Synchronization between remote sites for the MINOS experiment

Main
Injector
Neutrino
Oscillation
Search

National Institute of Standards and Technology
Time and Frequency Division

A collaboration
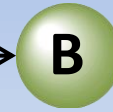
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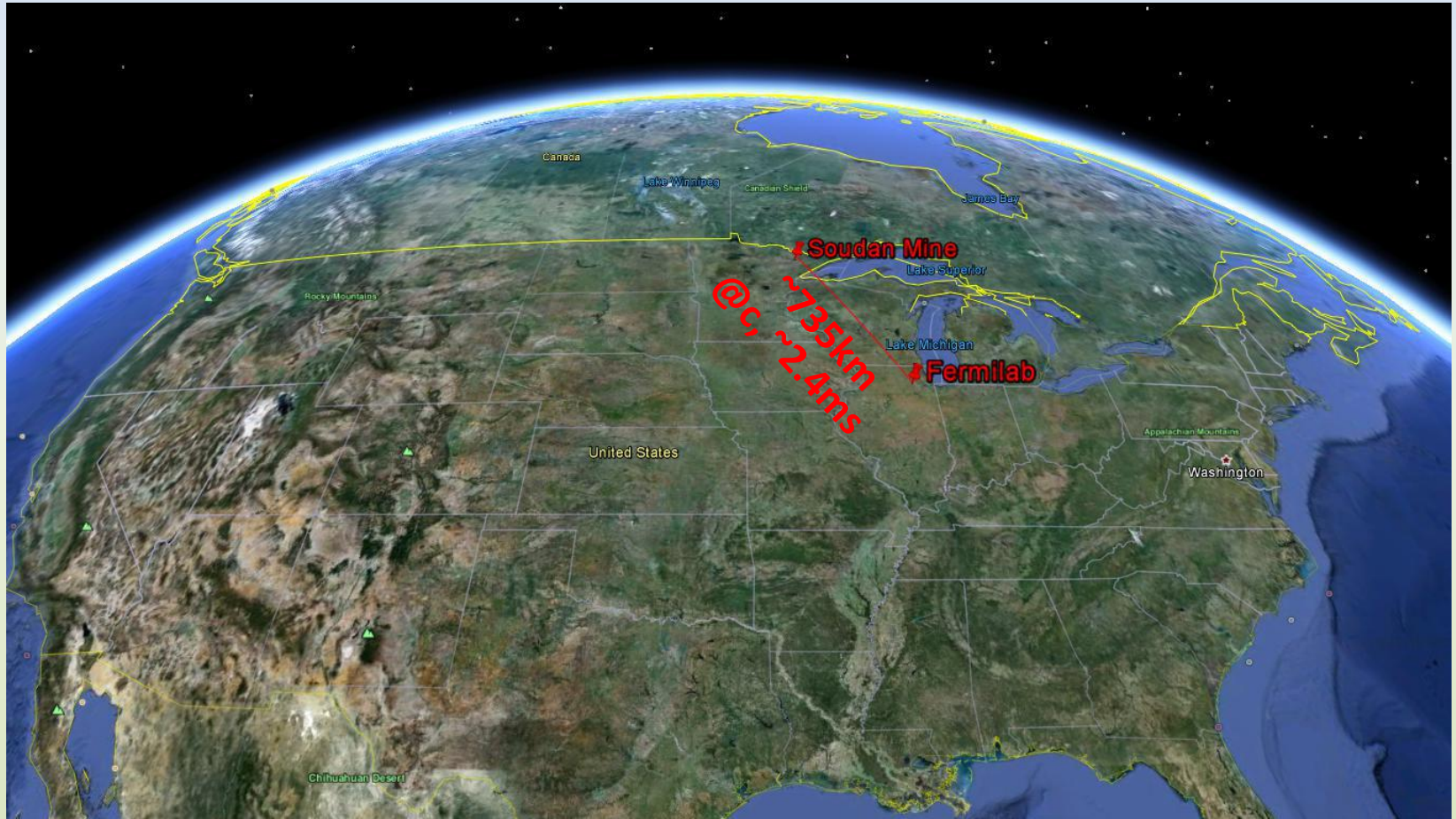R. Plunkett [Fermilab]
