Sub-ns long-haul dissemination of UTC(CH) using White Rabbit in Switzerland

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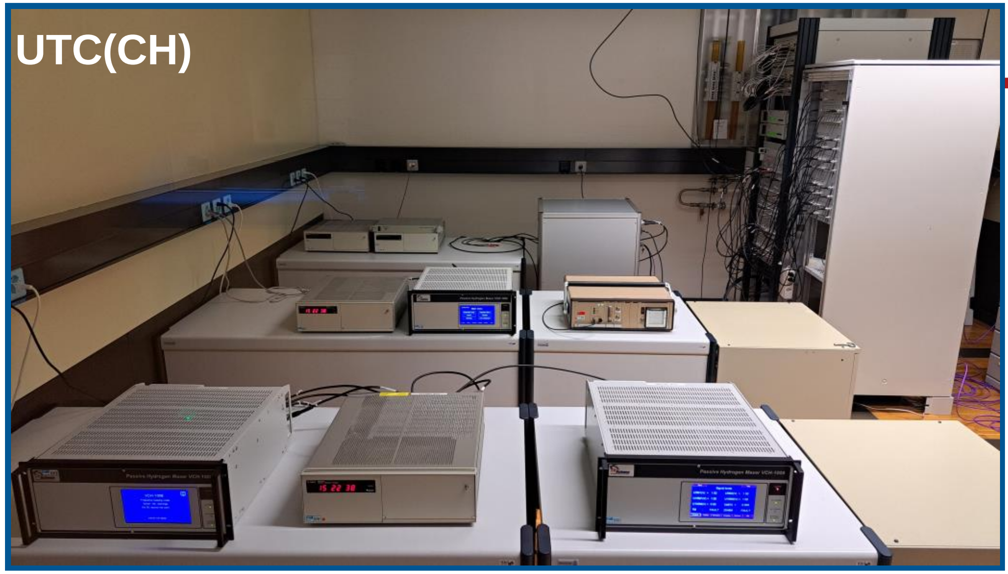
MJD 60390

Overview

1. UTC and UTC(CH)
2. How METAS disseminates time
3. TDIS project: UTC(CH) dissemination with White Rabbit
4. First results
5. Conclusion and outlook

METAS

UTC Coordinated Universal Time



BIPM
Bureau International des Poids et Mesures (Paris)

Monthly Analysis with ALGOS Algorithm

EAL (Echelle Atomique Libre)
stable, uncalibrated time scale

Calibration with Primary and Secondary frequency standards

TAI (Temps Atomique International)

UTC = TAI + N leap seconds

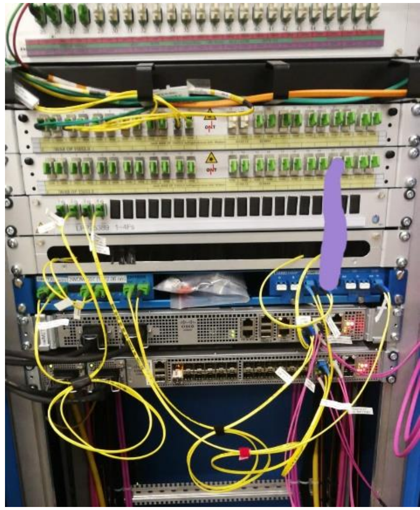
Around 70 countries have their own realization of UTC: **UTC(k)**

UTC(CH) is the Swiss realization of UTC

Only few countries have a physical realization of the SI-second

METAS has a PFS: FoCS-2

Time dissemination and comparison techniques with UTC(CH)



About timescales…

METAS

- Today UTC(CH) is already very accurate and stable
- In the future, it will be even better (new generation of atomic clocks, ...)
- But today, we require:
  - ➢ Improved **dissemination techniques**
    - **New definition of the second**
    - **Support for large scale projects (quantum networks, particle colliders, astronomy…)**
    - **Support for industry (distributed systems, telecom, transport…)**
  - ➢ Variety in techniques to provide **resilience**
    - **Resilience to satellite techniques**
    - **Solution for multi-site time scales**

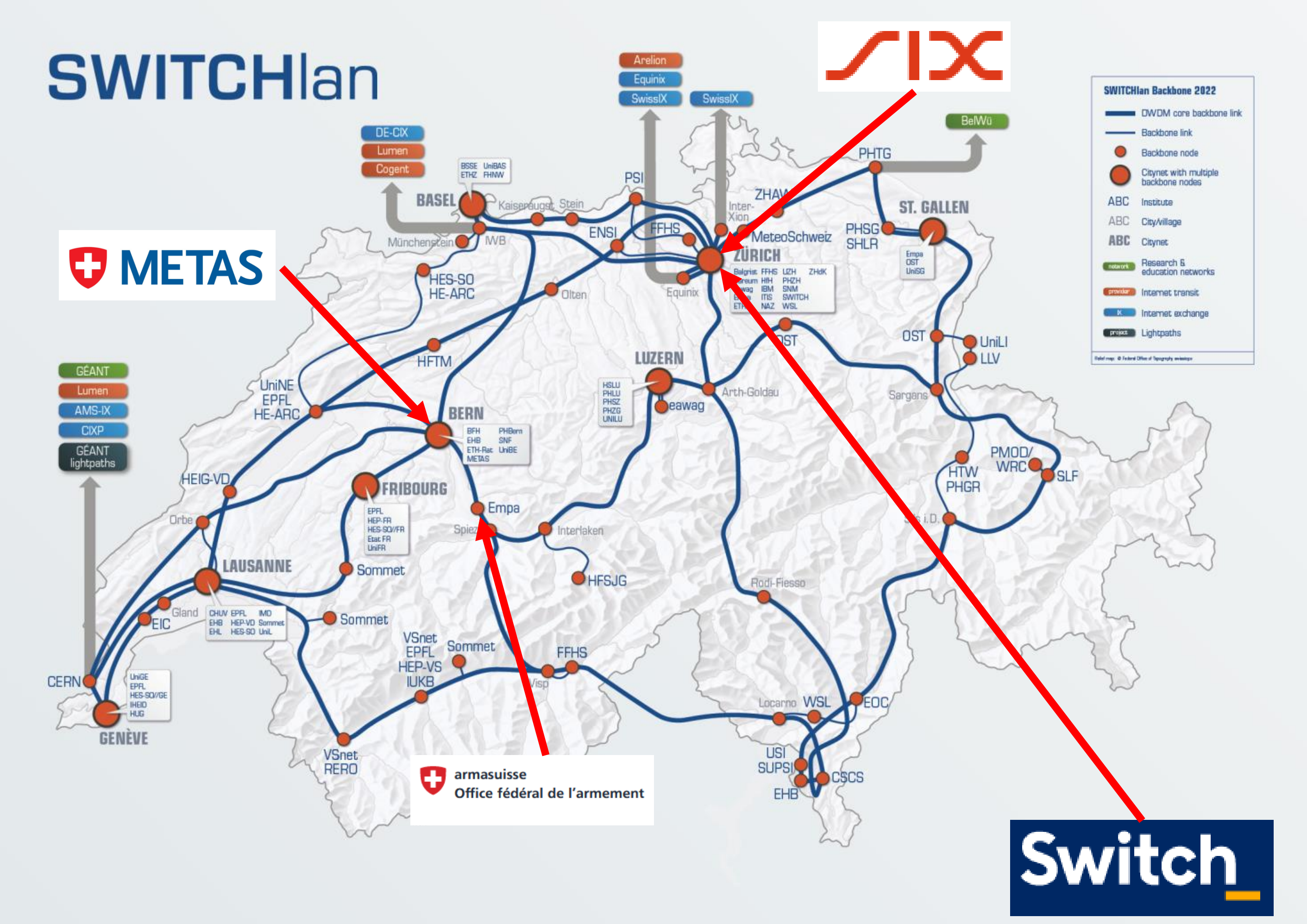
What is the TDIS project?

