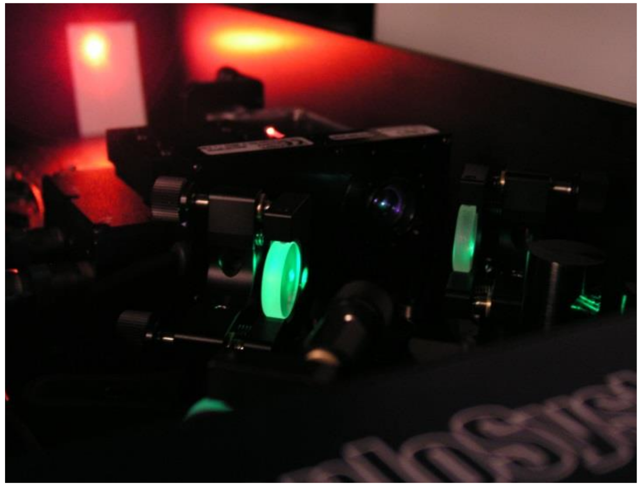
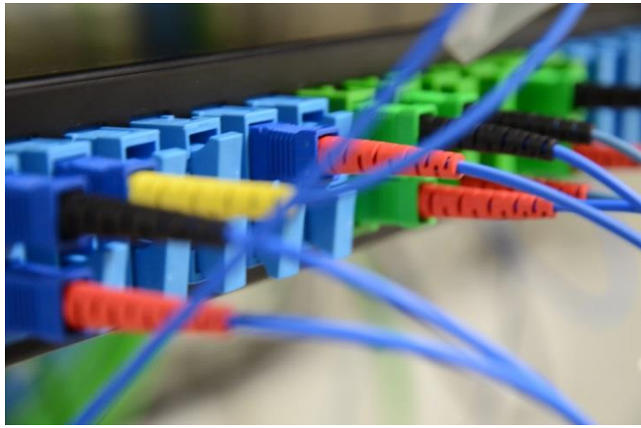


RISE - STRATEGY FOR TIME/FREQUENCY DISTRIBUTION IN SWEDEN USING COHERENT TRANSPONDERS FOR WHITE RABBIT



Sven-Christian Ebenhag

Research Institutes of Sweden

Safety and Transport
Measurement Science and Technology

Outline

- RISE the Time and Frequency NMI of Sweden
- Why do we do it?
- What have we done before
- What are we planning to do now
- So far

RISE the Time and Frequency NMI of Sweden

Swedish National Metrology Institute
National Laboratory of Standards

- RISE is appointed as the Swedish NMI by the Ministry of Enterprise and Innovation
- the NMI is funded from Vinnova Sweden's innovation agency and any decisions made by an advisory board from industry.
  - The level of NMI funding
  - Swedish level of participation in EMRP/EMPIR
- RISE is hosting the National Metrology Institute
  - RISE mission and strategies given by the Ministry of Enterprise.
    RISE has 2300 employees & the NMI 120.
    RISE mission is also the NMI mission.

Time Keeping

- UTC(SP) since 1/4 1996
- Main site in Borås, additional site in Stockholm since 2013
- Also reporting clocks at OSO
- T&F transfer using GNSS CV
- T&F transfer using fibers
- TWSTFT station in Borås

Clocks and Scales

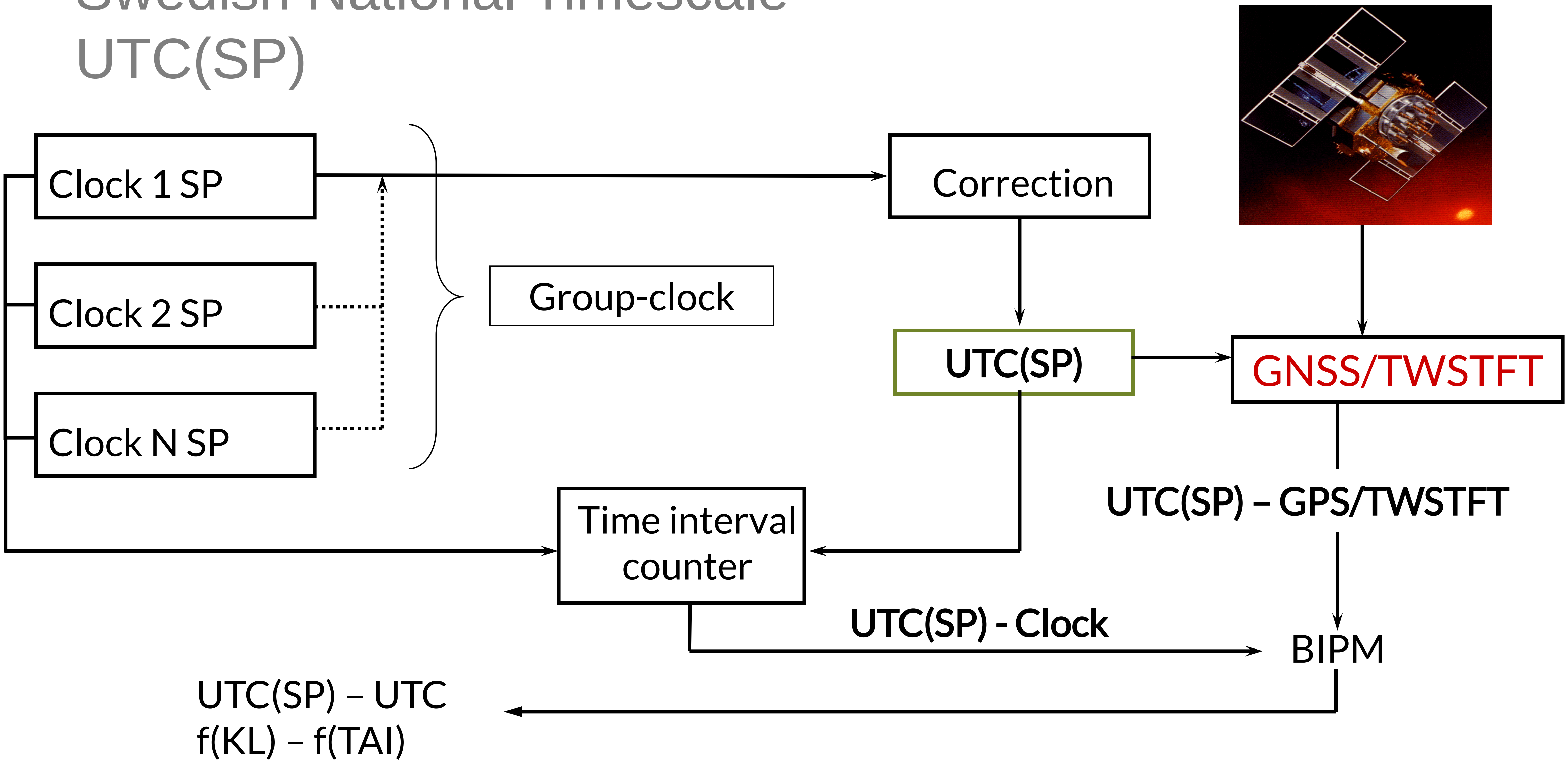
- 18 clocks reported to BIPM (September)
  - Typically 4-6 % weight in TAI
  - 7 H-masers

    SigmaTau 2010
    Kvarz CH1-95
    Vremya VCH1003M Opt L
  - 9 (high) +2 (standard) 5071A
- AOG and HROG based UTC time scales
  - 3xBorås, 2x Sthlm, 1xOSO,