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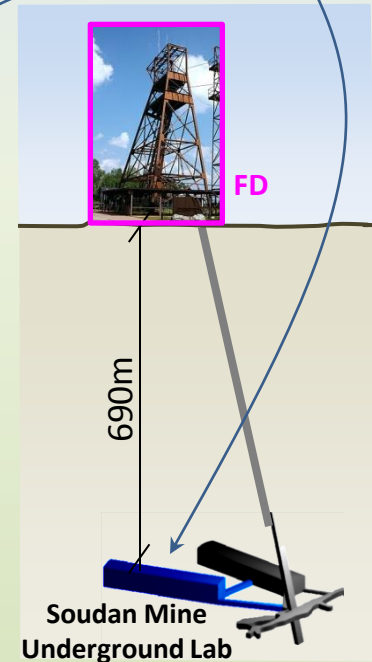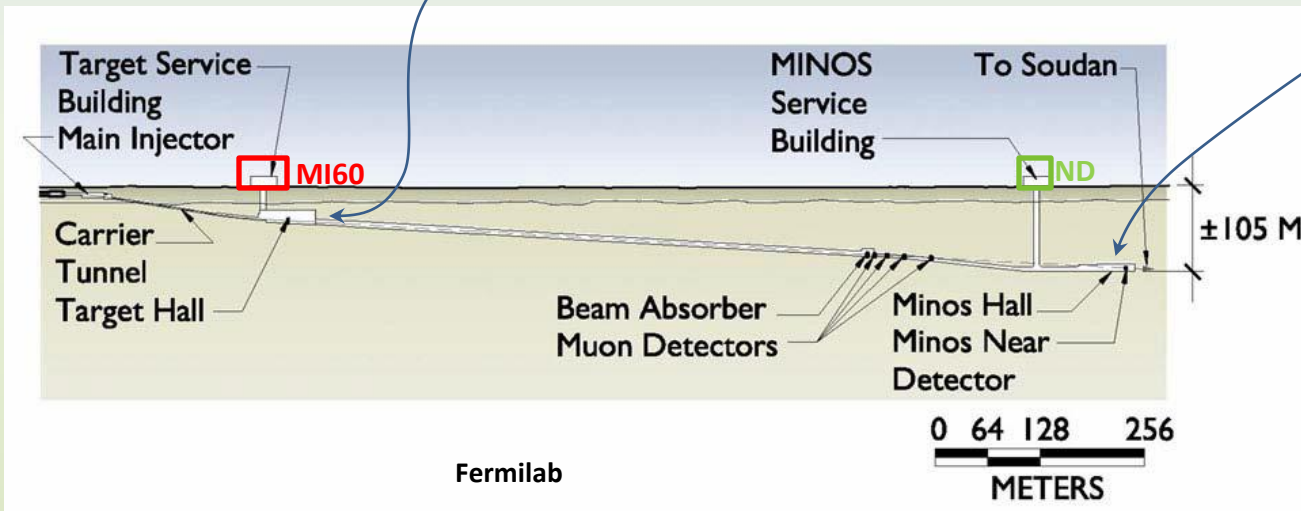B. Fonville
D. Matsakis
A. McKinley
E. Powers
J. Wright
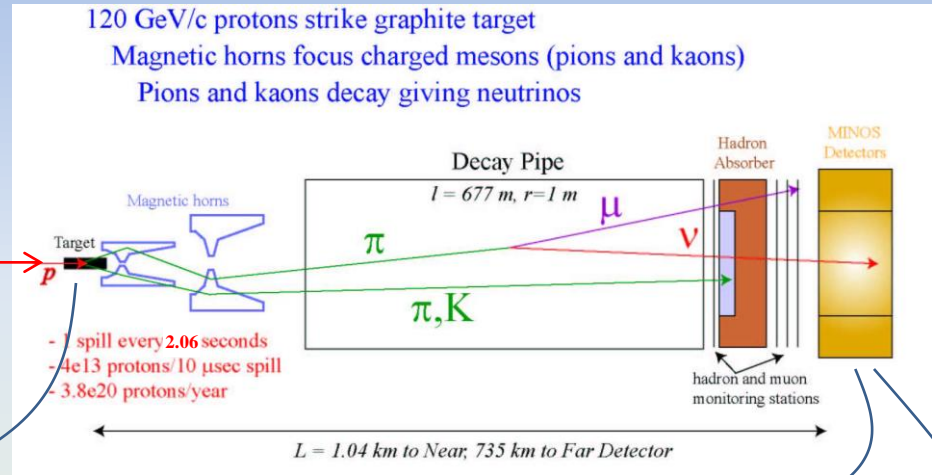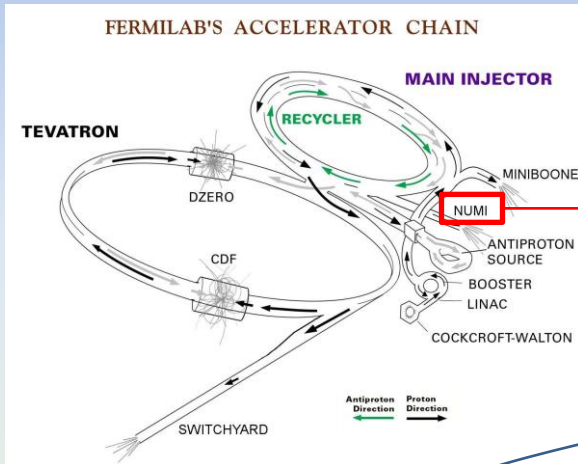
The experiment

