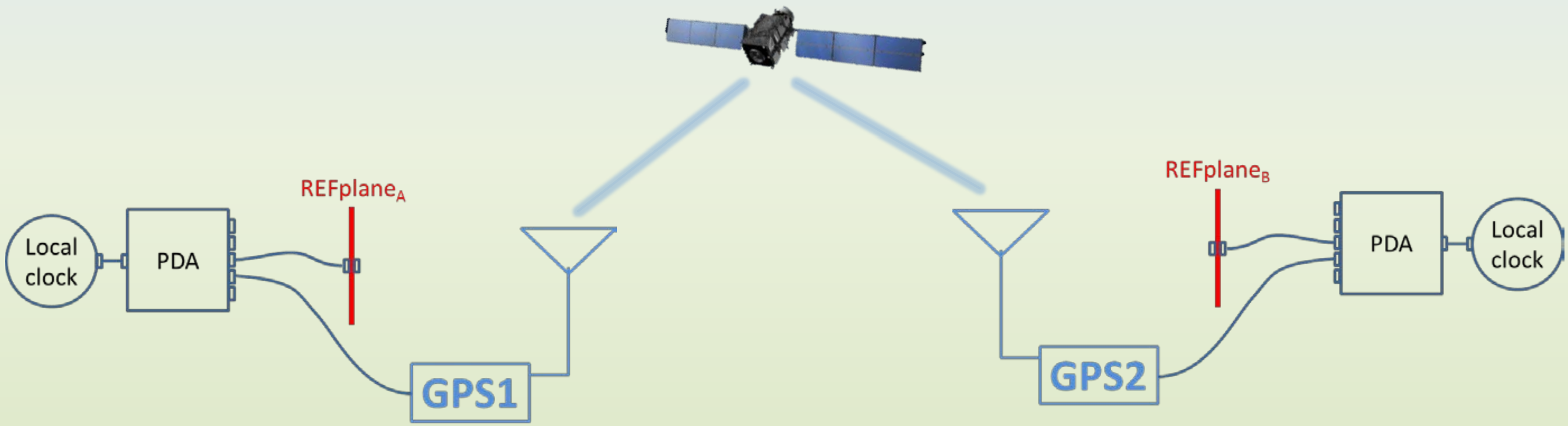
C/A: Common View

SEPARATE LOCATIONS

$$(\text{data} - \text{CABDLY} + \text{REFDLY})_1 - \text{INTDLY}_1 = PRNt_n - REFplane_A$$

$$(\text{data} - \text{CABDLY} + \text{REFDLY})_2 - \text{INTDLY}_2 = PRNt_n - REFplane_B$$

$$\Delta\text{data}_{1,2} - \Delta\text{CABDLY}_{1,2} + \Delta\text{REFDLY}_{1,2} - \Delta\text{INTDLY}_{1,2} = \text{REFplane}_B - \text{REFplane}_A$$



It measures the difference between the clocks at the two locations

C/A: Common View

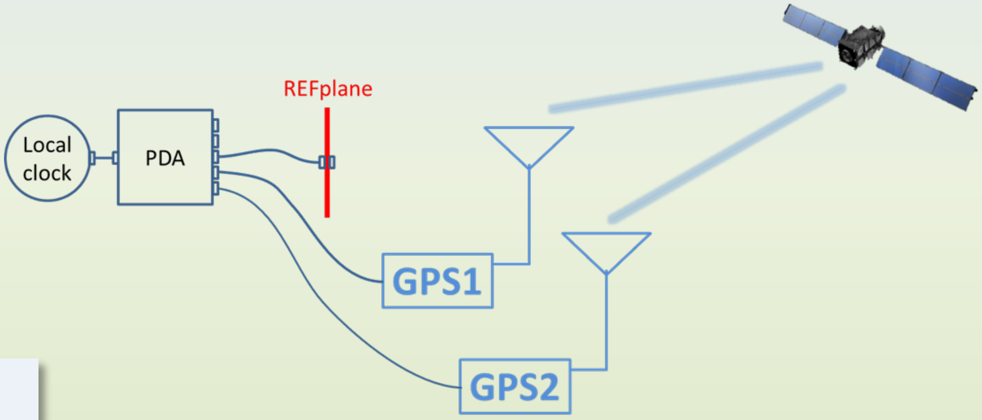
COMMON CLOCK

$$(data - CABDLY + REFDLY)_1 - INTDLY_1 = PRNt_n - REFplane_A$$

$$(data - CABDLY + REFDLY)_2 - INTDLY_2 = PRNt_n - REFplane_A$$

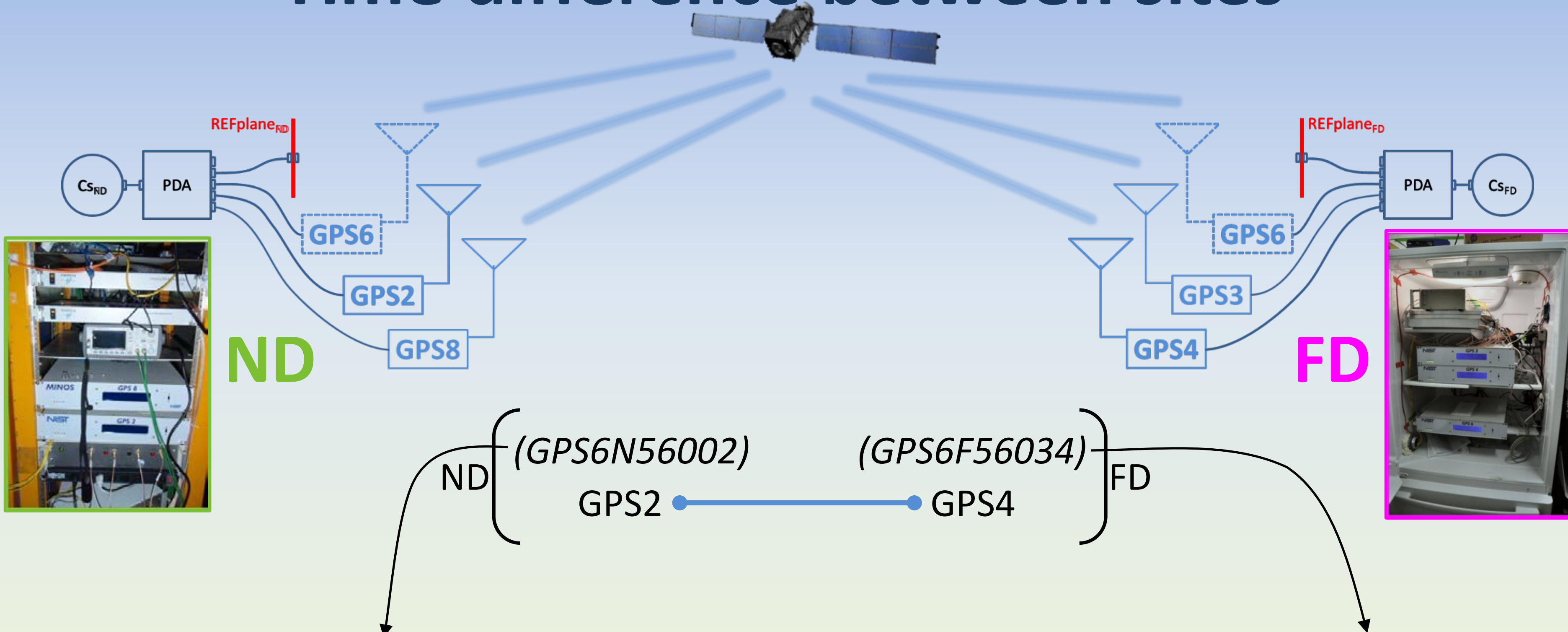
$$\Delta data_{1,2} - \Delta CABDLY_{1,2} + \Delta REFDLY_{1,2} = \Delta INTDLY_{1,2}$$

The local clock "drops out" so the time deviation of the time difference establishes a lower limit for the ***stability*** of the GPS link



If one of the two receivers is a travelling receivers, the time difference allows for a ***differential calibration*** of receivers

Time difference between sites



Date	MJD	DOY	MI60 (Rb)			ND (Cs)			FD			NIST	
			travel	GPS1	GPS7	travel	GPS2	GPS8	travel	GPS3	GPS4	GPS5	GPS6
13-Mar-12	55999	73		P	P	1	P	P	1 P	P	P		
14-Mar-12	56000	74		P	P	1	P	P		P	P		
15-Mar-12	56001	75		P	P	1	P	P		P	P		
16-Mar-12	56002	76		P	P	2	P	P		P	P		
17-Mar-12	56003	77		P	P	2	P	P		P	P		
18-Mar-12	56004	78		P	P	2	P	P		P	P		
19-Mar-12	56005	79		P	P	2	P	P	1 P	P	P		
20-Mar-12	56006	80		P	P	2 P	P	P	1 P	P	P		
21-Mar-12	56007	81	1 P	P	P	2 P	P	P	1 P	P	P		
22-Mar-12	56008	82	1 P	P	P		P	P	1 P	P	P		
23-Mar-12	56009	83	1 P	P	P		P	P	1 P	P	P		
24-Mar-12	56010	84	1 P	P	P		P	P	1 P	P	P		
25-Mar-12	56011	85	1 P	P	P		P	P	1 P	P	P		

