Fiber optic time and frequency transfer then and now

Netnod Meeting 2023

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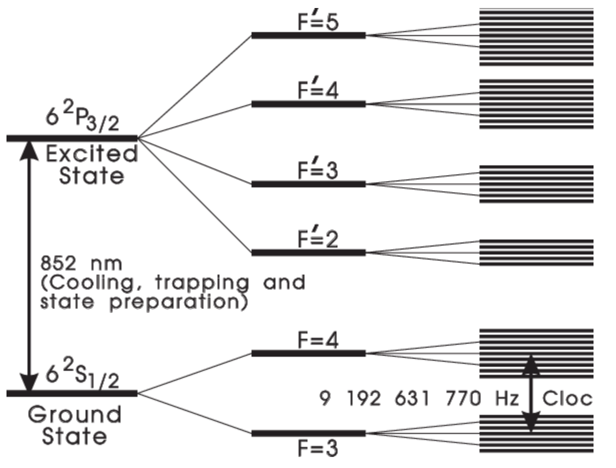
Outline

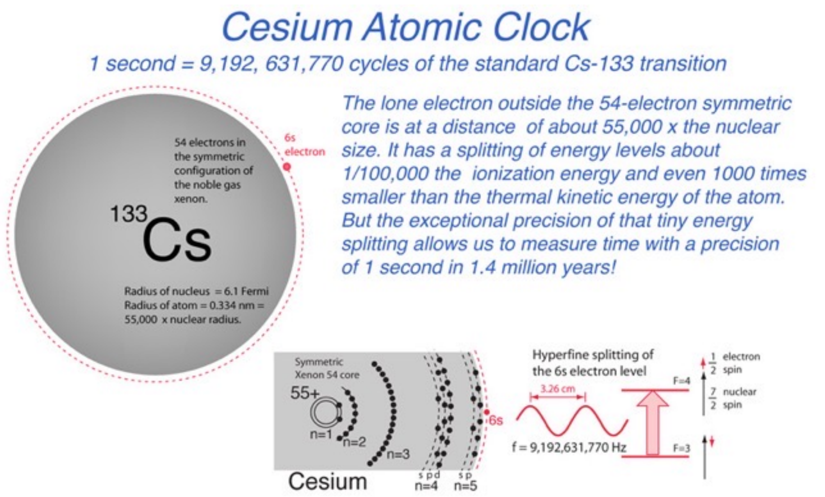
- Clocks
- Calculations
- Fiber-connections and techniques
- Recent experiments in Sweden
- What we are aiming for

Credit to all that I have posted images on the internet that I have used for this presentation

How long is a Second?

- From 1967 to present: *Atomic Second*
  - Based on radiations in the caesium 133 atom
    - Counting periods of electromagnetic radiation locked to an atoms resonant frequency
    - When an atom changes energy level, it either radiates or absorbs energy with a specific frequency
  - 1 second = “the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom”
    - The number of periods was chosen so as to make the atomic second equal to the ephemeris second