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

The experiment

FERMILAB'S ACCELERATOR CHAIN

MAIN INJECTOR

TEVATRON

RECYCLER

DZERO

MINIBOONE

NUMI

ANTIPROTON SOURCE

CDF

BOOSTER

LINAC

COCKCROFT-WALTON

SWITCHYARD

Antiproton Direction   Proton Direction

120 GeV/c protons strike graphite target

Magnetic horns focus charged mesons (pions and kaons)

Pions and kaons decay giving neutrinos

MINOS Detectors

Decay Pipe

Hadron Absorber

$l = 677$ m, $r=1$ m

Magnetic horns

Target

p

μ

π

ν

π, K

- 1 spill every 2.06 seconds
- 4e13 protons/10 µsec spill
- 3.8e20 protons/year

hadron and muon monitoring stations

$L = 1.04$ km to Near, 735 km to Far Detector

Target Service Building Main Injector

MINOS Service Building

To Soudan

MI60

ND

Carrier Tunnel Target Hall

±105 M

Beam Absorber Muon Detectors

Minos Hall Minos Near Detector

0   64 128   256

Fermilab

METERS

FD

690m

Soudan Mine Underground Lab

Beam structure

18.83ns

RF voltage — 53.103480 MHz

Bucket (3.5ns wide)

81 (+5empty) buckets

5 empty buckets ~94ns

Overlay of ~2 batches, assuming 18.83ns bunch spacing

3.5ns

1.6µs

| batch | batch | batch | batch | batch | batch |

6 batches (3 removed by notcher)

Spill ~9.7µs

2.06s

Bucket #0 is re-determined at each "cycle" which is the beginning of each spill

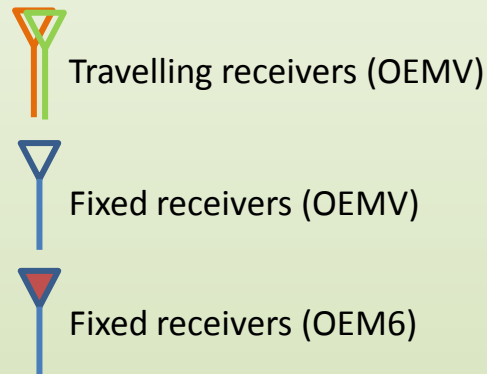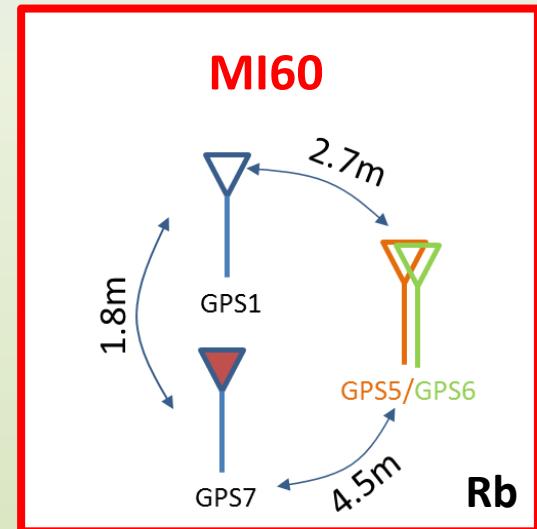synchronization accuracy and stability
~ ns

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

Synchronization setup

GPS

TWSTFT

NIST

GPS

MI60

GPS

GPS

GPS

Time
keeping
system

TWSTFT

USNO

GPS

GPS

GPS

GPS

Time
keeping
system

GPS

GPS

GPS

Time
keeping
system

TWTT
on fiber

TWTT
on fiber

TWSTFT

ND

TWSTFT

FD

TWTT
on fiber

The receivers

Far Detector (FD)   **Cs**
- 18m
- 1.7m
- 19m
- GPS5/GPS6
- GPS3
- GPS4

Near Detector (ND)   **Cs**
- 1.7m
- 20m
- 21m
- GPS2
- GPS8
- GPS5/GPS6

Travelling receivers (OEMV)

