THE EUROPEAN TW CALIBRATION CAMPAIGN 2014 IN THE SCOPE OF GALILEO (TGVF-FOC)

An opportunity to update TW link calibrations in Europe

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The Objectives

- To ensure time transfer between PTFI, PTFD and the involving UTC(k) labs (INRIM, OP, PTB, ROA and SP) via TWSTFT with an uncertainty (1σ) of less than 2ns.

Galileo System Time, is a key element of the core navigation function, but also is the **"metrological time-keeping"** to be broadcast in the Galileo Signal in Space.

Relationship between international time references (UTC, TAI) and the GST **well defined**.

The required support for such "metrological time-keeping" during Galileo deployment phase toward the FOC is provided by the Time Validation Facility as part of the TGVF. A WP was focused to ensure **good metrological quality of the TW links with PTF's**.

The calibration was extensive to **TW links among UTC(k) labs**, and **links with USNO**.

Background of PTF’s

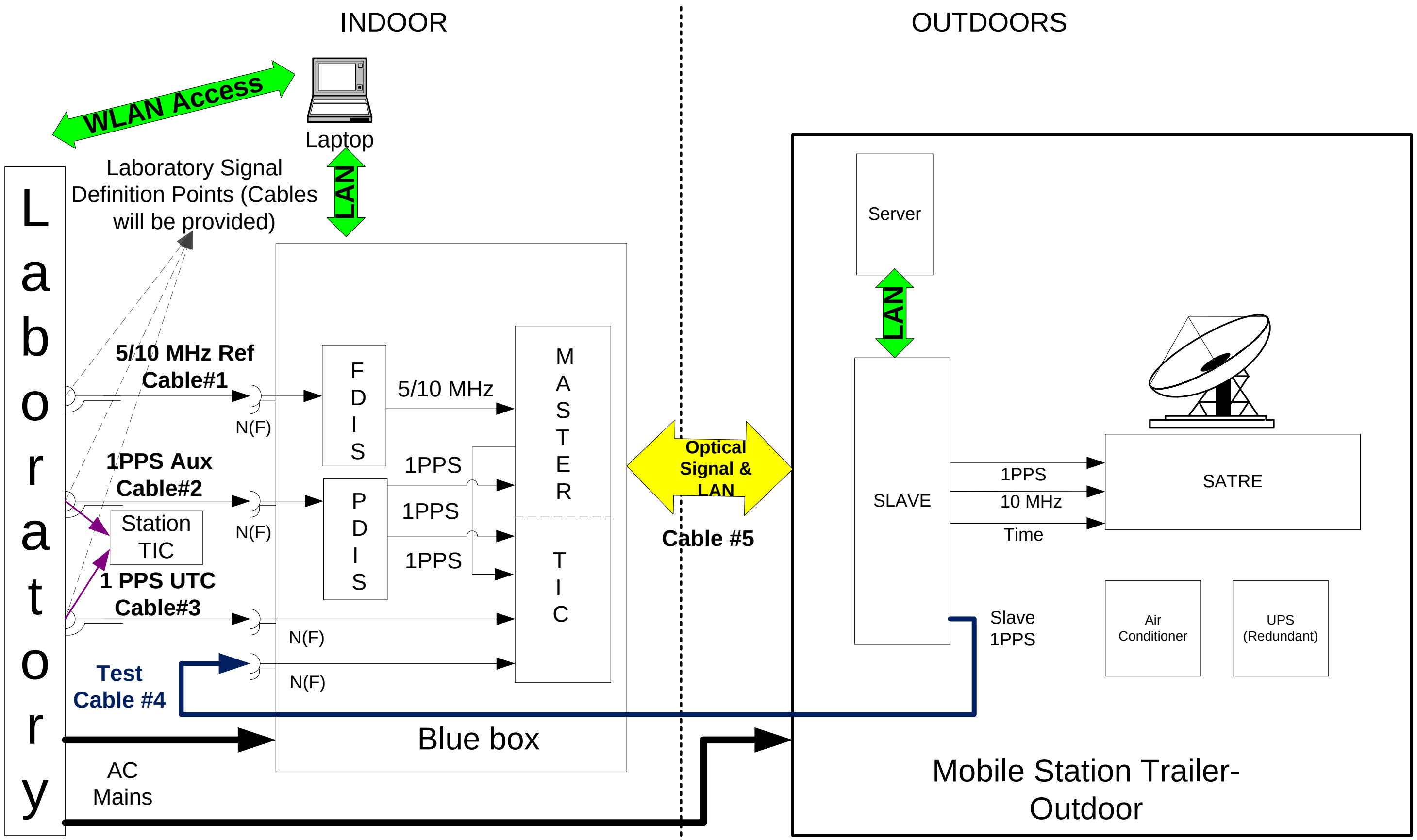
- TW Links with PTF1 were calibrated in autumn 2013 with a mobile TWSTFT station, in the frame of the IOV Galileo Time Validation Facility contract between TAS-F, INRIM, and PTB.
- This would be the first TW calibration for PTF(OBE), before accomplish its readiness in 2014, during the deployment and operations (“FOC”) phase of the Galileo Program.