Date	MJD	DOY	MI60 (Rb)			ND (Cs)			FD			NIST	
			travel	GPS1	GPS7	travel	GPS2	GPS8	travel	GPS3	GPS4	GPS5	GPS6
14-Apr-12	56031	105		P	P		P	P		P	P		
15-Apr-12	56032	106		P	P		P	P		P	P		
16-Apr-12	56033	107		P	P		P	P		P	P		
17-Apr-12	56034	108		P	P	2 P	P	P	2 P	P	P		
18-Apr-12	56035	109		P	P	2 P	P	P	2 P	P	P		
19-Apr-12	56036	110	TWSTT	P	P	2 P	P	P	2 P	P	P		
20-Apr-12	56037	111		P	P	2 P	P	P	2 P	P	P		
21-Apr-12	56038	112		P	P	2 P	P	P	2 P	P	P		
22-Apr-12	56039	113		P	P	2 P	P	P	2 P	P	P		
23-Apr-12	56040	114		P	P	2 P	P	P	2 P	P	P		
24-Apr-12	56041	115	2 P	P	P	2 P	P	P		P	P		
25-Apr-12	56042	116	2 P	P	P		P	P		P	P		
26-Apr-12	56043	117	2 P	P	P		P	P		P	P		
27-Apr-12	56044	118	2 P	P	P		P	P		P	P		

$$(\text{data} - \text{CABDLY} + \text{REFDLY})_1 - (\text{data} - \text{CABDLY} + \text{REFDLY})_2 - (\text{INTDLY}_1 - \text{INTDLY}_2)$$

$$=$$

$$\text{REFplane}_B - \text{REFplane}_A$$

Calibration with travelling receivers

RCVRs schedule

Date	MJD	DOY	MI60 (Rb) travel	MI60 (Rb) GPS1	MI60 (Rb) GPS7	ND (Cs) travel	ND (Cs) GPS2	ND (Cs) GPS8	FD travel	FD GPS3	FD GPS4	NIST GPS5	NIST GPS6
6-Feb-12	55963	37										1	
7-Feb-12	55964	38										1	1
8-Feb-12	55965	39										1	1
9-Feb-12	55966	40										1	1
10-Feb-12	55967	41										1	1
11-Feb-12	55968	42										1	1
12-Feb-12	55969	43										1	1
19-Feb-12	55976	50											
20-Feb-12	55977	51											
21-Feb-12	55978	52											
22-Feb-12	55979	53											
23-Feb-12	55980	54											
24-Feb-12	55981	55											
25-Feb-12	55982	56											
26-Feb-12	55983	57											
27-Feb-12	55984	58											
28-Feb-12	55985	59		P									
29-Feb-12	55986	60		P									
1-Mar-12	55987	61		P		1							
2-Mar-12	55988	62		P		1				P			
3-Mar-12	55989	63		P		1	P			P			
4-Mar-12	55990	64		P		1	P			P			
5-Mar-12	55991	65		P		1 P	P			P			
6-Mar-12	55992	66	1 P	P	P	1 P	P			P	P		
7-Mar-12	55993	67	1 P	P	P	1	P			P	P		
8-Mar-12	55994	68	1 P	P	P	1 P	P			P	P		
9-Mar-12	55995	69	1 P	P	P		P	P		P	P		
10-Mar-12	55996	70	1 P	P	P		P	P	1 P	P	P		
11-Mar-12	55997	71	1 P	P	P		P	P	1 P	P	P		
12-Mar-12	55998	72	1 P	P	P	1	P	P	1 P	P	P		
13-Mar-12	55999	73		P	P	1	P	P	1 P	P	P		
14-Mar-12	56000	74		P	P	[illegible]	P	P		P	P		
15-Mar-12	56001	75		P	P	1	P	P		P	P		
16-Mar-12	56002	76		P	P	2	P	P		P	P		
17-Mar-12	56003	77		P	P	2	P	P		P	P		
18-Mar-12	56004	78		P	P	2	[illegible]	P		P	P		
19-Mar-12	56005	79		P	P	2	[illegible]	P	1 P	P	P		
20-Mar-12	56006	80		P	P	2 P	[illegible]	P	1 P	P	P		
21-Mar-12	56007	81	1 P	P	P	2 P	P	P	1 P	P	P		
22-Mar-12	56008	82	1 P	P	P		P	P	1 P	P	P		
23-Mar-12	56009	83	1 P	P	P		P	P	1 P	P	P		
24-Mar-12	56010	84	1 P	P	P		P	P	1 P	P	P		
25-Mar-12	56011	85	1 P	P	P		P	P	1 P	P	P		
26-Mar-12	56012	86	1 P	P	P		P	P		P	P		
27-Mar-12	56013	87	1 P	P	P		P	P		P	P		
28-Mar-12	56014	88		P	P		P	P		P	P		
29-Mar-12	56015	89		P	P		P	P		P	P	2	
30-Mar-12	56016	90		P	P		P	P		P	P	2	2
31-Mar-12	56017	91		P	P		P	P		P	P	2	2
1-Apr-12	56018	92		P	P		P	P		P	P	2	2
2-Apr-12	56019	93		P	P		P	P		P	P	2	2
3-Apr-12	56020	94		P	P		P	P		P	P	2	2
4-Apr-12	56021	95		P	P		P	P		P	P	2	2
5-Apr-12	56022	96		P	P		P	P		P	P	2	2
6-Apr-12	56023	97		P	P		P	P		P	P	2	2
7-Apr-12	56024	98		P	P		P	P		P	P	2	2
8-Apr-12	56025	99		P	P		P	P		P	P	2	2
9-Apr-12	56026	100		P	P		P	P		P	P	2	2
10-Apr-12	56027	101		P	P		P	P		P	P	2	2
11-Apr-12	56028	102		P	P		P	P		P	P	2	2
12-Apr-12	56029	103		P	P		P	P		P	P	2	2
13-Apr-12	56030	104		P	P		P	P		P	P		
14-Apr-12	56031	105		P	P		P	P		P	P		
15-Apr-12	56032	106		P	P		P	P		P	P		
16-Apr-12	56033	107		P	P		P	P		P	P		
17-Apr-12	56034	108		P	P	2 P	P	P	2 P	[illegible]	P		
18-Apr-12	56035	109		P	P	2 P	P	P	2 P	P	P		
19-Apr-12	56036	110	TWSTT	P	P	2 P	P	P	2 P	P	P		
20-Apr-12	56037	111		P	P	2 P	P	P	2 P	P	P		
21-Apr-12	56038	112		P	P	2 P	P	P	2 P	P	P		
22-Apr-12	56039	113		P	P	2 P	P	P	2 P	[illegible]	P		
23-Apr-12	56040	114		P	P	2 P	P	P	2 P	P	P		
24-Apr-12	56041	115	2 P	P	P	2 P	P	P		P	P		
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26-Apr-12	56043	117	2 P	P	P		P	P		P	P		
27-Apr-12	56044	118	2 P	P	P		P	P		P	P		
28-Apr-12	56045	119	2 P	P	P		P	P		P	P		
29-Apr-12	56046	120	2 P	P	P		P	P		P	P		
30-Apr-12	56047	121	2 P	P	P		P	P		P	P		
1-May-12	56048	122	2 P	P	P		P	P		P	P		
2-May-12	56049	123	2 P	P	P		P	P		P	P		
3-May-12	56050	124	2 P	P	P		P	P		P	P		
4-May-12	56051	125	2 P	P	P		P	P		P	P		
5-May-12	56052	126	2 P	P	P		P	P		P	P		
6-May-12	56053	127	2 P	P	P		P	P		P	P		
7-May-12	56054	128	2 P	P	P		P	P		P	P		
8-May-12	56055	129	2 P	P	P		P	P		P	P		
9-May-12	56056	130	2 P	P	P					P	P		
10-May-12	**56057**	131	2 P	P	P								

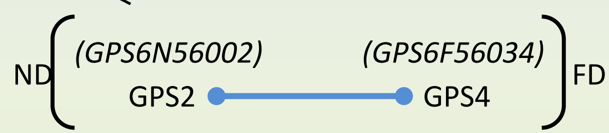
It is a ***differential*** calibration

⇓

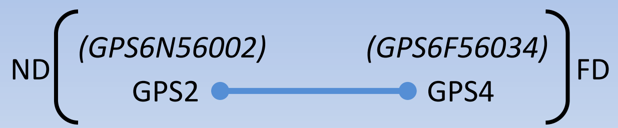
It doesn't determine INTDLY for a receiver

It determines $\Delta INTDLY_{i,j}$ for a pair of receivers

Absolute calibrations generally require a GPS simulator and an anechoic chamber

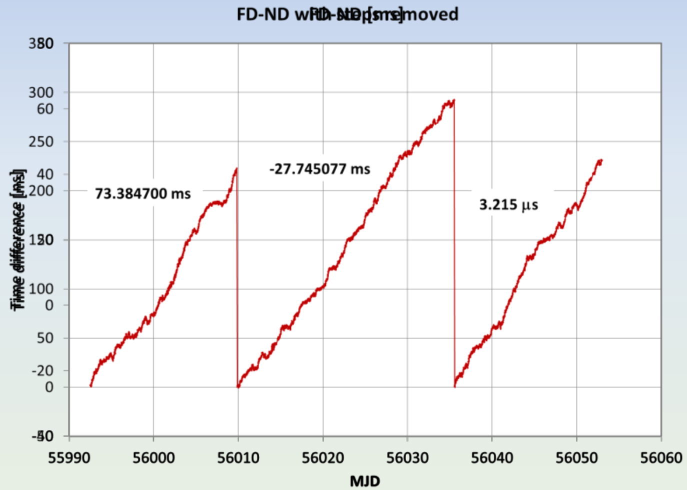


Calculation of time difference



$\Delta data_{1,2} - \Delta CABDLY_{1,2} + \Delta REFDLY_{1,2} - \Delta INTDLY_{1,2} = REFplane_B - REFplane_A$

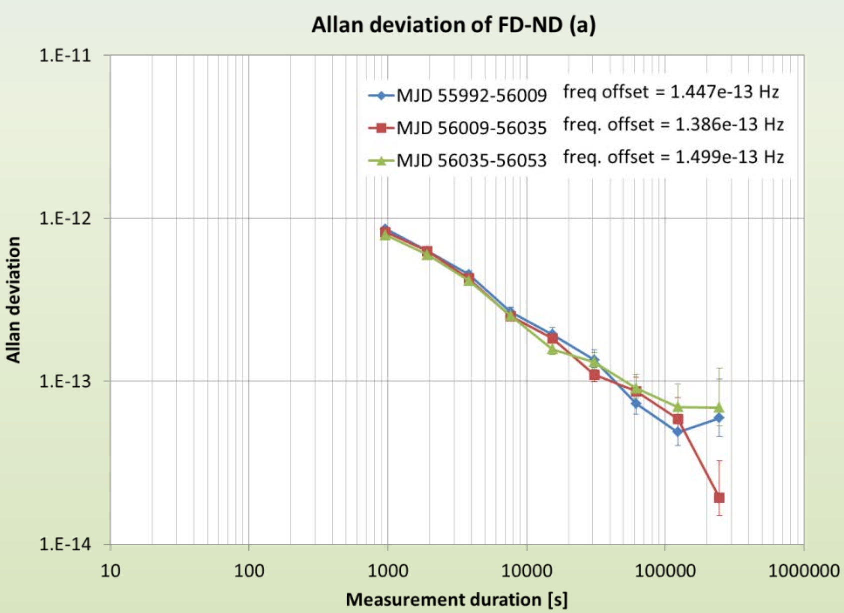
$INTDLY_2 - INTDLY_4$
0.23 ns

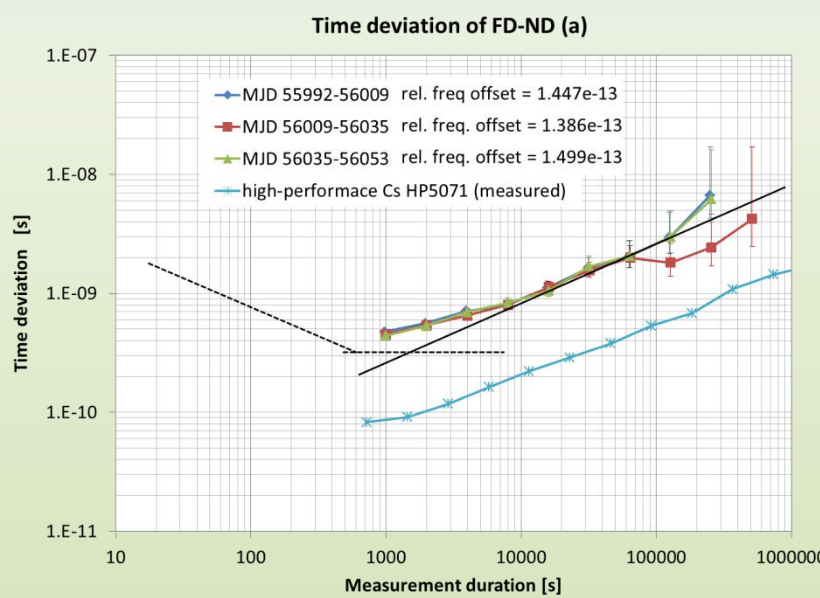


The stability of the time difference is consistent with the stability of standard performance HP5071 Cs clocks