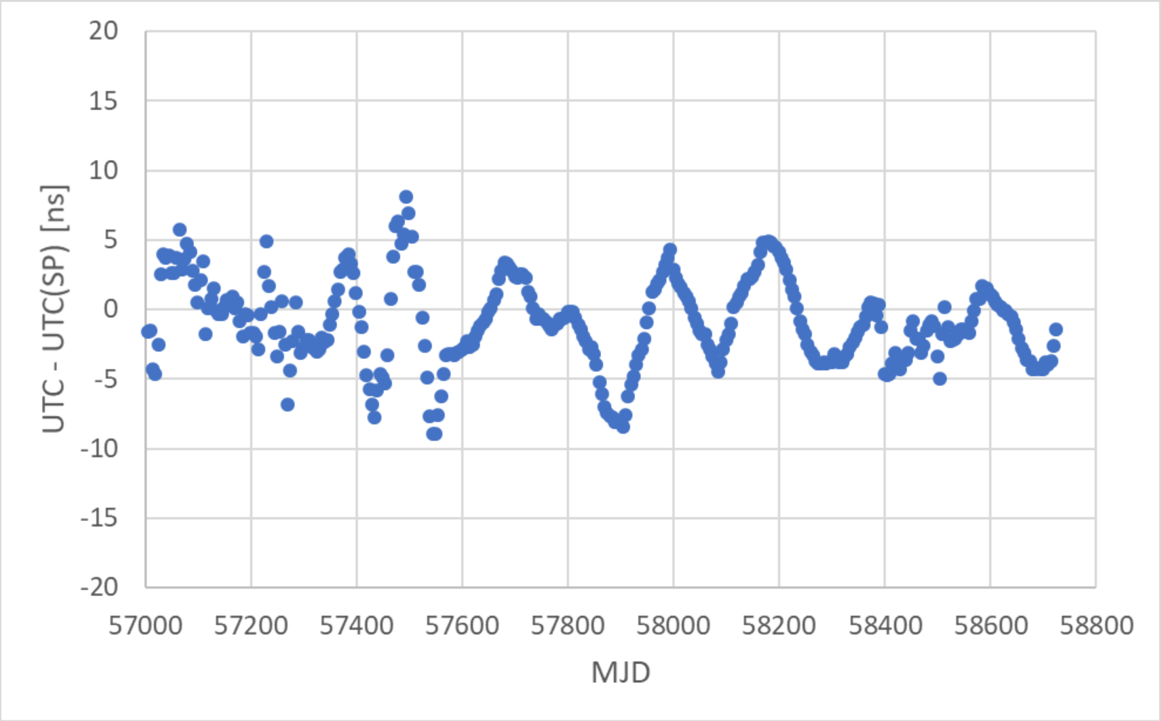
Secure Clock Site Stockholm

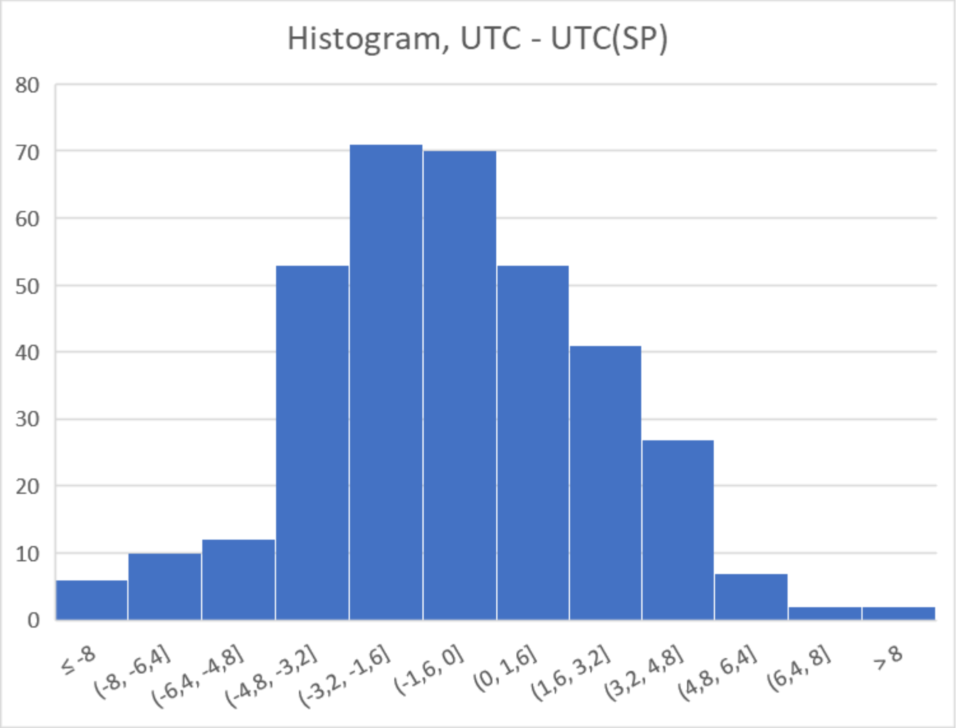
- Stockholm area, > 15 m below surface level
- EM-shielded, vibration absorbers,
  shock wave protection
- UPS, 24/48VDC backup and 3 diesel generators
- Climate control, with redundancy
- Separate redundant power and cooling supplies
- Locations divided in two separate, identical labs
  - 3 Cs and 1 active HM, UTC time scale
- Identical set of timing and communication equipment in both, separate communication paths
  - NTP, customer in Stockholm area

Swedish National Timescale UTC(SP)



Historical Deviation from UTC





Last 5 years within ± 10 ns from UTC
typically ± 5 ns

Standard Deviation = 3.5 ns
typical frequency ±5e-15

Why do we do it?

Why UTC(SP)? Who needs it? Why does it have to be secured T&F?

Autonomy/positioning

Avaiation

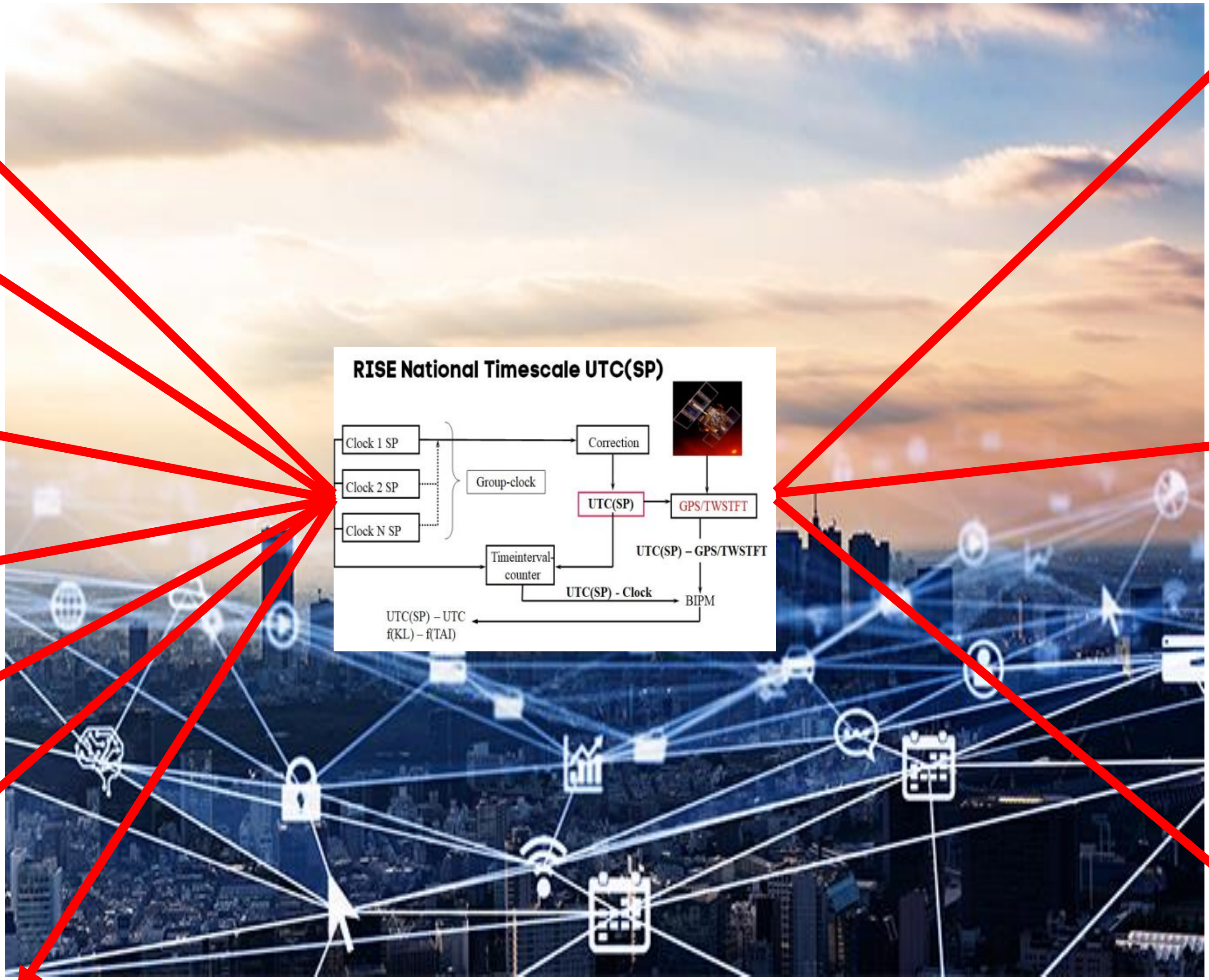
Defense

Economy

EU-projects Research

HPC/Storage

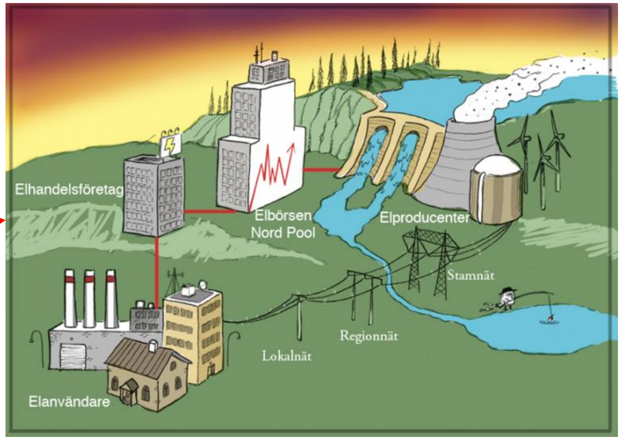
Research



Authorities

ARBETSMILJÖ VERKET
BERGSSTATEN
Boverket
ELSÄKERHETSVERKET
Energimarknadsinspektionen
Energimyndigheten
FÖRSVARSMAKTEN
LANTMÄTERIET
SJÖFARTSVERKET
NATUR VÅRDS VERKET
RIKSANTIKVARIEÄMBETET
SMHI
SVENSKA KRAFTNÄT
Länsstyrelserna
PTS
TRAFIKVERKET
TRANSPORT STYRELSEN
SKOGSSTYRELSEN
Sveriges Kommuner och Landsting
SGU

The energy sector



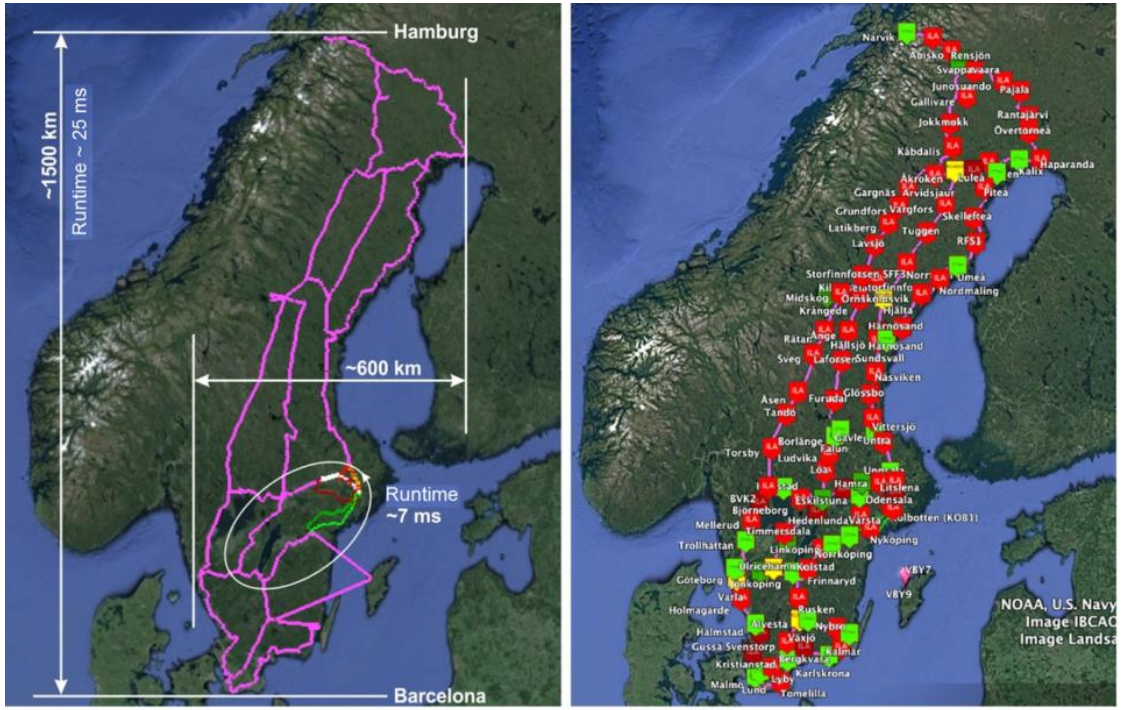
Requirements from the authority for social security and preparedness