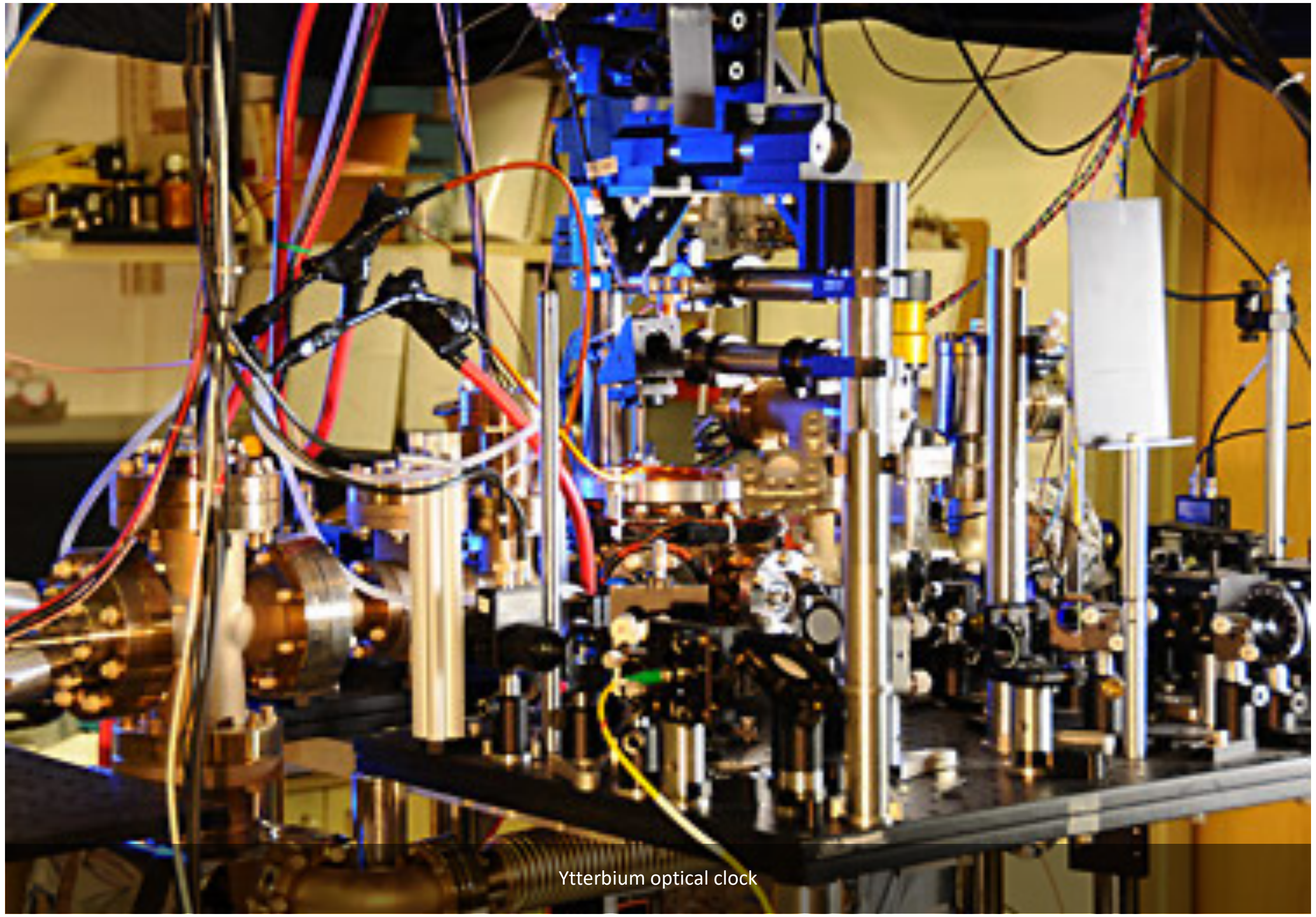
Atomic clocks

Commercial Caesium clock

Commercial Hydrogen maser

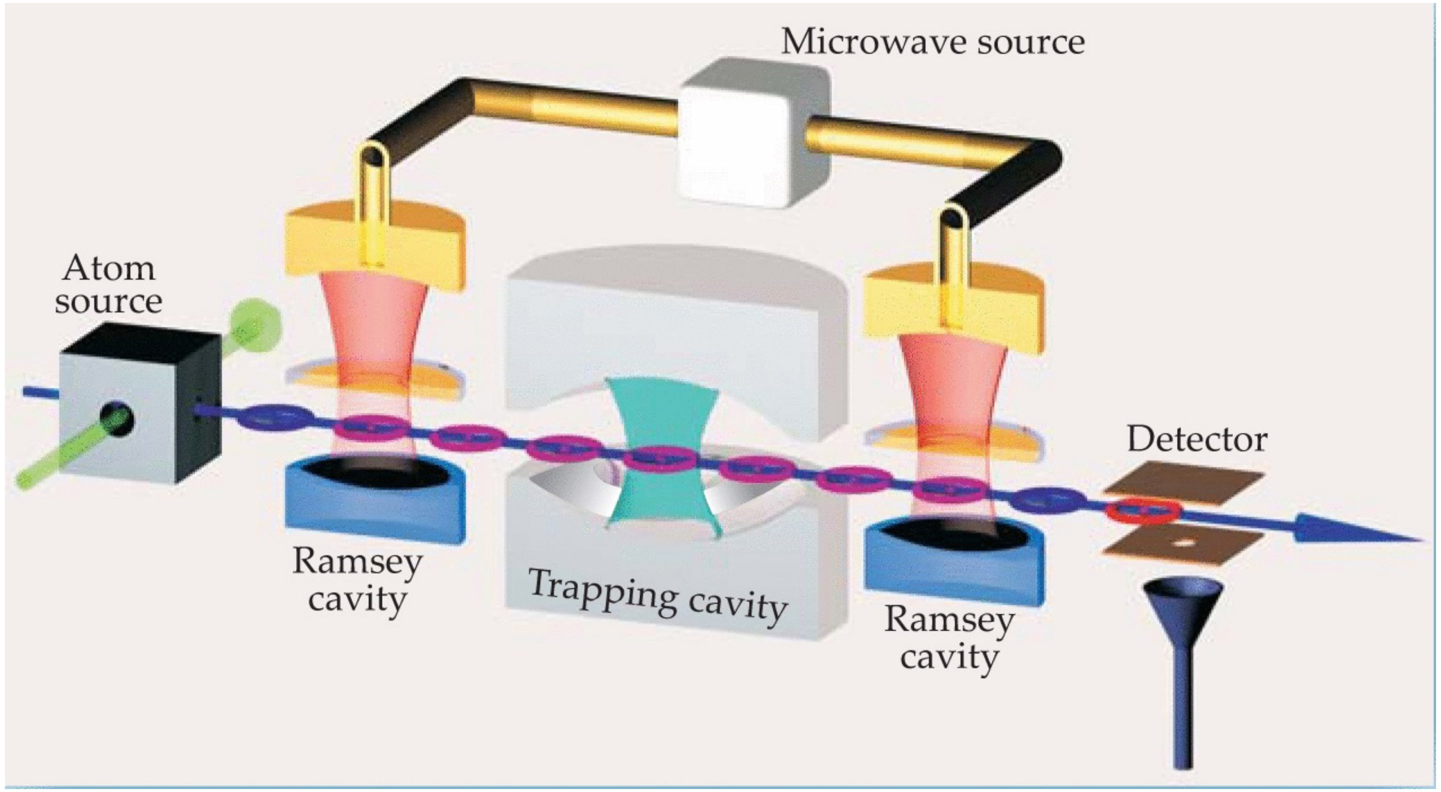
Caesium fountain clock

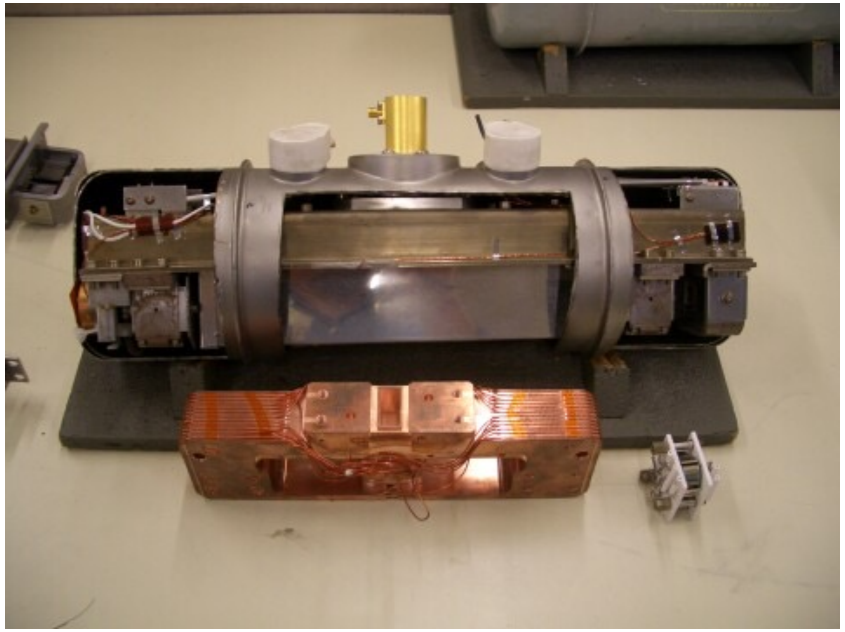
Small Rubidium clock



Ytterbium optical clock

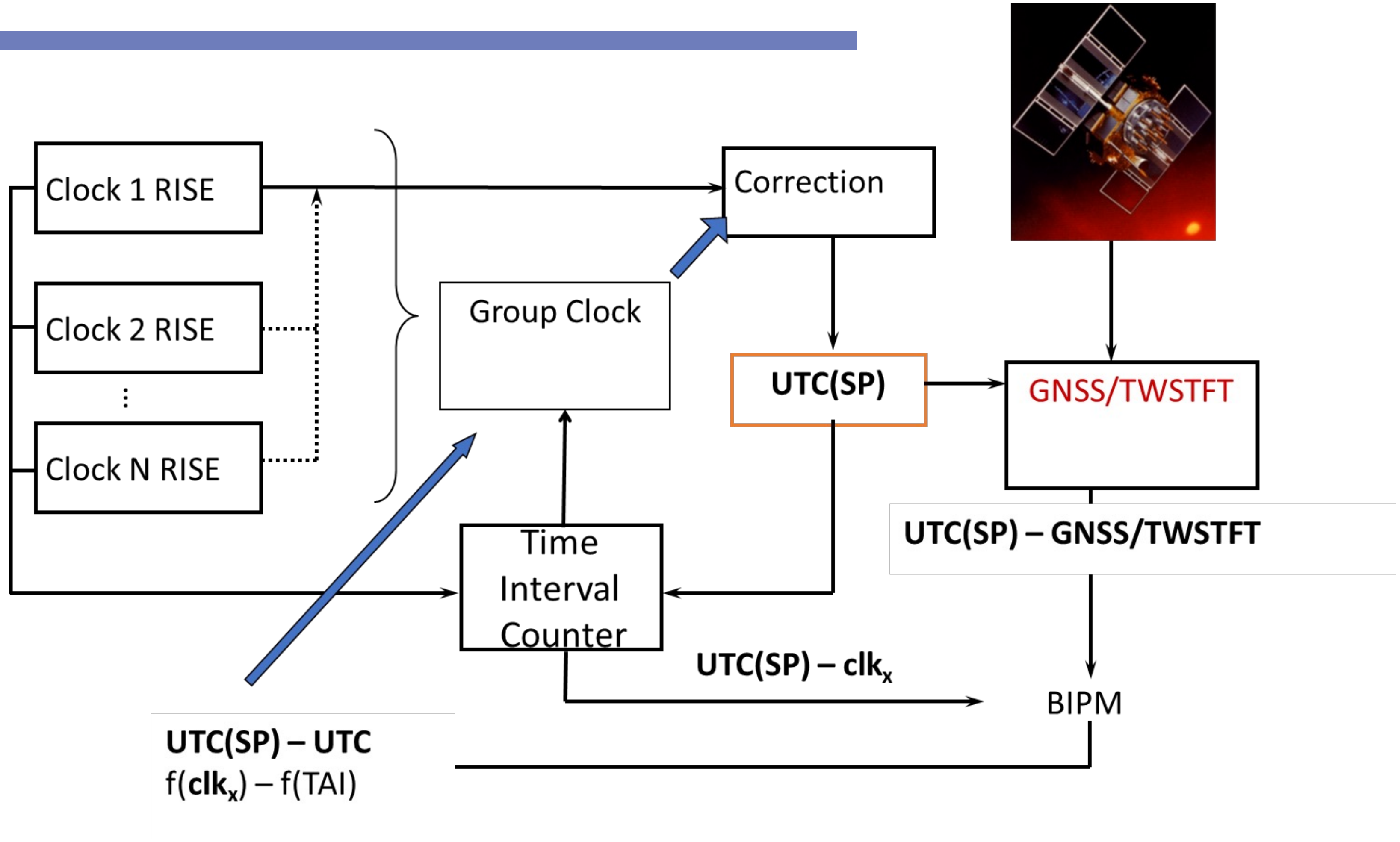
Cesium beam tube





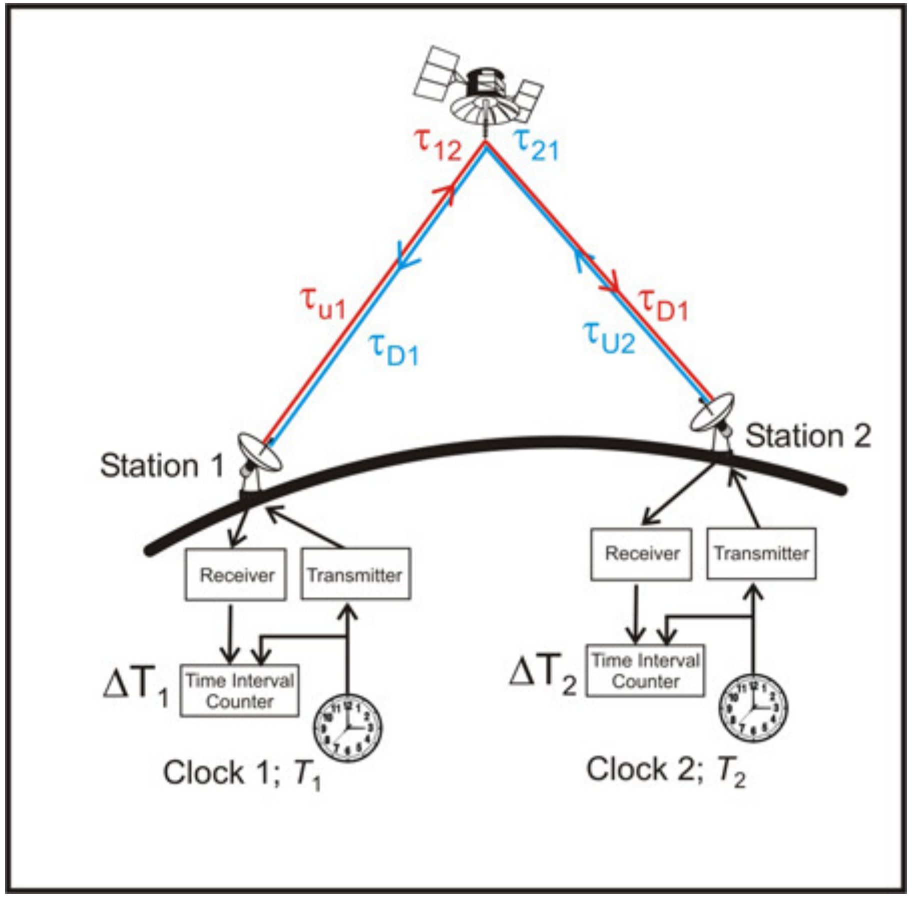
CREDIT
Microchip

Swedish National Time Scale UTC(SP)



Time Links

- To calculate UTC, BIPM relies on time differences between clocks located worldwide
- These differences are calculated by using so called Time Links between institutes
- The Time Links are based on satellite techniques such as GNSS, often called Time Transfer Techniques



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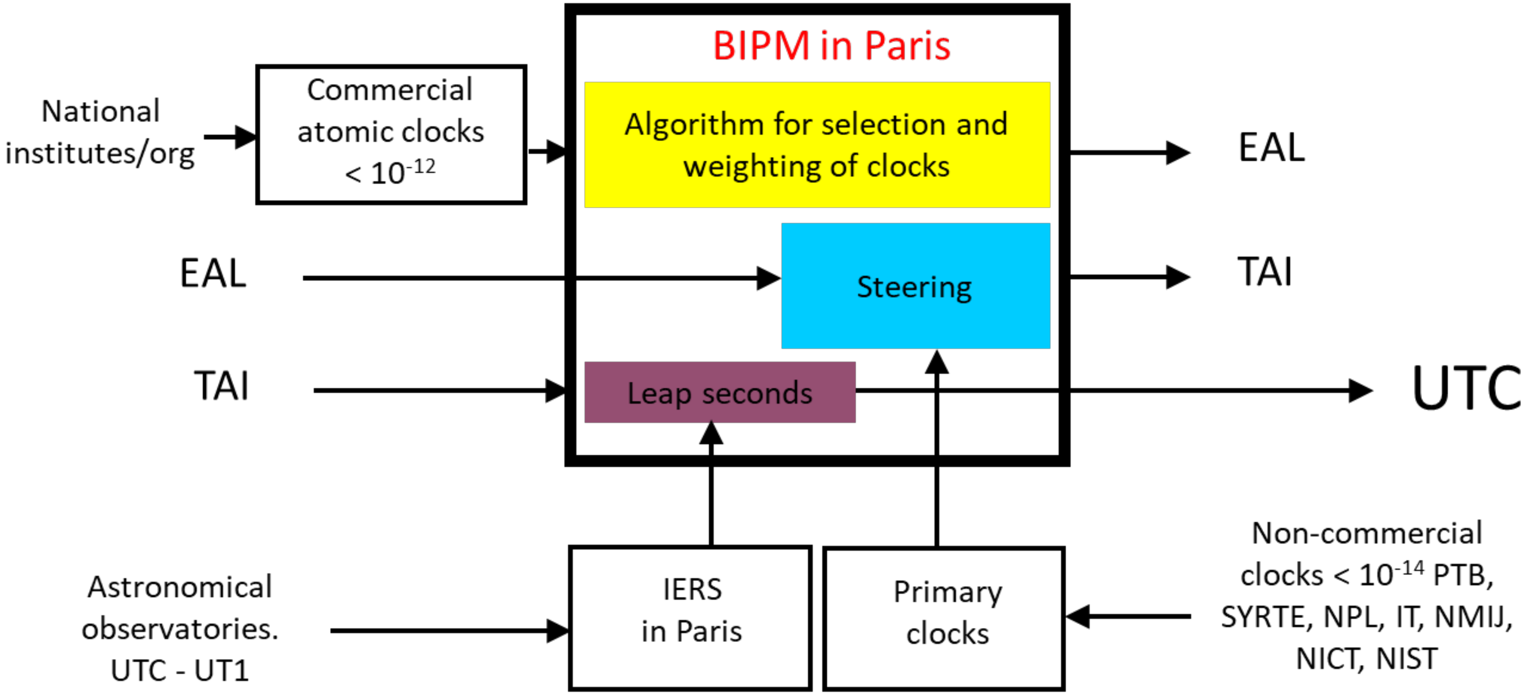
BIPM calculates UTC



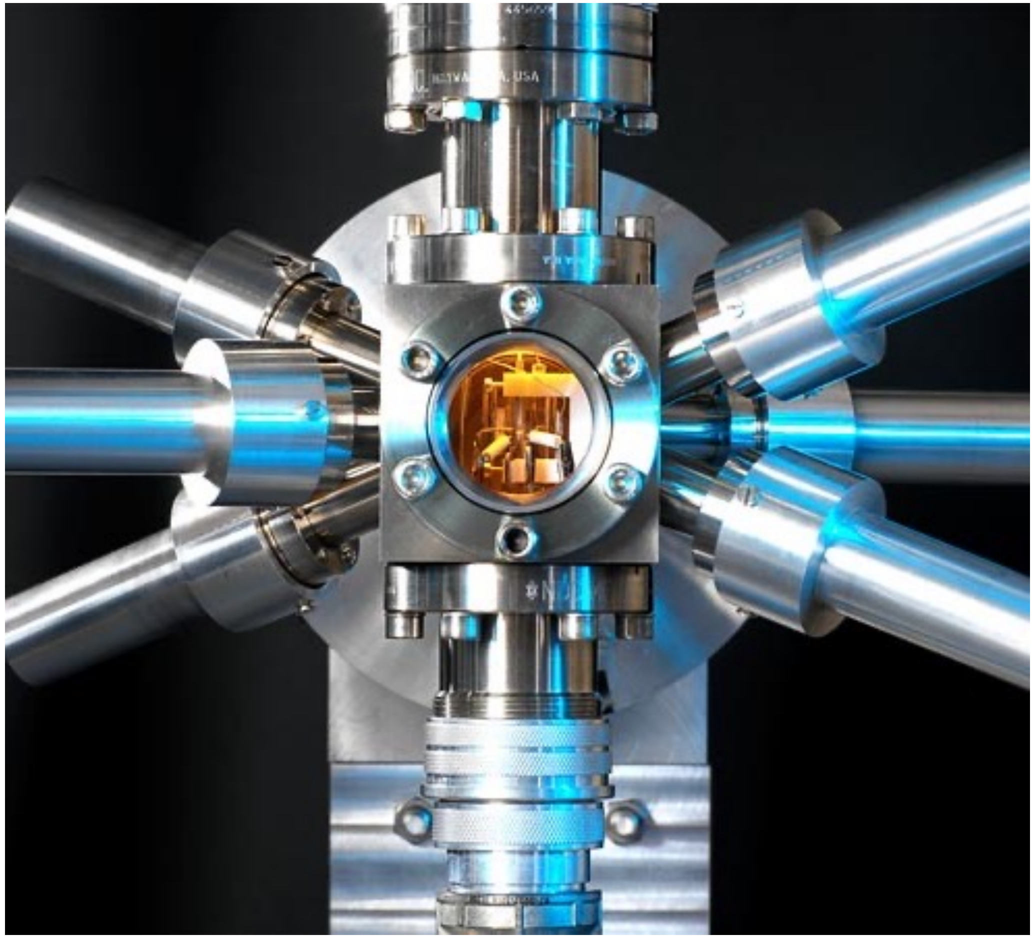
BIPM is the International Bureau of Weights and Measures

IERS is the International Earth Rotation and Reference System Service

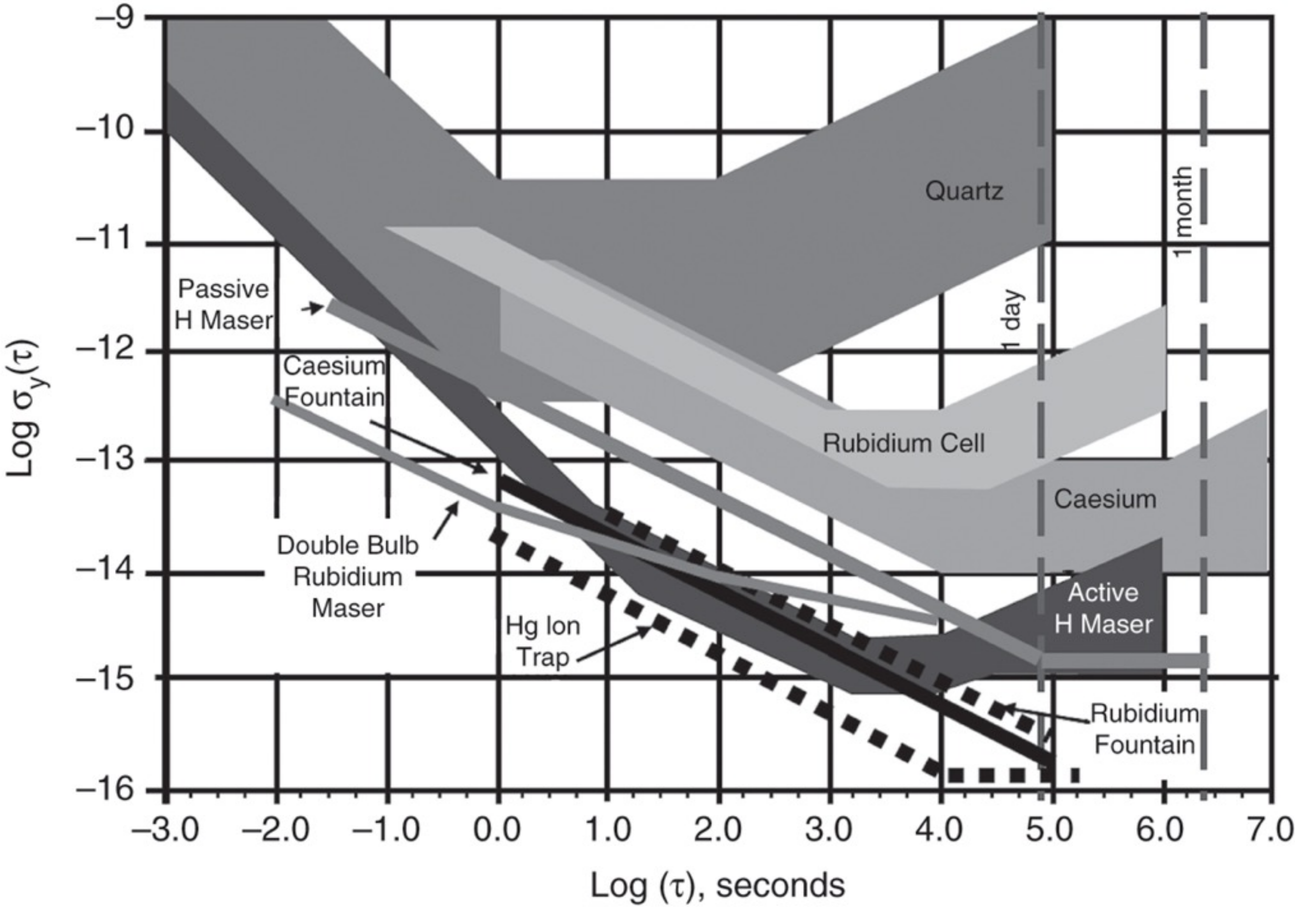
EAL (*É*chelle *A*tomique *L*ibre, free atomic time scale)