- TDIS for Time DISsemination
- Main goal: Build a prototype network to demonstrate the feasibility to disseminate of UTC(CH) with sub-ns performance level using WR in an operational data-carrying network
- TDIS is project initiated by METAS with Swiss partners

Partners of the project

- The project is a collaboration between 4 entities:

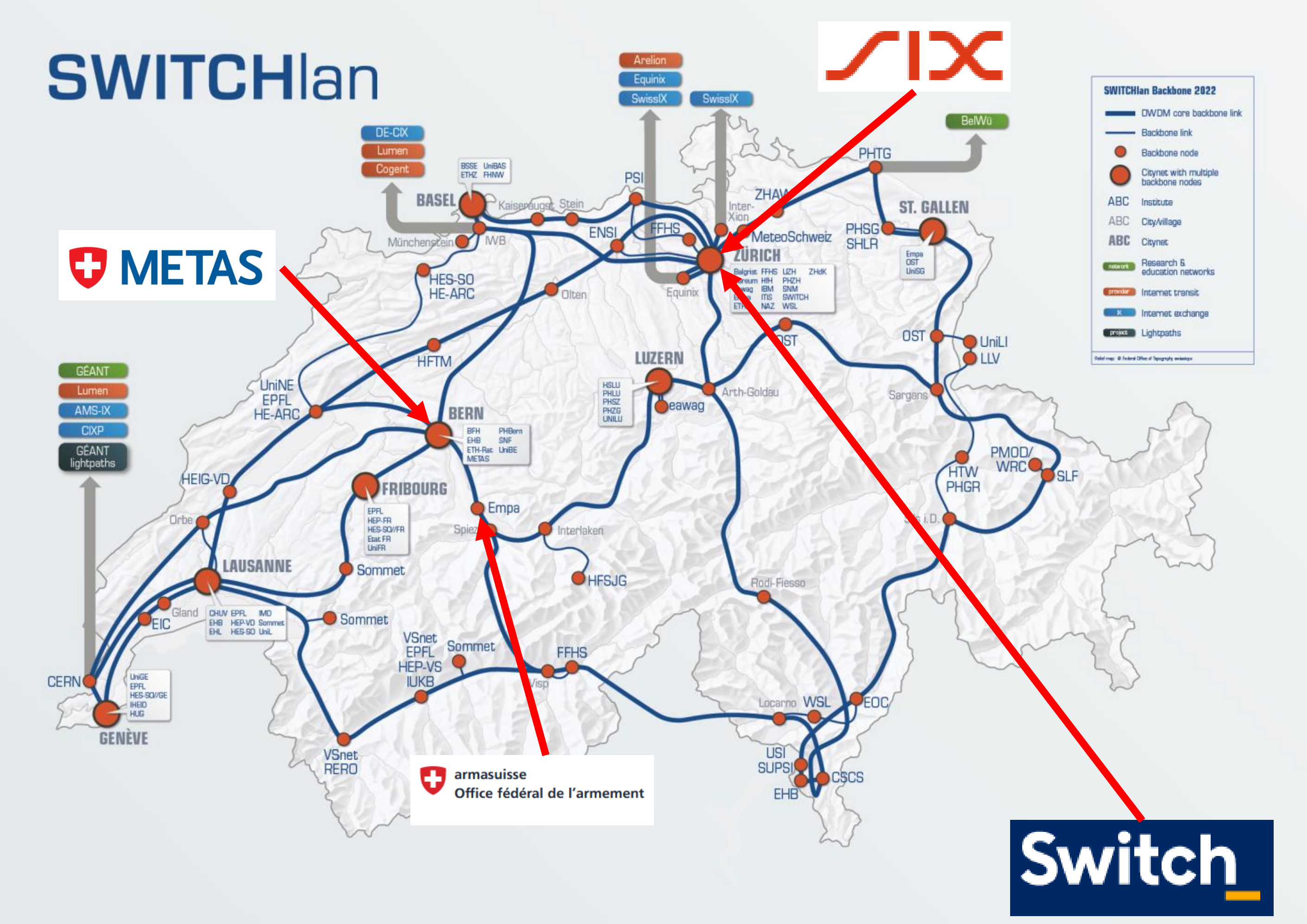
Topology of the network



- **Foundation SWITCH:**
- Connects all universities
- Around 50 points of presence all over Switzerland

- **Which prototype network can we build?**

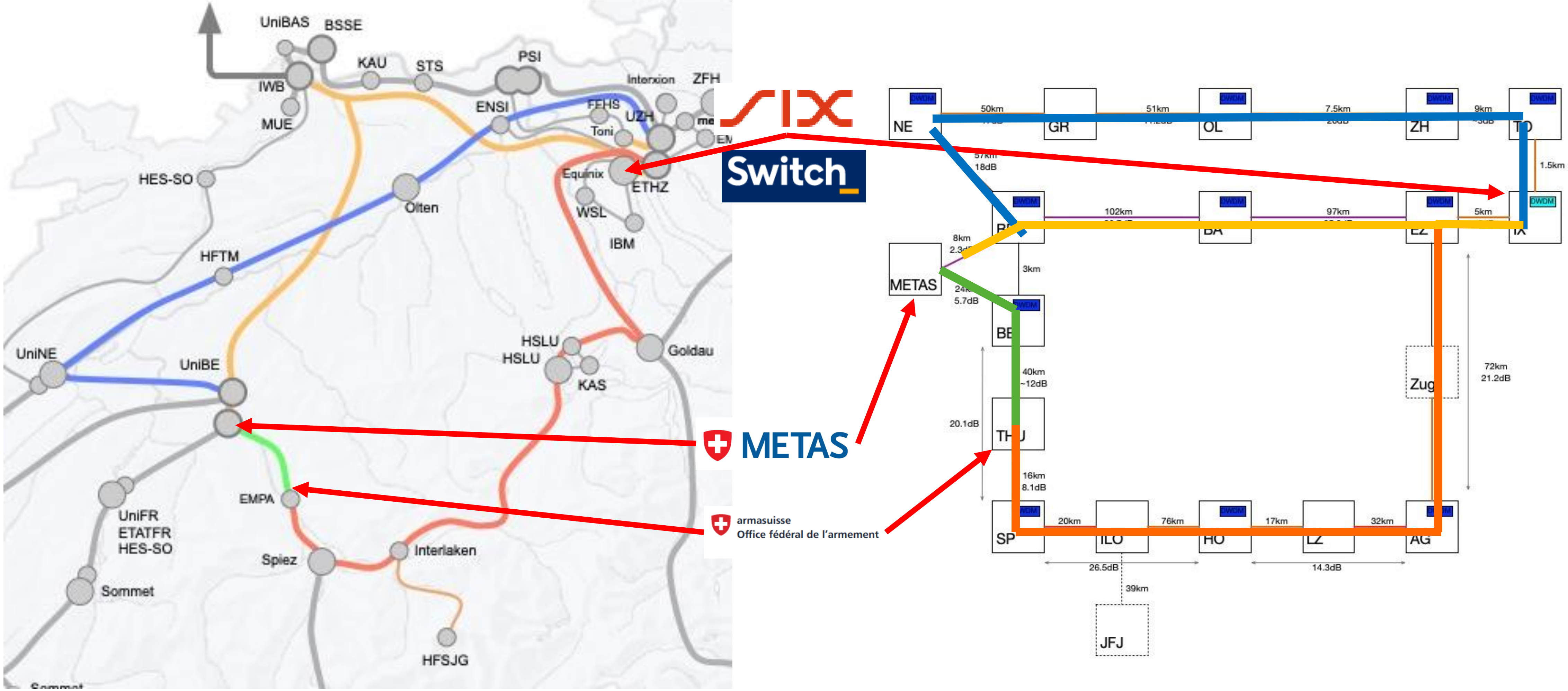
Topology of the network



- **Several criteria:**
  - Connect all participants
  - Ring-network (for redundancy)
  - Lowest complexity as possible

- **We have identified 4 sections:**
  - Green: METAS-Armasuisse
  - Red: Armasuisse-Zurich
  - Orange: METAS-SIX (via Basel)
  - Blue: METAS-SIX (via Neuchâtel)