TW Cal. Campaign in numbers

- **7 sites visited** plus the reference station at TimeTech.
- **Duration of the campaign**: From the 10th June to 1st of August: **53 days** (minus the break of 8 days coinciding with the EFTF at Neuchatel).
- **Distance travelled**: About **10000 km**.
- **Time required** for travelling: **130 hours**.
- **Effective measurement time**: **604 Hours** (**25 days aprox.**, or the **56%** of the length of the campaign)
- Number of links calibrated: **26**
  - 10 by means of link method.
  - 10 by site method.
  - 6 by triangle closure method.

The TTech TWSTFT mobile station I

- Is the short name for the transportable TWSTFT ground station used in this calibration experiment.



The TTech TWSTFT mobile station 2

- The optical link refers all TWSTFT measures to 1 PPS(Aux) input from fixed station, independent of the phase of the reference frequency.
- The optical link presents coherent and phase stable 1 PPS and 10 MHz to the SATRE modem in the mobile station (the frequency input to SATRE modem follows 1 PPS(Aux).
- The #4 is a cable for test purpose. This cable allows to check there is no error synchronising both units.

The TTech TWSTFT mobile station 3

View of the mobile station at ROA

View of the ROA fixed station antenna with mobile station antenna at the bottom

Planning of the campaign

- Different station codes for **regular** (even hours) and **extra** sessions (odd hours).
- PTFs not disturbed. For links with PTFs, the **link method** were used. The necessary independent time transfer link in this mode was provided with a TWSTFT link by using the mobile station (in CC with the each PTF).
- Links between UTC(k) labs were based on standard **site method**.
- REFDELAY differences (fixed station – mobile station) were measured and subsequently considered (constant at each site), instead the REFDELAY parameters from ITU files.

Stability of the mobile station during the trip

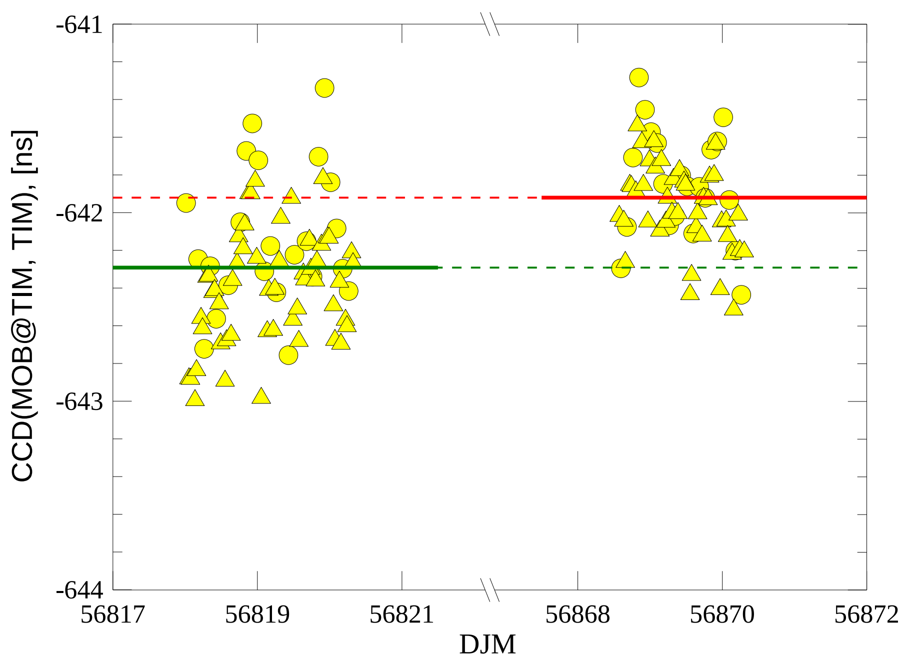
- Fixed station at TimeTech worked as reference.