Future (optical clocks)

- New atomic clocks with other atoms
  - Energy transitions at 700 THz (blue light)
  - 10,000 times higher precision
  - Must be connected over fiber for maximum performance
- Ongoing research projects in several countries
- Important part of the coming redefinition of the second
- Improves precision measurements in basic research

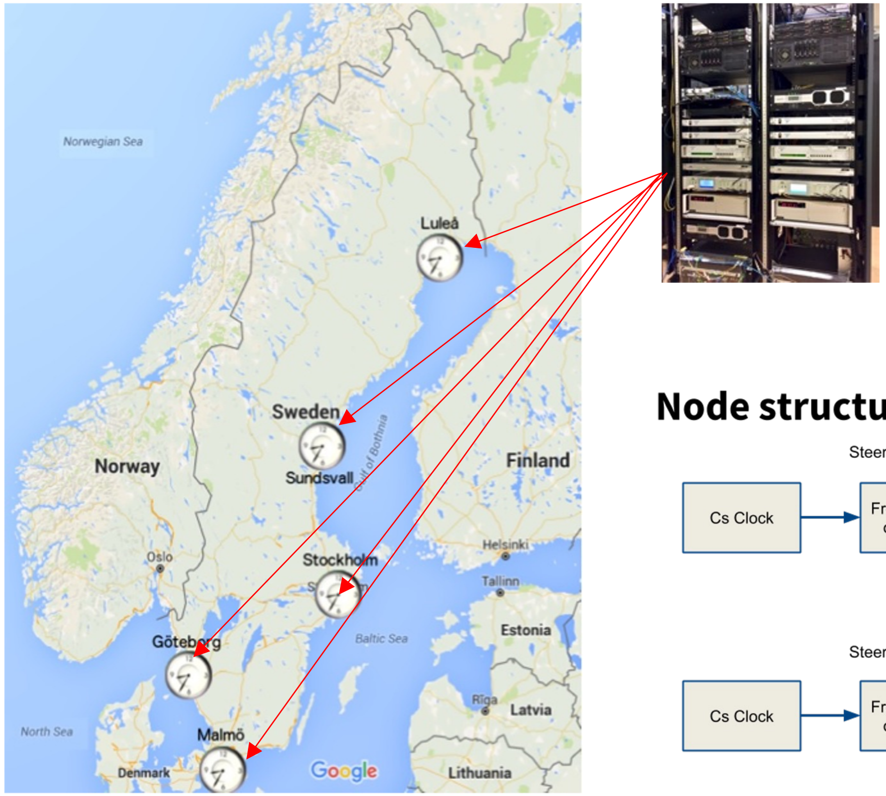


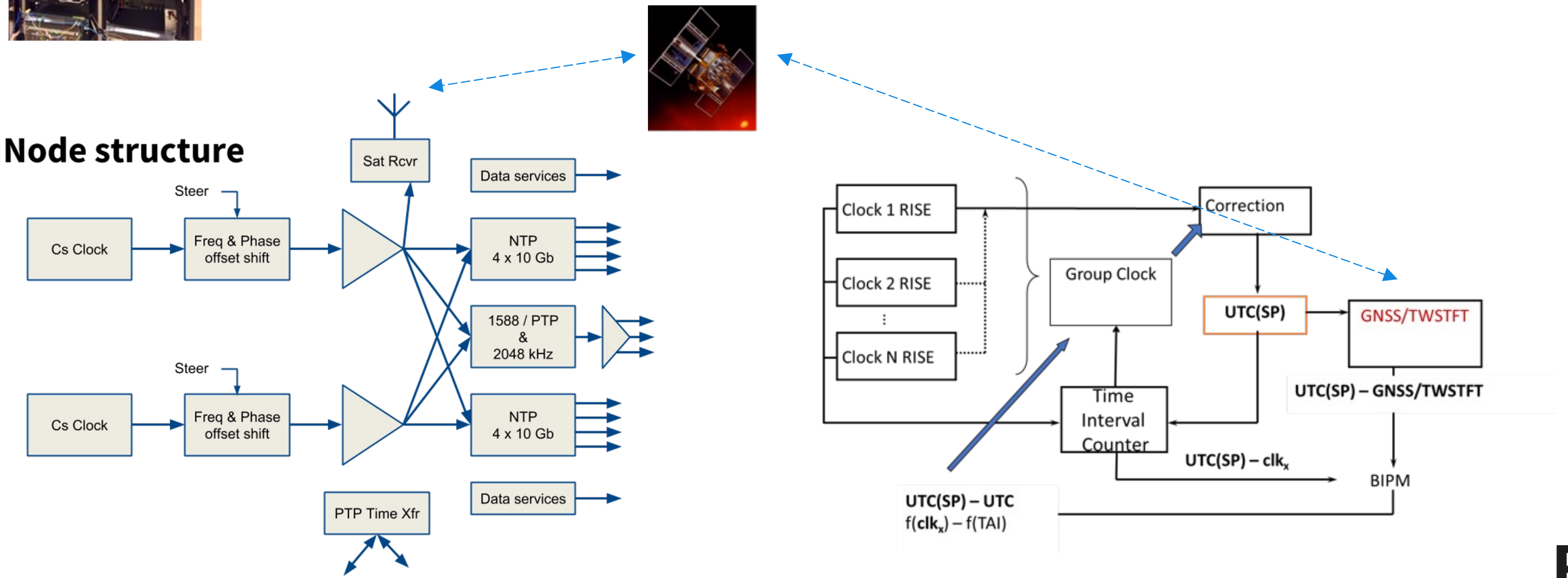
Frequency stability of common atomic clocks



CREDIT
Univeristy of Cambridge

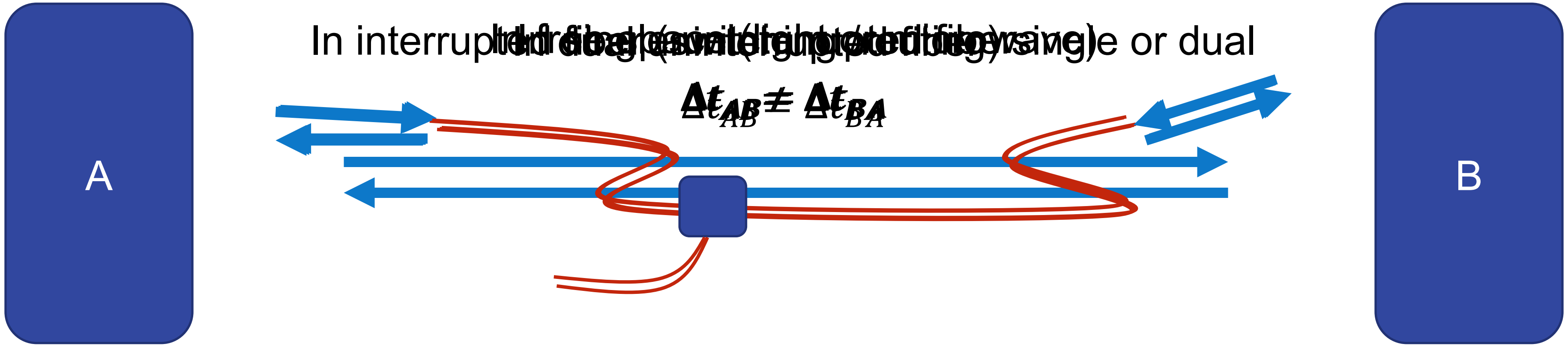
Redundant Distributed Timescale Traceable to UTC(SP)





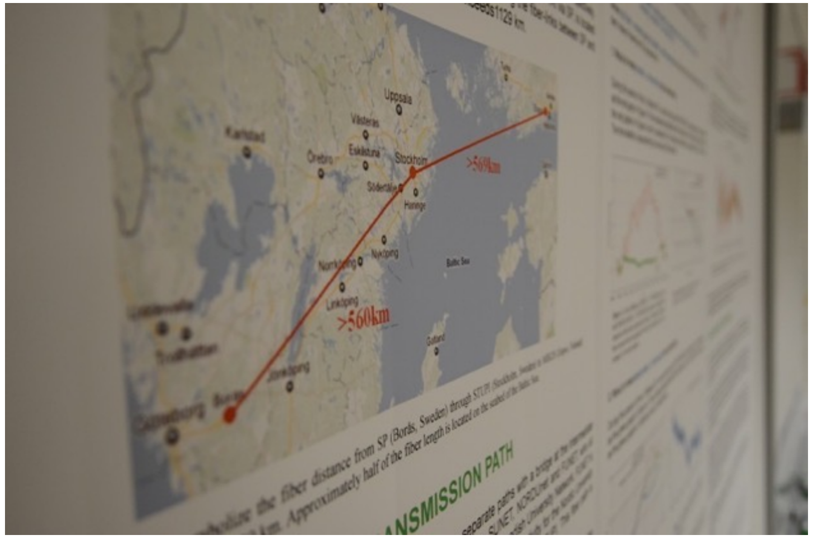
Two-way Time Transfer

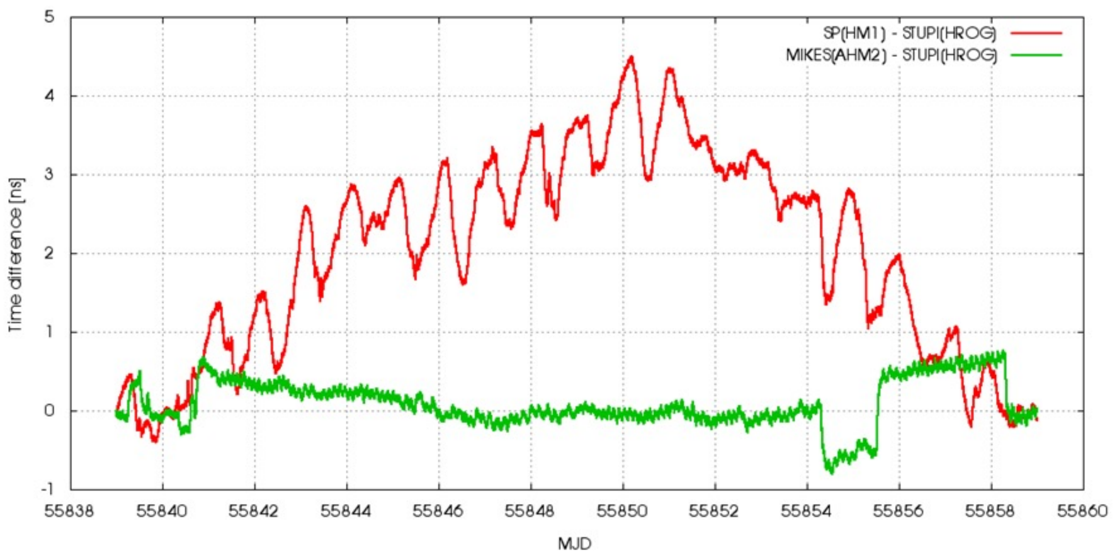
- All precise time transfer uses two-way communication
  - Presumes bi-directional symmetry of delay



Environmental influences

- Fiber influenced by temperature even when deployed in ground
- Fiber delay varies approx. 30 ps/nmkm°C
- Ground temperature (1 m depth) varies up to ± 10 °C over the year
- Indoor temperature in network cross-connects varies up to ± 2°C over the day



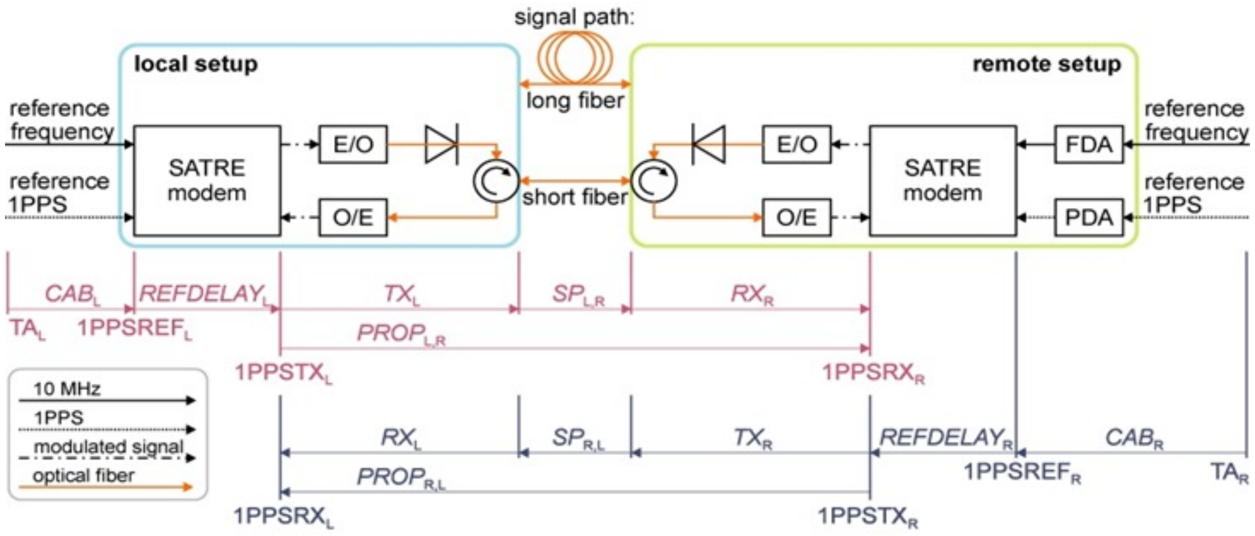


Time Transfer vs Frequency Transfer

- Time Transfer: the timing data is transmitted, and the receiver can set the clock from the link
- Time Delay Transfer: the link delay is monitored and transmitted, and the receiver can compare the clock using the link
- Frequency Transfer: the frequency is transmitted, and the receiver can compare the oscillator using the link