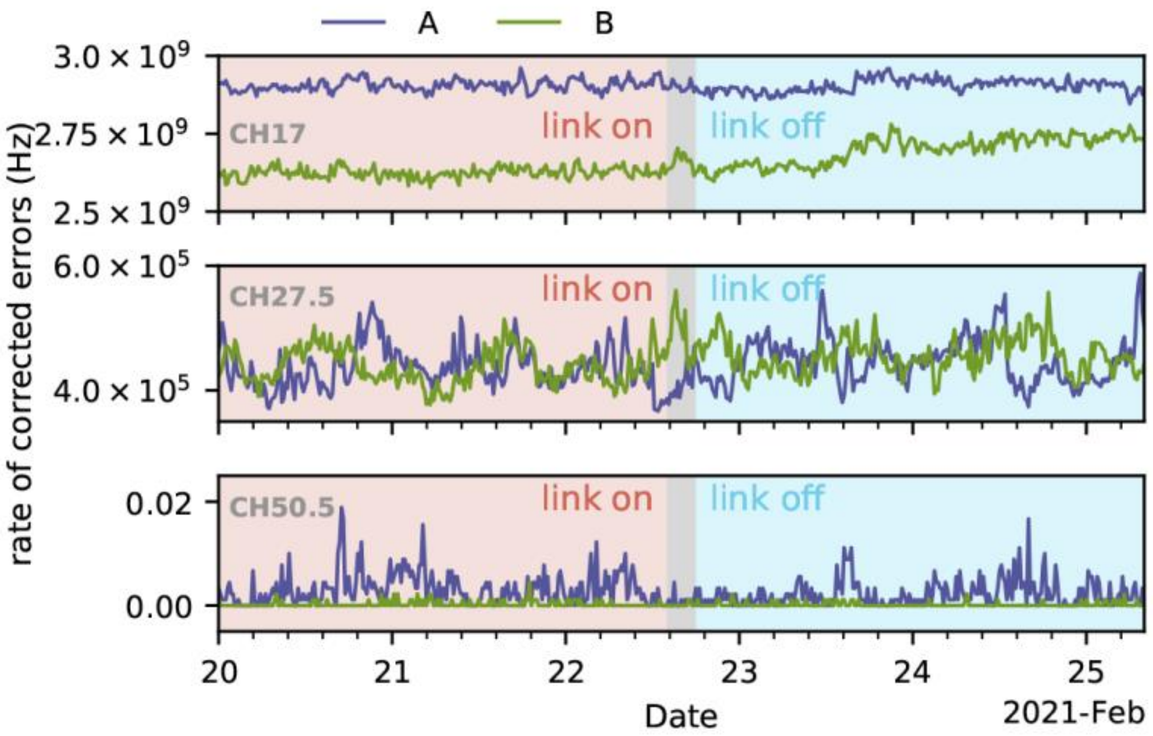
Topology of the network



What wavelength?

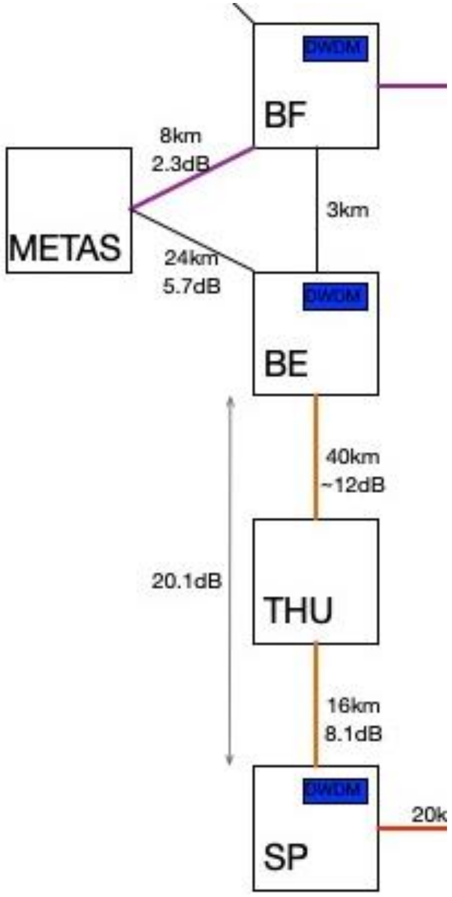
- **SWITCH network is operational with data traffic**
  - ➢ C-band is not available
- **We choose to work in the L-band**
  - ➢ We choose DWDM SFP with
    - ➢ $\lambda(T_X = 1590.411)\, nm$ (L84)
    - ➢ $\lambda(R_X = 1591.255)\, nm$ (L85)
    - ➢ ± 0.1 nm stability
  - ➢ T_X and R_X are separated by 100 GHZ
    - ➢ Low chromatic dispersion shift
- **Is there detrimental crosstalk between the C-band and our metrology application in L-band?**
  - ➢ Husmann D et.al.: SI-traceable frequency dissemination at 1572.06 nm in a stabilized fiber network with ring topology. Vol. 29, No. 16 /2 August 2021 (Optics Express)

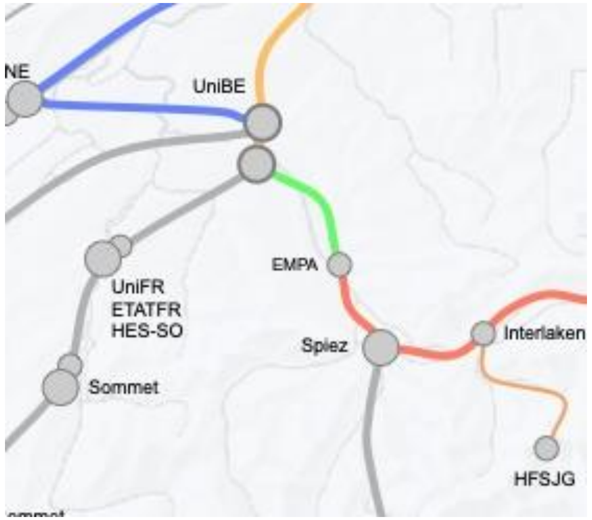
Monitoring of the bit error rate in the fibers shared with our metrological frequency signal



What are the results?