The clocks at the two locations are two HP5071 (Cs) standard performance

Time steps were manually introduced to bring the two clocks closer in time



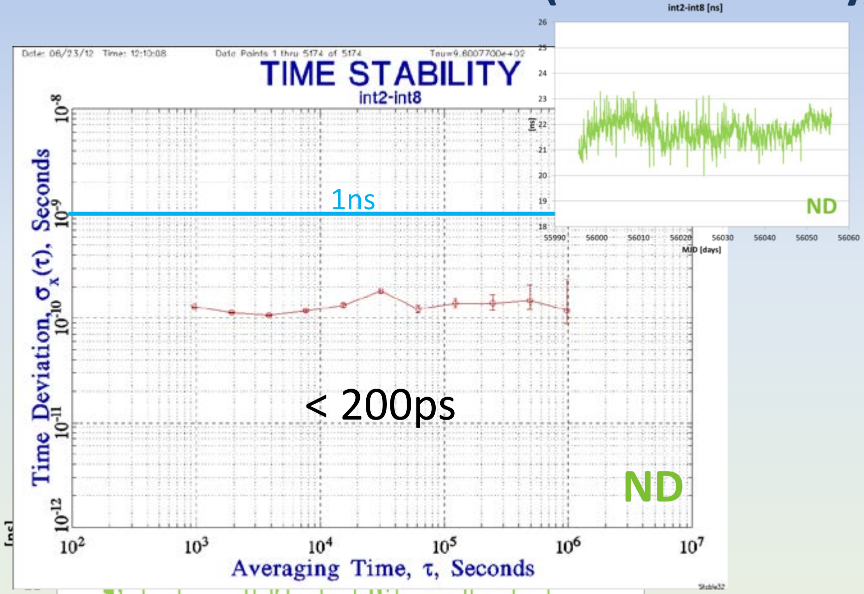


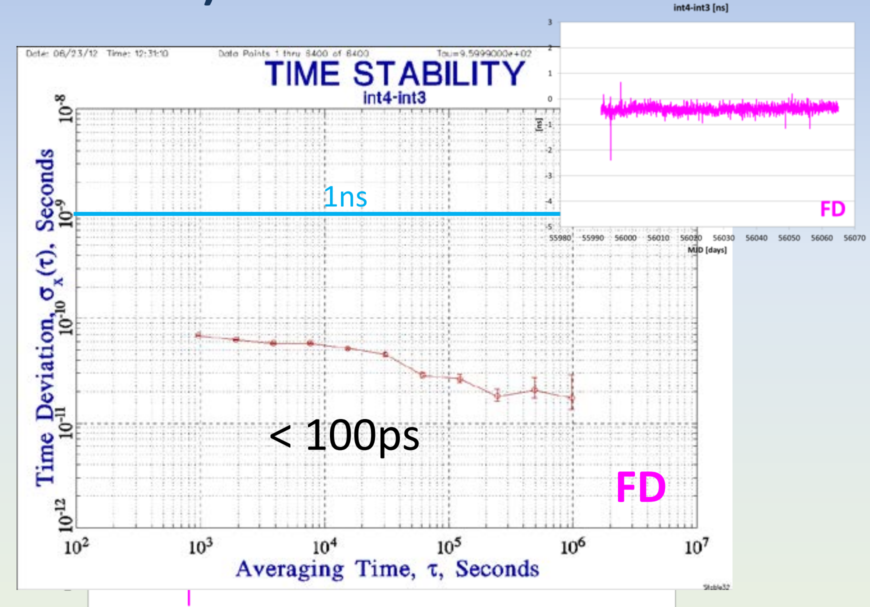
Tools for evaluating the uncertainty of the GPS link

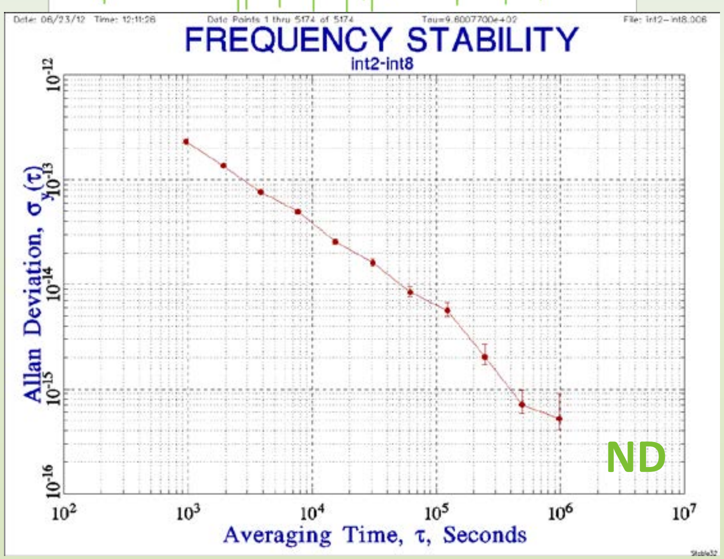
- Common-clock, short-baseline measurement
  - Lower limit for the ***stability*** of the receivers. The iono/troposphere effects cancel as well as other effects of the shared local environments (multipath, temperature, etc.)
- Differential calibration of INTDLY with travelling receiver
  - Common-clock, short-baseline measurement, it determines the ***accuracy*** of the link in the short term.
- Calibrated double-difference between remote sites
  - The mean is a (optimistic) measure of the ***accuracy*** of the link in the long term. It uses only one calibration, so it doesn't include the calibration repeatability, and it cannot show all the "common-mode effects" intrinsic in the GPS link (multipath, code interference, etc.).
  - The time deviation sets a lower limit for the ***stability*** of the link. The iono/troposphere effects still cancel, but the other local effects do so to a lesser extent than in the common-clock measurement.
- Repeated differential calibrations with travelling receivers
  - It determines the ***accuracy*** of the link on in the long(er) term by showing the long-term behavior (slow variations) of the differential calibrations.
- Comparison with independent synchronization systems (TWSTFT, TW in fiber, clock trips)
  - ***Accuracy***: the means may or may not be statistically consistent…

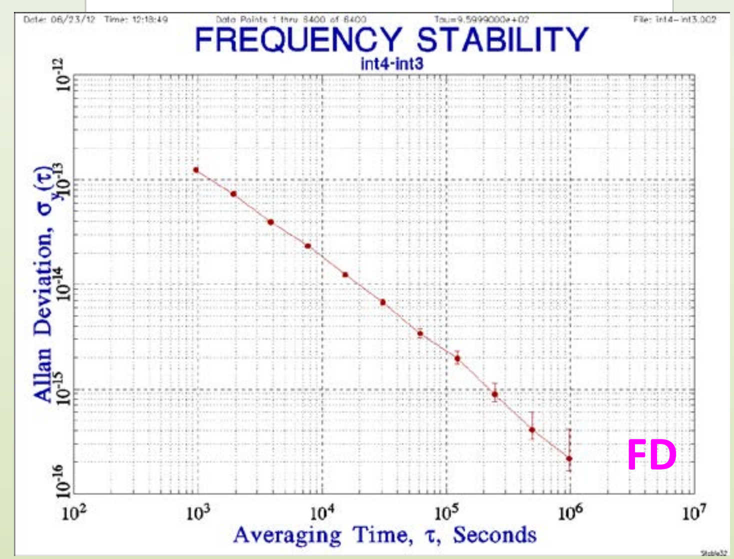
Common-clock, short-baseline measurement

(RCVR stability, lower limit)







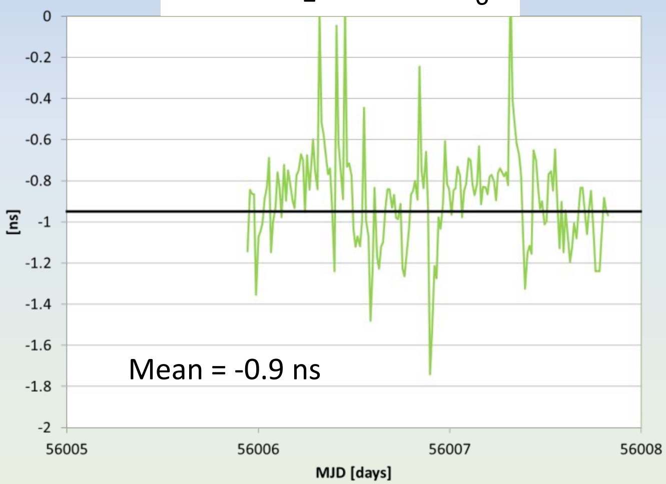


Differential calibration of the receivers

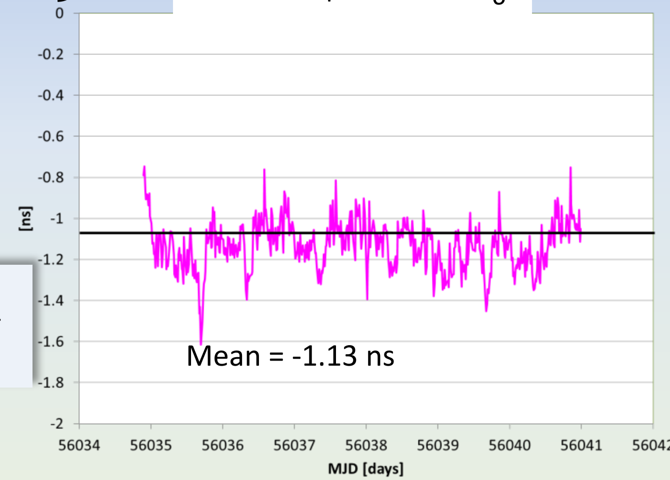
(accuracy, lower limit)