SATRE via Fiber

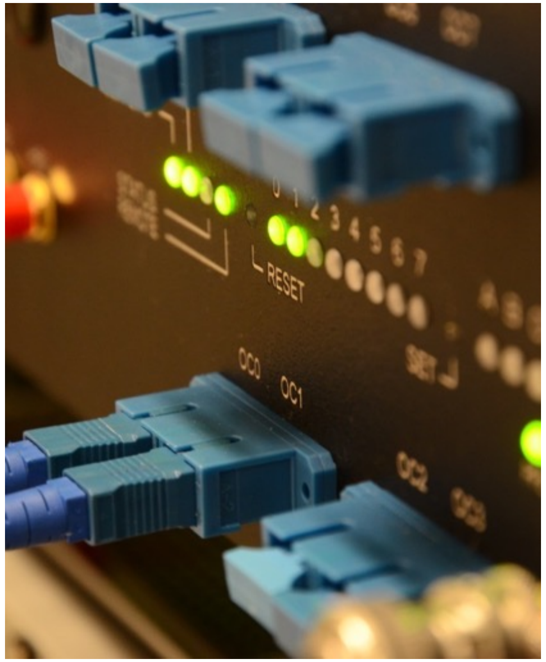
- Connect a SATRE-modem at each end of the fiber
  - Satellite Time and Ranging Equipment
  - Same equipment as used in TWSTFT
- Replace satellite transceivers with Optoelectronics



1) "Time transfer through optical fibres over a distance of 73 km with an uncertainty below 100 ps", M. Rost et al, Metrologia (2012)

Utilizing SDH protocol

- Telecom standardized protocol for synchronized telecommunication networks
- Synchronous Digital Hierarchy (SDH)
  - ITU, EU & Asia, based on Synchronous Transport Module (STM)
  - STM-1 = 155.52 Mbit/s, STM-64 = 64*155.52 = 9.95328 Gbit/s
- Synchronous Optical Network (SONET)
  - Telcordia, US, based on Optical Carrier (OC)
  - OC-1 = 51.84 Mbit/s, OC-192 = 192*51.84 = 9.95328 Gbit/s



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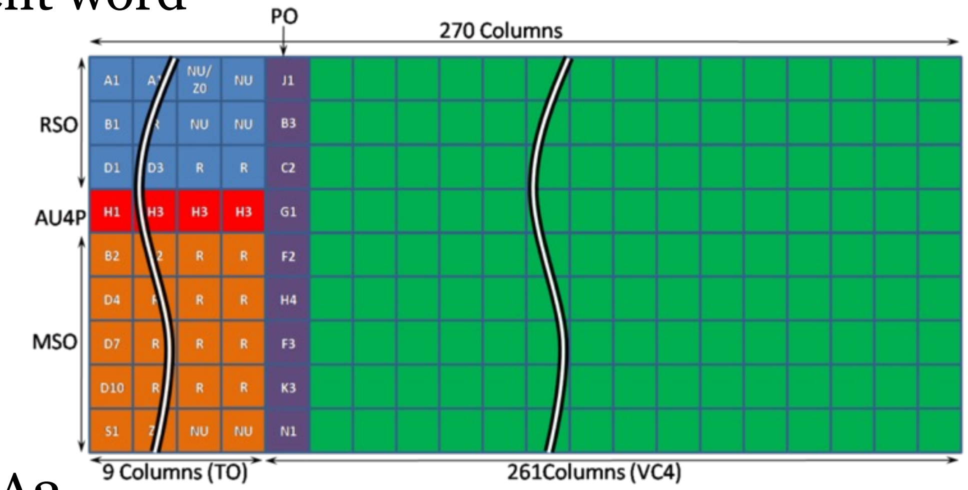
Utilizing SDH protocol

- Both SDH and SONET based on equally sized frames
  - 125 µs long
  - Consists of Overhead and Payload
  - Each frame starts with a 38.2 ns frame alignment word
  - Overhead includes undefined, empty, bit slots



- Frame alignment word:
  - A1: 1111 0110 (hexF6)
  - A2: 0010 1000 (hex26)
  - STM-1 (oc-3) alignment word: A1,A1,A1,A2,A2,A2
  - STM-64 (oc-192) alignment word: A1,...,A1, A2,...,A2 (192 of each)

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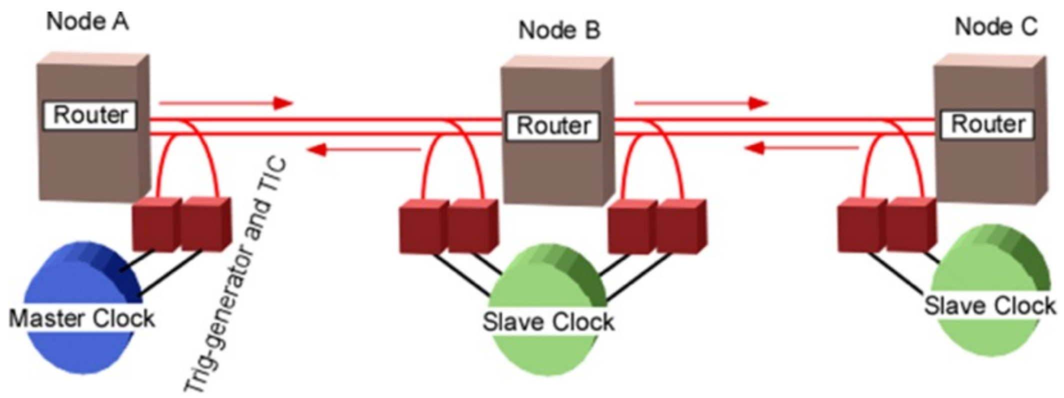
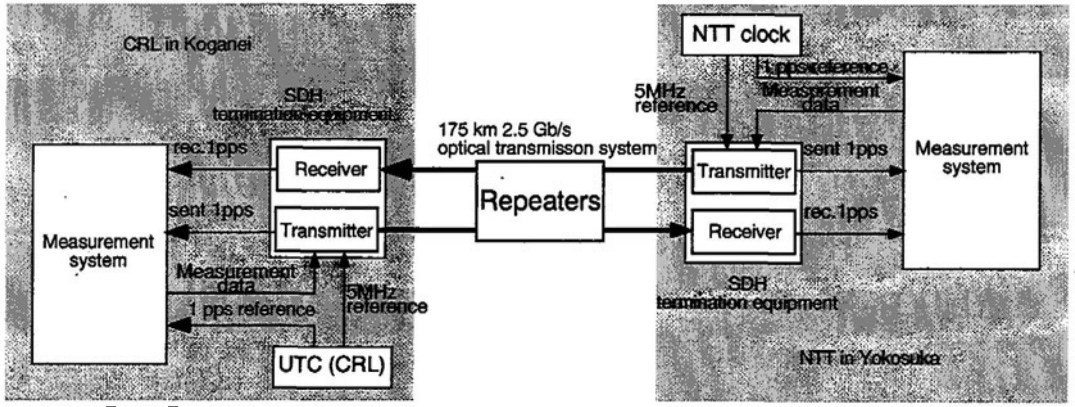
SDH passive listening technique

- Time stamping frame alignment words on optical side[1]
  - Reference to local 1 pps
  - Mod 125 µs
  - Long distances must be estimated within ± 10 km
  - Sensitive photodetectors necessary
  - Reduces optical power margin of system.
  - TIC data transmitted in bulk
- Standard transmission equipment.
  - Operations in optical domain



1) “Time Transfer between UTC(SP) and UTC(MIKE) Using Frame Detection in Fiber-Optical Communication networks”, S.C. Ebenhag, et al. Precise Time and Time Interval (PTTI) Systems and Applications Meeting, (2011).

SDH active insertion technique

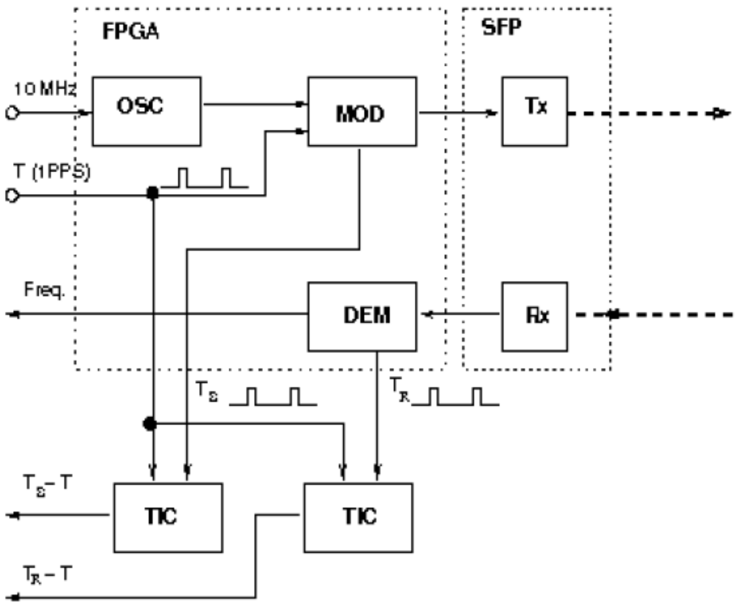


- Two-way transfer utilizing unused bytes in OH[1,2]
  - ”reserved for national use”
  - One byte set with timing data and on-time marker 1/s, 0 the other 7999 frames
- Two way transfer in payload[3]
  - IRIG-B signal in payload
  - Immediate return to calculate delay
  - Frequency locking of SONET modulation frequency
- Customizing transmission equipment.
  - Operations in electrical domain

1) ”SDH-Based Time and Frequency Transfer System”, M. Kihara et al., 9th EFTF (1995)
2) ”Two-way Time and Frequency Transfer in SONET”, M.A. Weiss et al, IEEE IFCS (1996)
3) ”Precision Time and Frequency Transfer utilizing SONET OC-3”, M. Calhoun et al., 28th PTTI (1996)

Transmitting customized protocol

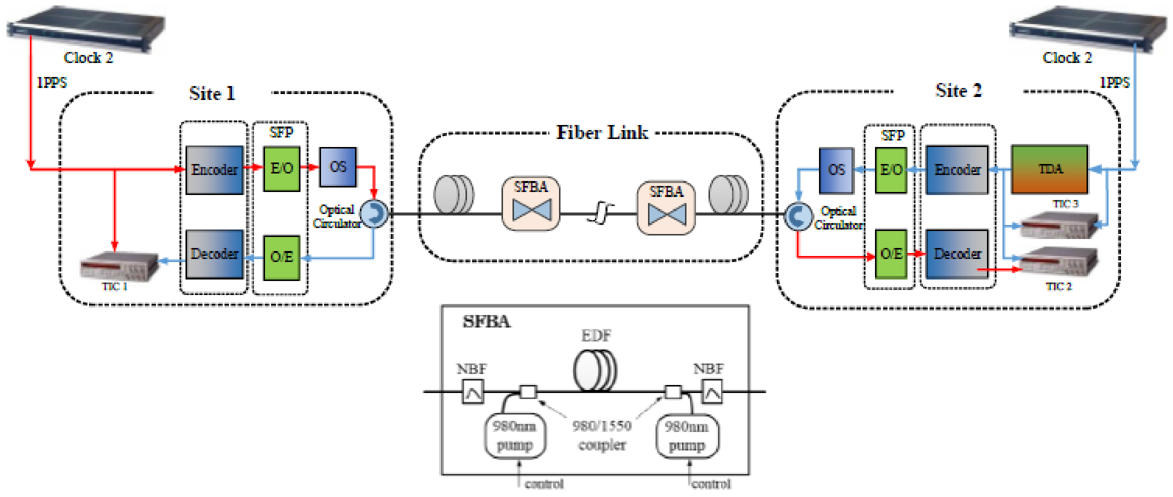
- Transmission of 1 pps on RF carrier
- Measure time of transmit and receive at both ends
- Calculate round trip time and transmit correction data.
- Demonstrated on duplex fiber[1]
  - Coexisting in DWDM-network



1) “Time Transfer in Optical Network", V. Smotlacha et al., 42nd PTTI (2010)

Same wavelength, different time

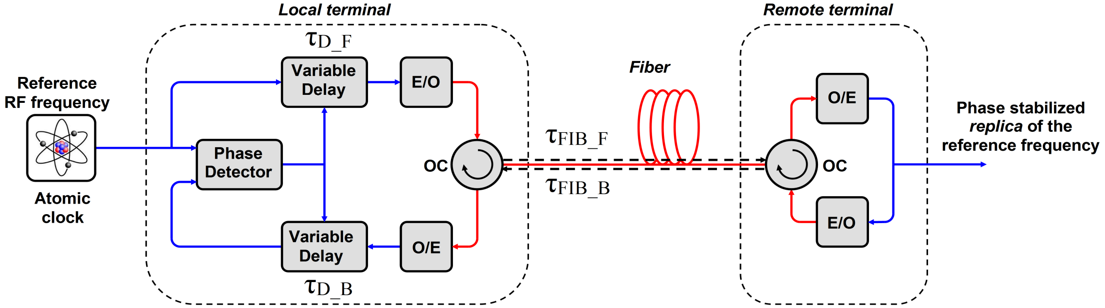
- Transmission of 1 pps pulses at same wavelength in both directions
- Only one pulse present in fiber at any instance
- Avoid interference from Rayleigh scattering by time differentiation

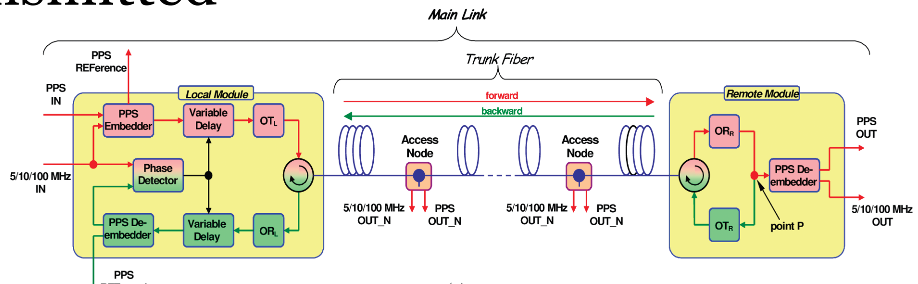


1) “A 300-Kilometer Optical Fiber Time Transfer Using Bidirectional TDM Dissemination", L. Hu et al., 46th PTTI (2014)