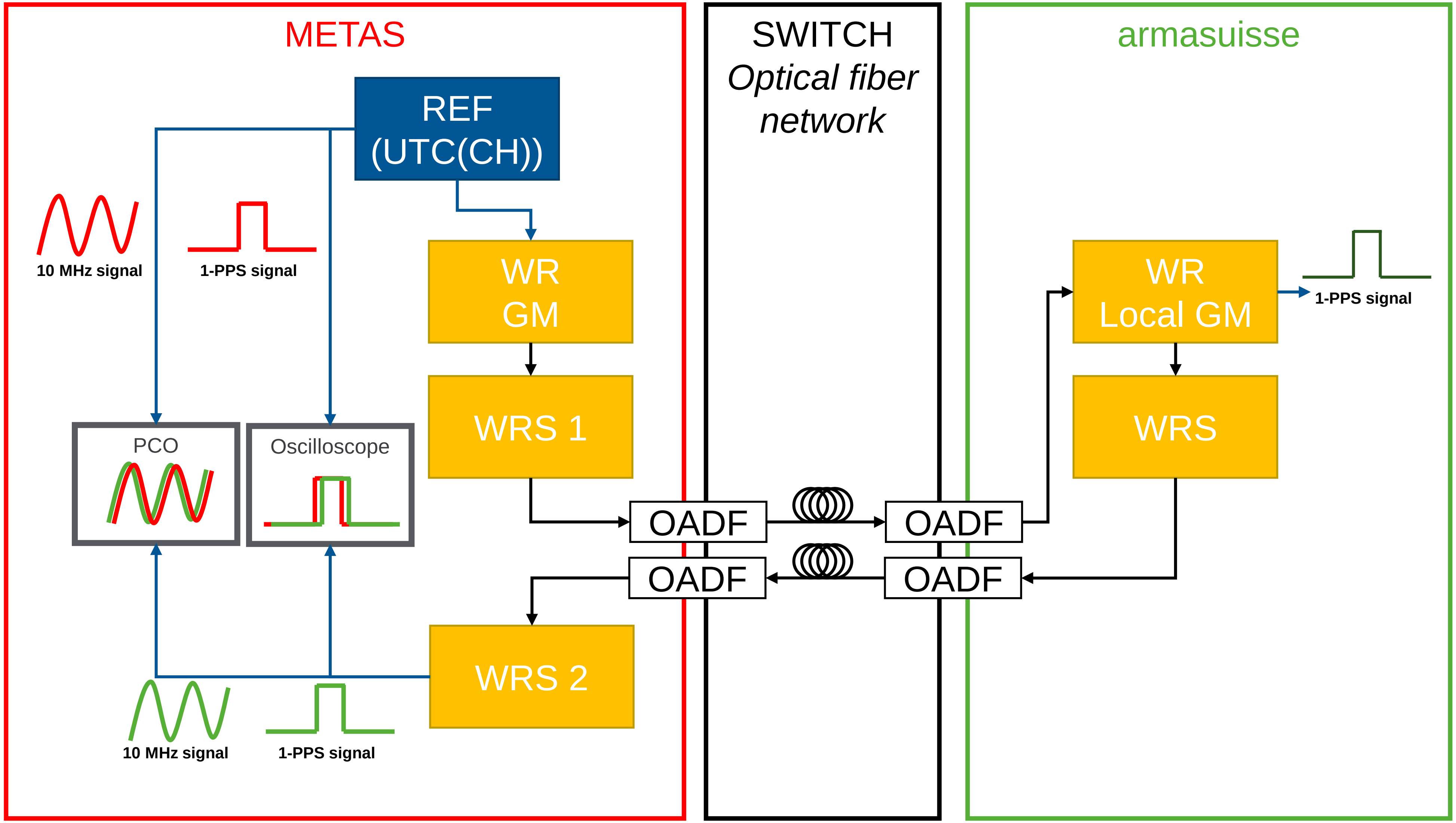
- Results from the METAS-armasuisse link



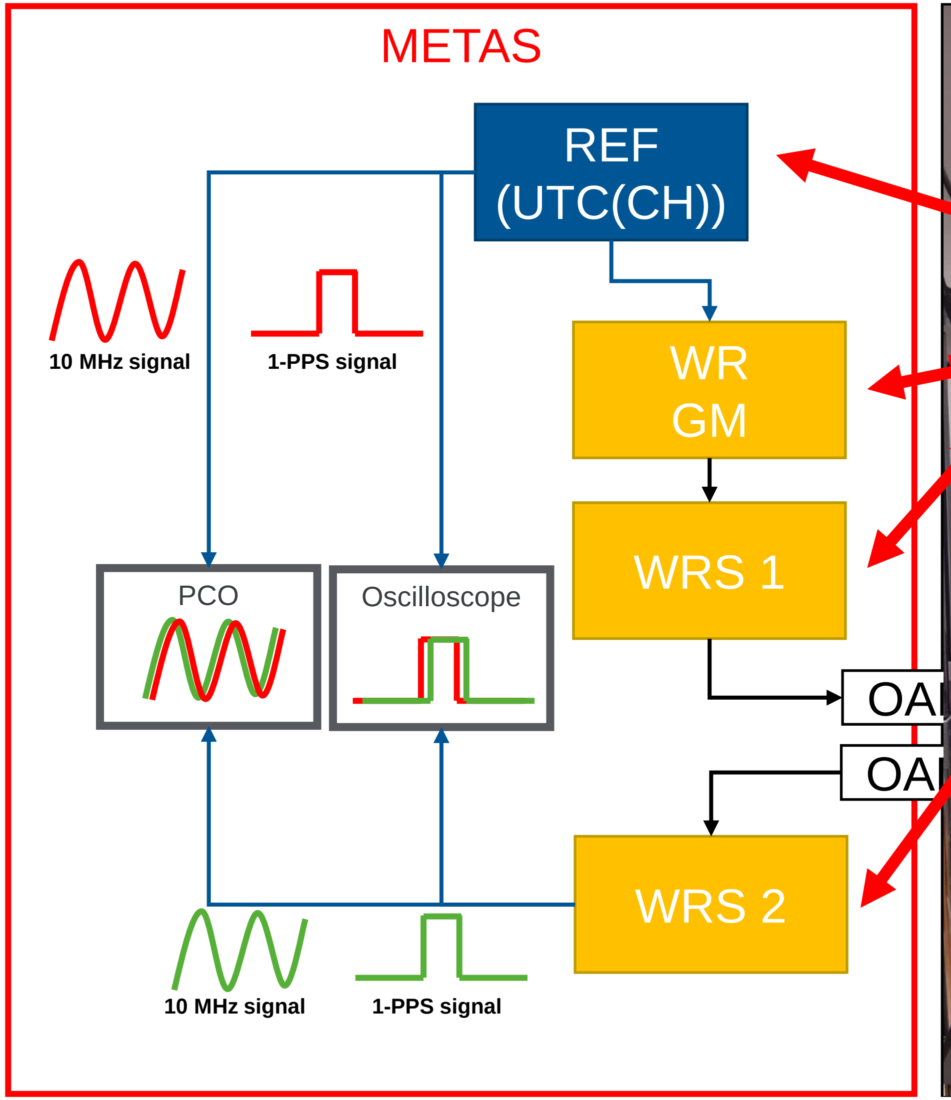


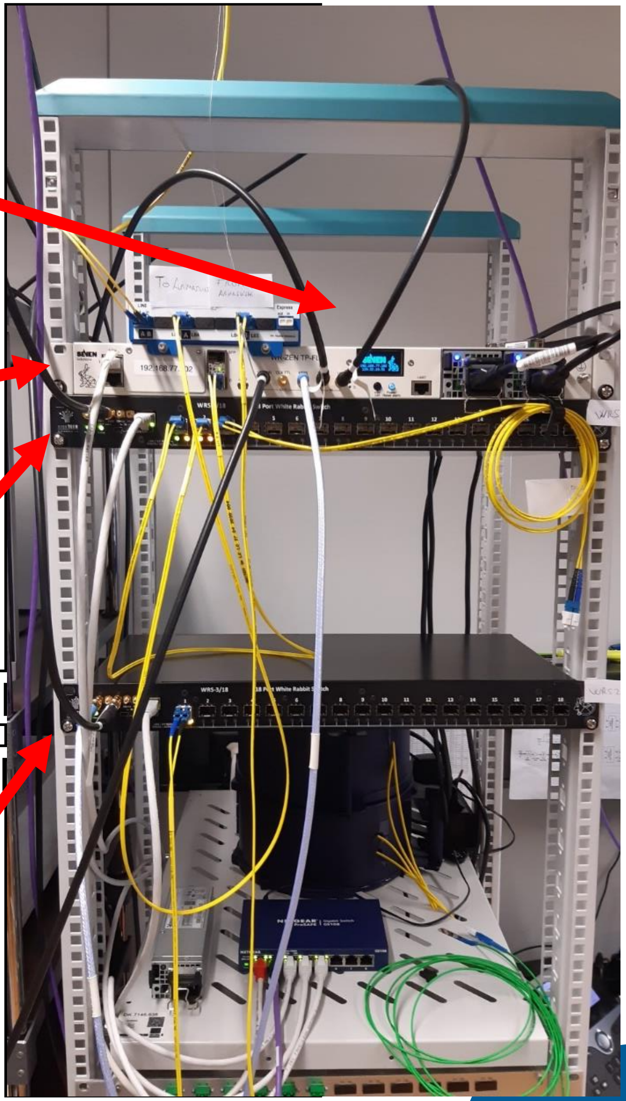
- Some information:
  - ➢ Distance: 24 + 40 = 64 km
  - ➢ No regeneration station
  - ➢ 2 fibers available: we build a small loop
  - ➢ Round trip distance: 2*64 km = 128 km
  - ➢ L-band (around 1590 nm): no data traffic