MSB
Vikten av var och när
Samhällets beroende av korrekt tids- och positionsangivelse

RI. SE

SUNET C

- Distance from North to South is comparable to the distance between Hamburg and Barcelona
- ROADMs in every university city
  - Reconfigurable Optical Add Drop Multiplexer
- Optical In-line Amplifiers
  - EDFA and Raman combined



Backbone without nodes

Backbone with nodes

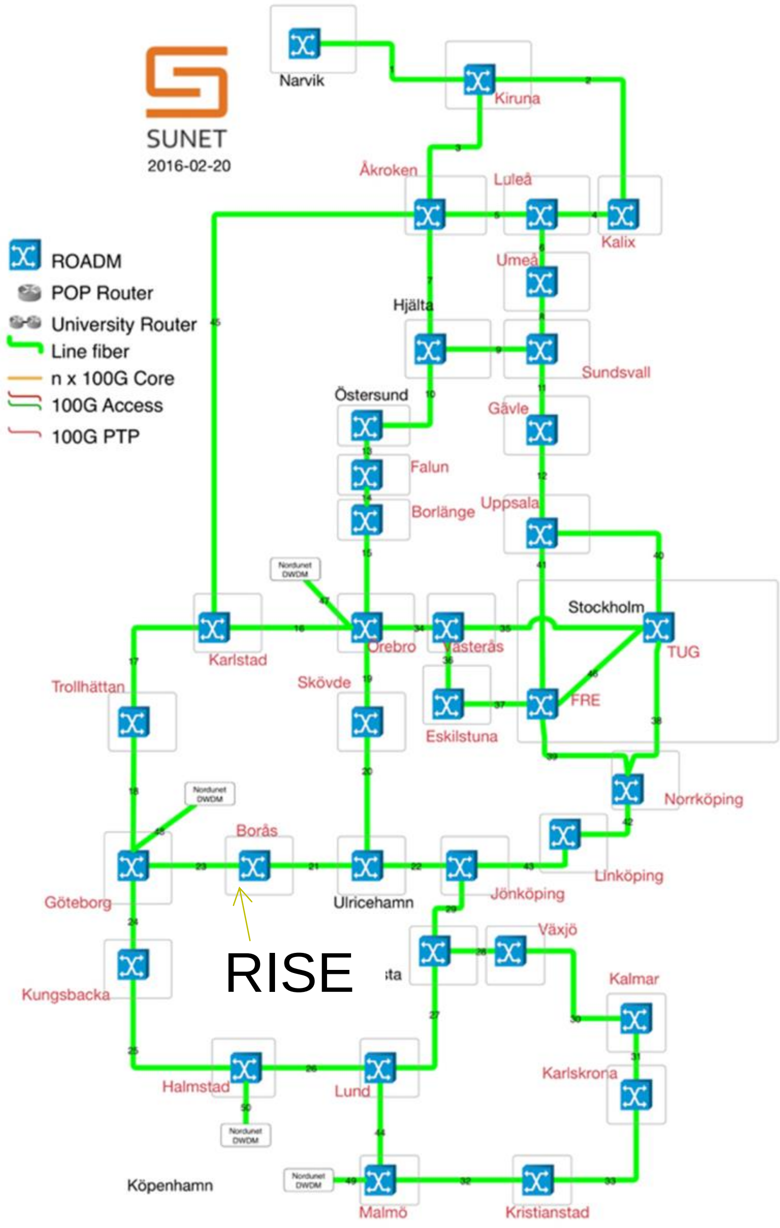
ILA, In-Line Amplifier, optical amplifier

POP, Point of Presence

The Figure presents all drop-off of wavelengths in the major cities and single amplifiers in between, which are a total of 88 Inline Amplifier sites (ILA) and 36 backbone Point of Presence (POP) with Reconfigurable Optical Add Drop Multiplexer (ROADM)

Network scheme

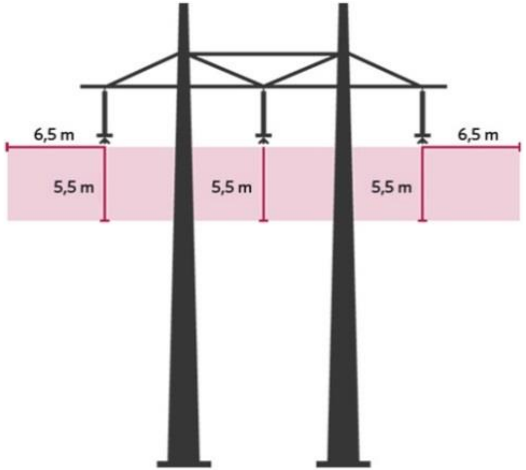
- 100 Gb/s routers at each client and in Stockholm
  - Two central hubs for robustness
  - 25 Gbaud, 4 QAM, dual polarization
  - Upgrade to 200 or 400 Gbit/s possible
  - No optical dispersion compensation, no optical polarization tracking, all handled by DSP at Rx
- Wavelength routed through ROADMs along shortest open path
- Point-to-point connection between two clients can be enabled dynamically



RISE

Utilizing power grid fiber

- SUNET C are utilizing optical fiber along the power grid within Sweden
- It result in 50Hz interference and variations in polarization along the fiber path.
  - When the magnitude of the interference is substantial, harmonic frequencies of 50 Hz appears in the polarization variation.
- The 50Hz interference is might due to the fact that the fiber for some part introduce an angle to the power cable and that induce a interference related to the Faraday effect



Summary SUNET C

- SUNET C is an all-optical network connecting all University-cities in Sweden
- Capacity for each client to have 100 Gb/s on predefined wavelength
- Flexible ROADMs enables arbitrary wavelength at a grid of 12,5 GHz
- Robust network with 2 or more spatially separated fiber pairs to each client
- Most of the fiber are in aerial installations along power lines

SUNET C

What have we done before

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

WRITE

JRP 17IND14 http://empir.npl.co.uk/write/

WRITE - White Rabbit Industrial Timing Enhancement

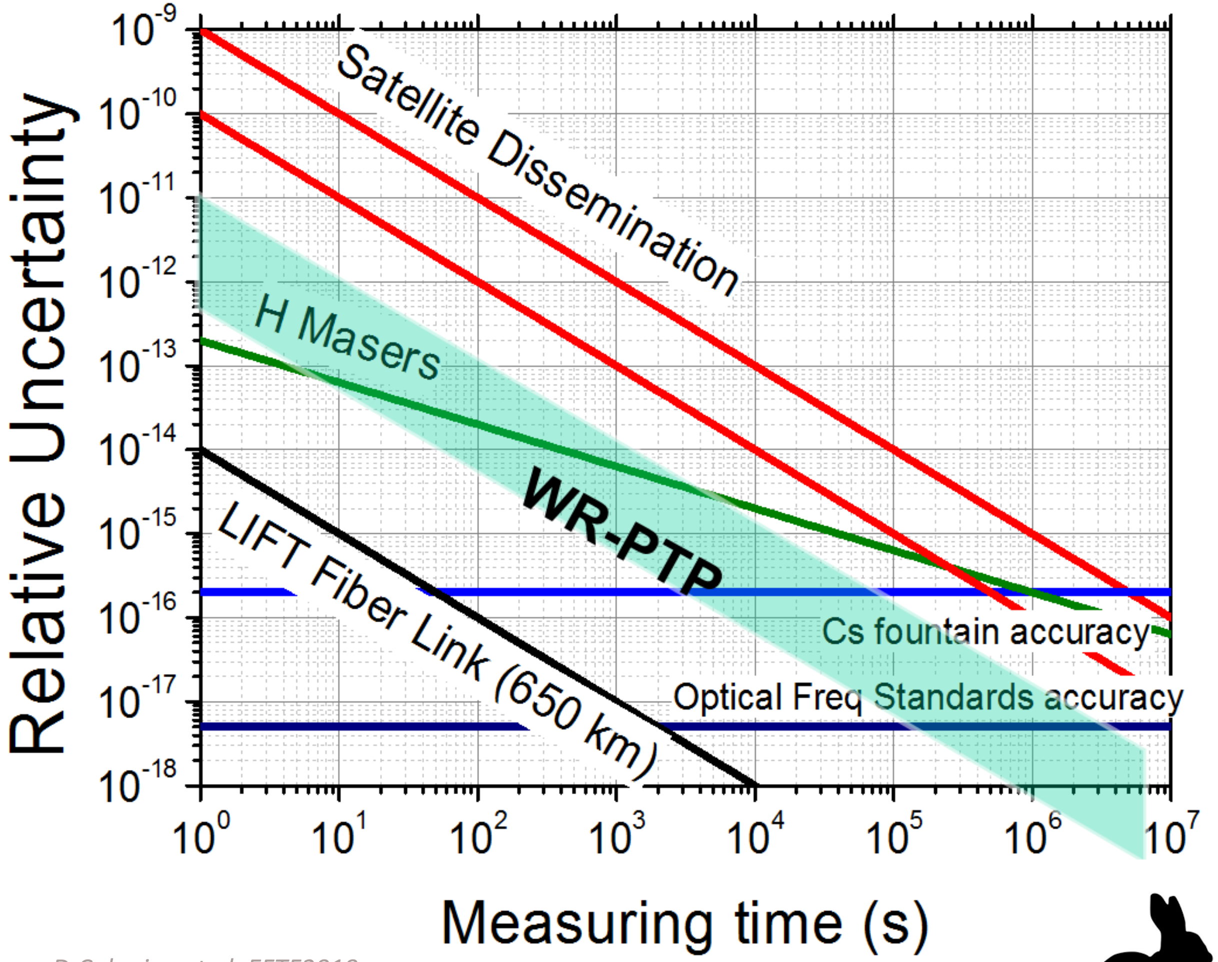
WRITE White Rabbit Industrial Timing Enhancement