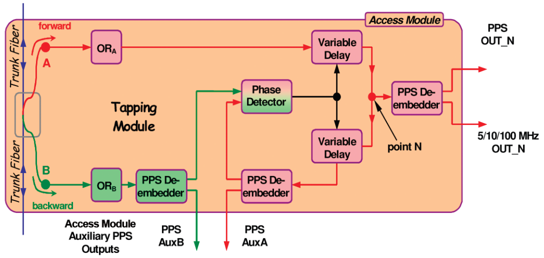
Dynamic delay adjustments

- Equal variable electrical delay in transmitter and receiver
- Measured round-trip delay measured and transmitted
- Demonstrated in simplex fiber [1]
- Developed to commercial product *ELSTAB*





(a)



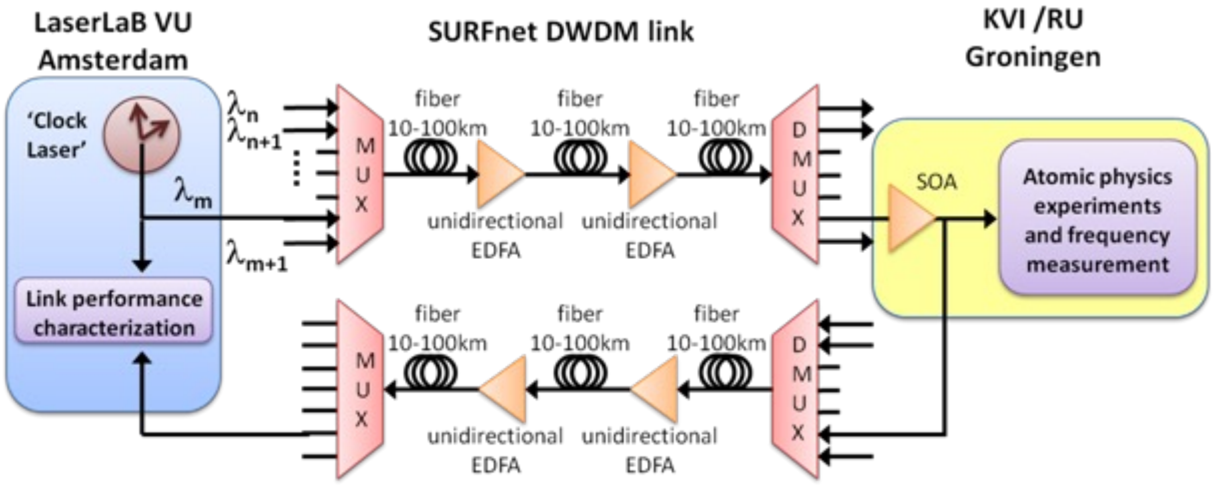
(b)

1) "Multipoint Joint Time and Frequency Dissemination in Delay-Stabilized Fiber Optic Links", Ł. Śliwczyński, et al, IEEE Trans. UFFC 2015

2) "Long Haul Time and Frequency Distribution in Different DWDM Systems," K. Turza et al, IEEE Trans. on Ultrason. Ferroel. and Freq. Contr., vol. 65, no. 7, pp. 1287-1293, July 2018.

3) "ELSTAB- fiber optic time and frequency distribution technology - a general characterization and fundamental limits", P. Krehlik et al, IEEE Trans. Ultrason. Ferroel. Freq. Contr., 63, 993-1004, 2016

SURFnet optical fiber link VU -KVI

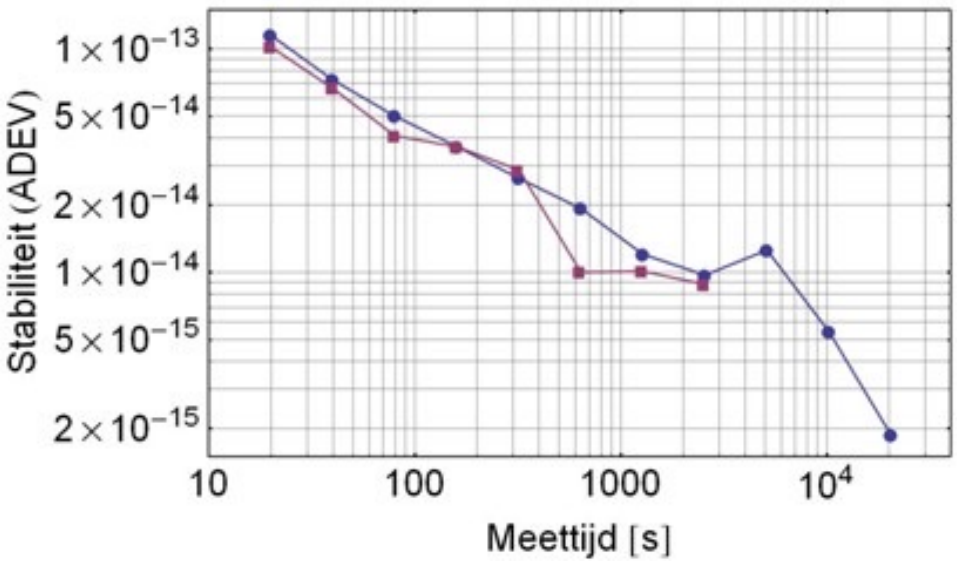


Resulting Frequency stability (Allan deviation)

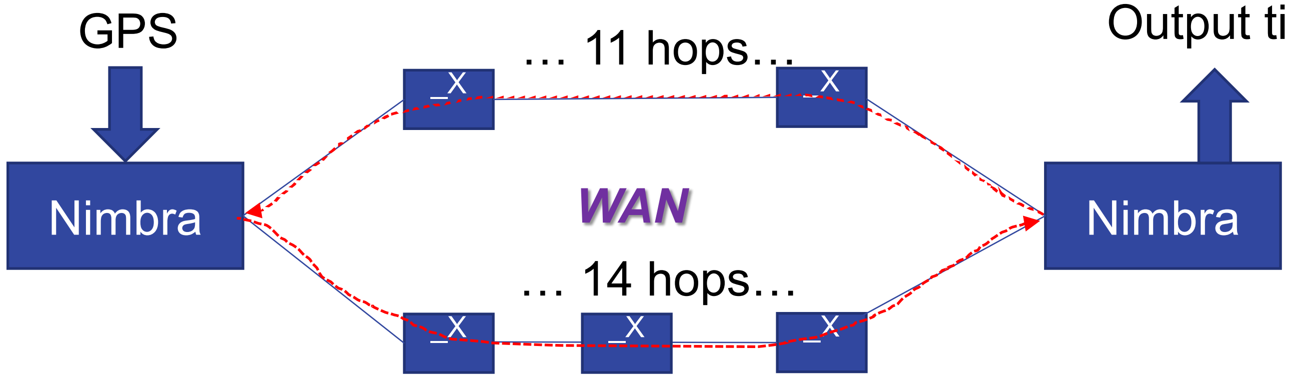
6×10^{-13} @ 1 s

1×10^{-14} @ 1200 s (20 min)

2×10^{-15} @ 20000 s (5,5 hr)



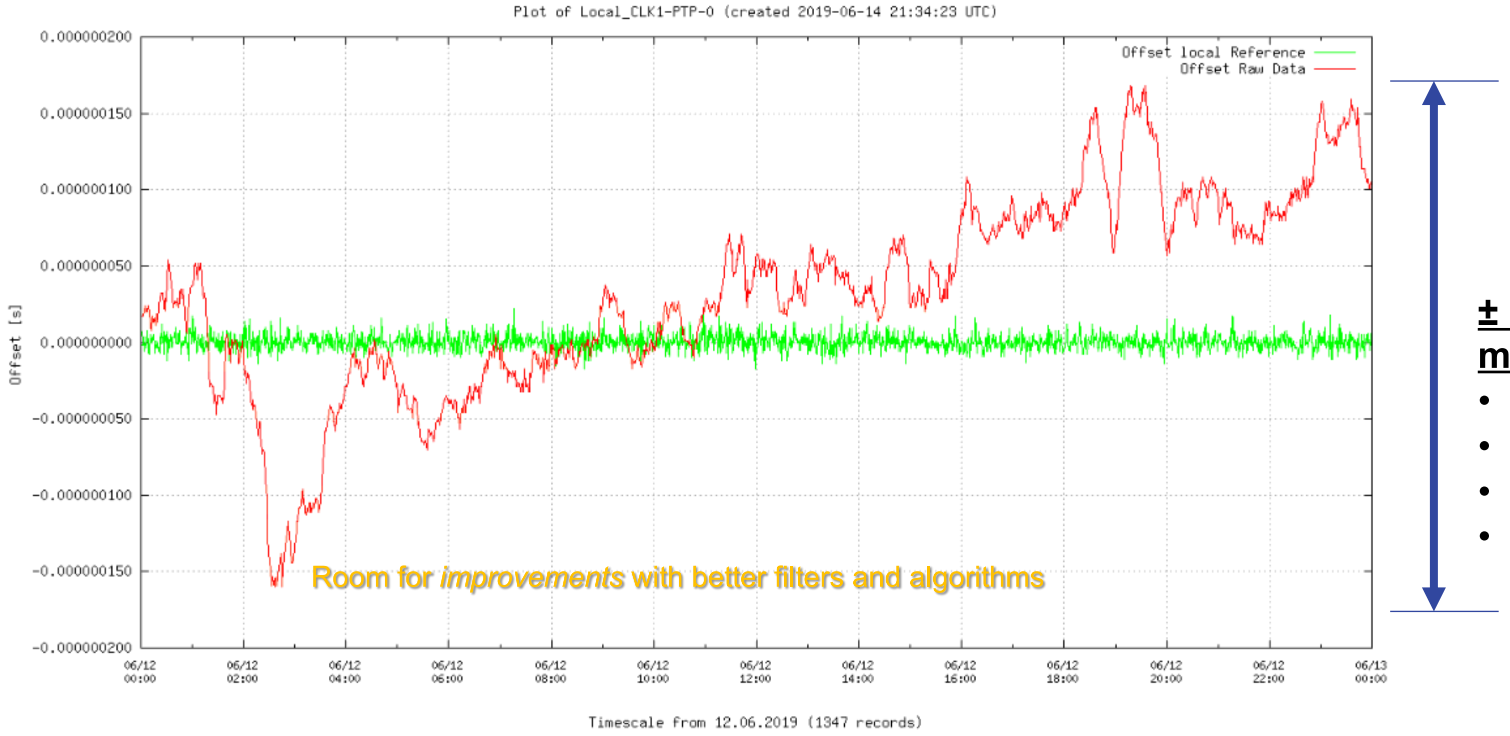
… alternative solution for transport of time…



Output time ± 1.5 us offset time error accuracy

Calnex Insight and Innovation

Measured &Verified



<u>± 160 ns for one day measurement</u>

- 1200 km over telecom operator
- mix of WDM and IP/MPLS
- No timing support from network
- 11/14 nodes with asymmetries

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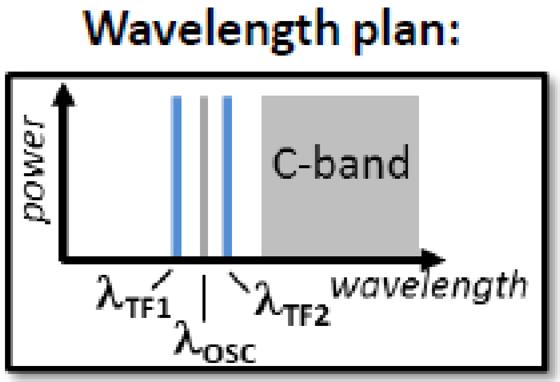
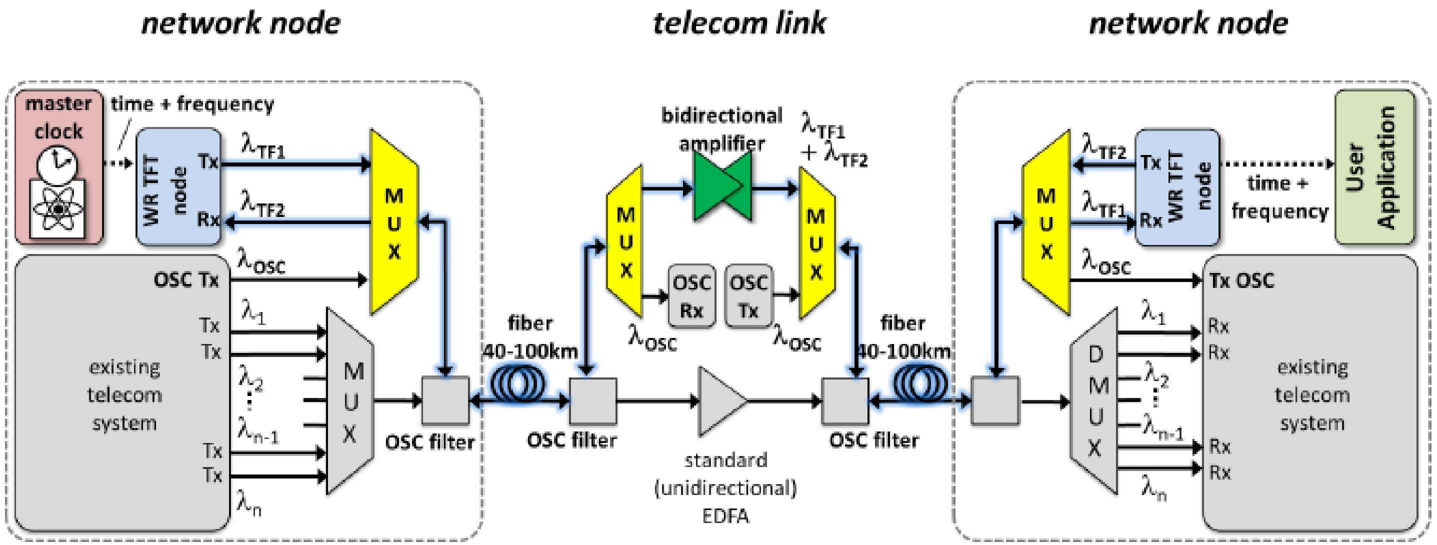
Utilize Surveillance Channel