METAS-Armasuisse link: implementation

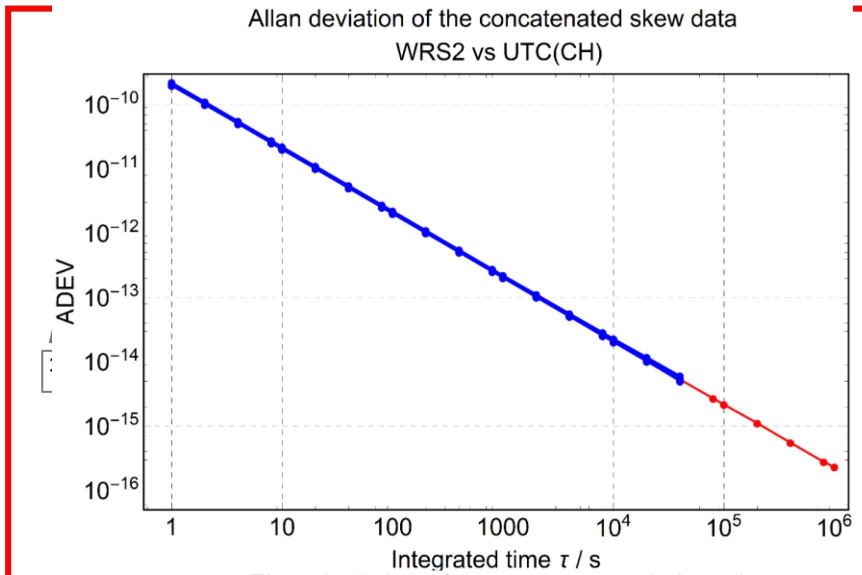


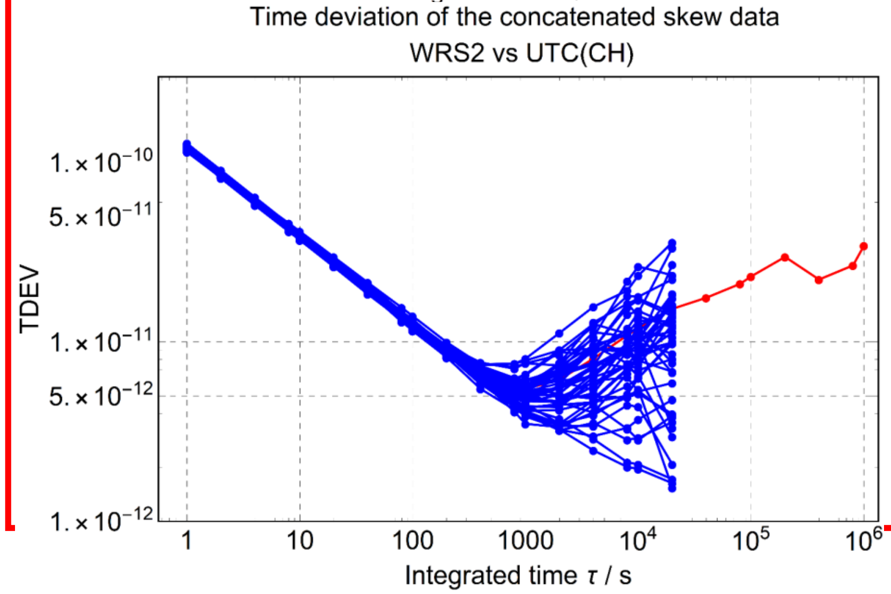
METAS-Armasuisse link: implementation



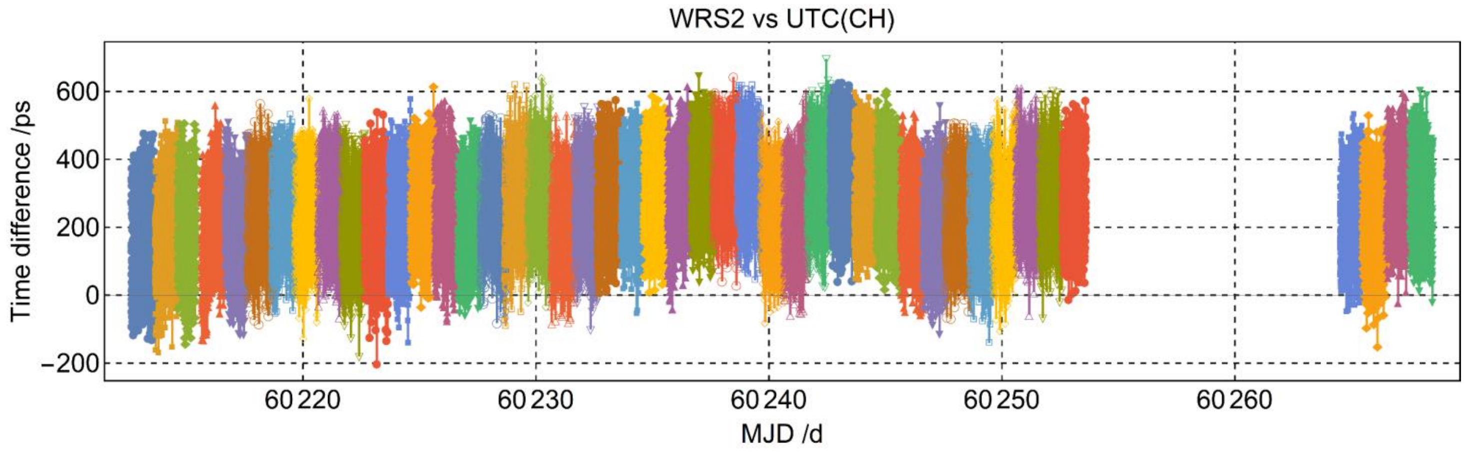


METAS-Armasuisse link: results





- All devices are calibrated
- 45 days of measurement
- 9 days deadtime

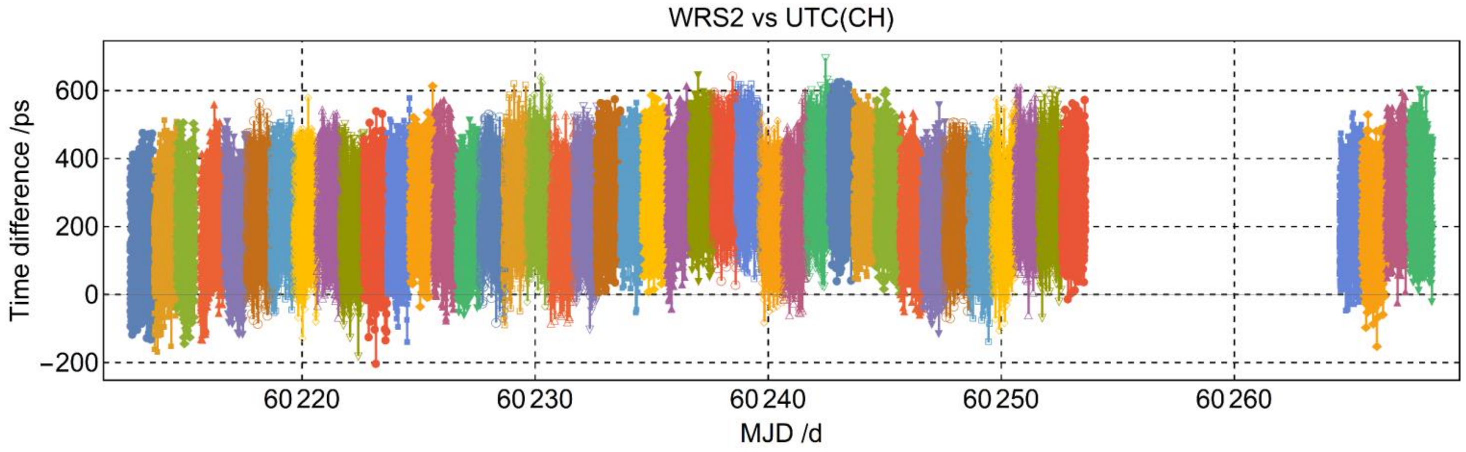


- **There is still a small deviation**
- **No noticeable drift**
- **Statistical uncertainty: 120 ps @ 1s (single shot measurement)**