CCD(MOB@TIM, TIM)_1:

- mean = -642.29 ns
- sigma = 0.23 ns; TDEV = 0.14 ns
- N: 76 values

CCD(MOB@TIM, TIM)_2:

- mean = -641.92ns
- sigma = 0.18 ns; TDEV = 0.09 ns
- N: 63 values.



CSD = 0,17 ns

|CCDD| = 0,37 ns

CSD < |CCDD|

Link Mode at PTF's: The theoretic approach 1

- New LS fitting approach for statistical analysis was designed:
  - We are supposing that MOB station is at site 2.
  - In general, the trends of TS(1) and TS(2) are different, what implies that differences between TW(1) and TW(2) (or between TW(1) and TW(MOB@2) are not stationary.
  - 0,5*[(TW(1) – TW(MOB@2)) – (TW(1) – TW(2))] in equation for CALR(1, 2) should be however a **constant**.
  - This constant cannot be estimated directly from the set of TW data because these are not strictly contemporary.
  - Denoting:
    - 0,5*(TW(1) – TW(MOB@2)) = $X_{1o}(t)$
    - 0,5*(TW(1) – TW(2)) = $X_{2o}(t)$
  - We search for the "best" fit of two straight lines, with the same slope: $X_{1e}(t)$ and $X_{2e}(t)$

Link Mode at PTF's: The theoretic approach 2

- $X_{1e}(t) = a*t + b_1, X_{2e}(t) = a*t + b_2$,
- We search for the **"best" estimates** of **a**, $\mathbf{b_1}$ and $\mathbf{b_2}$ based on the data $X_{1o}(t)$ and $X_{2o}(t)$.
- $\mathbf{b_1 - b_2}$ provides the constant of interest to be estimated.
- Expression to be minimized: **Residual Sum of Squared**.

$$E^2 = \Sigma_i (X_{1o} - X_{1e})^2 + \Sigma_j (X_{2o} - X_{2e})^2$$

- Equations after setting to zero the derivatives (with respect to a, b_1 and b_2):

$$\text{(1)}\quad a * \Sigma\, t^2 + b_1 * \Sigma_i\, t_i + b_2 * \Sigma_j\, t_j = \Sigma\, t * X$$

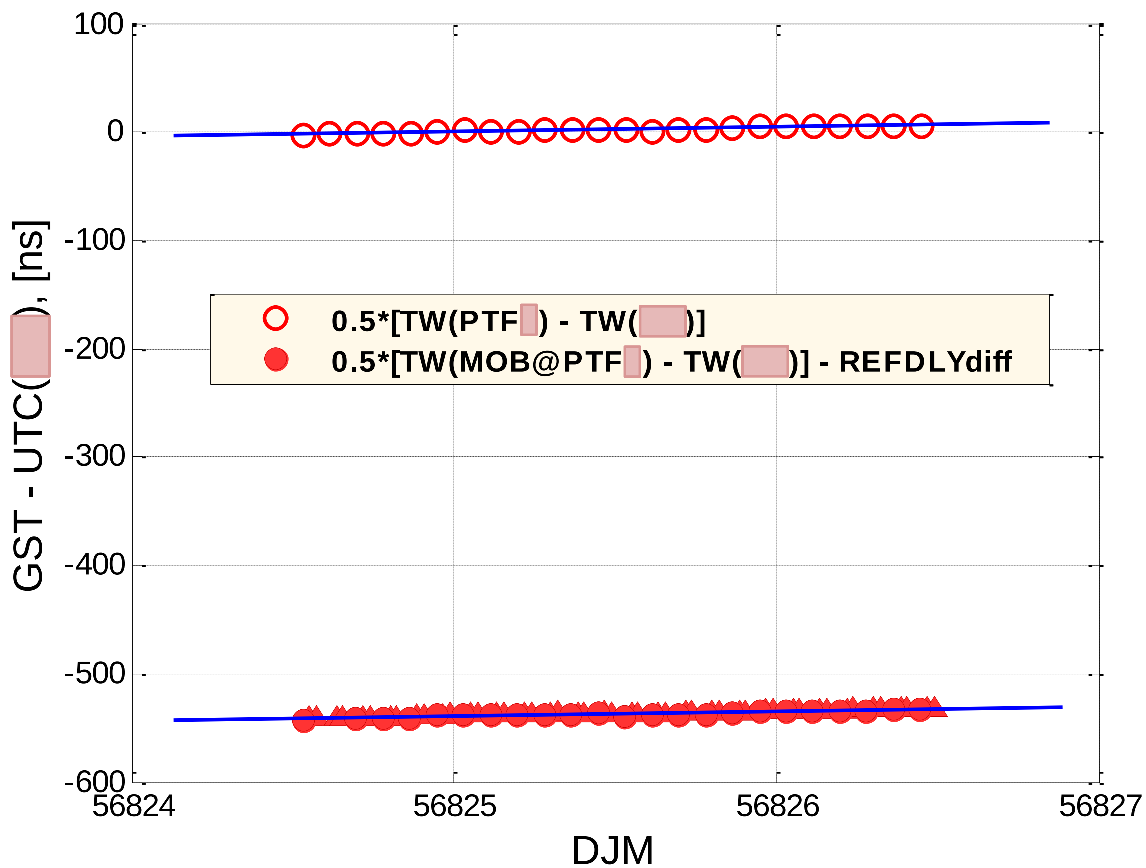
$$\text{(2)}\quad a * \Sigma_i\, t_i + N_1 * b_1 = \Sigma_i\, X_{o1i}$$