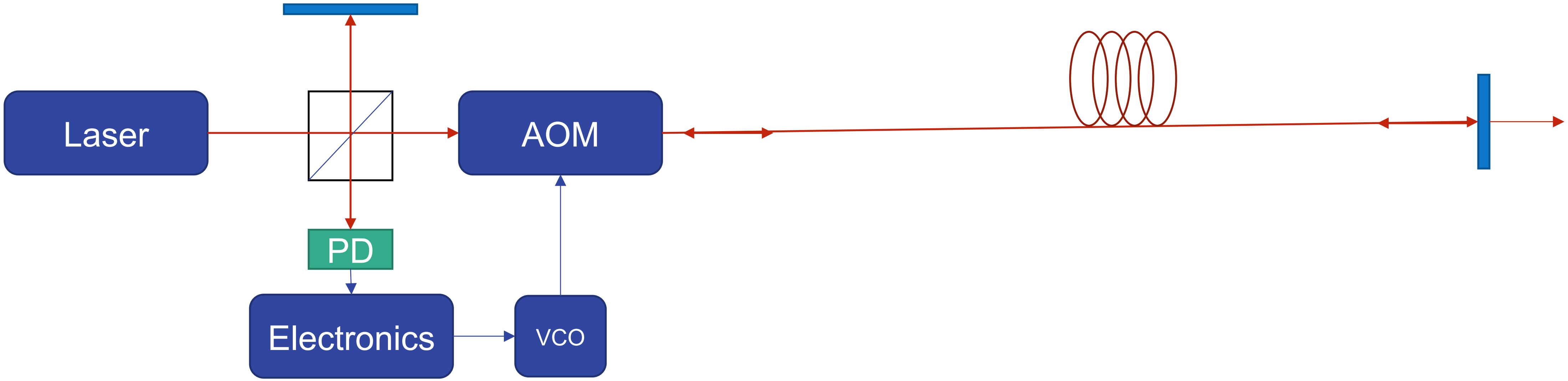
- Optical Surveillance Channel connects routers and network equipment for control
  - Low bandwidth requirements
  - SOA amplifiers
  - Bi-directional time and frequency transfer via simplex fiber, with special amplifiers at each node.



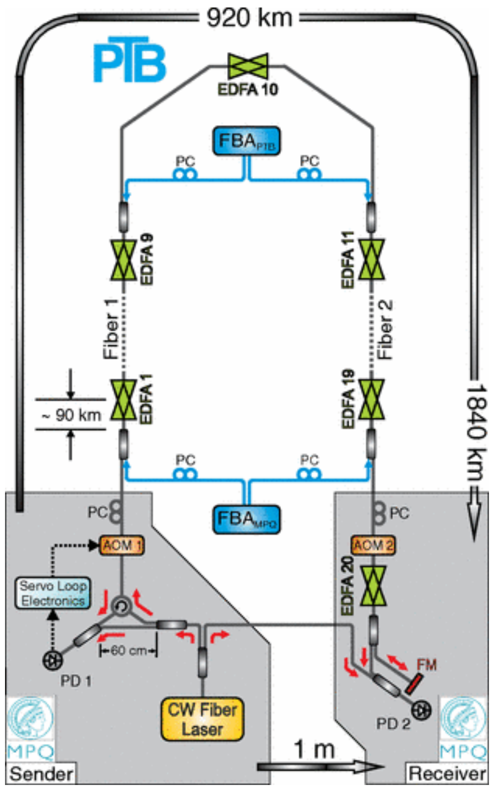
1) "System and Method for Network Synchronization and Frequency Dissemination", R. Nuijts et al., Patent application WO2012NL50367 20120524 (pending)

Optical Frequency Transfer

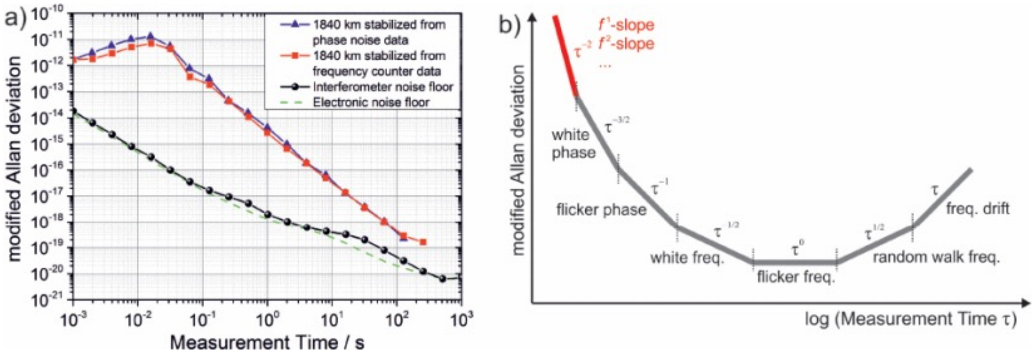
- Requires bi-directional transmission in single fiber
- Ultra-narrow linewidth laser, Acousto-optic modulator and faraday mirror
- Stable output at Tx and Rx



Optical Frequency Transfer



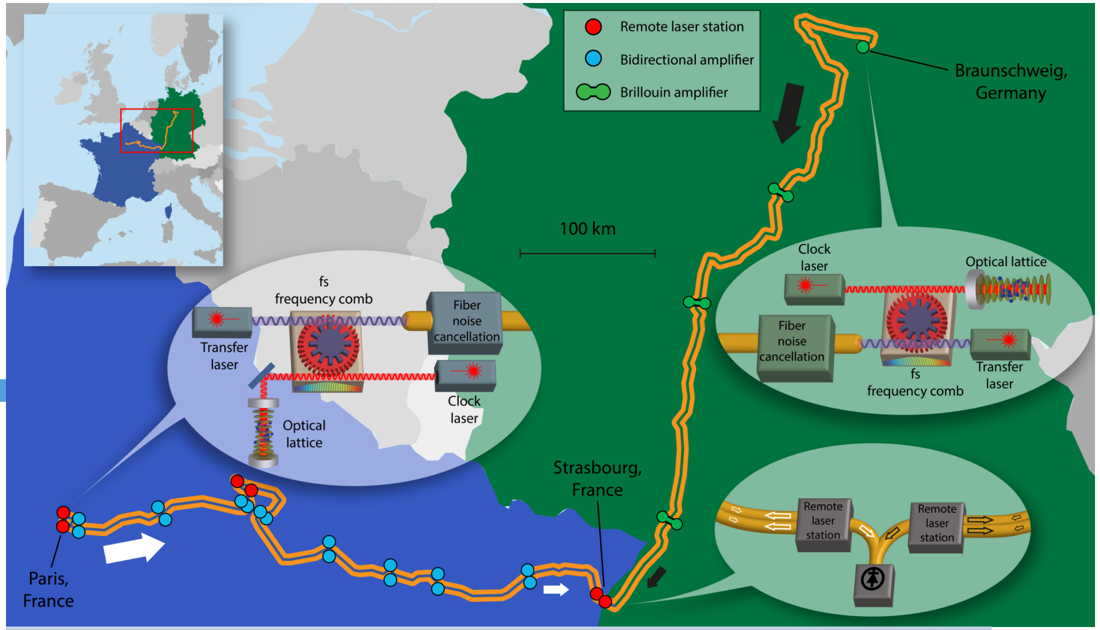
- Light of a commercial cw fiber laser locked to an optical cavity is launched into an underground telecommunication fiber. After a 1840-km loop the light arrives back where a fraction of it is retroreflected.
- The round-trip light is used to derive an error signal for a servo loop with AOM 1 as the actuator.
- EDFA: erbium-doped fiber amplifier
- FBA: fiber Brillouin amplifier
- AOM: acousto-optic modulator
- PC: polarization controller
- FM: Faraday
- PD: photo diode.



1) S. Droste et al., "Optical frequency transfer via 1840 km fiber link with superior stability," 2014 Conference on Lasers and Electro-Optics (CLEO) - Laser Science to Photonic Applications, San Jose, CA, 2014, pp. 1-2.

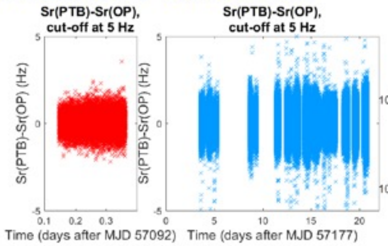
Optical Frequency Comparison

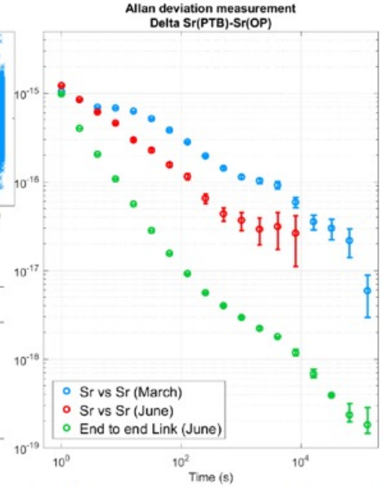
- Optical frequencies accurately compared through a 1400 km optical fiber link
- LNE-SYRTE and PTB, compares two accurate optical Sr optical lattice clocks distant by a geographical distance of 700 km with an unrivaled fractional uncertainty of 5×10^{-17}



Results

2 Measurement campaigns





Total clocks	650.3	4.1	496.3	1.9
Ratio Sr_{PTB}/Sr_{SYRTE}	Campaign I Unc. (10^{-17})		Campaign II Unc. (10^{-17})	
Systematics Sr_{SYRTE}	4.1		4.1	
Systematics Sr_{PTB}	2.1		1.9	
Statistical uncertainty	2		2	
fs combs	0.1		0.1	
Link uncertainty	<0.1		0.03	
Counter synchronization*	10		<0.01	
Gravity potential correction**	0.4		0.4	
Total clock comparison	11.2		5.0	

Statistical uncertainty 2×10^{-17} after $\simeq 1$ hour   150 hours of data

$Sr_{PTB}/Sr_{SYRTE} - 1 = (4.7 \pm 5.0) \times 10^{-17}$ C. Lisdat *et al.*, Nature Comm. **7** 12443 (2016)

1) "A clock network for geodesy and fundamental science". Lisdat, C. et al, Nat Commun. 7:12443 doi: 10.1038/ncomms12443 (2016).

FREE-SPACE TIME AND FREQUENCY TRANSFER

- Performed by NIST, on campus
- Two-way transmission, optical single mode.
  - 200 MHz optical pulse train from optical comb
  - Gated single comb pulse
- 4 km transmission distance, folded path
  - Air turbulence
  - offset of -5.4×10^{-20} +/- 1.9×10^{-19},
- Residual frequency instabilities well below the absolute frequency instability of optical clocks for timescales longer than 1 second.
- Can support timing deviations of below 1 femtosecond for a synchronized system.

N. R. Newbury et al., "Free-space time and frequency transfer," 2015 IEEE Avionics and Vehicle Fiber-Optics and Photonics Conference (AVFOP), Santa Barbara, CA, 2015, pp. 57-58, doi: 10.1109/AVFOP.2015.7356636.

RI. SE

Limitations in duplex fibers

- Unknown asymmetries limits time transfer performance
- Constant asymmetries must be identified through alternative calibration technique
- Asymmetric variations must be estimated through additional parameters

RI.
SE

Limitations in simplex fibers

- Maximum distance limited by attenuation
  - Cannot be fully compensated by amplification
- Any duplex sections must be within climate control
  - Path lengths as identical as possible

Where precise time & frequency matters

Transport

Navigation

Power Grids

Finance

Science

Telecommunication (ICT)

Defence

Security

What precision can we get?

ms **NTP**

µs

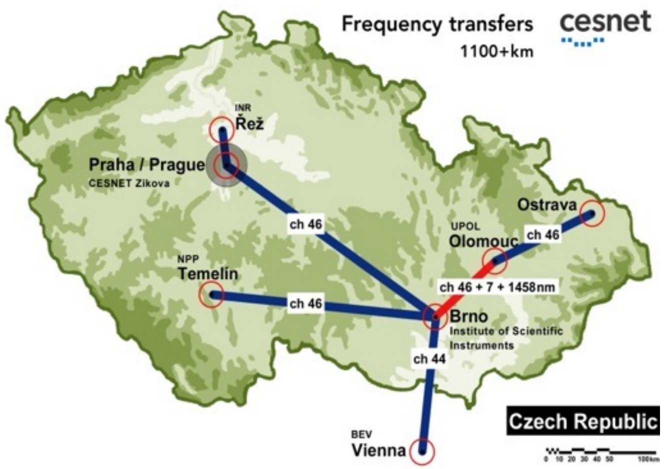
ns **GNSS**
White Rabbit

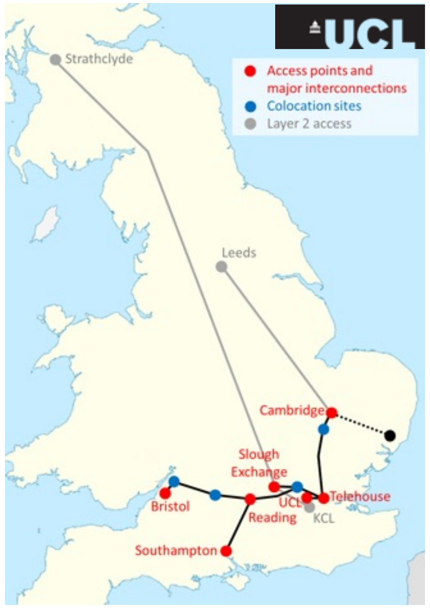
ps **Optical Time Transfer**

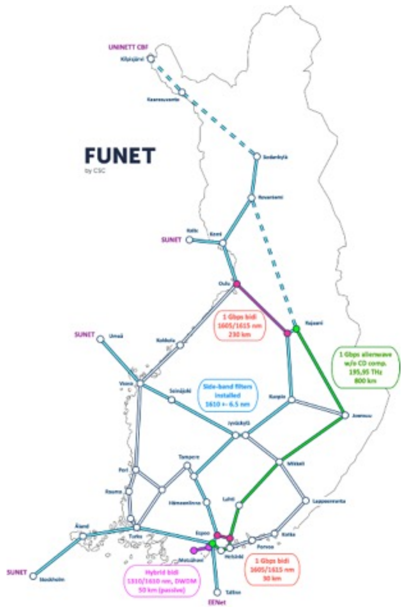
	Existing advanced techniques		Performances Frequency (instability) Time (precision, Time Deviation TDEV)	TRL	Distance
Frequency	Optical Carrier (Carrier Wavelength)	Active cancellation	10^{-15} @1s; 10^{-20}@1d	8	>1000 km
	RF Carrier (Modulated Wavelength)	Active cancellation with optical delays	10^{-14} @1s; 10^{-18} @1d	4	0-100 km
		Active cancellation with electronic delays (ELSTAB)	10^{-13} @1s; 10^{-17} @1d	8	500-1000 km
			10^{-16} @1d (unidirectional)	8	>1000 km
		White Rabbit PTP	10^{-15} @1d (unidirectional)	8-9	>1000 km
		Phase conjugation	10^{-19} @1d	5-6	0-100 km
Time	Two-way comparison		TDEV ≈ 2ps	5-6	100-500 km
			TDEV ≈ 30ps calibration through GPS (unidirectional)	6	100-500 km
	Optical frequency comb		Calibration uncertainty <40ps TDEV 500 fs @1s	4-5	0-100 km
	Active cancellation with electronic delays (ELSTAB)		TDEV < 1ps calibration uncertainty <40 ps	8	>1000 km
	Protocol based (White Rabbit PTP)		Verified with GPS disagreement ±2ns	8-9	>1000km
			Calibration uncertainty <10ns	8-9	0-100 km