METAS-Armasuisse link: results

METAS

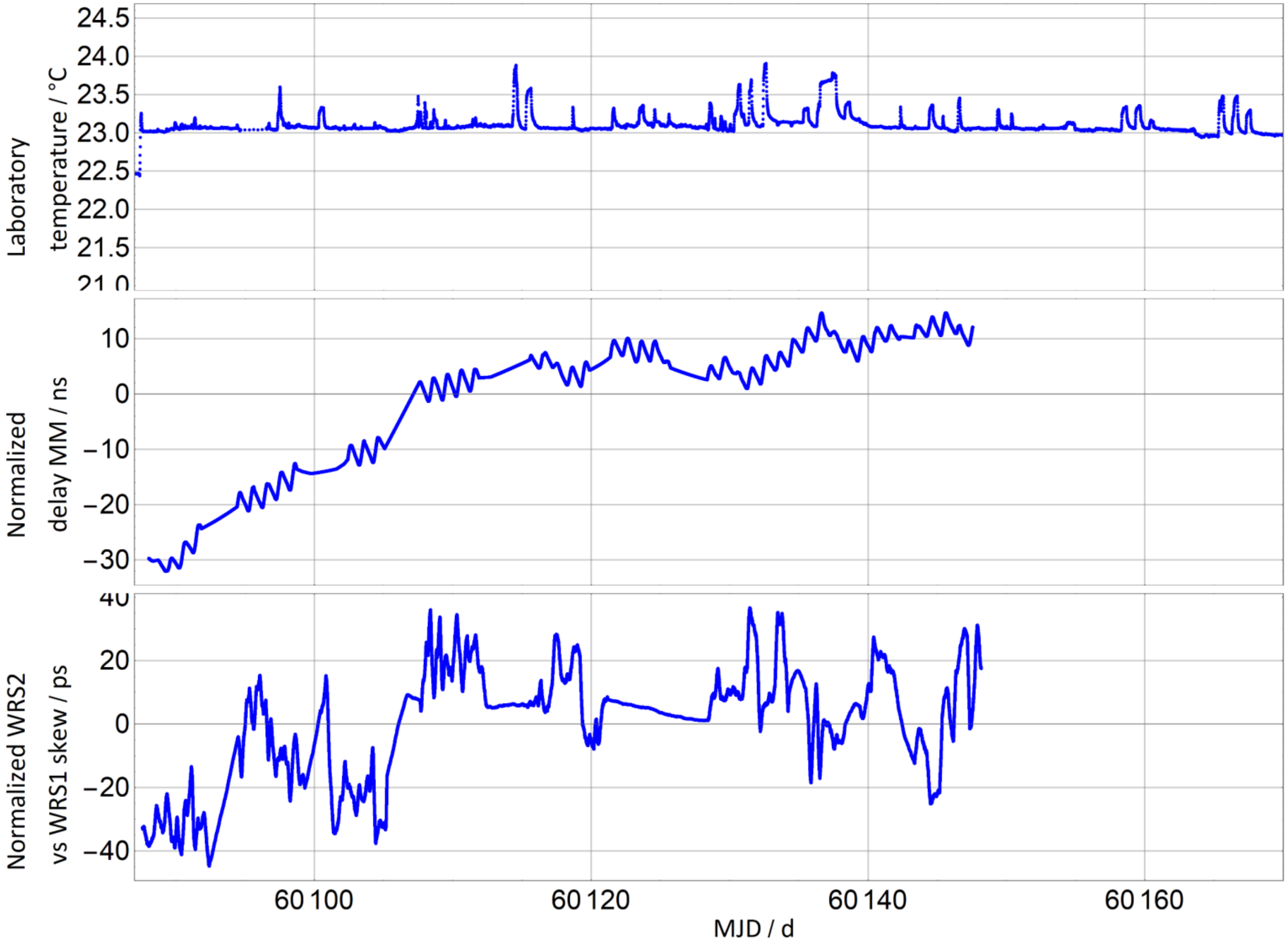
#	location	description	offset (ps)	uncertainty (ps)
1	METAS	UTC(CH) /calibration of the master clock	0	58
2	METAS	Coaxial cable KA-KB#1	233800	100
3	METAS	WR Zen TP FL (Slave + Master ports + GM offset)		38
4	METAS	Link between 2 WR devices / calibration of the α value / here the fiber is short (< 2m) so no uncertaintey	0	0
5	METAS	WRS (Master + Slave ports)		21
6	METAS	Fiber		0
7	METAS	OADF / uncertainty is the same as a WR device as the measurement protocol is quite the same		15
8	Outside	Calibration α value		100
9	Customer	OADF		15
10	Customer	short fiber		0
11	Customer	WR GM (slave + master port)		21
12	Customer	short fiber		0
13	Customer	WRS (slave + master port)		21
14	Customer	short fiber		0
15	Customer	OADF		15
16	Outside	Calibration α value		100
17	METAS	OADF		15
18	METAS	WRS (Slave port)		15
		Total uncertainty of the calibrated link		193
19	/	Statistical uncertainty (depending on the duration of the measurement)	0	120
Total uncertainty of a the dissemination of UTC(CH) to DUT				227



- **Statistical uncertainty: 120 ps @ 1s (single shot measurement)**
- **Uncertainty from uncertainty budget: 193 ps**
- **Total uncertainty (k=1) = 227 ps**

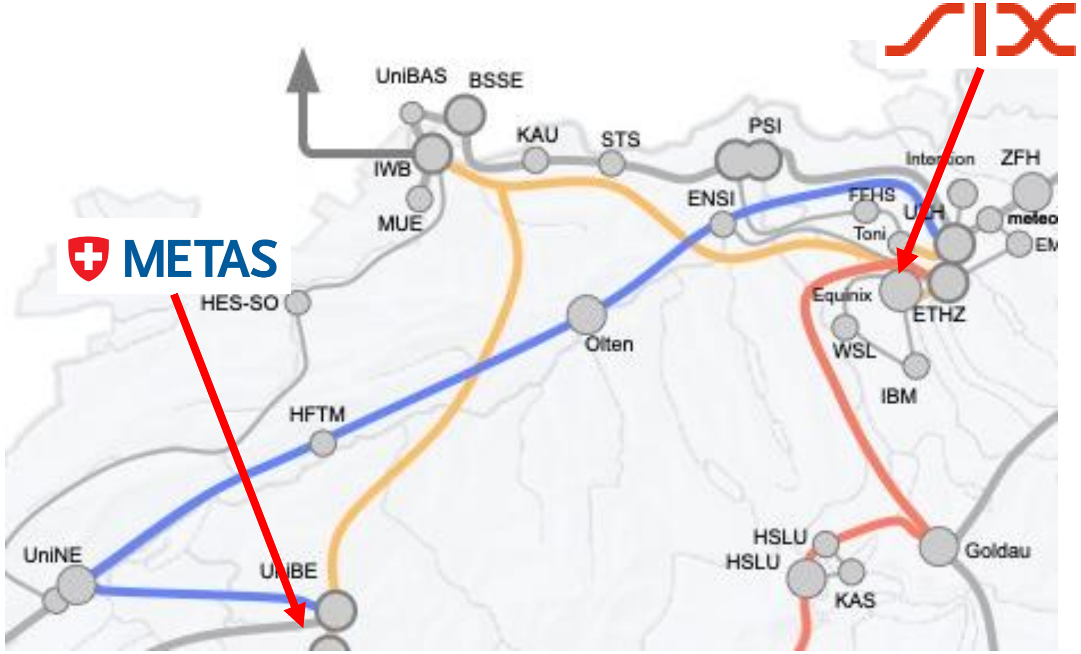
- Main limitation today:
  - Noise from devices
  - Estimation of the α value