Fixed receivers (OEMV)

Fixed receivers (OEM6)

MI60
- 2.7m
- 1.8m
- 4.5m
- GPS1
- GPS7
- GPS5/GPS6
- **Rb**
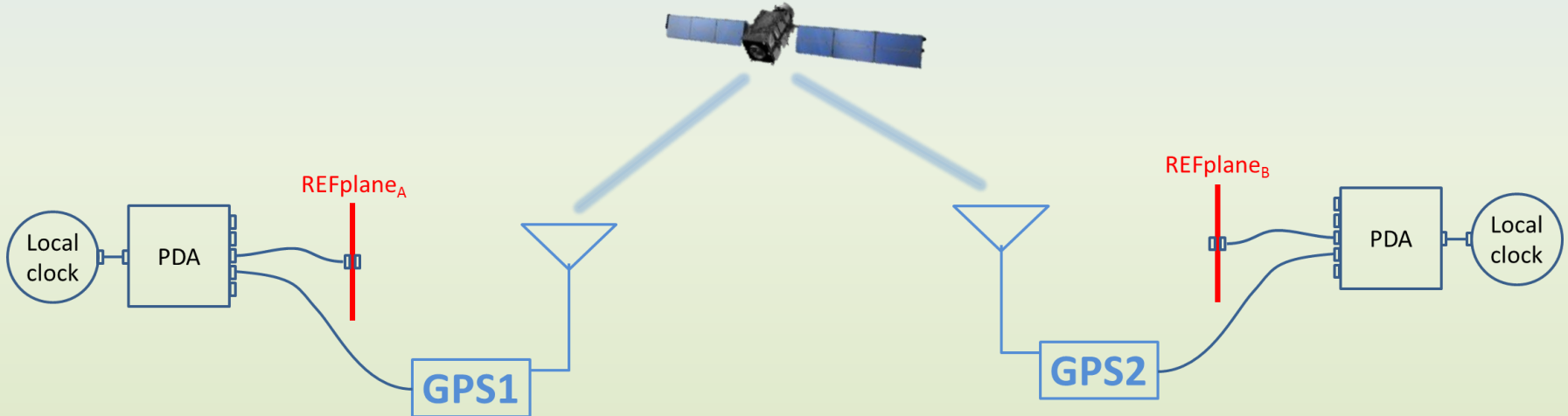
C/A: Common View

SEPARATE LOCATIONS

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

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

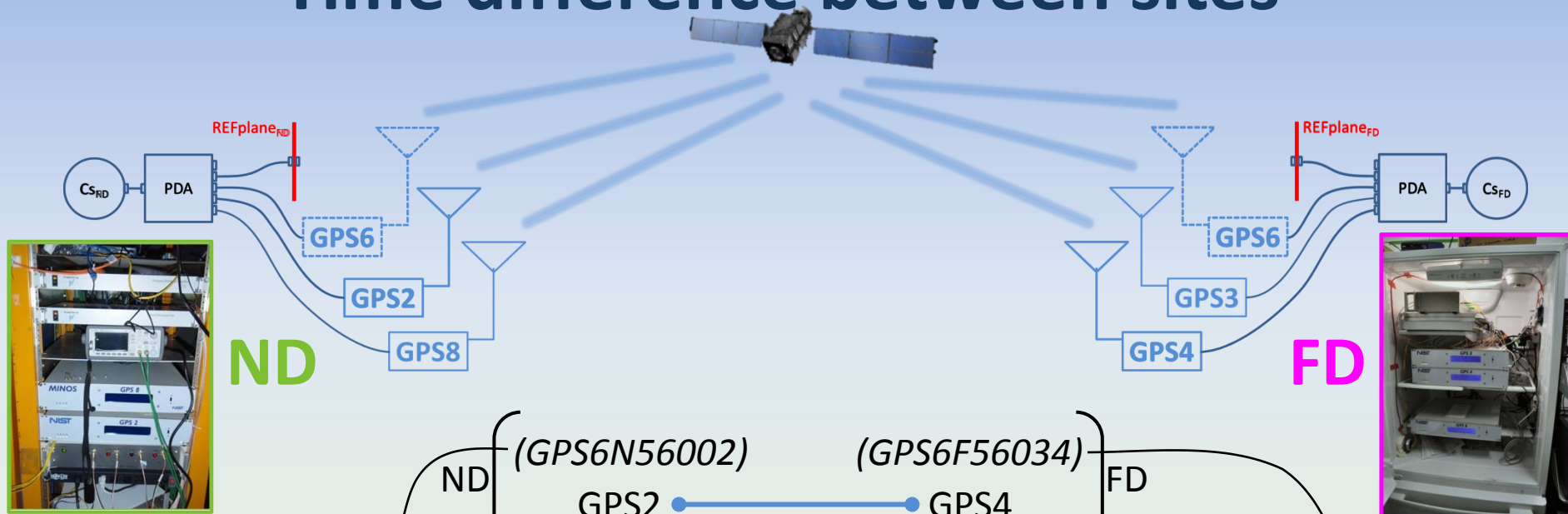$$(\text{data} - \text{CABDLY} + \text{REFDLY})_1 - (\text{data} - \text{CABDLY} + \text{REFDLY})_2 - (\text{INTDLY}_1 - \text{INTDLY}_2)$$
$$=$$
$$REFplane_B - REFplane_A$$