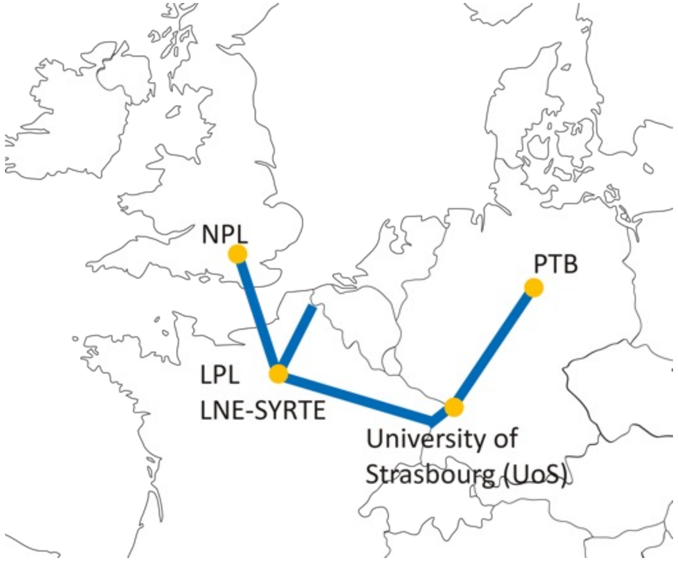
Based on CLONETS D1.5 – Fibre-based time and frequency transfer techniques

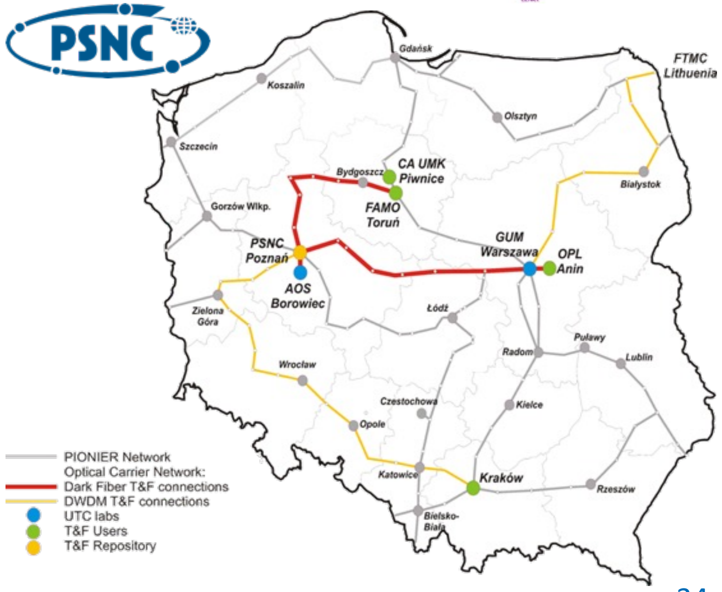
National T&F connections in Europe - examples