ND (*GPS6N56002*) GPS2 — GPS4 (*GPS6F56034*) FD

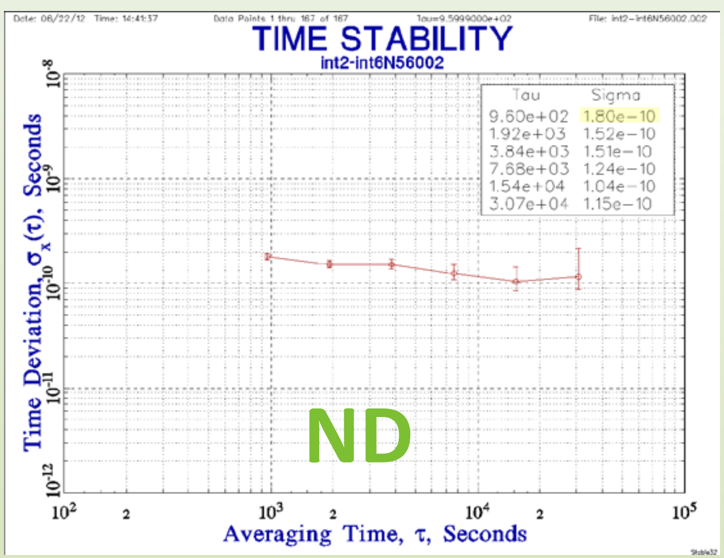
INTDLY$_2$ – INTDLY$_6$



INTDLY$_4$ – INTDLY$_6$

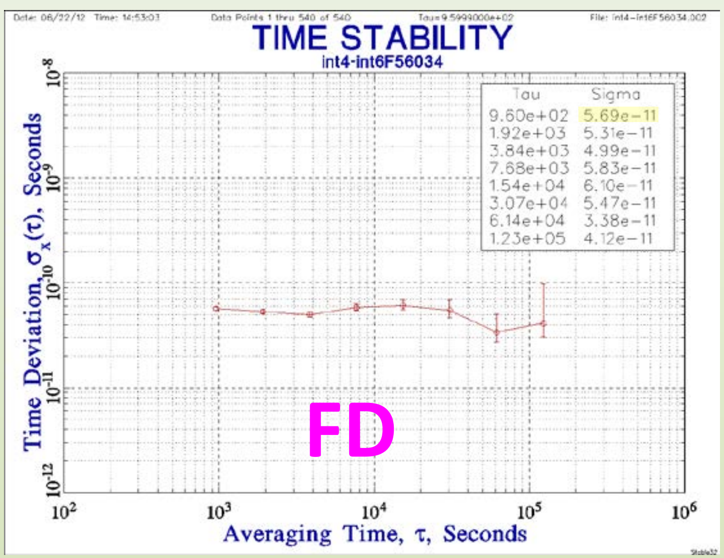


INTDLY$_2$ – INTDLY$_4$
0.23 ns



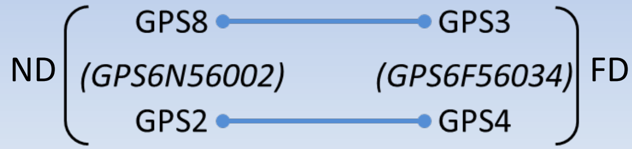
The uncertainties are summed in quadrature

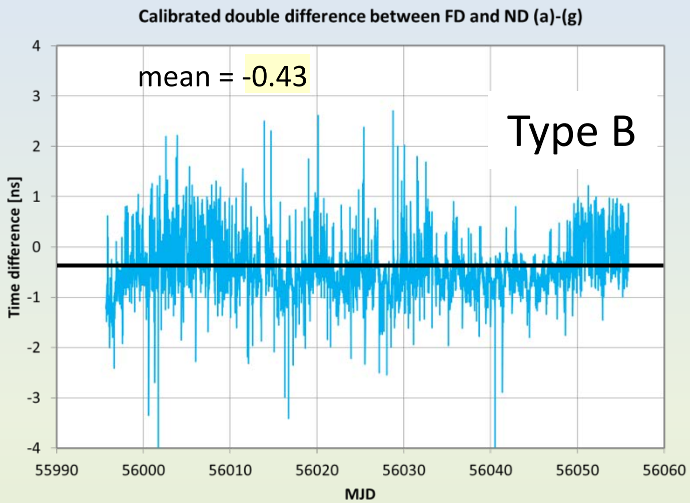
uncertainty
0.2 ns

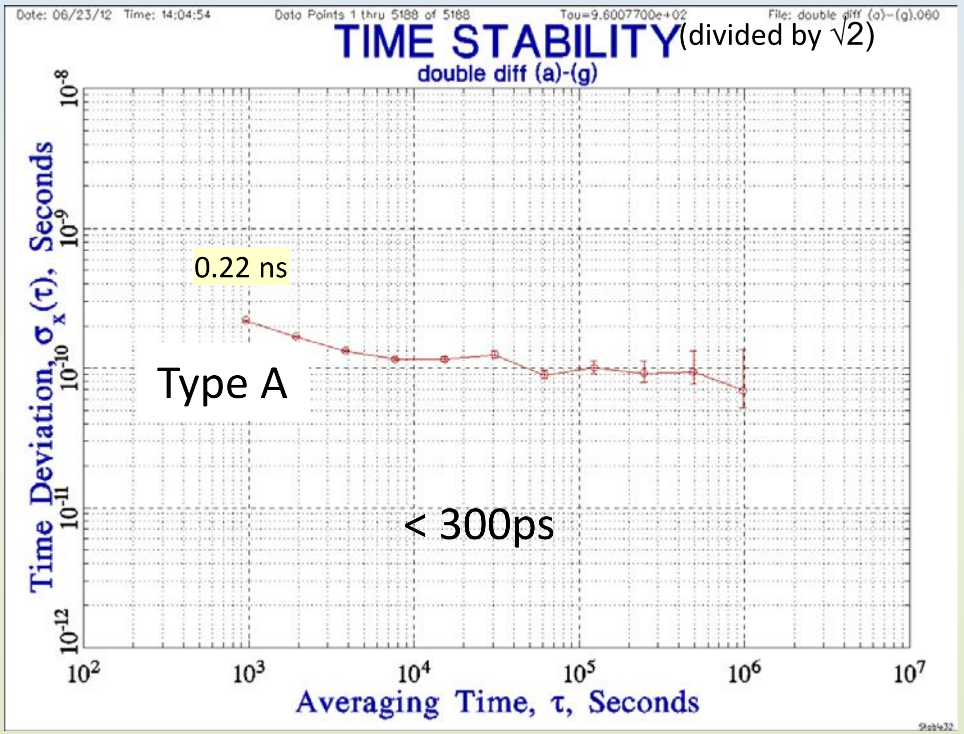


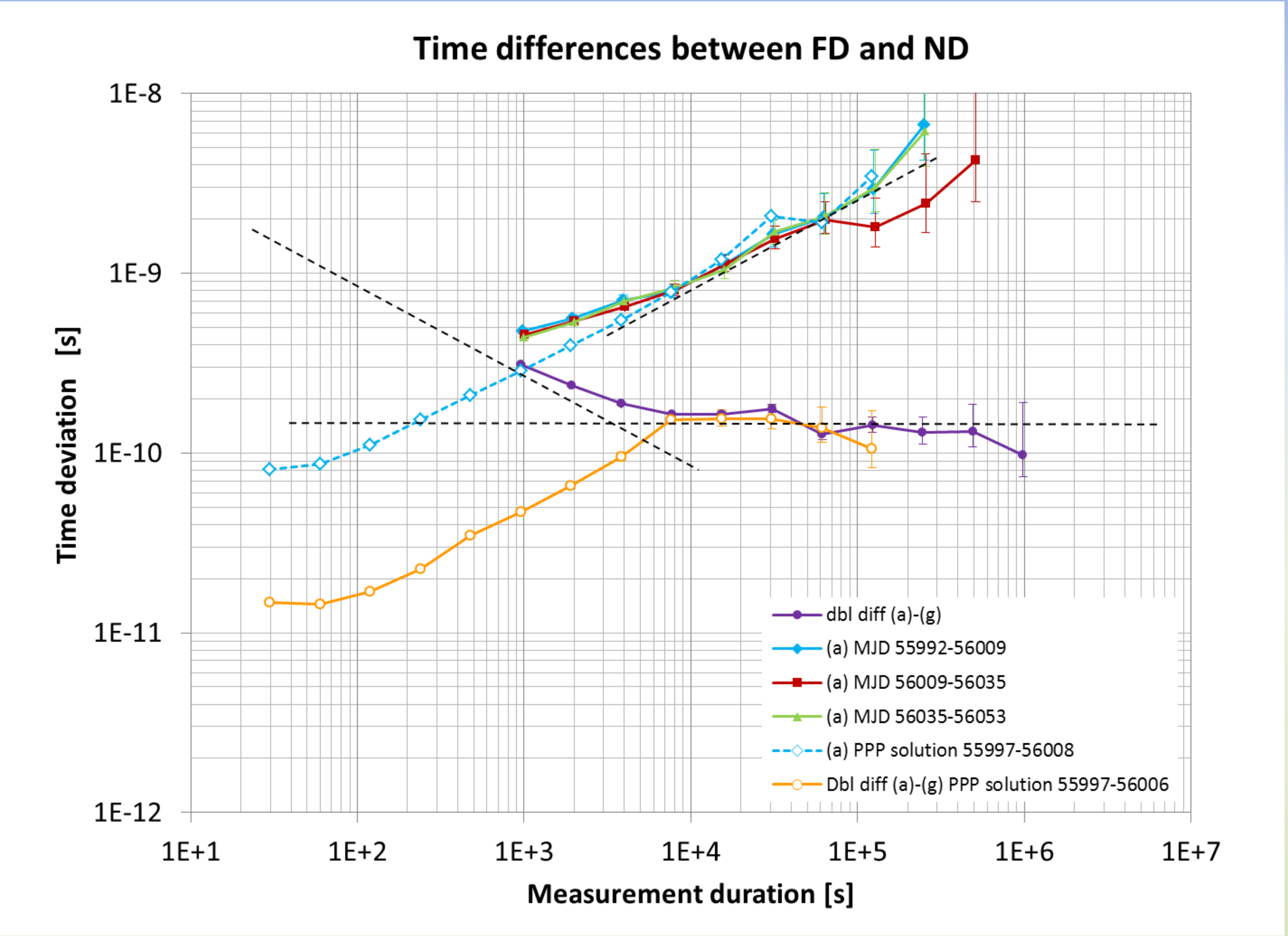
Calibrated double-difference between sites