It measures the difference between the clocks at the two locations

Time difference between sites

ND $\{$ *(GPS6N56002)* ... *(GPS6F56034)* $\}$ FD
GPS2 — GPS4

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		

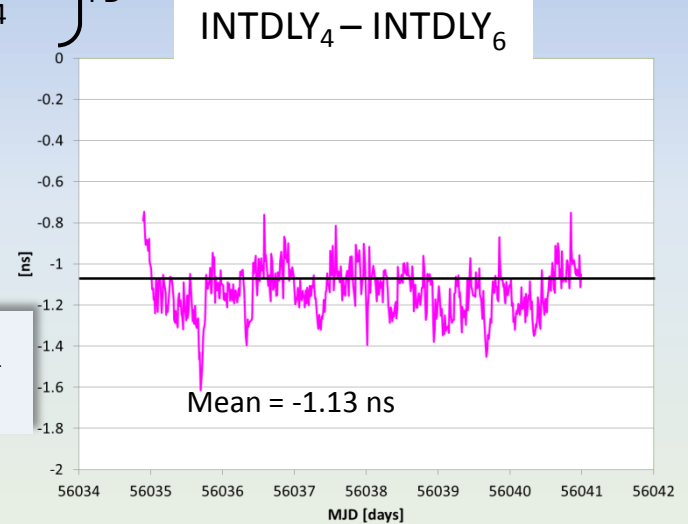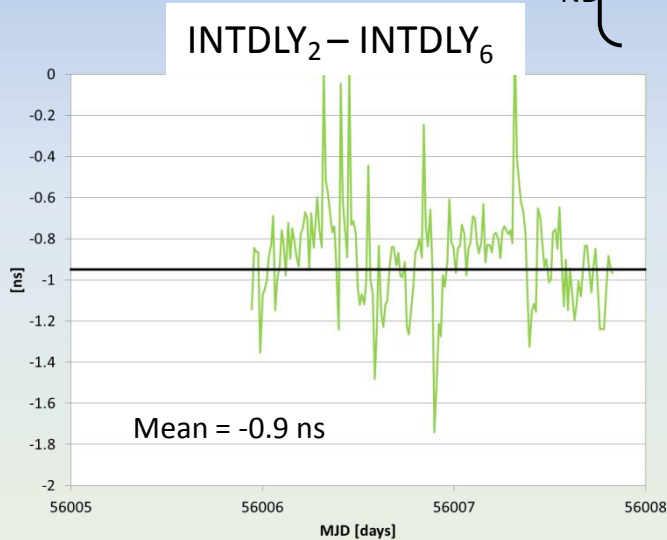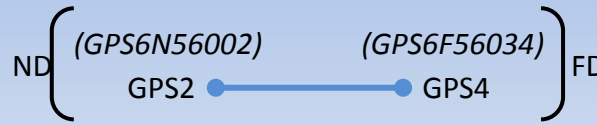| Date	MJD	DOY	MI60 (Rb)			ND (Cs)			FD			NIST	
			travel	GPS1	GPS7	travel	GPS2	GPS8	travel	GPS3	GPS4	GPS5	GPS6
14-Apr-12	56031	105		P	P		P	P		P	P		
15-Apr-12	56032	106		P	P		P	P		P	P		
16-Apr-12	56033	107		P	P		P	P		P	P		
17-Apr-12	56034	108		P	P	2 P	P	P	2 P	P	P		
18-Apr-12	56035	109		P	P	2 P	P	P	2 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		

$$(\text{data} - \text{CABDLY} + \text{REFDLY})_1 - (\text{data} - \text{CABDLY} + \text{REFDLY})_2 - (\text{INTDLY}_1 - \text{INTDLY}_2)$$
$$=$$
$$\text{REFplane}_B - \text{REFplane}_A$$