Aim

To use metrological developments accelerating the industrial adoption of PTP-WR

Motivation

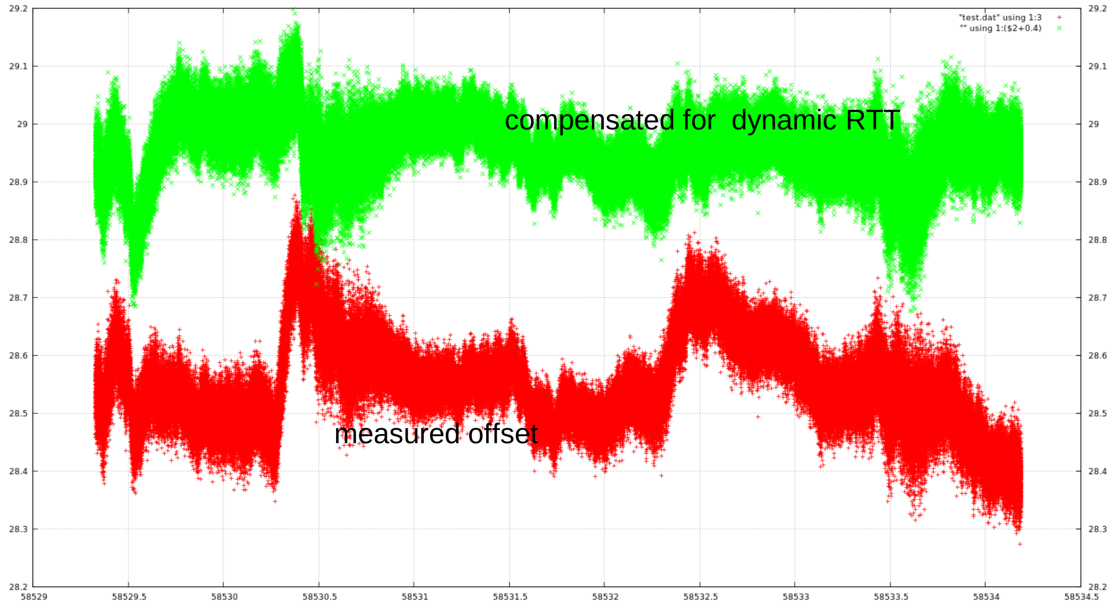
- **Scalability**
  Develop scalable calibration techniques for PTP-WR, 200 ps uncertainty using existing fiber configurations.
  Propagation Calibration - Absolute calibration- In Field protocols
- **Resiliency**
  Develop validated techniques for redundant and resilient time transfer Topology - Holdover- Monitor
- **Performance**
  New PTP-WR devices, with improved performance and better compatibility with existing protocols and standards. Target freq. instability: < 1e-13 @100s
  Improved local oscillators – SPEC7 hardware - protocol compatibility PTP
- **Real Field**
  Demonstrate the use of PTP-WR to deliver UTC to industrial users Space FR/IT - Financial NL - Telecom SE



D.Colonico et al. EFTF2019

WR and Coherent Communications

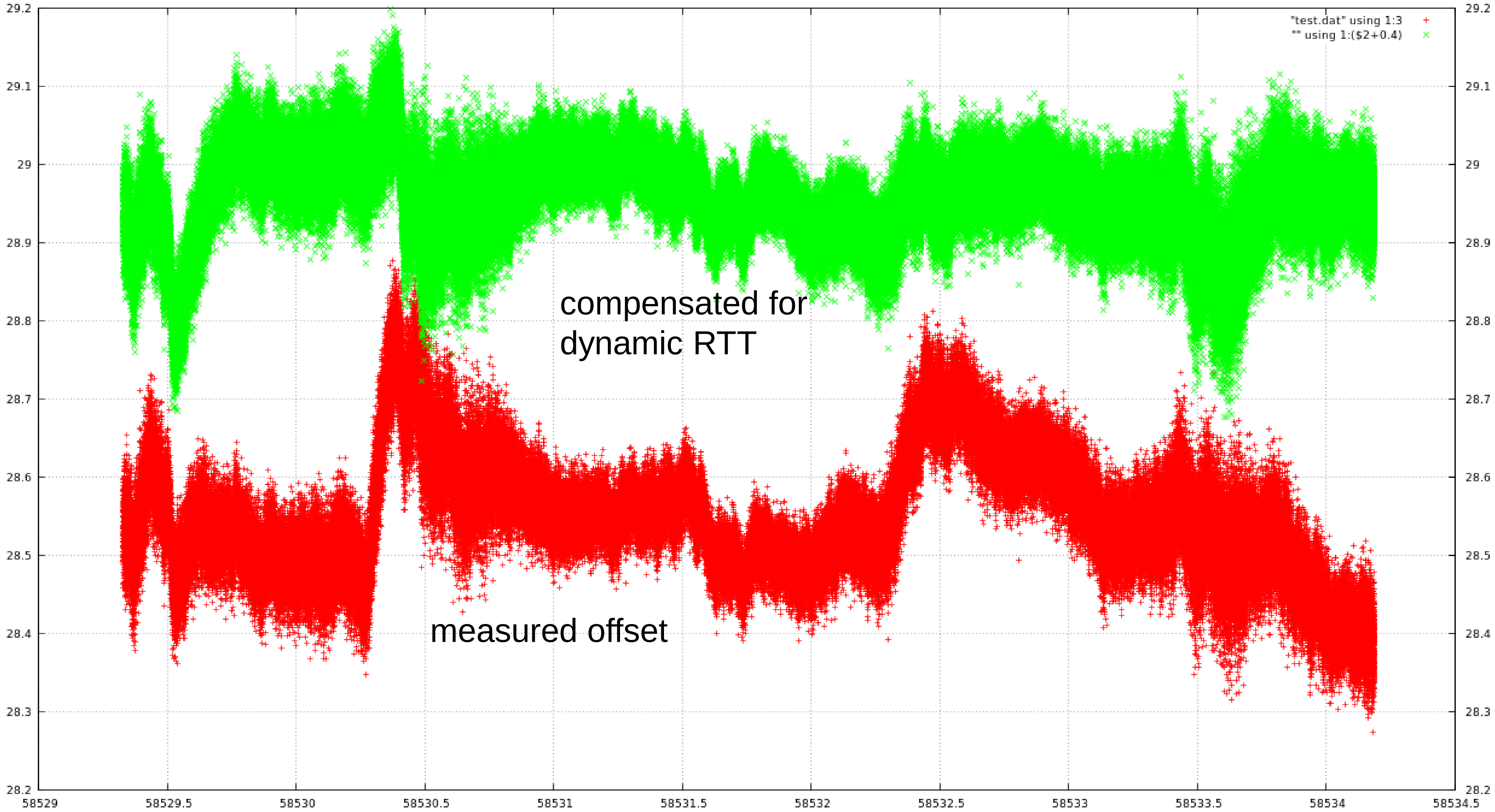
- Run AM light beside coherent 100G slots in SUNET-C
  - ROADM based, no dispersion compensation
  - Unidirectional, two fiber, same wave length
- 800 km (**8 ms** RTT) in southern Sweden 7SOL LEN GM/SL @RISE , 13 hops
- C36, with several empty slots space to next carrier
- Initial DCM+AMP, but expect less than 100 ps broadening,
- works without DMC,
  need about zero dBm input
- High jitter, both on 1pps and
  the LEN reported clock offset
- Uncorrected alpha,
  change in offset correlates
  with RTT changes of several
  hundred nanoseconds



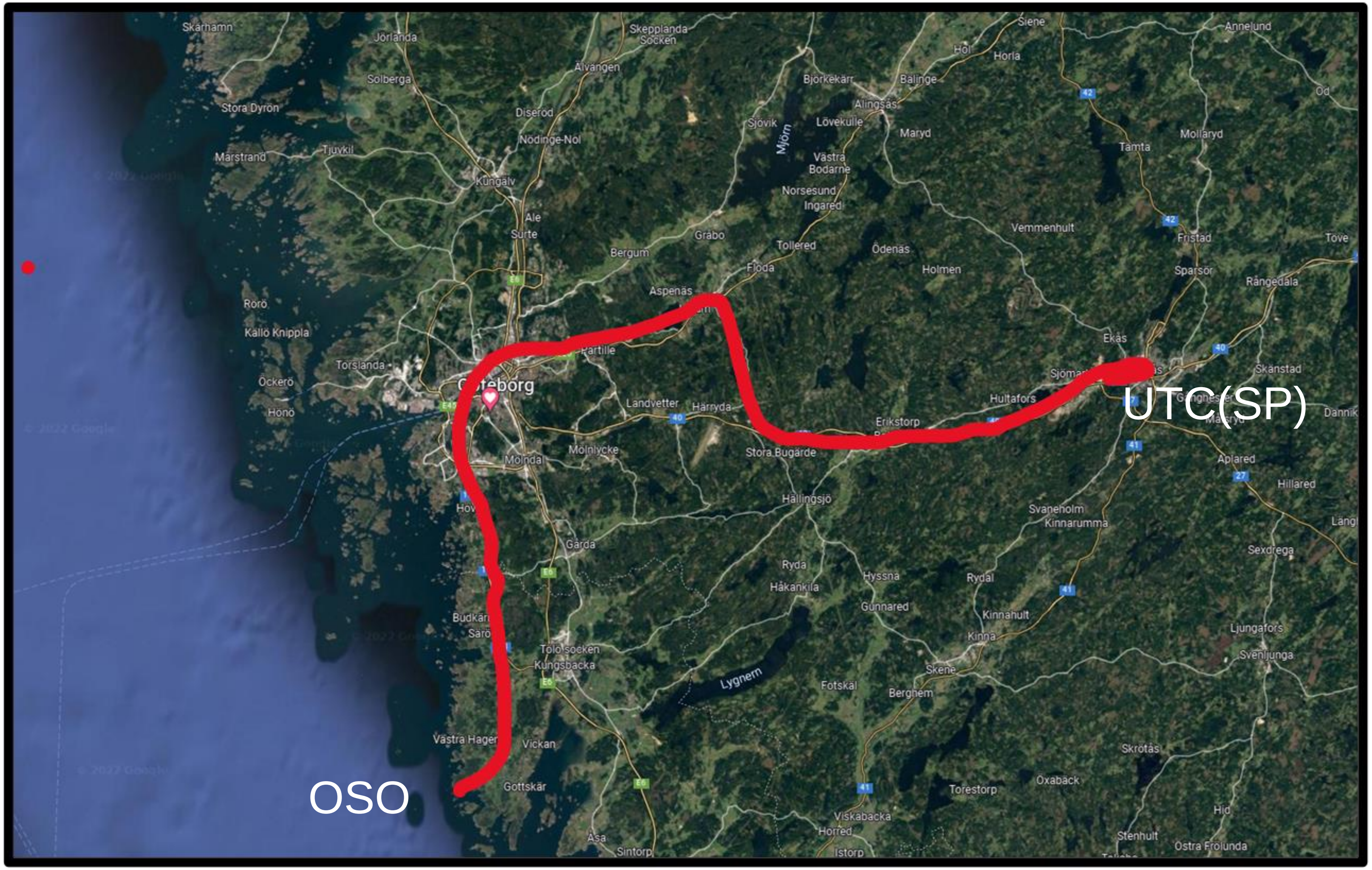
SUNET

https://kt.cern/sites/knowledgetransfer.web.cern.ch/files/styles/slideshow_image_style/public/images/success-stories/story-white-rabbit.png?itok=GwFMCIDk