$$\text{(3)}\quad a * \Sigma_j\, t_j + \quad + N_2 * b_2 = \Sigma_j\, X_{o2j}$$

- N_1 and N_2 mean the number of data X_{1o} and X_{2o} respectively.
- Care must be taken estimating the uncertainty of $b_1 - b_2$ (**cubic spline**)

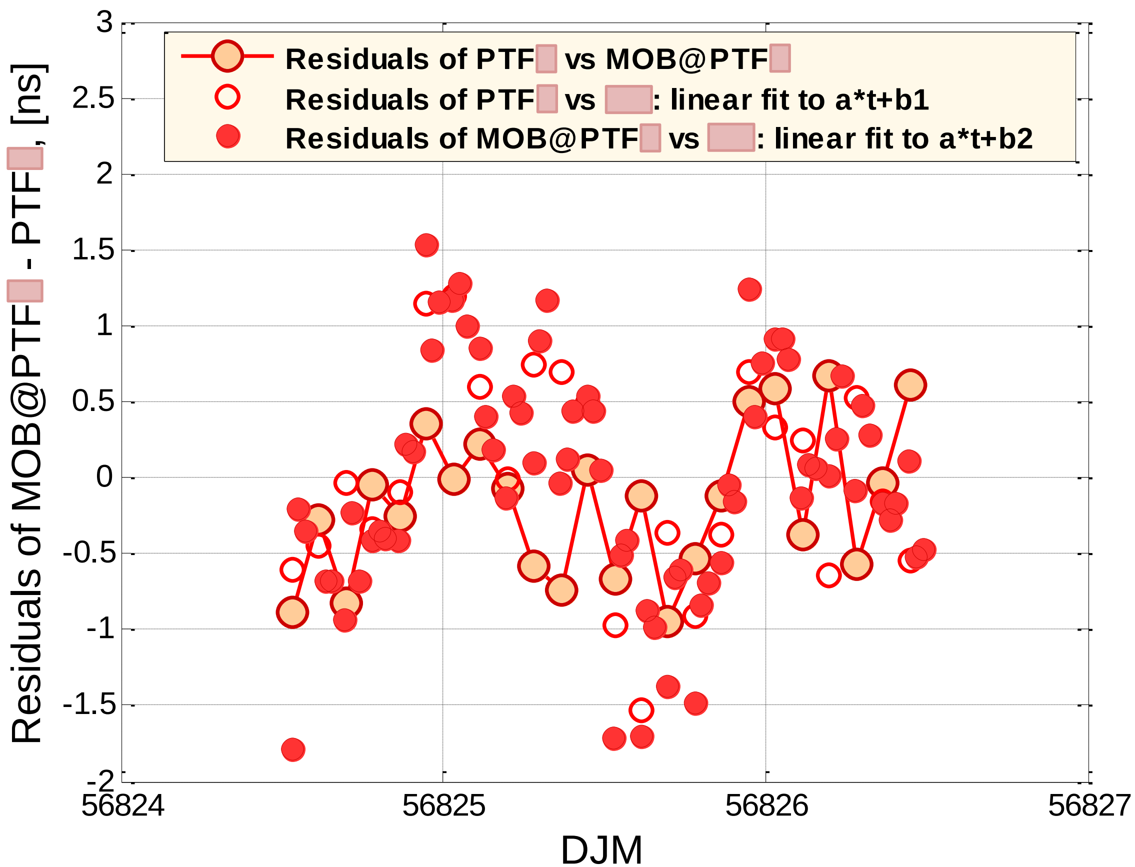
Link Mode at PTF's: An example (1)