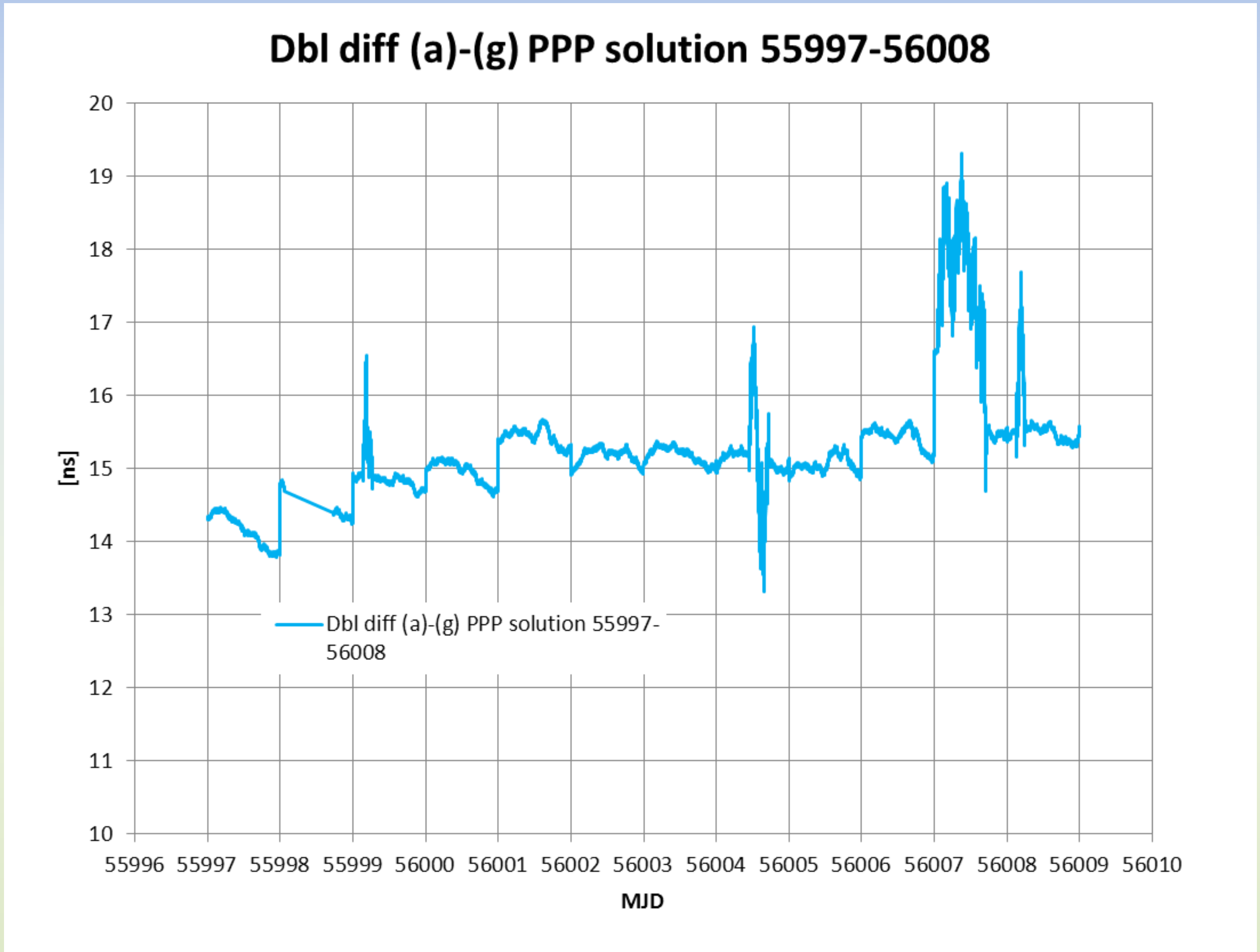
(stability and accuracy, lower limit)







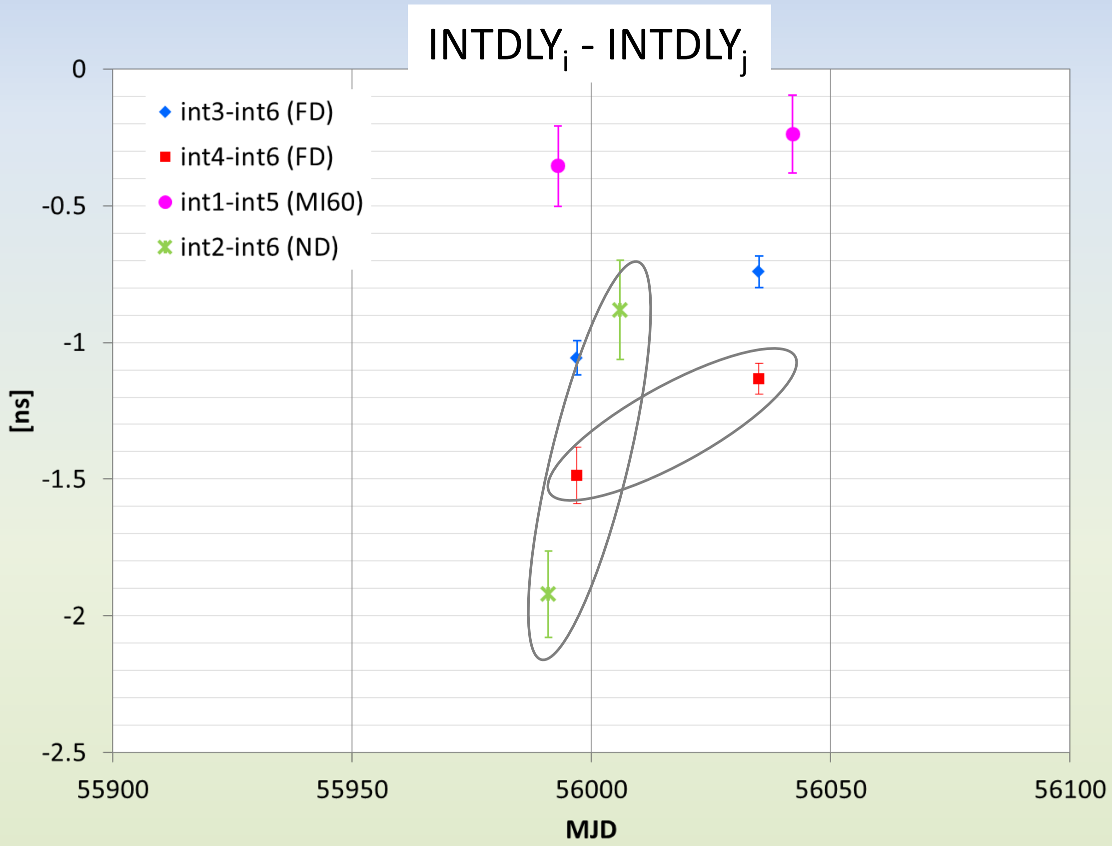

Time differences between FD and ND
Time deviation [s]
Measurement duration [s]
1E-8
1E-9
1E-10
1E-11
1E-12
1E+1
1E+2
1E+3
1E+4
1E+5
1E+6
1E+7
dbl diff (a)-(g)
(a) MJD 55992-56009
(a) MJD 56009-56035
(a) MJD 56035-56053
(a) PPP solution 55997-56008
Dbl diff (a)-(g) PPP solution 55997-56006



Dbl diff (a)-(g) PPP solution 55997-56008
20
19
18
17
16
15
14
13
12
11
10
[ns]
55996 55997 55998 55999 56000 56001 56002 56003 56004 56005 56006 56007 56008 56009 56010
MJD
Dbl diff (a)-(g) PPP solution 55997-56008

Repeated differential calibrations

(accuracy in the longer term)



Deterministic behavior (i.e. annual term) also recognizable in the calibrated double difference

⇓

The "trend" can be use to correct the data

The scatter of calibration data is stochastic

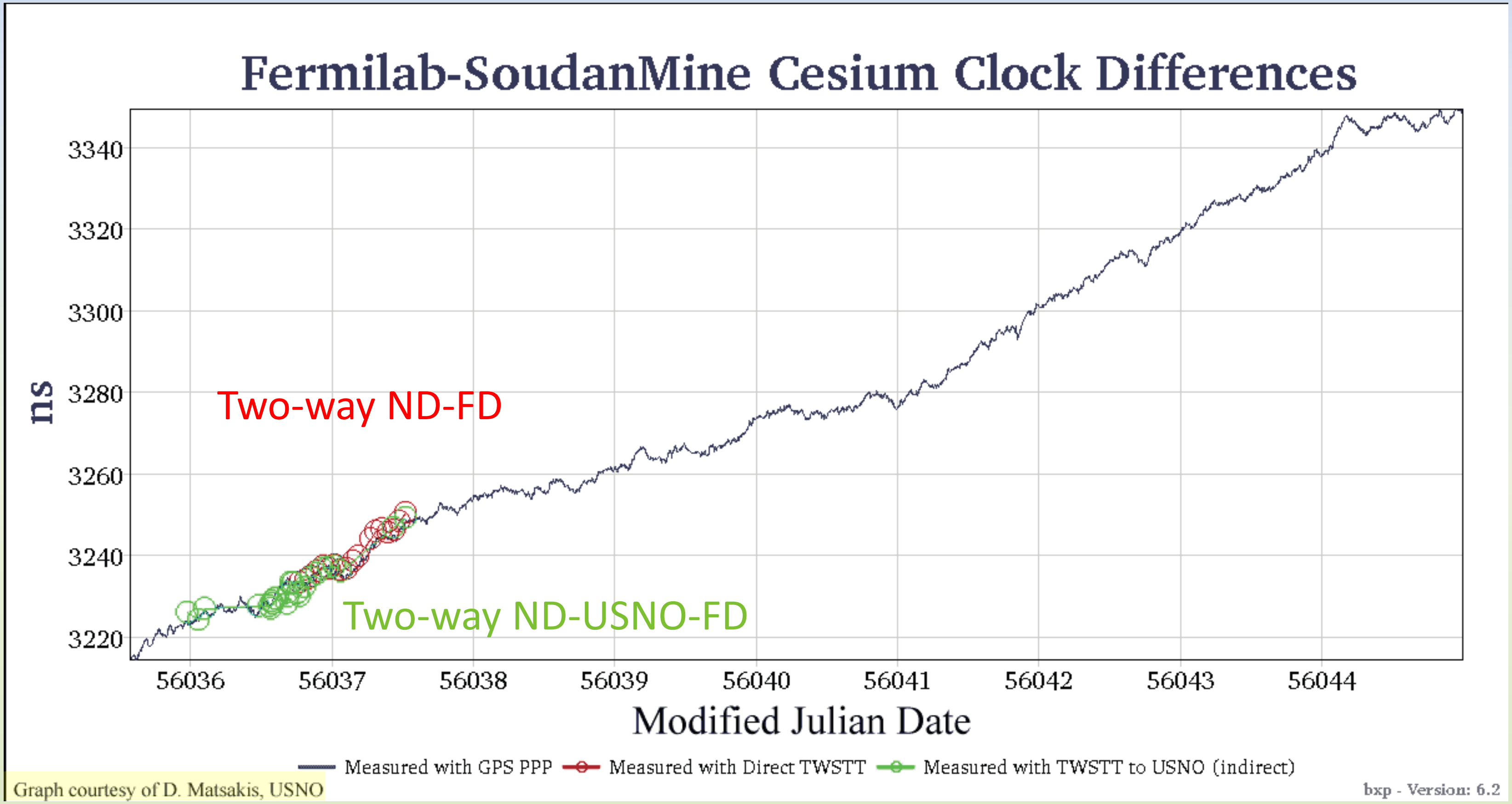
⇓

The uncertainty of the calibrations is increased until all results are statistically consistent