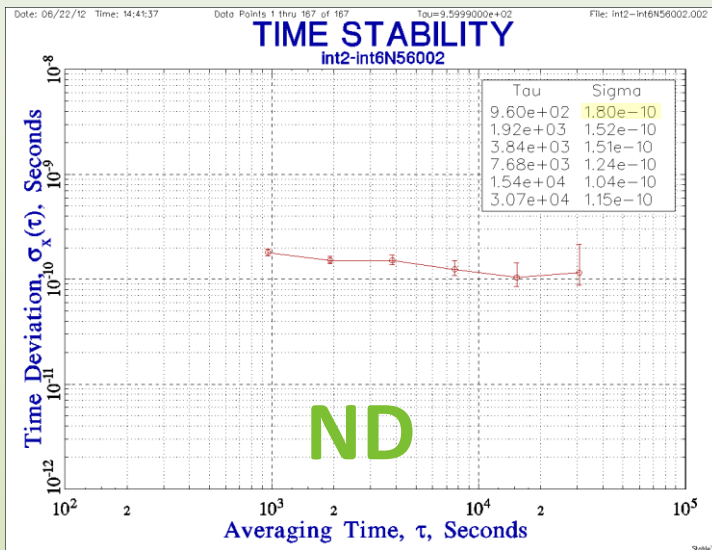# Common-clock, short-baseline measurement
(RCVR stability, lower limit)
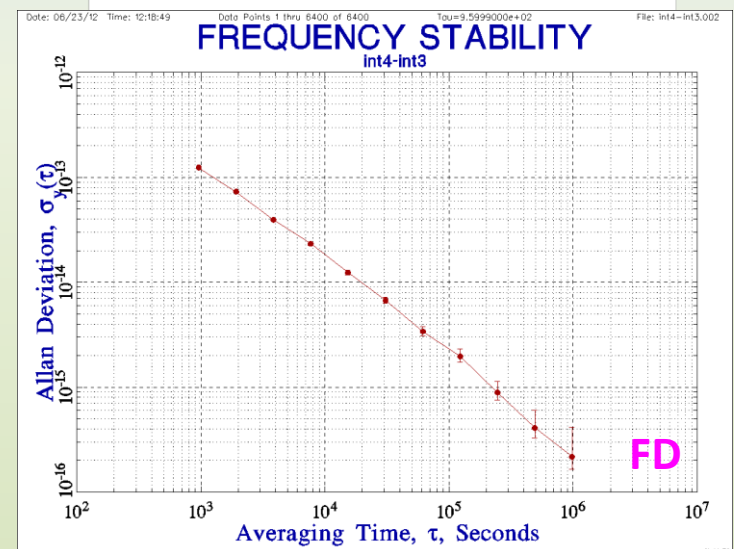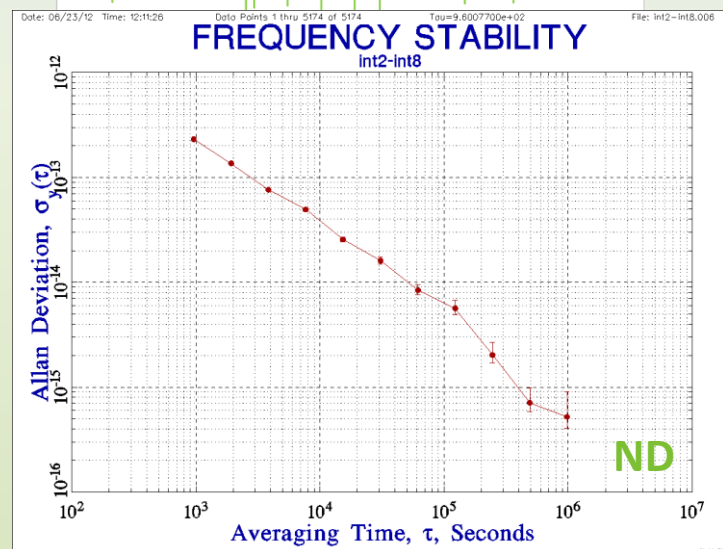