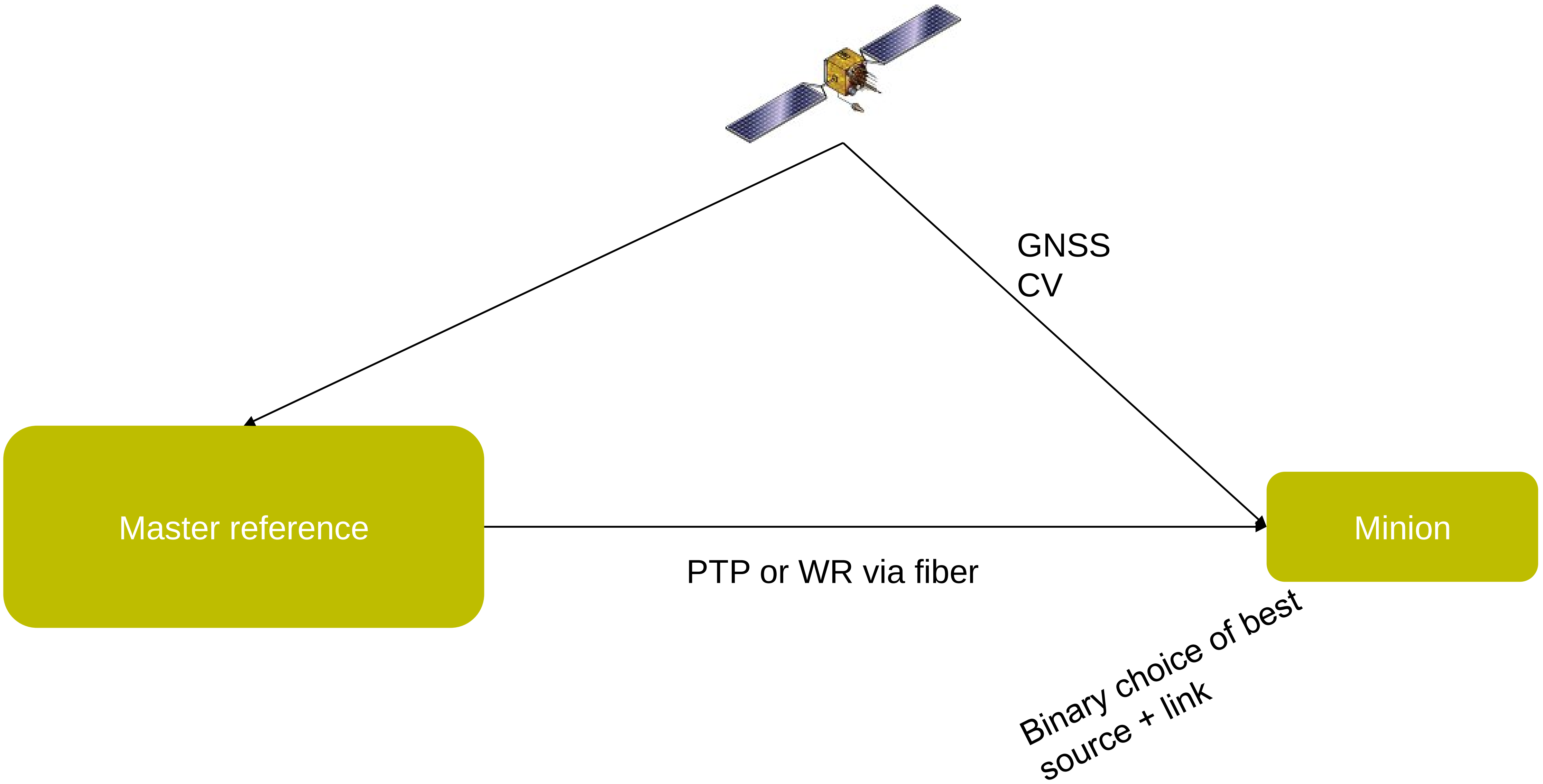
Redundant UTC(SP) dissemination to a telecom user



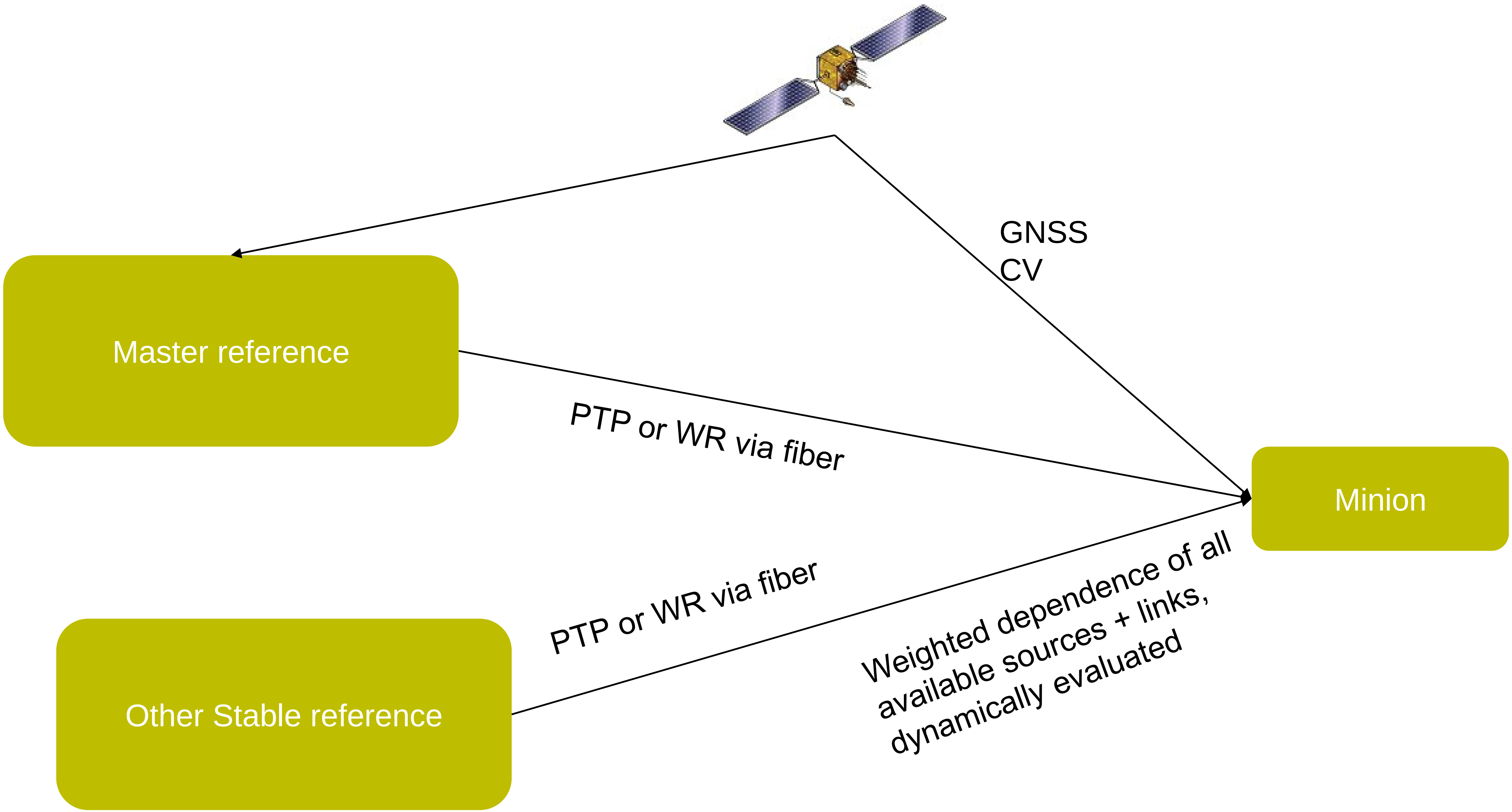
The setting, on the west coast of Sweden



Present Implementation



Proposed Implementation



What are we planning to do now

Field Trial of FPGA-Based Real-Time Sensing Transceiver over 524km of Live Aerial Fiber

Mikael Mazur[1], Dennis Wallberg[2], Lauren Dallachiesa[1], Erik Borjesson[3], Roland Ryf[1], Magnus Bergroth[2], Borje Josefsson[2], Nicolas K. Fontaine[1], Haoshuo Chen[1], David T. Neilson[1], Jochen Schroeder[4], Per Larsson-Edefors[3] and Magnus Karlsson[4]