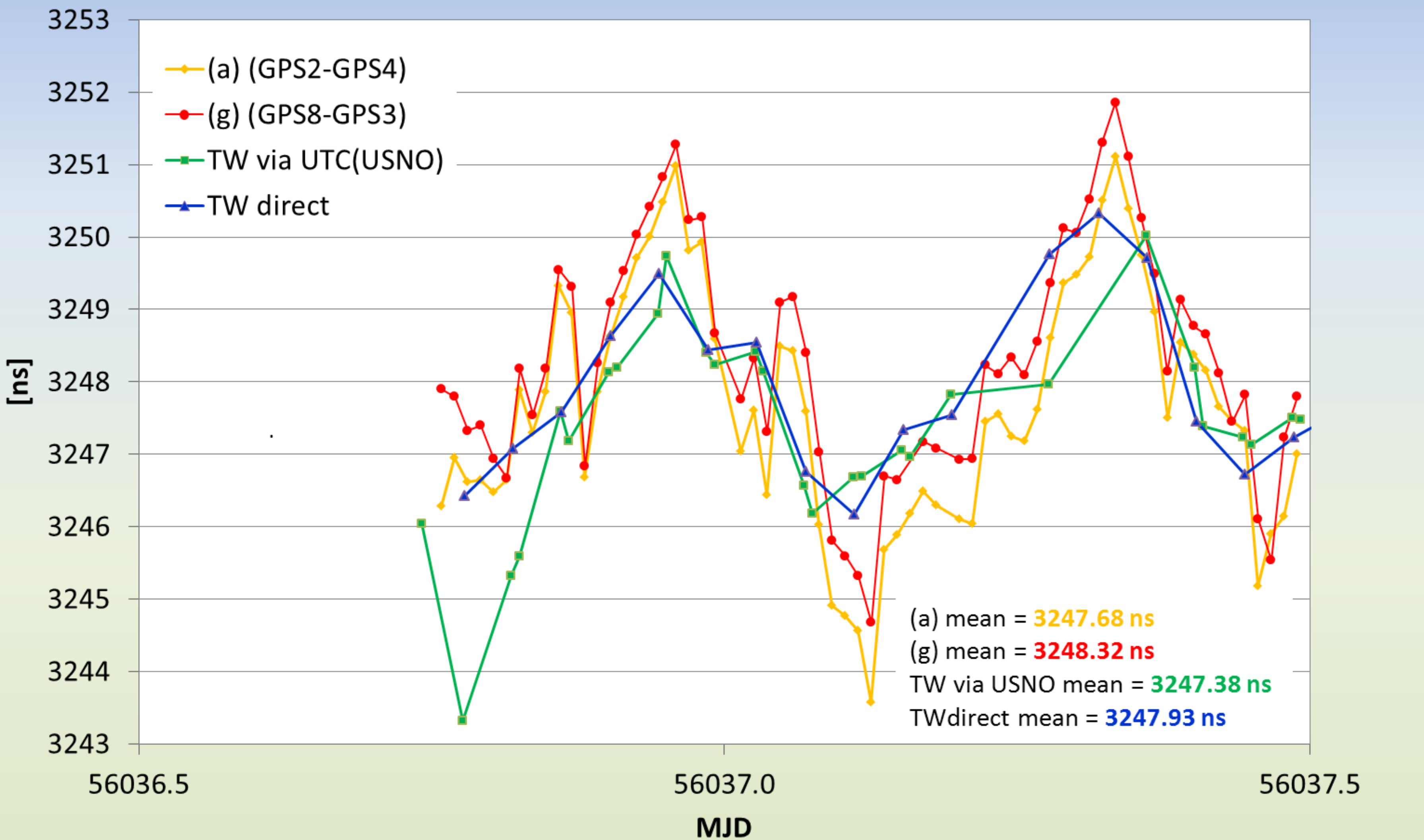
Comparison with independent systems

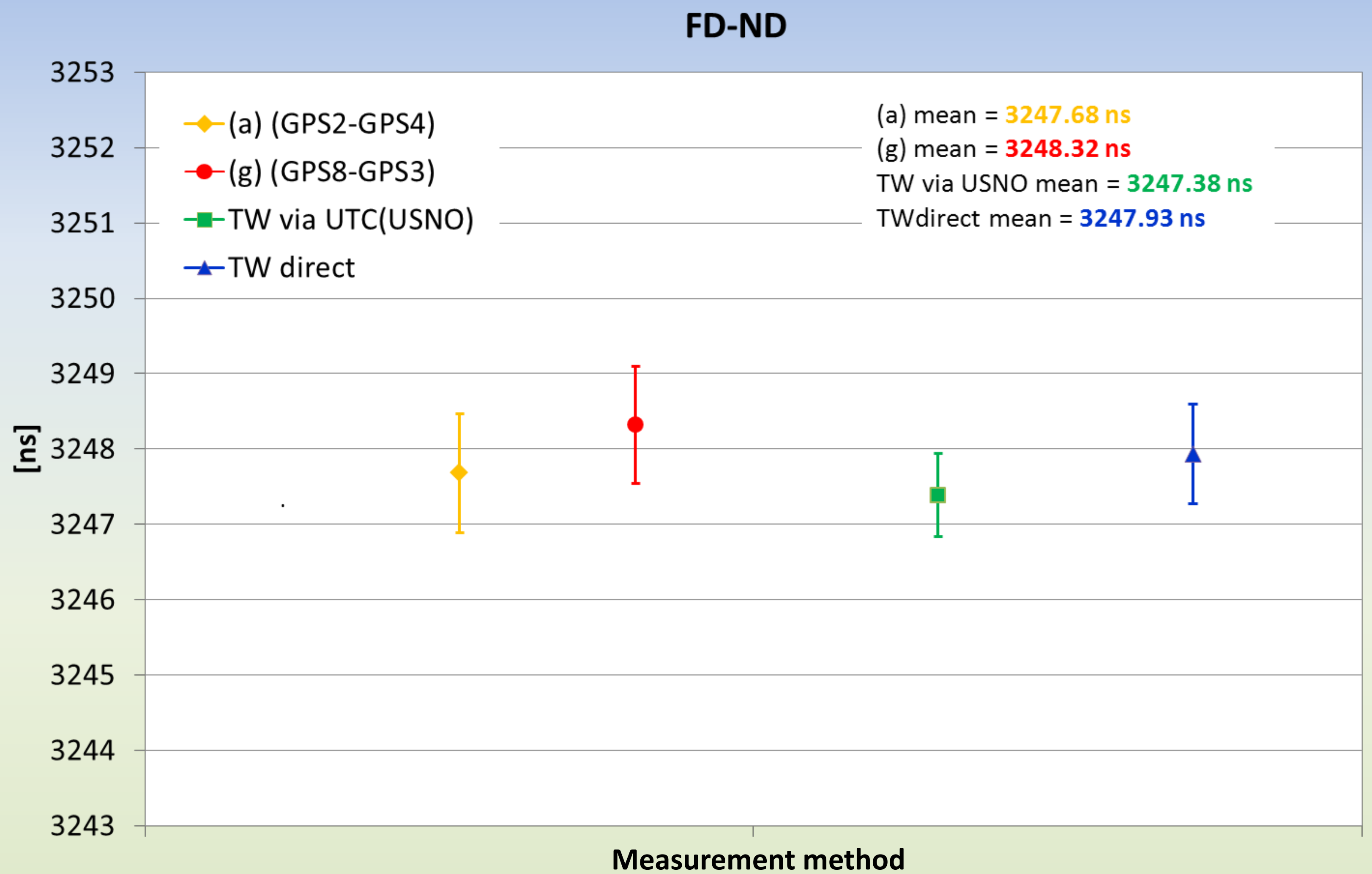
(stability and accuracy)

USNO TWSTFT



FD-ND quadratic drift removed





Error bars are Tdev @ ~1h

Uncertainty estimates for GPS link

	Stability	Accuracy
Common clock	< 200ps	
Differential calibration		200ps
Calibrated double-difference	< 300ps	< 400ps
Repeated calibration		~500ps
Comparison with TWSTFT		~1 ns

NIST – Clock Trip

Backward from traditional clock trips – here we have a “good” traveling clock and not so good fixed clocks at the ends.

Analysis suggests this is really bad…..so we probably have to get 3 good clocks for the calibration, one in Fermilab, one in Soudan and one flying between.

Accuracy of calibration is given by the clock stability at one round trip time

Soudan has Airport (Tower Muni 12D) about 10min drive, Fermilab (DuPage County KDPA) is 25 min. A/C 250knts ~ 2hours. So we can get ~ 6hour loop – should give well less than 2ns calibration accuracy.

Must make special/general relativistic corrections quite well to achieve this – FUN!

Conclusions

- The uncertainty seems to be (so far) at the ns level compatible with the width of a “bucket” of particles, but we clearly need more data.