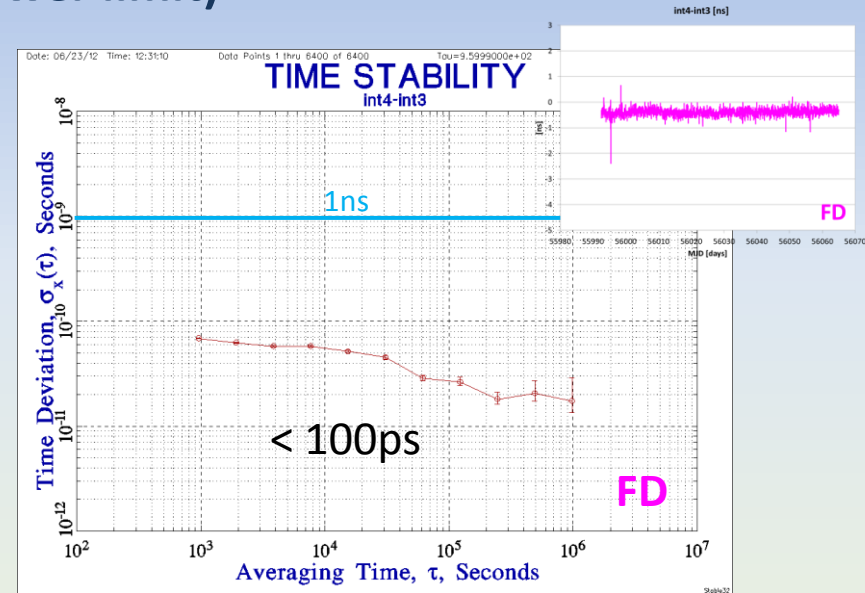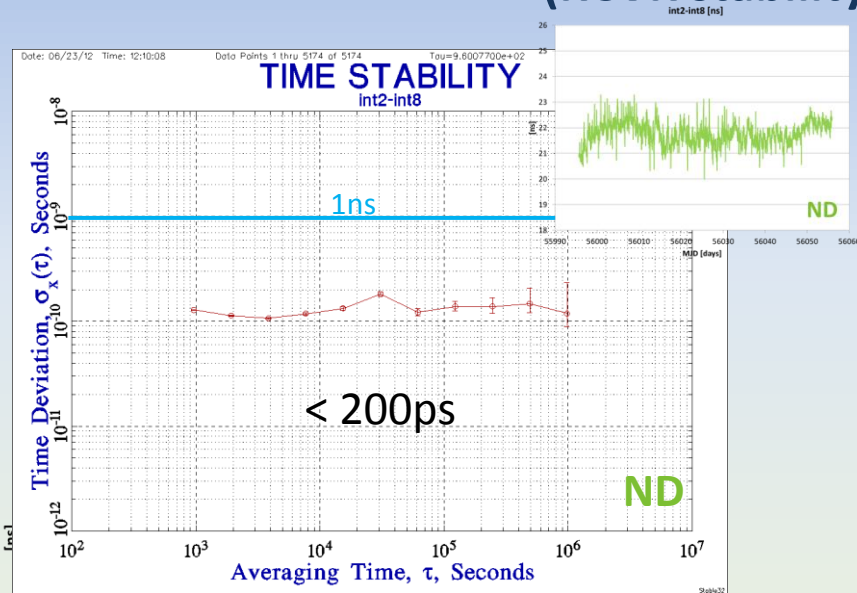
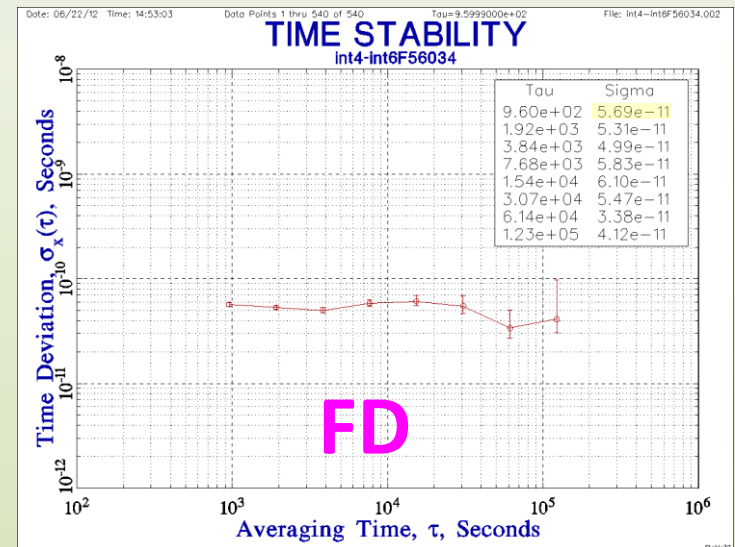# Differential calibration of the receivers