(1) Nokia Bell Labs, Murray Hill, USA
(2) Sunet, Tulegatan 11, Stockholm, Sweden
(3) Department of Computer Science and Engineering, Chalmers University, Sweden
(4) Department of Microtechnology and Nanoscience, Chalmers University, Sweden

mikael.mazur@nokia-bell-labs.com

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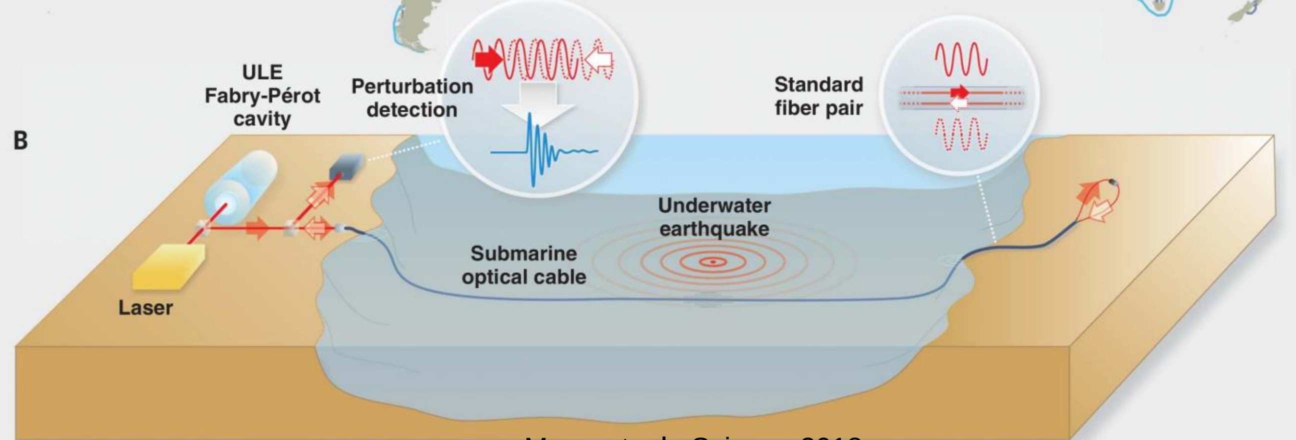
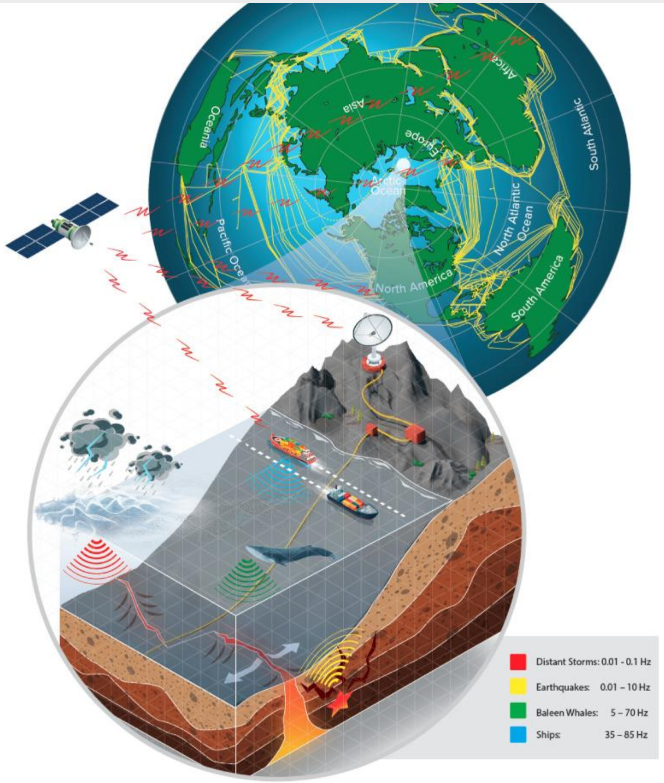
Fiber Sensing

Bridging the community gap



Marra et. al., Science 2018

- Fiber sensing
  - Tones of single-mode fibers deployed for sensing purposes
  - Fiber is very sensitive: Strain, temperature, mechanical perturbations,...
  - The fiber sensitvity enables the fiber sensing field…
    but is also the reason we need dynamic DSP tracking!
- Example of sensing effects/techniques
  - Phase interferometry, polarization interferometry
  - Rayleigh, Brillouin and Raman scattering
- Why use telecom networks for sensing?
  - Improve the network reliability and protect against outages
  - Deployed fibers can expand coverage to new areas
  - Overall improve the role of fiber infrastucture in our society



M. Landro et. al., Sci. Rep. 2022

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Transceiver-based Fiber Sensing

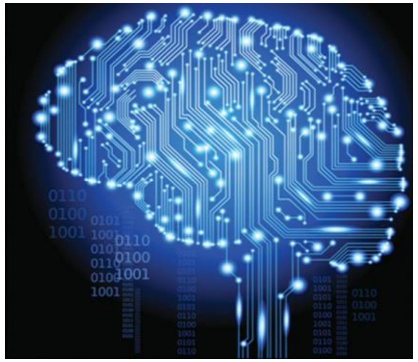
Unlocking another use-case

- Coherent transceiver with DSP
  - Full-field detector → Polarization and phase interferometer
  - Dynamical DSP engine to "eliminate" the effects of the fiber as a sensor
  - Can we turn these block into sensors
- Key challenges
  - Much lower SNR, ENOB: 100+GS/s ADCs
  - High-speed parallel DSP engine. Data cannot be stored and processed offline
  - Sensing filtering/implementation must be compatible with ASIC architectures
- Potential
  - Complimentary technique to dedicated sensing systems
  - Very large number of coherent transceivers out there
  - Inherently compatible telecom systems, it's a transceiver!!!

Compensate any physical distortions

Sensing

Monitoring network environment
Active outage prevention



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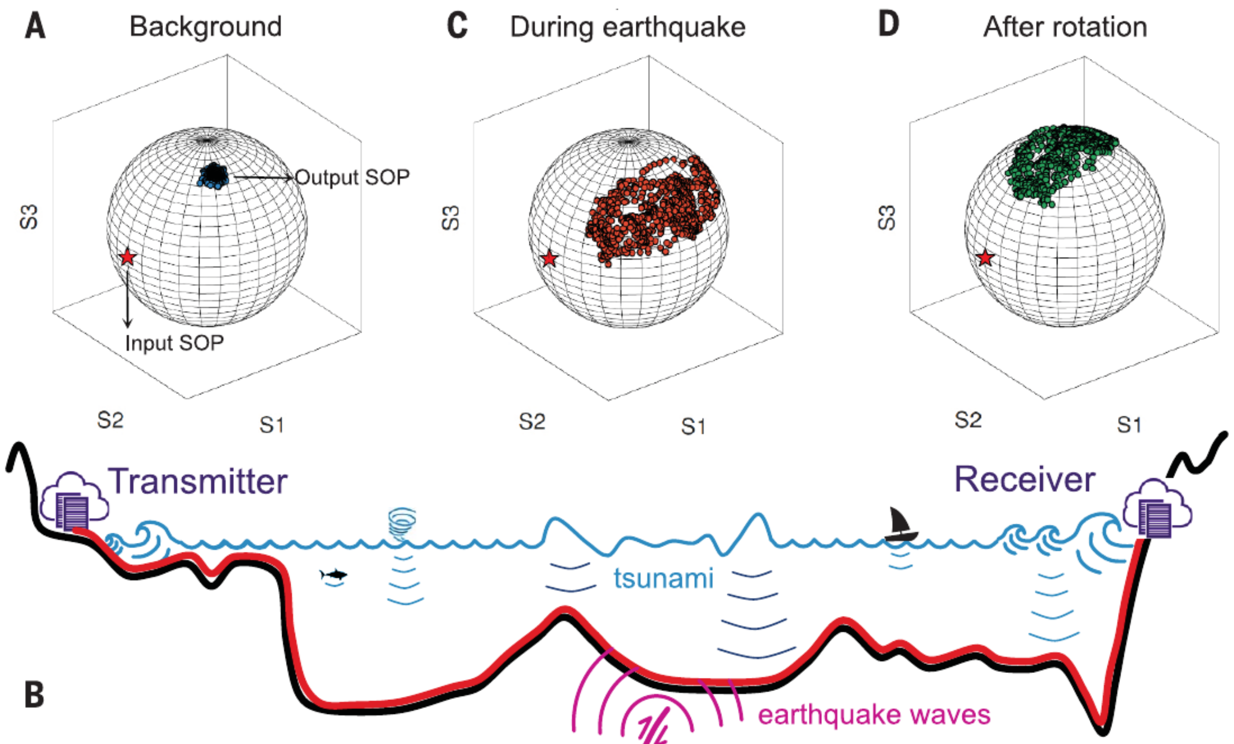
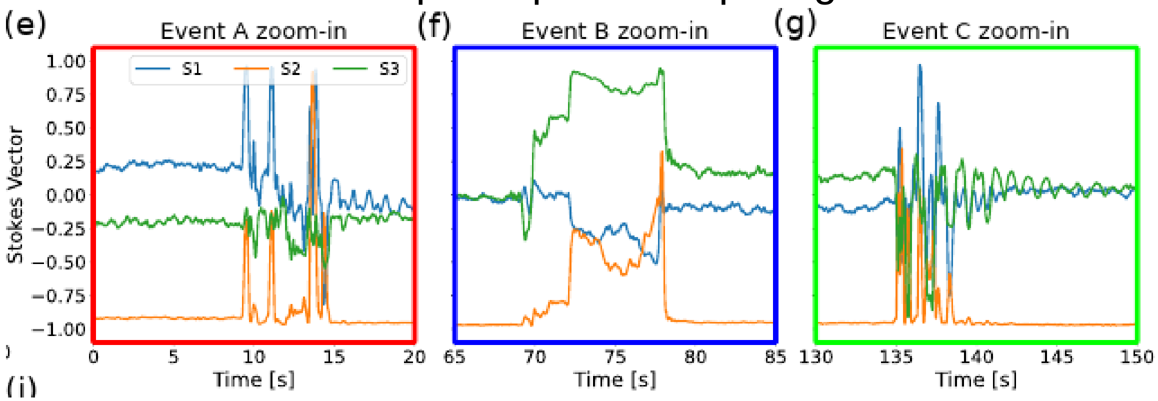
Examples of Transceiver-based Sensing