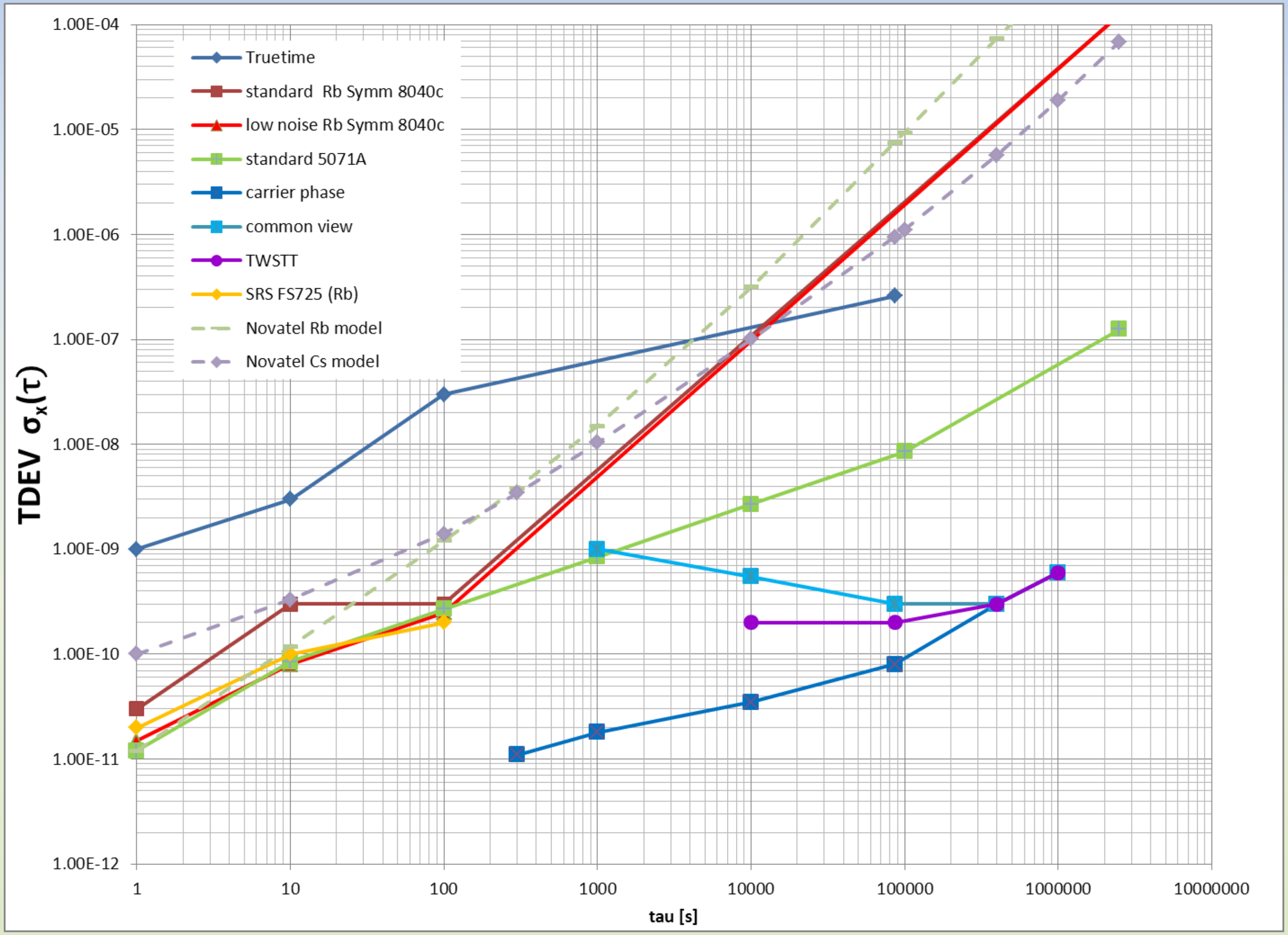
  “So far, so good…..,” said the man falling from the Empire State Building

- We are planning to continue into 2013 the synchronization with periodic calibrations with travelling receivers, totaling one year of differential calibrations .

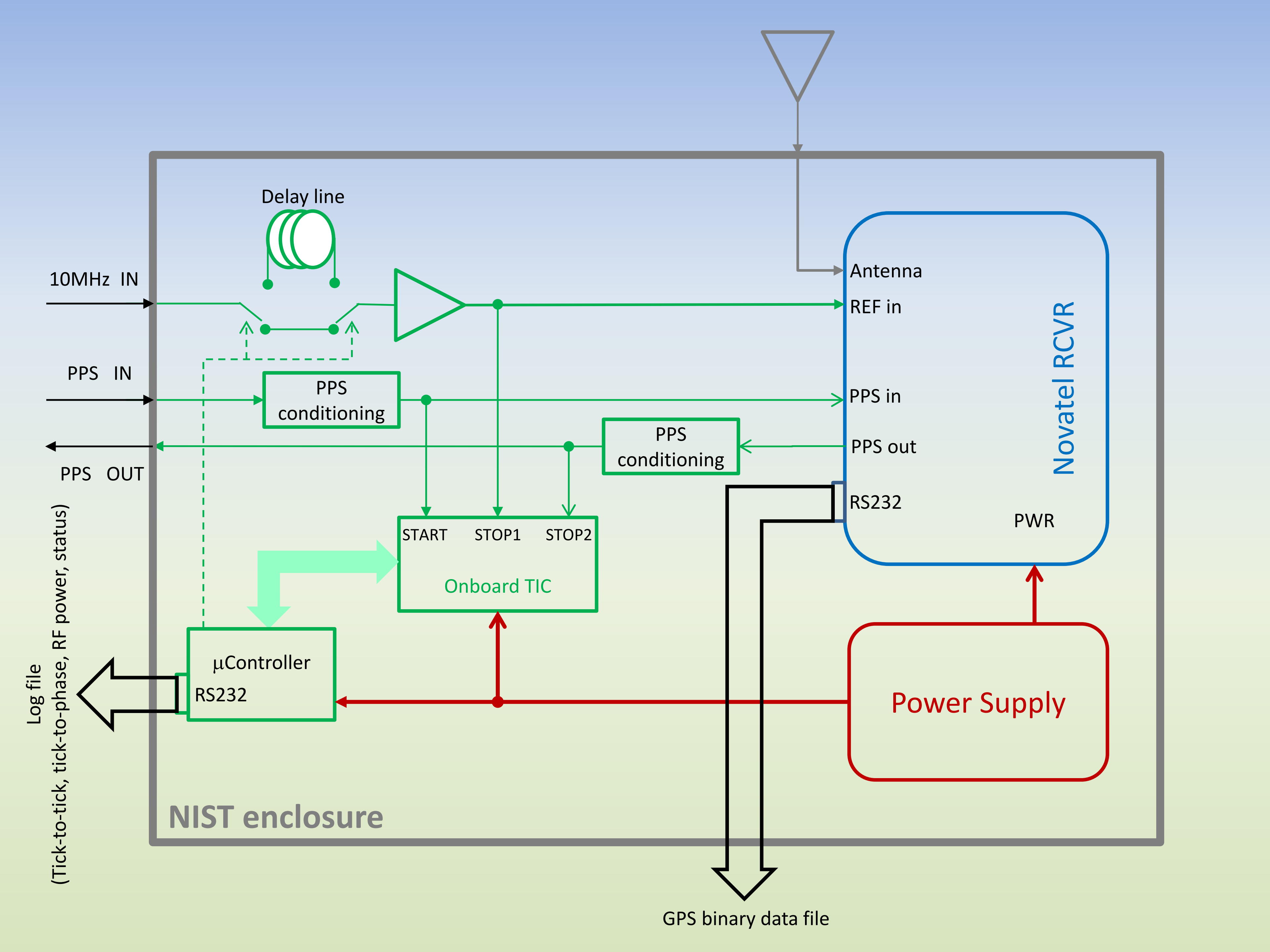
- We are also planning a clock trip between MINOS sites.

- The beam at Fermilab is presently shut-down for a scheduled upgrade of the facilities. The measurements on neutrinos will resume in the summer of 2013.

Backups



1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
TDEV $\sigma_x(\tau)$
1
10
100
1000
10000
100000
1000000
10000000
tau [s]
Truetime
standard Rb Symm 8040c
low noise Rb Symm 8040c
standard 5071A
carrier phase
common view
TWSTT
SRS FS725 (Rb)
Novatel Rb model
Novatel Cs model

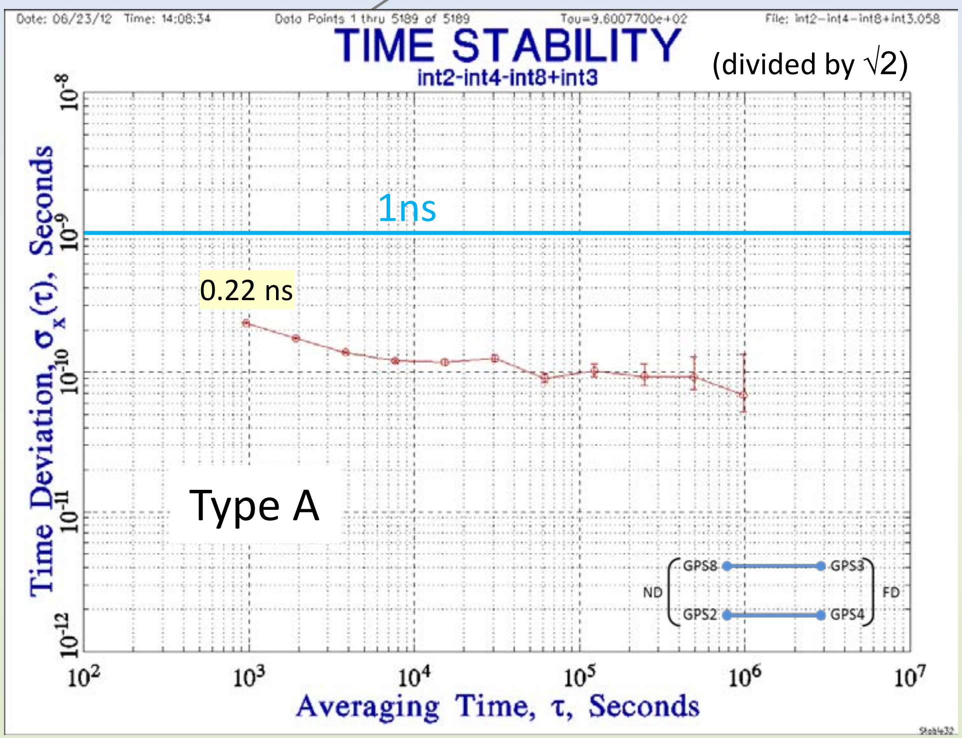

Delay line
10MHz IN
PPS IN
PPS conditioning
PPS conditioning
PPS OUT
Antenna
REF in
PPS in
PPS out
RS232
PWR
Novatel RCVR
START
STOP1
STOP2
Onboard TIC
µController
RS232
Power Supply
Log file
(Tick-to-tick, tick-to-phase, RF power, status)
NIST enclosure
GPS binary data file

Uncertainty of the time difference (1)

$(data - CABDLY + REFDLY)_1 - (data - CABDLY + REFDLY)_2 - (INTDLY_1 - INTDLY_2)$

$REFplane_B - REFplane_A = (data_1 - data_2) + (REFDLY - CABDLY)_1 - (REFDLY - CABDLY)_2 - (INTDLY_1 - INTDLY_2)$

$REFplane_B - REFplane_A$



(divided by $\sqrt{2}$)

< 0.05 ns

$INTDLY_2 - INTDLY_4$
0.25 ± **0.19 ns**

Type B

Total uncertainty = $\sqrt{(\text{Type A})^2 + (\text{Type B})^2}$

0.30 ns (@16min)

(GPS6N56002) *(GPS6F56034)*

GPS2 — GPS4

Uncertaint(ie)s

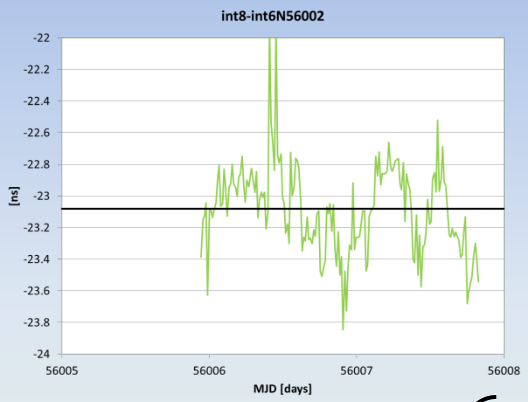
Total uncertainty = $\sqrt{(\text{Type A})^2 + (\text{Type B})^2}$