Sensitivity to the temperature

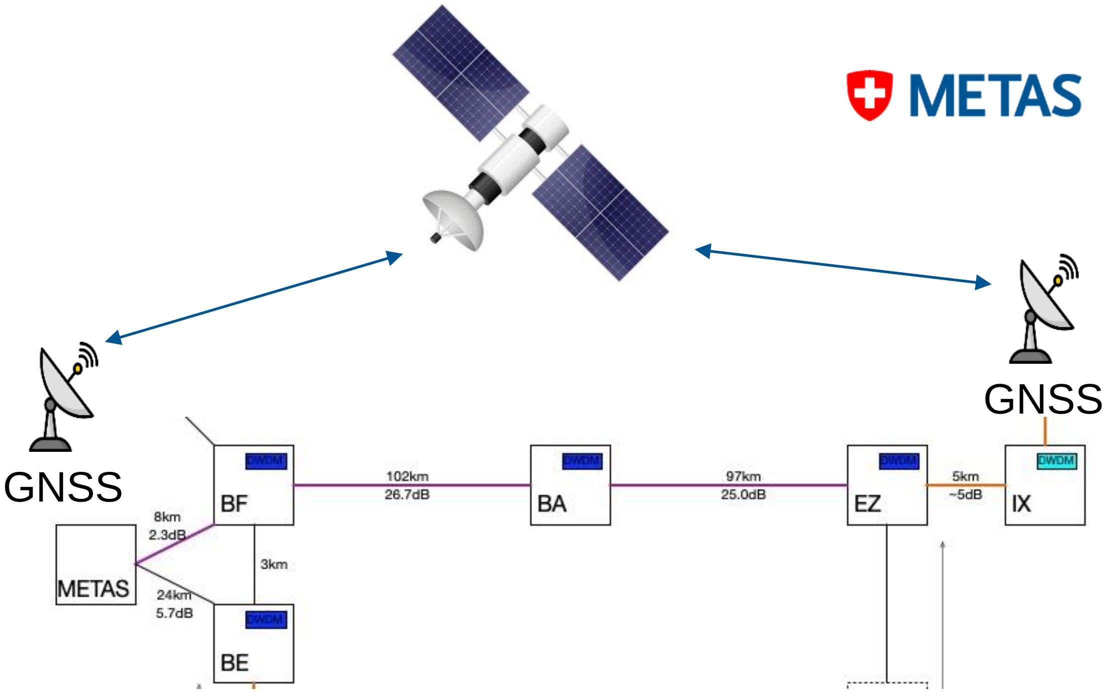


- Lab temperature is very stable
- On the round-trip time delay we clearly see the day/night temperature fluctuations
  - Amplitude around 5 ns
- These fluctuations are not visible on the 1-PPS signals generated by the WRS

Next steps of the project



- Realization of the connection to SIX is in progress
- Loop will be finished by closing the link SIX→METAS via Neuchâtel



- Estimated uncertainty for the dissemination of UTC(CH) to SIX: around 300 ps
- With SIX, we will be able to compare the dissemination via WR with a satellite comparison

Conclusion

- White Rabbit is a good candidate for next gen. time dissemination
- We achieved a dissemination of UTC(CH) with sub-ns precision over more than 100 km
- This project already created awareness for high quality timing dissemination in Swiss industry

Thank you for your attention!

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2024 MARCH 12, 09h UTC

BUREAU INTERNATIONAL DES POIDS ET MESURES
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METAS

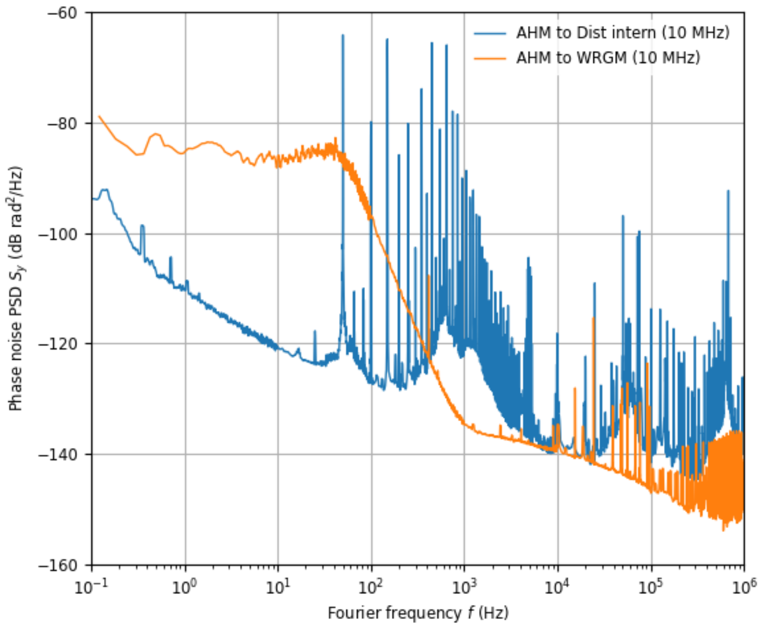
The contents of the sections of BIPM Circular T are fully described in the document "Explanatory supplement to BIPM Circular T"
available at https://webtai.bipm.org/ftp/pub/tai/other-products/notes/explanatory_supplement_v0.6.pdf

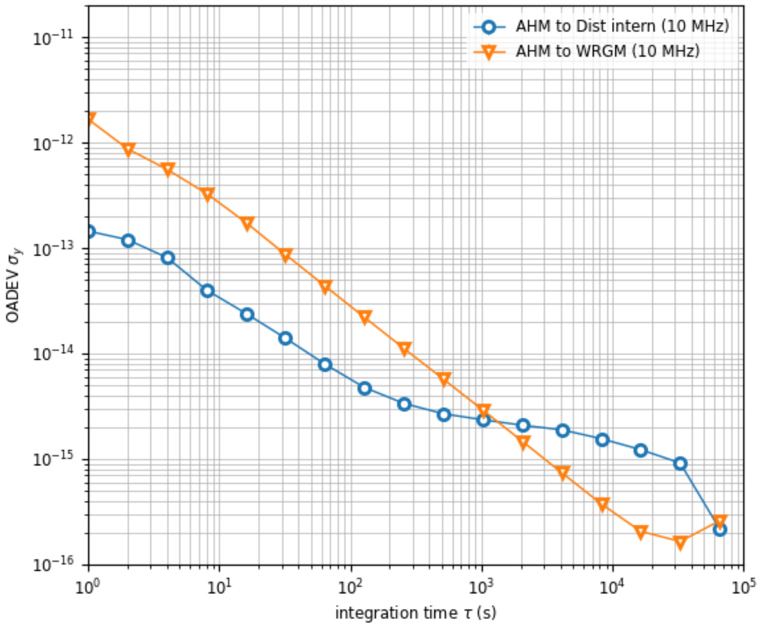
1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties.
From 2017 January 1, 0h UTC, TAI-UTC = 37 s.