Earthquake detection using commercial transceivers



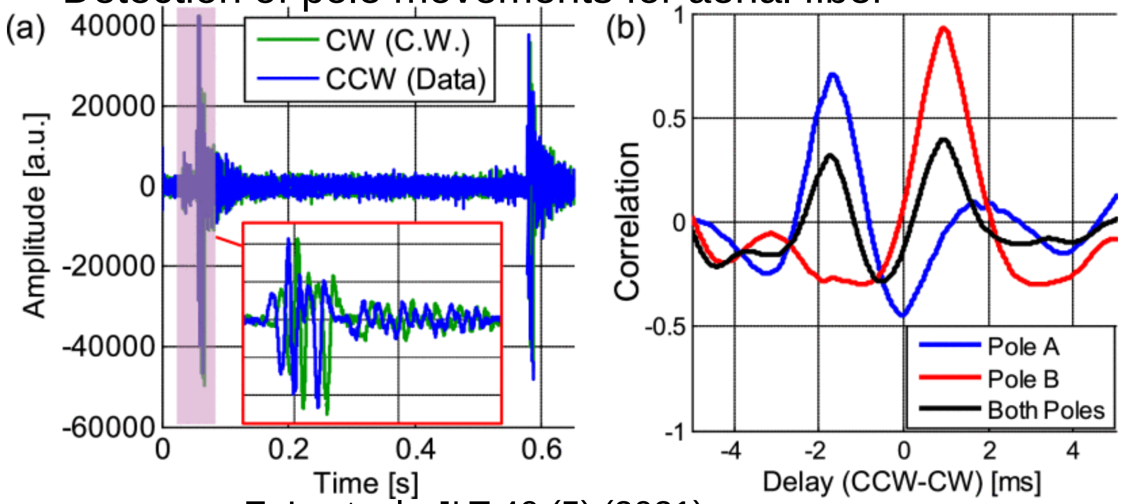
Zhan et. al., Science (2021)

Detection of fiber patch panel tampering over field link



M. Mazur et. al., Proc. ECOC (2022)

Detection of pole movements for aerial fiber



E. Ip et. al., JLT 40 (5) (2021)

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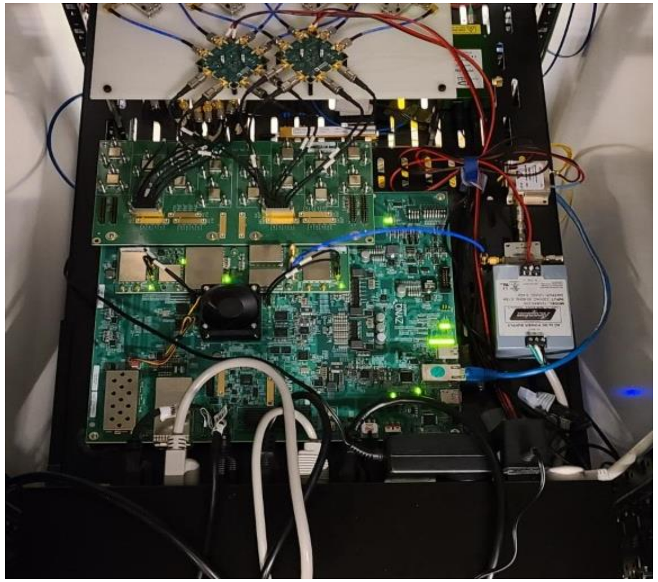
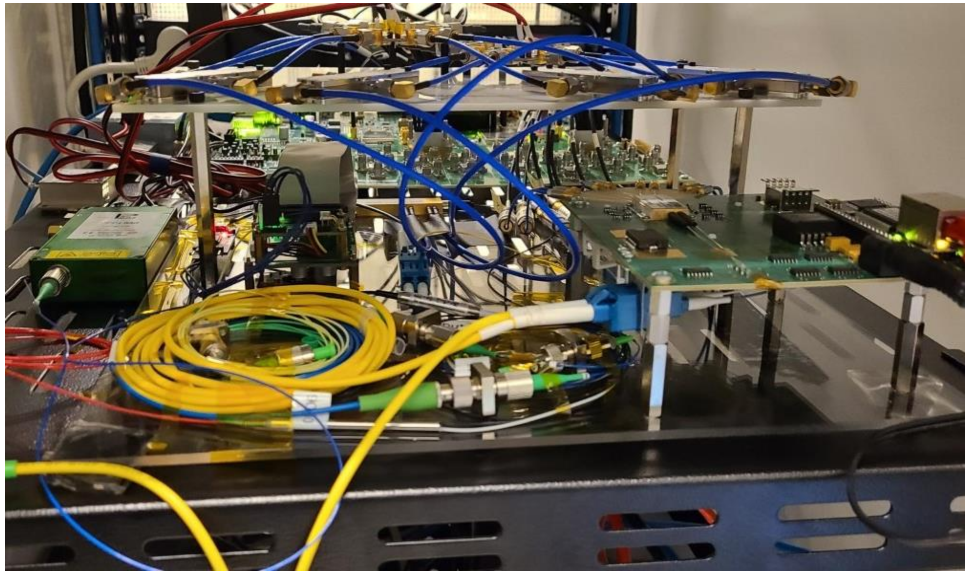
Coherent Transceiver Prototype

- FPGA-based coherent DSP Engine
  - 1GBd transmission
  - 125MHz DSP clock rate, 8 parallel lanes
  - Complete pilot-based coherent DSP written in VHDL
  - All DSP blocks updated every clock cycle



- Sensing capabilities
  - Polarization and phase sensing
  - This work focus on equalizer-based sensing
  - Complete streaming of equalizer state at MHz rate
  - Both hardware and software-level filtering implemented



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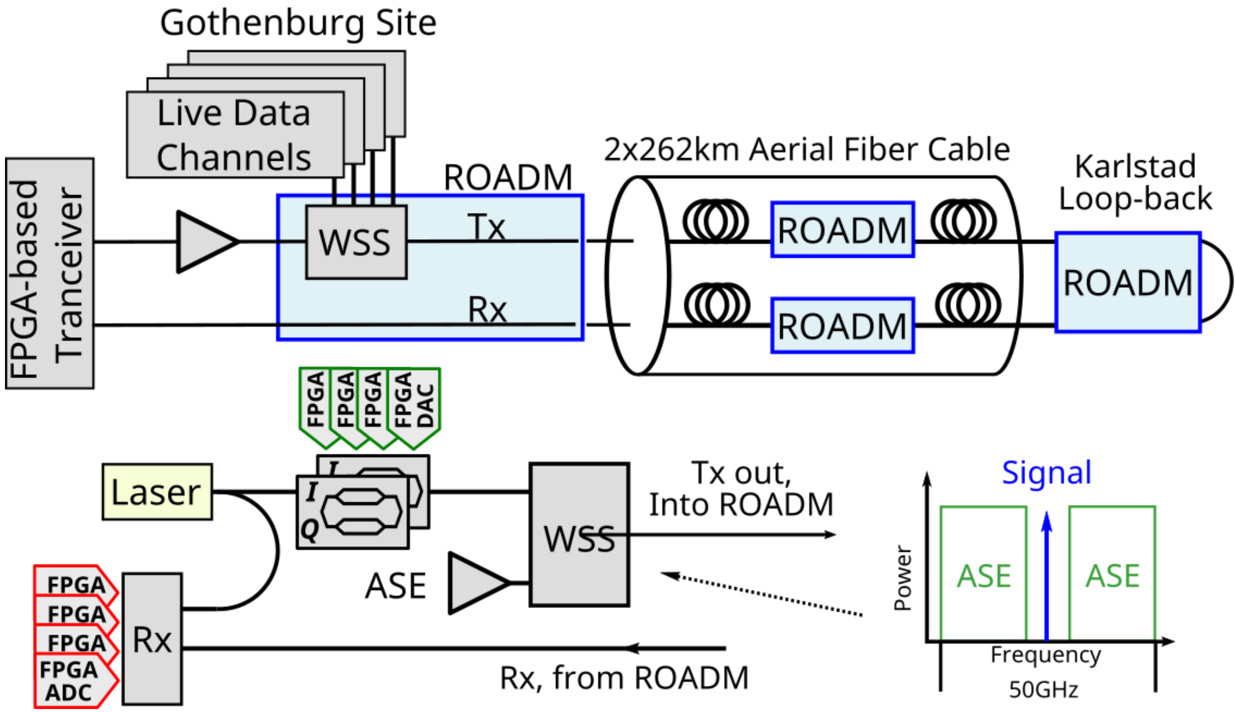
Live Network Trial

- Connected to ROADM node in Gothenburg
  - 50GHz channel emulated by combining with ASE
  - Combined with multiple live coherent transceivers
  - Launch power equalized using ROADM WSS
- Loopback in Karlstad
  - Channel extracted using ROADM node
  - Physical loopback to transmit signal back to Gothenburg
- Receiver implementation
  - Full band drop-node, passive splitter
  - No optical filter present due to equipment limitations
  - Coherent Rx in homodyne configuration