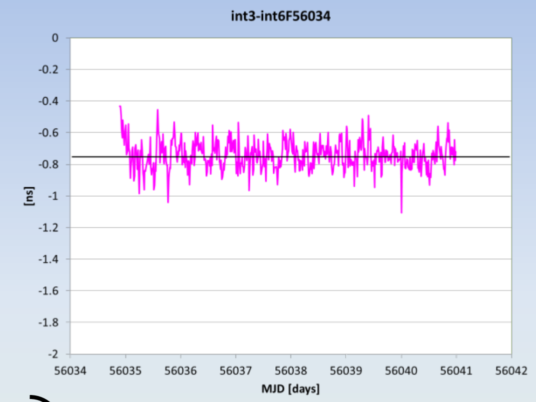
0.297 ns (@16min)

Total uncertainty = $\sqrt{(\text{Type A})^2 + (\text{Type B})^2}$

0.376 ns (@16min)

Calibration (again)



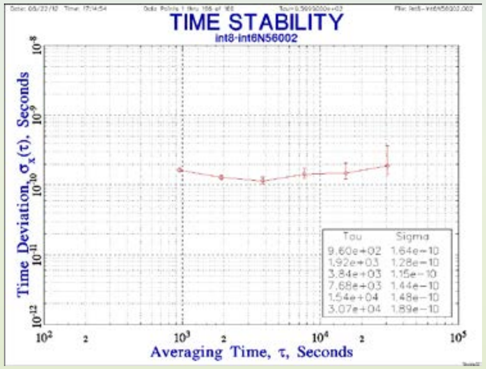


$INTDLY_8 - INTDLY_6$
-23.08 ± 0.164 ns

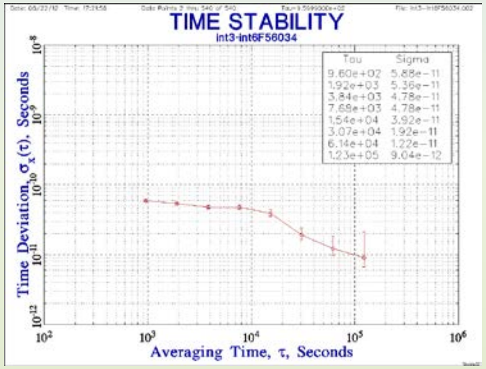
(GPS6N56002) *(GPS6F56034)*

GPS8 — GPS3

$INTDLY_3 - INTDLY_6$
-0.74 ± 0.059ns



$INTDLY_8 - INTDLY_3$
22.34 ± 0.174 ns

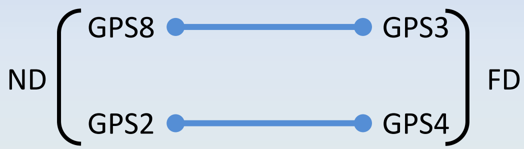


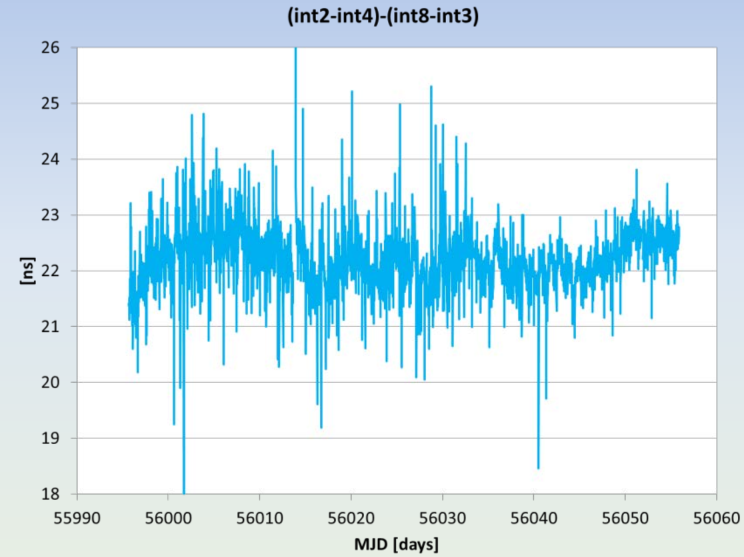
ND

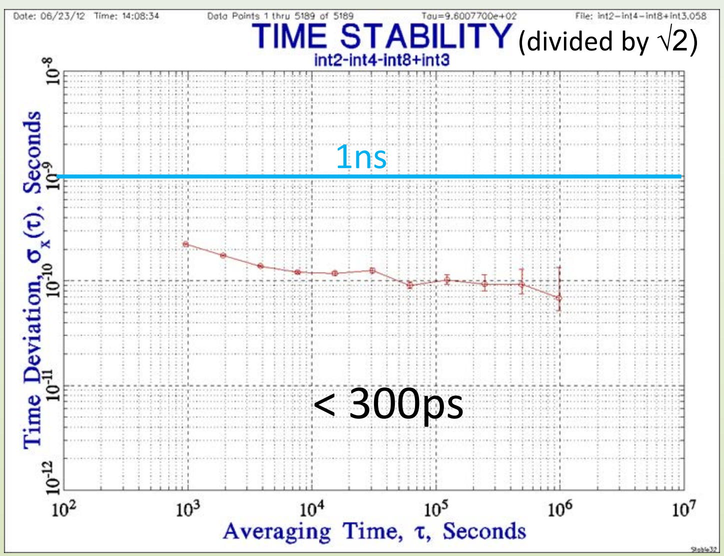
FD

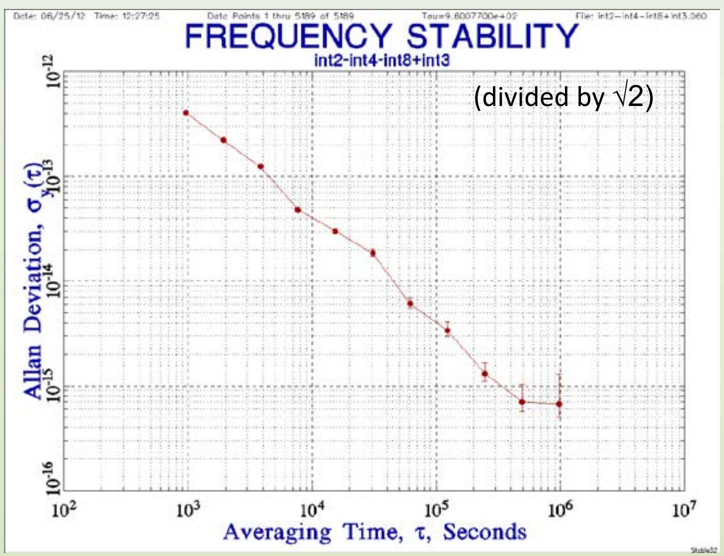
Double-difference between remote sites

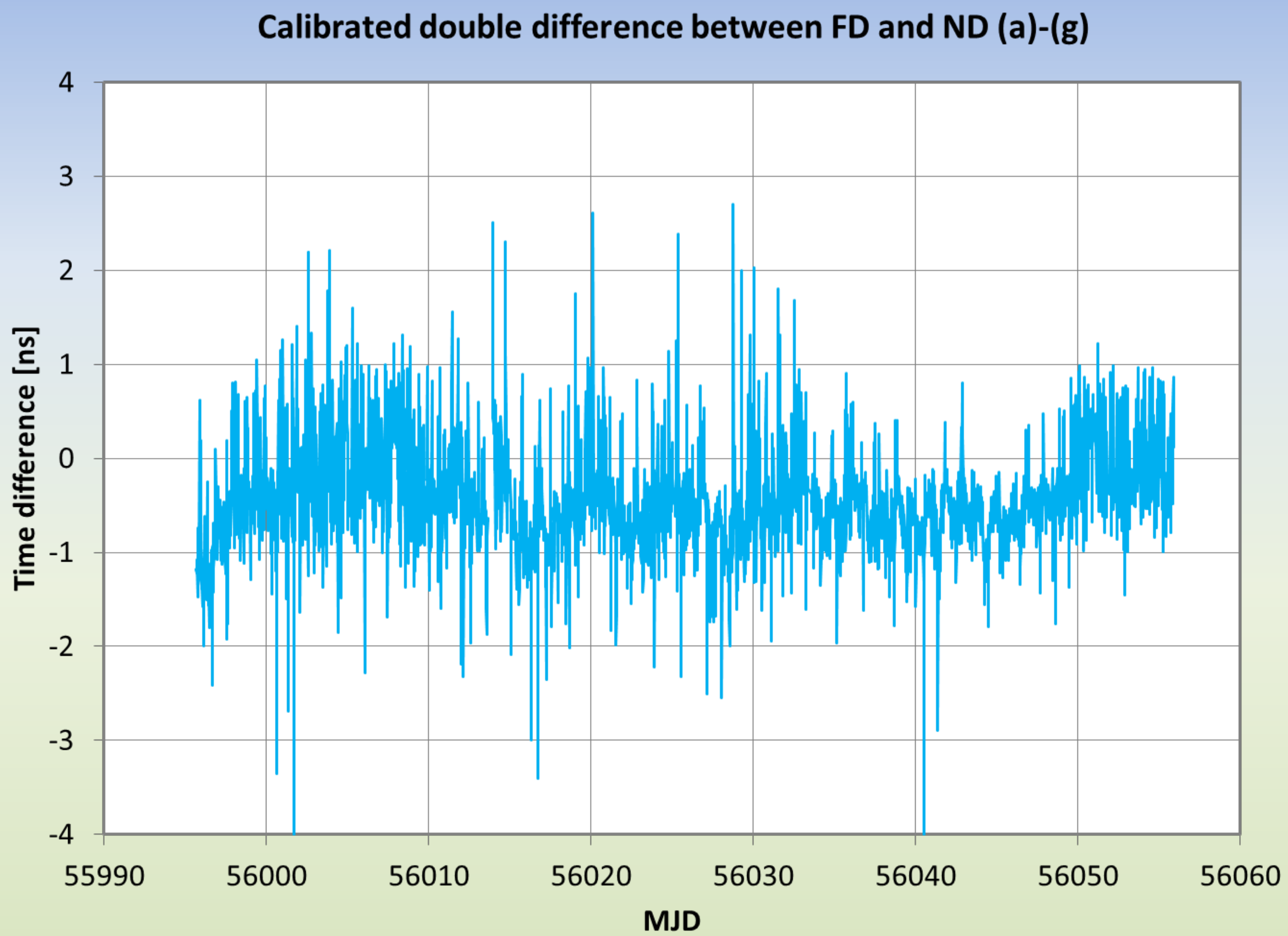
(Stability)










Calibrated double difference between FD and ND (a)-(g)
Time difference [ns]
4
3
2
1
0
-1
-2
-3
-4
55990
56000
56010
56020
56030
56040
56050
56060
MJD