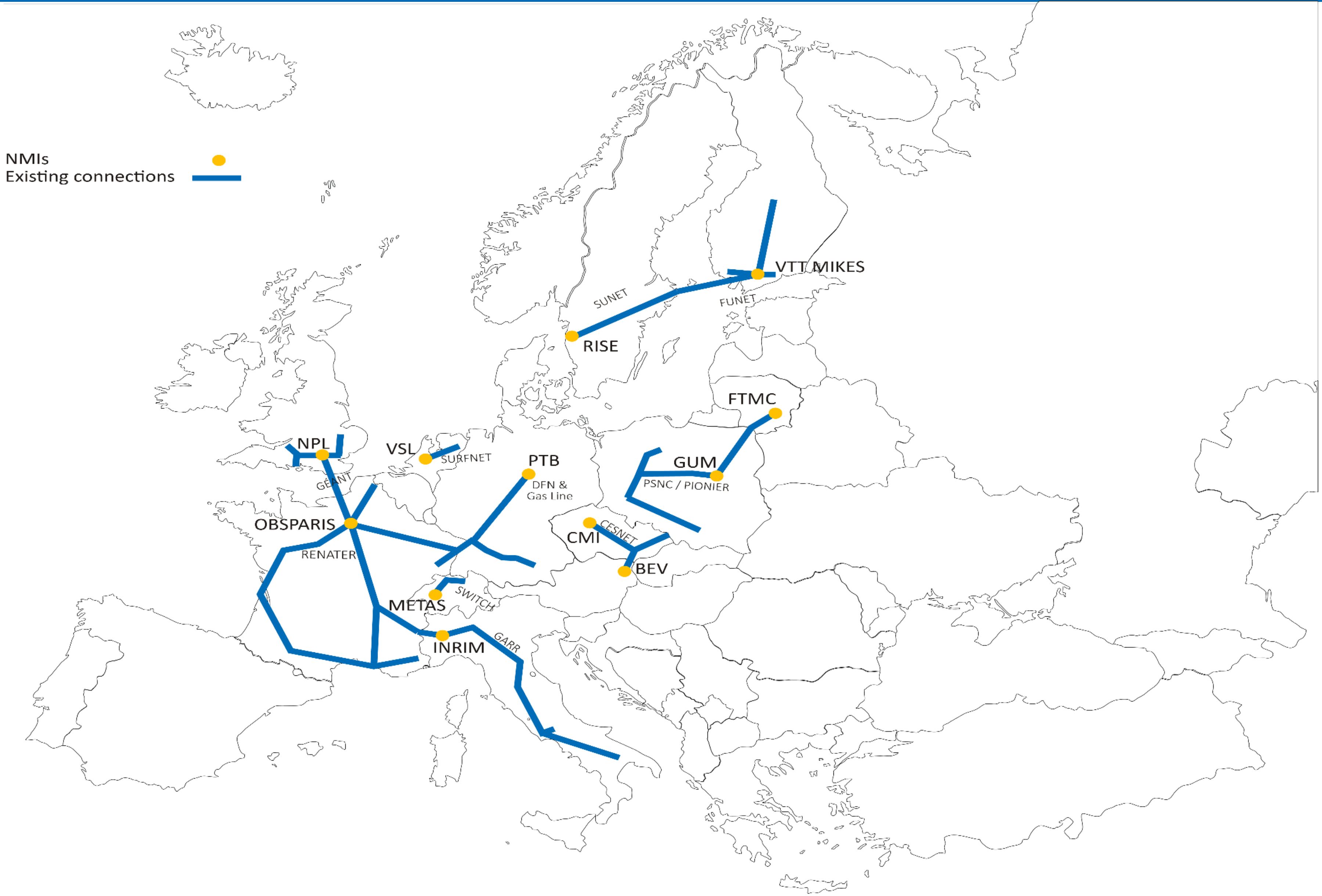




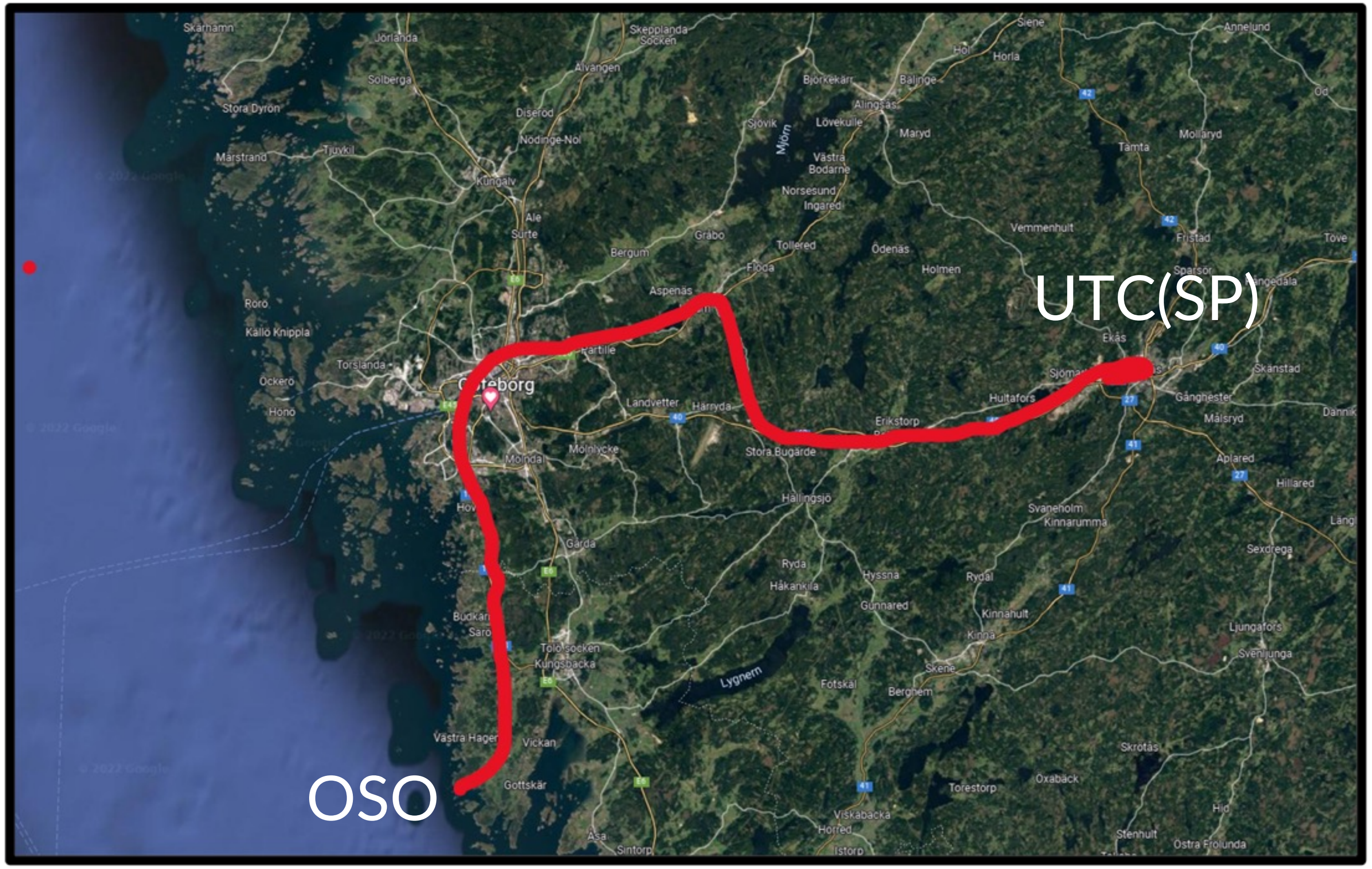


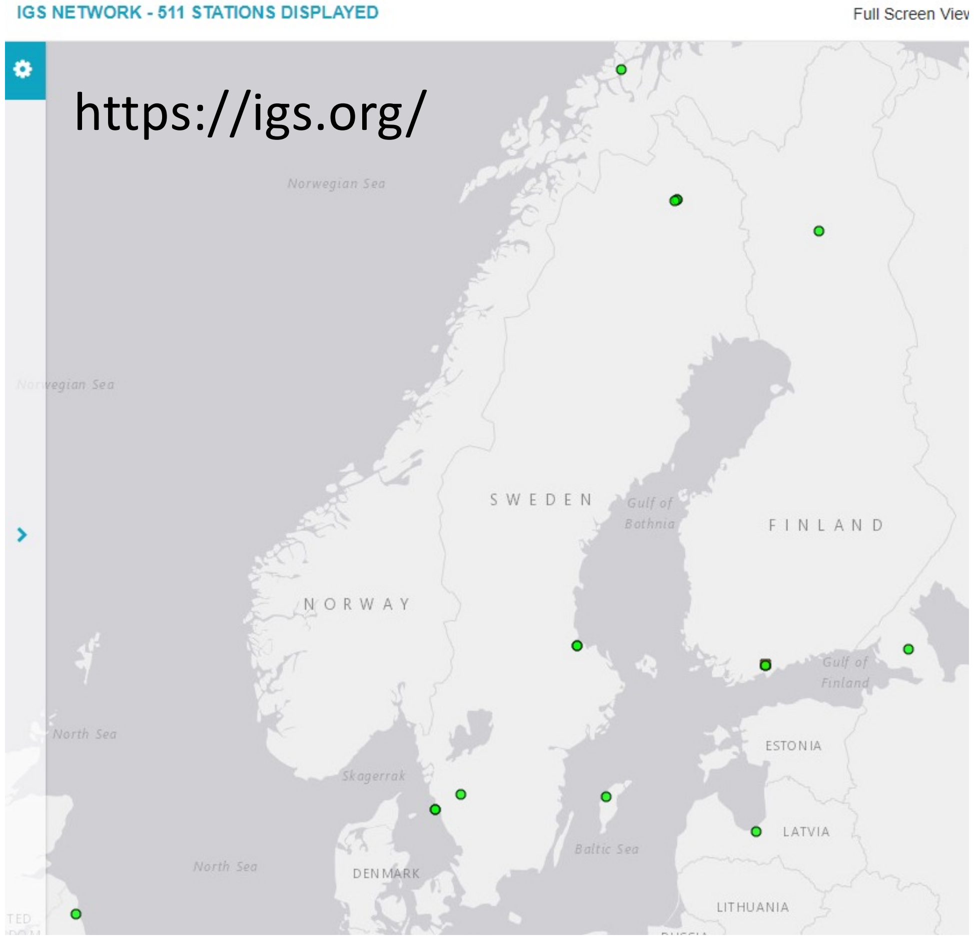


T&F connections in Europe



The setting, on the west coast of Sweden





IGS INTERNATIONAL GNSS SERVICE

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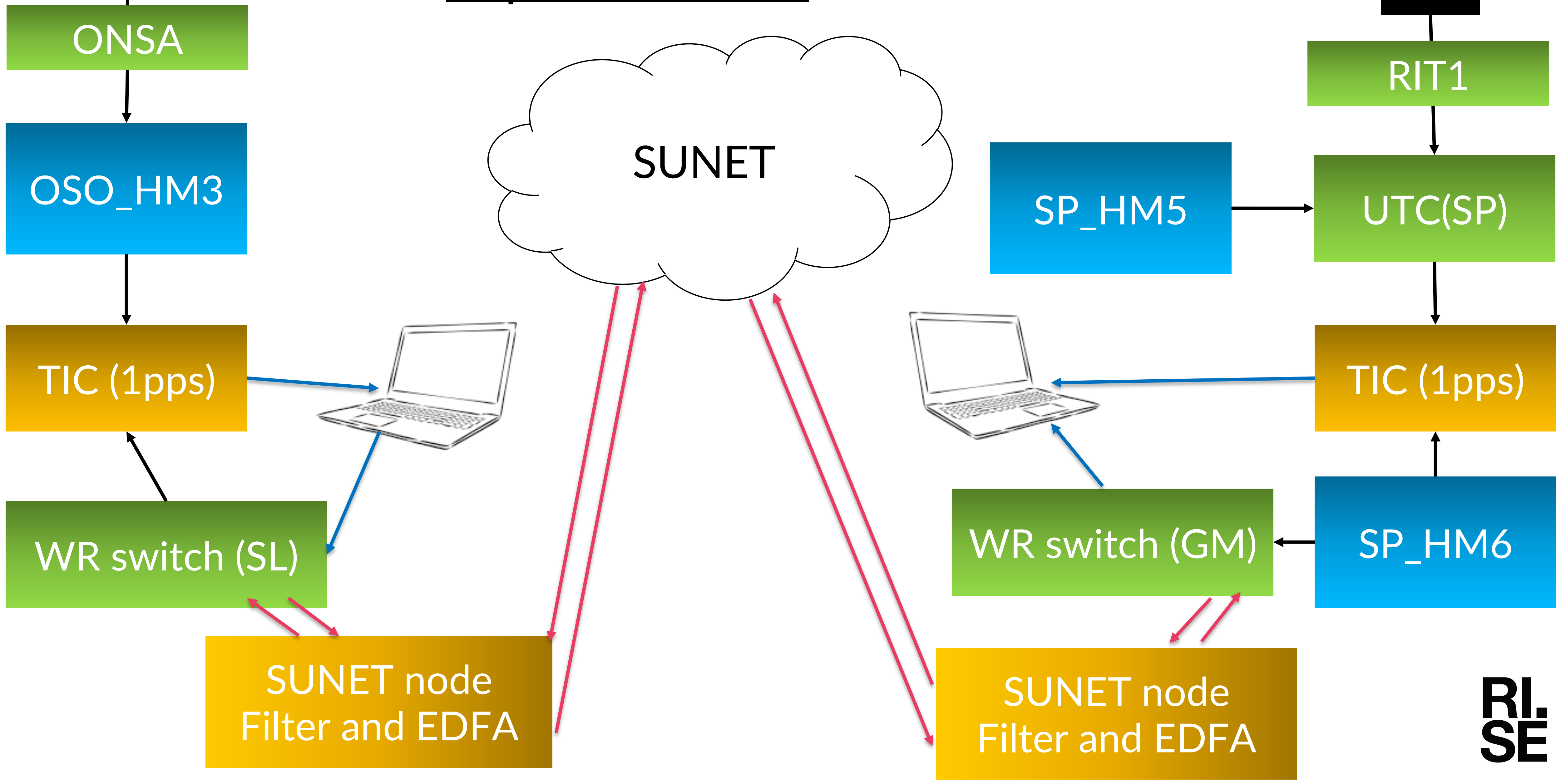
Implementation



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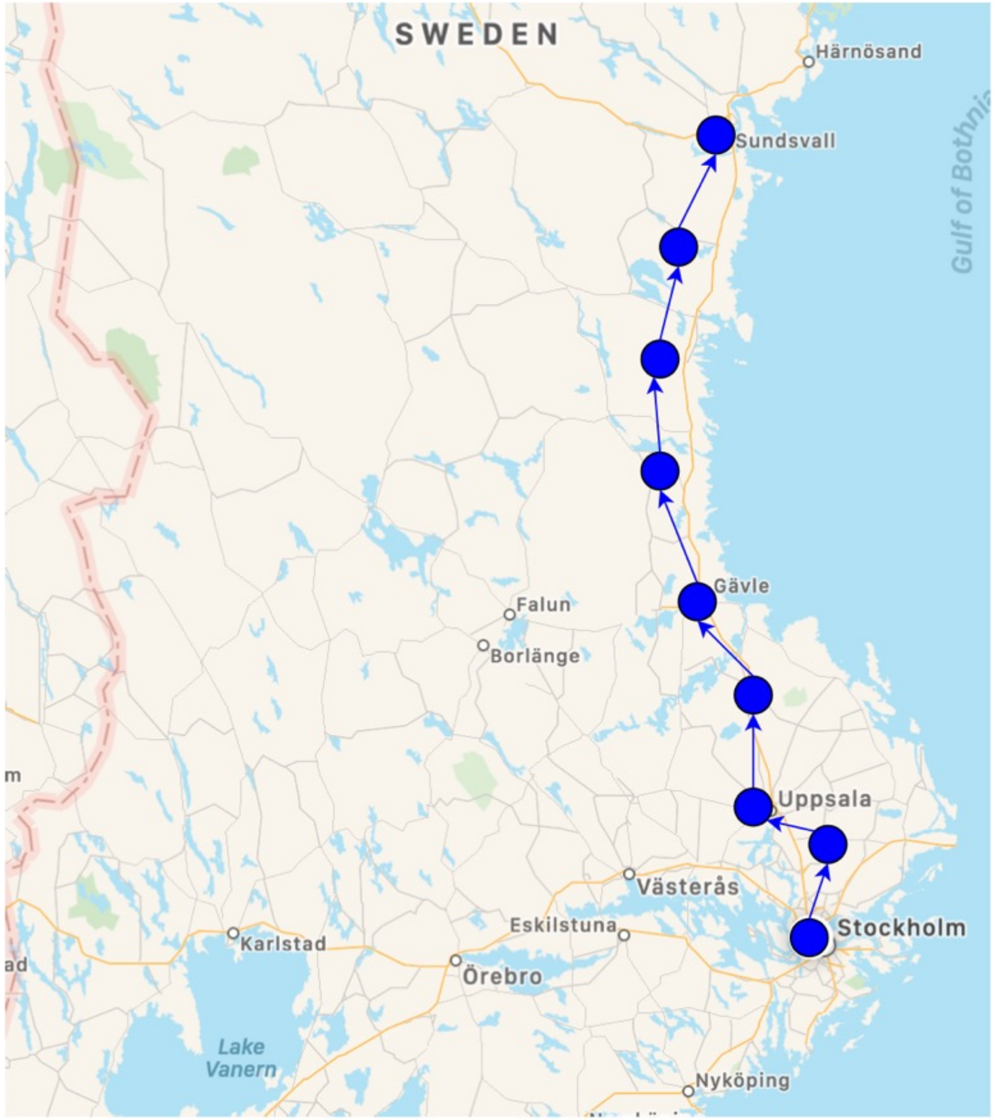
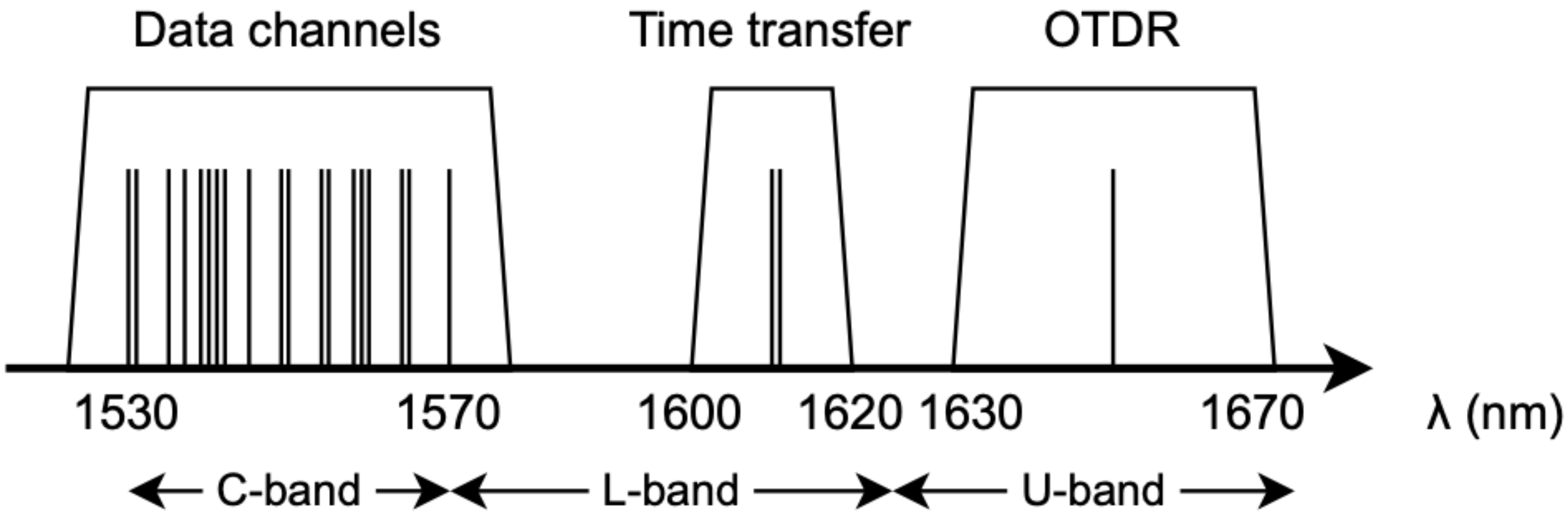
Link Stockholm - Sundsvall

- SUNET
- 8 intermediate jumps, 440 km
- BiDi
  - – asymmetries in the fibers,
  - – calibration
- Power grid top wire fiber

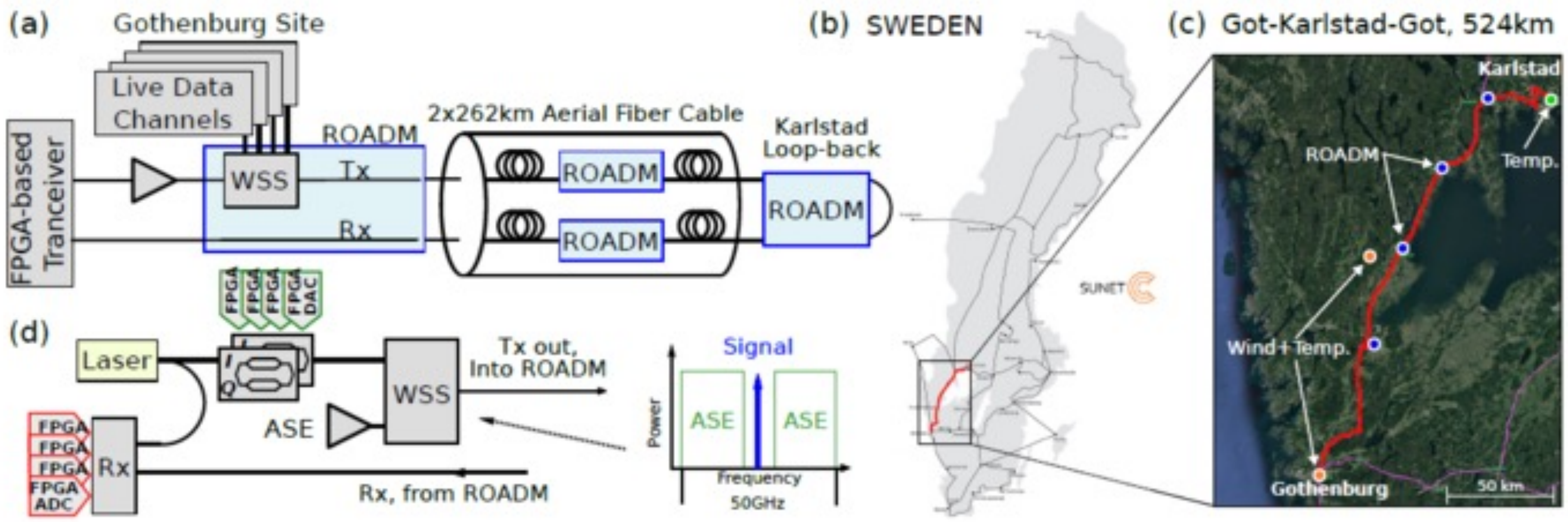


BiDi in a traditional optical network

- The ROADM network uses unidirectional transmission in the C-band
- SUNET utilizes OTDR using 1650 nm +/- 20 nm
- Break out an extra band for BiDi with WDM filters



Real-time transceiver prototype to a live network



Scientists take real-time environmental measurements over 524 kilometers of live air fiber

CREDIT
Nokia Bell Labs, Mazur

Proposed project

- We propose a project that shall deliver
  - a technical solution, a comprehensive applicable algorithm
  - adapted hardware
  - knowledge on how to work to compensate for asymmetric uncertainties that arise during wavelength-based coherent transmission in fiber.

After the completion of the project, a scalable technology must be available to apply in a real network.

Aims

- Be able to operate in SUNET C
- Be able to change wavelength
- Operate with duplex fiber
- Track polarization and compensate for it
- Use for time and frequency transmission, independent on protocol
- Work with intermediate clocks
- Stability better than GNSS
- For transmission of clocks with stability better than H-masers

Thank you for your attention

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