Date 2024 0h UTC	JAN 30	FEB 4	FEB 9	FEB 14	FEB 19	FEB 24	FEB 29	Uncertainty/ns			Notes
MJD	60339	60344	60349	60354	60359	60364	60369	uA	uB	u	
Laboratory k	[UTC-UTC(k)]/ns										
AGGO (La Plata)	782.2	778.6	769.9	759.1	740.5	738.4	752.2	0.7	3.0	3.1	
AOS (Borowiec)	-6.8	-6.8	-6.7	-6.5	-6.9	-7.1	-7.7	0.3	3.5	3.5	
APL (Laurel)	0.5	-0.8	-1.0	-1.6	0.6	-0.4	-0.8	0.3	19.8	19.8	
AUS (Sydney)	-411.8	-402.9	-408.0	-412.2	-407.1	-392.0	-390.9	0.3	3.0	3.0	
BEV (Wien)	-10.4	-6.2	-0.1	-1.5	-6.2	-6.2	-5.2	0.3	3.0	3.0	
BFKH (Budapest)	9603.3	9652.7	9697.4	9745.3	9787.6	9833.5	9874.2	1.5	20.0	20.1	
BIM (Sofiya)	18789.2	18817.6	18816.7	18860.8	18866.6	18906.5	18945.0	0.3	3.0	3.0	
BIRM (Beijing)	-1.5	-1.8	0.6	5.9	-	0.3	-2.9	0.3	3.4	3.4	
BY (Minsk)	-0.6	0.3	0.3	-0.7	-1.1	-2.2	-2.4	1.5	3.1	3.4	
CAO (Cagliari)	-10622.4	-10737.1	-10853.8	-10968.6	-11090.9	-11210.0	-11317.1	1.5	20.0	20.1	
CH (Bern-Wabern)	2.2	2.2	2.3	2.2	2.4	-0.7	-3.3	0.5	1.9	1.9	
CNES (Toulouse)	-2.4	-1.5	0.6	-0.5	-4.2	-5.5	-2.6	0.3	3.0	3.0	
CNM (Queretaro)	-1.9	-1.7	1.4	1.8	1.0	-1.5	-2.7	2.0	4.3	4.7	
CNMP (Panama)	-0.2	-2.7	-	-	-	-12.5	2.3	0.3	5.5	5.5	
DFM (Horsholm)	-6.2	-7.0	-7.6	-8.8	-9.5	-10.5	-10.7	0.3	3.0	3.0	
DFNT (Tunis)	-740.9	-840.1	-948.3	-1054.6	-1131.6	-1214.7	-1312.1	0.7	20.0	20.0	
DLR (Oberpfaffenhofen)	-	-	-	-	-	-	-				
DMDM (Belgrade)	14.4	9.7	11.3	13.3	25.4	6.4	-7.7	0.3	3.9	3.9	
DTAG (Frankfurt/M)	17.4	22.5	24.2	24.6	26.7	30.0	30.9	0.3	3.3	3.3	
ESA (Noordwijk)	-1.1	-1.5	-1.5	-2.0	-1.4	-0.8	-1.1	0.3	2.9	3.0	

BONUS

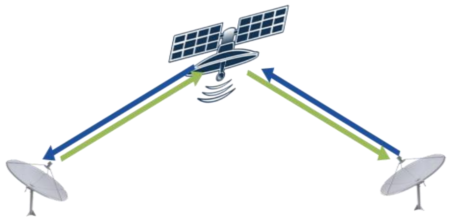
- WR may also be used in METAS to disseminate Time (1-PPS) and Frequency (10 MHz) signals
- Comparison between actual distribution (blue) and WR (Orange)



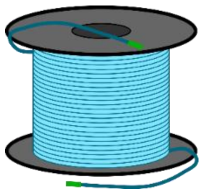


State of the art

- **Satellite techniques** (GNSS, TWSTFT)
  - Based on RF (1-12 GHz) frequencies
  - Actual limit $\sim 10^{-16}$, reached after days
  - Actual limit ~1 ns level



BUT with optical fiber networks we can push those limits



- **Optical fiber networks**
  - Based on optical telecom (190 THz) frequencies
  - Limit $\sim 10^{-19}$, reached after hours
  - Limit ~1 ps level
  - Redundancy to satellite techniques
  - New method/protocol (Whi… B, Phase cancellation)

OPEN ACCESS
IOP Publishing | Bureau International des Poids et Mesures — Metrologia
Metrologia 54 (2017) 348–354 — https://doi.org/10.1088/1681-7575/aa65fe

First international comparison of fountain primary frequency standards via a long distance optical fiber link

Time and frequency networks: Situation in Europe

- **Past and current international projects**
  - EMRP NEAT-FT
  - EMPIR OFTEN
  - EMPIR TiFOON
  - Horizon 2020 CLONETS (-DS)
  - EMPIR ROCIT

H. Schnatz: Towards a European fiber network, ESA ACES Workshop, Zürich, June 2017

- **Very long WR links in Italy**

UTC(IT) transferred to Aerospace industry premises over 200 km and 1000 km

Levi et al., IFCS/EFTF 2022

- **In Germany and Poland: ELSTAB timing (for 5G)**

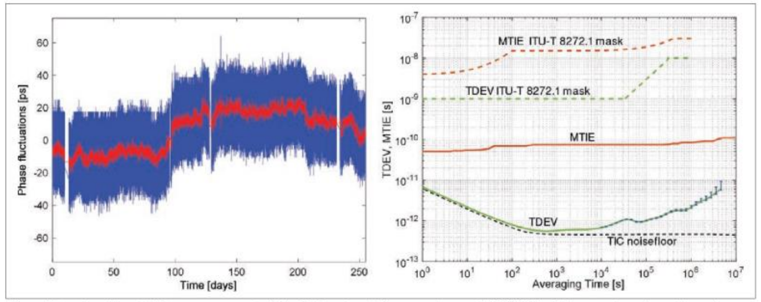


Figure 4. Results of the stability measurements of the OTT system: left: comparison of UTC(PTB) with its copy transferred through three concatenated links; right: calculated TDEV and MTIE compared to relevant ITU masks.

Sliwczynski, et al., IEEE Communications Magazine, 2020

Time and frequency networks: Situation worldwide

- **Clock comparison**

Measuring the frequency of a Sr optical lattice clock using a 120 km coherent optical transfer

F.-L. Hong, M. Musha, M. Takamoto, H. Inaba, S. Yanagimachi, A. Takamizawa, K. Watabe, T. Ikegami, M. Imae, Y. Fujii, M. Amemiya, K. Nakagawa, K. Ueda, and H. Katori

- **Time transfert**

Stabilized Time Transfer via a 1000-km Optical Fiber Link Using High-Precision Delay Compensation System

by Bo Liu [1,2,3], Xinxing Guo [1,2,3], Weicheng Kong [1,2,3], Tao Liu [1,2,3,*], Ruifang Dong [1,2,3] and Shougang Zhang [1,2,3]

1 National Time Service Center (NTSC), Chinese Academy of Sciences, Xi'an 710600, China
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3 Key Laboratory of Time and Frequency Standards, Chinese Academy of Sciences, Xi'an 710600, China
* Author to whom correspondence should be addressed.

Photonics 2022, 9(8), 522; https://doi.org/10.3390/photonics9080522

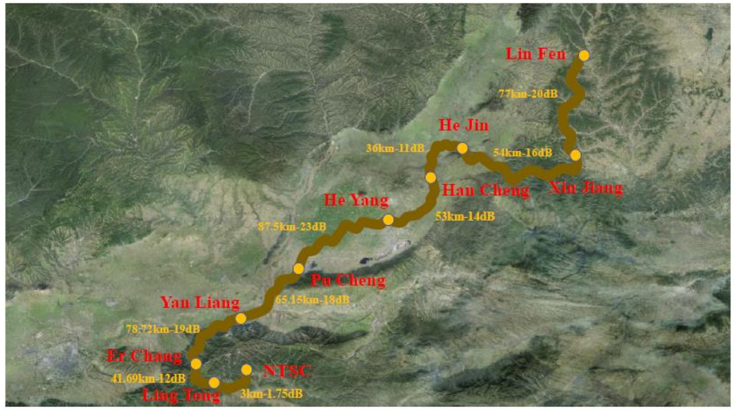
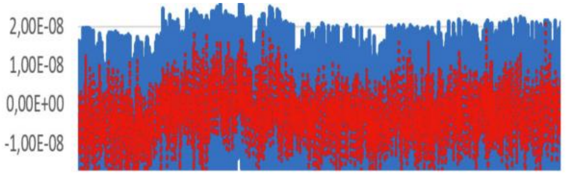


Figure 8. Route of the 988.52-km field optical fiber link.

- **Very long WR links in USA**



White Rabbit makes leap for time over fiber

September 13, 2021 - By Tracy Cozzens   Est. reading time: 5 minutes

Seven Solutions sets new record for long-distance White Rabbit high-accuracy time-over-fiber link

The White Rabbit link has an approximate distance of 1,350 km (840 miles) and was deployed in collaboration with Optiver U.S., a financial company, to connect Chicago and New Jersey trading locations. This link is formed by six long-distance White Rabbit hops using WR-Z16 and WR-ZEN TP devices connected by a combination of DWDM and SyncE-compliant transponders over a public telecommunication fiber network.

Sub-ns accuracy on loop-back