- TWSTFT between PTFx and UTC(k) lab using fixed and mobile stations at PTFx, circles: data taken at even hours, triangles: data taken at odd hours



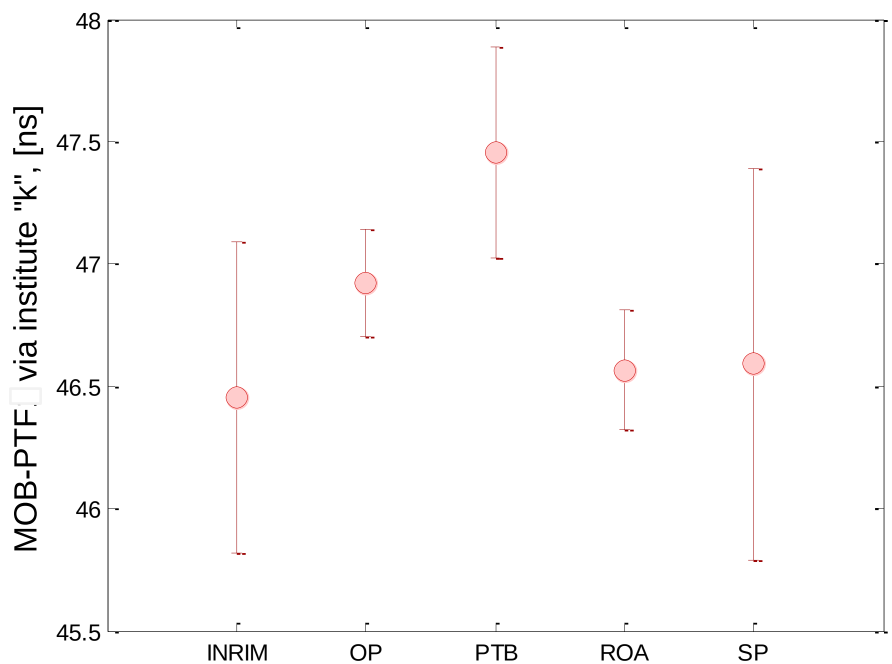
Link Mode at PTF's: An example (2)

- Residuals of linear fits of TWSTFT between PTFx and UTC(k) lab, and residuals of MOB@PTFx – PTFx



Link Mode at PTF's: Discrepancy of results

- Results of TWSTFT between MOB and PTFx stations with UTC(k) laboratories as bridging stations. Error bar equal TDEV. Discrepancies are not significant.
- Results were combined by a weighted average.
- In all cases, combined TDEV around 0,2 ns



TW link calibration values

- CALR were calculated taken into account that **ESDVAR** will be **re-set to zero** after the calibration.
- The same for links with PTF's and USNO (not shown here).

Link	CALR(old)	U_CALR_old	$CALR_{interim}$	CALR variation
INRIM–OP	+6821.756	2.0	+6835.60 (*)	+2.14
INRIM–PTB	-479.209	1.3	-465.41 (*)	+2.10
INRIM–ROA	-317.141	6.0	-307.73 (*)	-2.29
INRIM–SP	-283.892	2.0	-275.59 (*)	-3.40
OP–PTB	-7300.704	1.2	-7301.02	-0.32
OP–ROA	-7137.879	6.0	-7143.33	-5.45
OP–SP	-7105.715	2.0	-7111.19	-5.47
PTB–ROA	+298.673	5.0	+293.99	-4.68
PTB–SP	+194.939	1.2	+189.83	-5.11
ROA–SP	+32.071	6.0	+32.14	+0.07

TW link calibration values

- The "a priori" consistency of new CALR values against the old one. In Orange discrepancies higher than 2*U, in yellow discrepancies from U to 2*U, the rest in green, U represents the old combined uncertainty.

CALR Variation	INRIM	OP	PTB	ROA	SP
INRIM		+2.14	+2.10	-2.29	-3.40
OP	-2.14		-0.32	-5.45	-5.47
PTB	-2.10	+0.32		-4.68	-5.11
ROA	+2.29	+5.45	+4.68		+0.07
SP	+3.40	+5.47	+5.11	-0.07	

Uncertainties contribution (1)

All contributions are added geometrically:

- **u_a(i)** and **u_a(j)**: Statistical uncertainties at lab i and lab j, respectively.