(accuracy, lower limit)

ND $\left[\begin{array}{c} \text{(GPS6N56002)} \quad\quad \text{(GPS6F56034)} \\ \text{GPS2} \bullet\!\!-\!\!-\!\!-\!\!-\!\!-\!\!-\!\!-\!\!-\!\!\bullet \text{GPS4} \end{array}\right]$ FD

INTDLY$_2$ − INTDLY$_6$

Mean = -0.9 ns

INTDLY$_2$ − INTDLY$_4$
0.23 ns

INTDLY$_4$ − INTDLY$_6$

Mean = -1.13 ns

ND

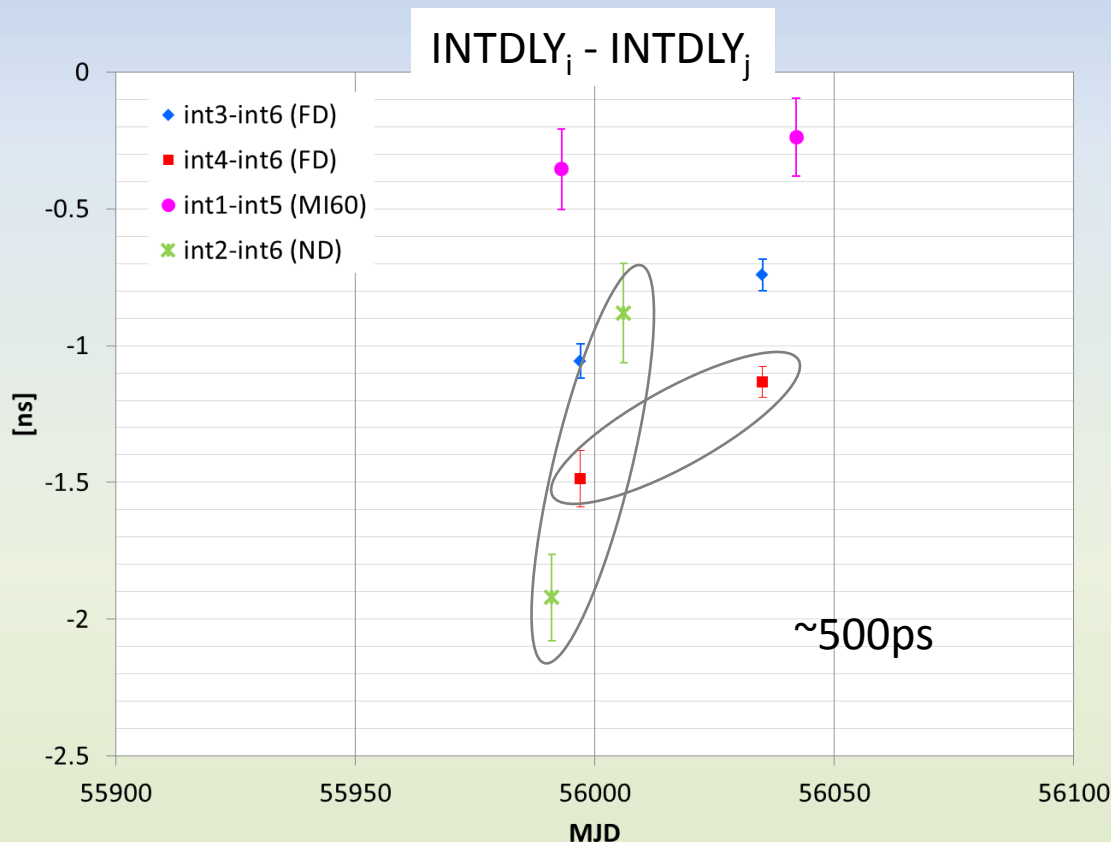The uncertainties are summed in quadrature

uncertainty
0.2 ns

FD

Repeated differential calibrations
(accuracy in the longer term)

INTDLY$_i$ - INTDLY$_j$

int3-int6 (FD)
int4-int6 (FD)
int1-int5 (MI60)
int2-int6 (ND)

[ns]

MJD

~500ps

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

Uncertainty estimates for GPS link

	Stability	Accuracy
Common clock	< 200ps	
Differential calibration		200ps
Calibrated double-difference	< 300ps	< 400ps
Repeated calibration		~500ps
Comparison with TWSTFT		1-2 ns?

Conclusions

☼ The uncertainty doesn't seem to be so far from the desired few ns 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 (for the first time!) 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.

There will be an invited session of Neutrino TOF Metrology during the PTTI 2012 (www.pttimeeting.org)