  Statistical uncertainties based on worst TDEV for the range of useful averaging time.

- **$u_{b,1}$**: Uncertainty of the portable station (0,37 ns).
- **$u_{b,2}$**: Uncertainty of the connection of the fixed stations to the local TS (from 0,2 to 0,5 ns).
- **$u_{b,3}$**: Uncertainty of the connection of the mobile station to the local TS ((from 0,2 to 0,28 ns).

Uncertainties contribution (2)

u_{b2} and u_{b3} are derived from a high performance TIC. It includes a) the instability of the connection to the local TS, b) TIC trigger level timing error, c) nonlinearities of the ensemble TIC-ref freq used.

- **u_{b4}(i)**: Uncertainty of the Sagnac corrections (0,1 ns for couple of stations).
- **u_{b5}(i)**: All other suspected possible type "b" contributions (0,4 ns).
- This includes, for example, the instability of satellite communication parameters (signal power, C/N0, codes), atmospheric parameters (ionosphere, troposphere), and satellite motion (residual diurnals, residual Sagnac, path delay difference).

Uncertainties contribution (3)

- Uncertainty contributions and combined uncertainty U (1 sigma).
- Uncertainties for links with PTF's and USNO not shown here.
- Combined uncertainty with PTF 0,9 – 1,0 ns. With USNO around 1,2 ns.

Case	$u_a(1)$	$u_a(2)$	$u_b,1$	$u_b,2(1)$	$u_b,2(2)$	$u_b,3(1)$	$u_b,3(2)$	$u_b,4$	$u_b,5$	U
CALR(INRIM, OP)	0.30	0.18	0.37	0.20	0.20	0.20	0.28	0.10	0.40	0.8
CALR(INRIM, PTB)	0.30	0.21	0.37	0.20	0.20	0.20	0.20	0.10	0.40	0.8
CALR(INRIM, ROA)	0.30	0.34	0.37	0.20	0.21	0.20	0.20	0.10	0.40	0.8
CALR(INRIM, SP)	0.30	0.27	0.37	0.20	0.21	0.20	0.20	0.10	0.40	0.8
CALR(OP, PTB)	0.18	0.21	0.37	0.20	0.20	0.28	0.20	0.10	0.40	0.8
CALR(OP, ROA)	0.18	0.34	0.37	0.20	0.21	0.28	0.20	0.10	0.40	0.8
CALR(OP, SP)	0.18	0.27	0.37	0.20	0.21	0.28	0.20	0.10	0.40	0.8
CALR(PTB, ROA)	0.21	0.34	0.37	0.20	0.21	0.20	0.20	0.10	0.40	0.8
CALR(PTB, SP)	0.21	0.27	0.37	0.20	0.21	0.20	0.20	0.10	0.40	0.8
CALR(ROA, SP)	0.34	0.27	0.37	0.21	0.21	0.20	0.20	0.10	0.40	0.8

Triangle calibrations for links with USNO

- Method used: Triangle Closure Analysis.
- Built on the calibration of link USNO-PTB (by means of the USNO portable X-band TWSTFT station, June 2014).
- Used 120 data points (MJD 56816 to 56825) for PTF's and UTC(k) labs.
- Contribution of uncertainties:
  - $\mathbf{u_a}$: Statistical uncertainty from the equation for CALR by triangle closure analysis (0,4 to 0,5 ns).
  - $\mathbf{u_{b1}}$: The uncertainty of CALR(lab, PTB)$_{New}$ as obtained in this campaign (0,8 ns).
  - $\mathbf{u_{b2}}$: Uncertainty of the calibration of link USNO-PTB (0,64 ns).
- Combined uncertainty (square root of the sum of squares) around 1,2 ns in all cases.

Conclusions

- New CALR determined with uncertainties of 1,0 ns and below (1,2 ns for triagle closure method with USNO).
- Similar order to those got in previous campaigns.
- Excellent quality of data collected. Measurement noise at the standard level.
- CALR value for SP differs from the previous value in a significant way. Previous CALR were obtained from TWSTFT-based calibrations. CALR variation justified by equipment changes, station reconfiguration and restoration of time links calibration after satellite and frequency changes.
- Results for the triangular calibration were clearly improved for the small contribution of the uncertainty in the calibration of the link USNO-PTB by a portable X-band TWSTFT station.

Many thanks!