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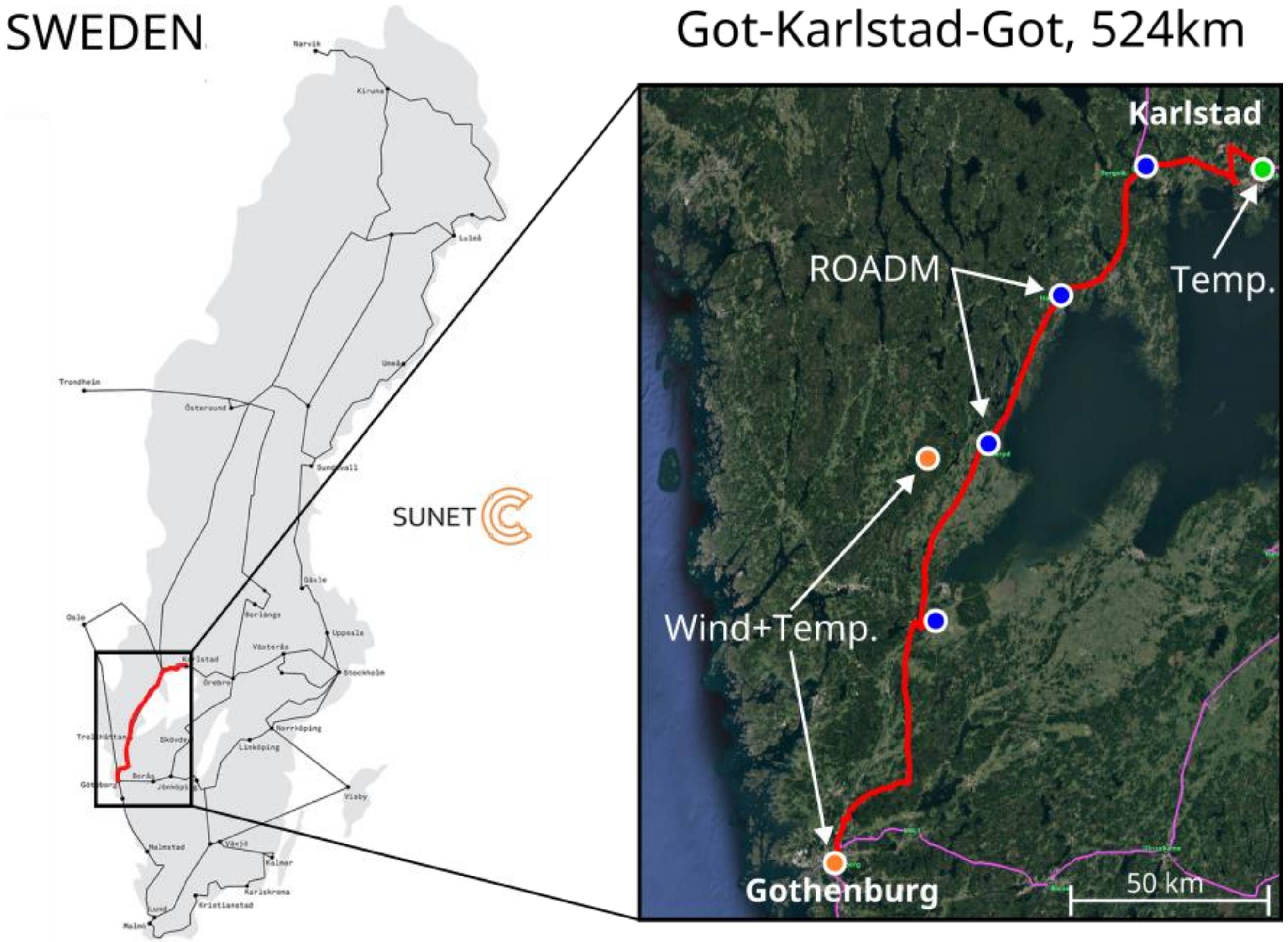
Field Trial – 524km of Aerial Fiber

- Sunet Network
  - Provides connectivity to universities
  - Part of Nordnet, connects Scandinavia
  - Different links with a high degree of redundancy
- Specific test link
  - Gothenburg-Karstad
  - 262km one way
  - Passes 5 live ROADMs
- Aerial fiber link
  - Fiber wound around high power lines
  - Very exposed to the environment



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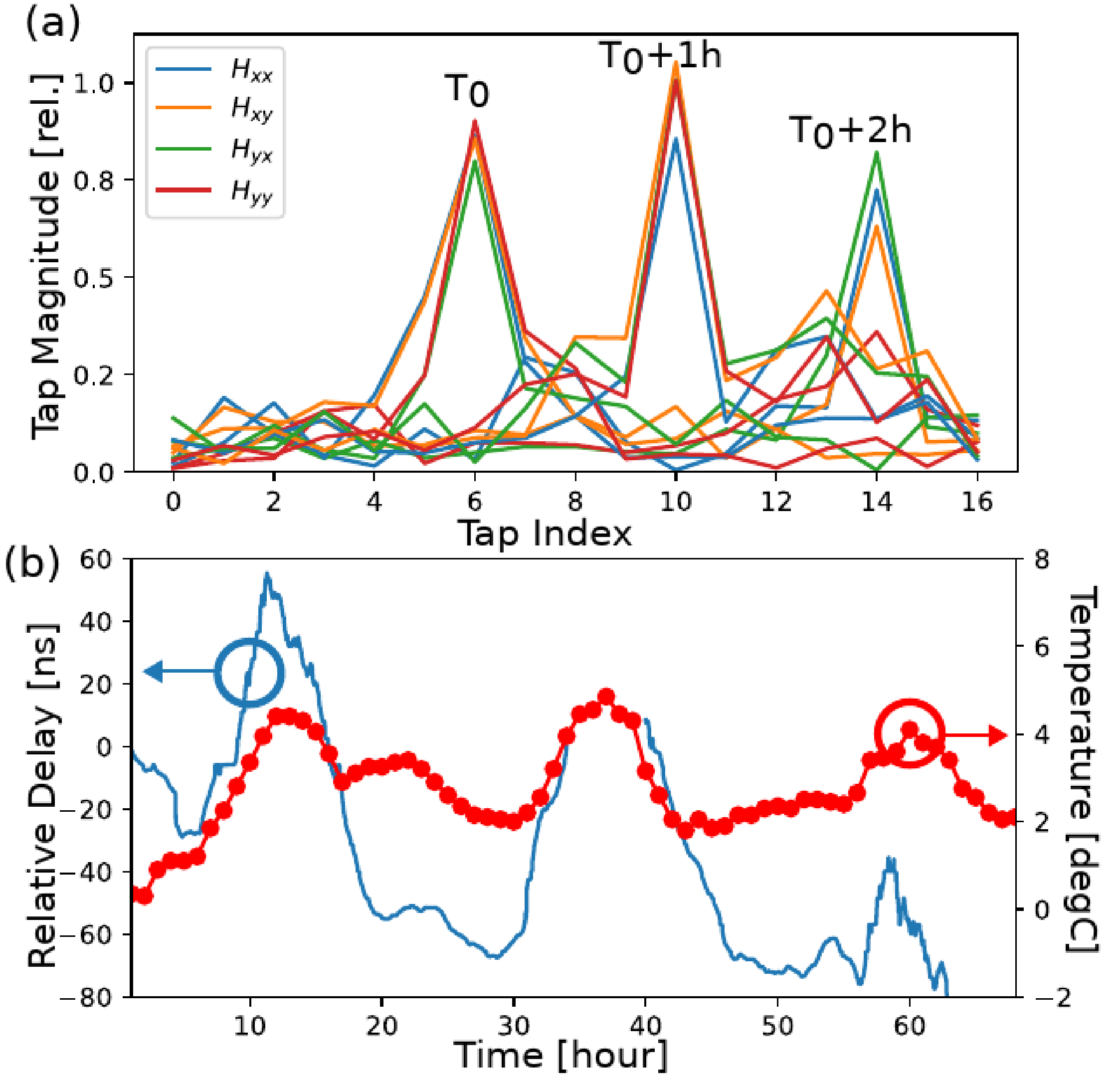
Results – Time-of-flight measurements

What can be learned from timing recove

- Dynamic equalizer for timing recovery
  - Stochastic gradient descent to optimize sampling position
  - Fiber stretch is an example of link-induced delay
- Time-of-flight measurements
  - Typically done using time-domain pulses
  - Transmitted signal is a continous pulse train
  - Monitoring sampling position and phase → time-of-flight (ToF) measurements
- Correlation with weather stations along the link
  - Good qualitative agreeement
  - Very dynamic link, lot of length change!
  - Requires clock tracking/referencing for non-loopback configs



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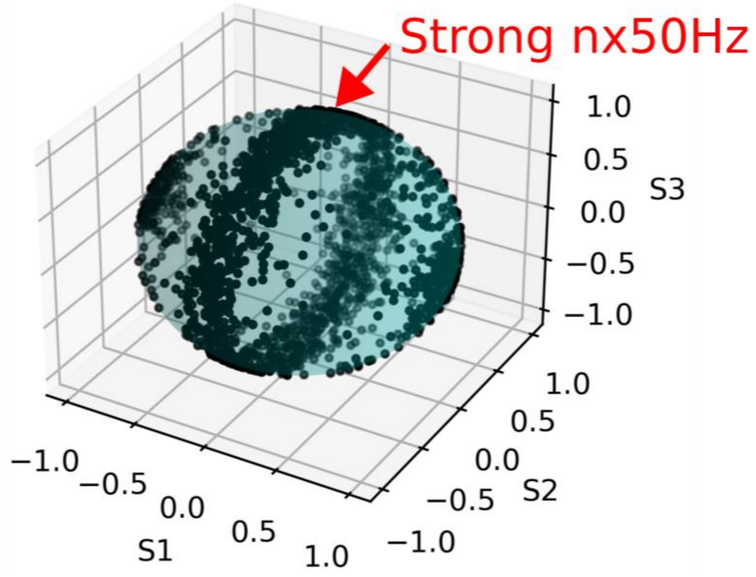
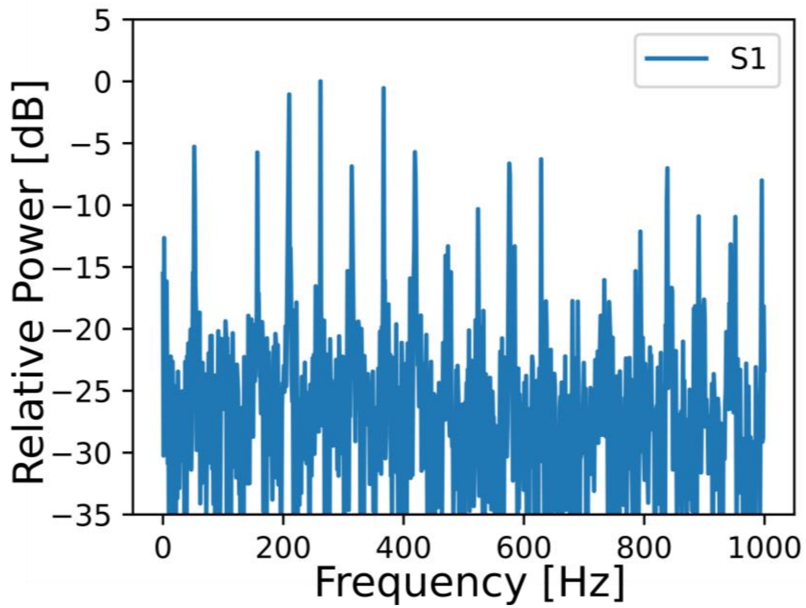
Results – State of Polarization

Aerial fiber wound around high voltage cables

- Measured polarization
  - Stokes vector extracted from received X-polarization
  - Strong 50Hz and overtones
  - Tones present for all Stokes parameters
- Strong tones dominates the polarization response
  - Similar to system noise
  - Must be filtered out to enable environmental sensing
- Correlation with weather stations along the link
  - Good qualitative agreeement
  - Very dynamic link, lot of length change!
  - Requires clock tracking/referencing for non-loopback configs





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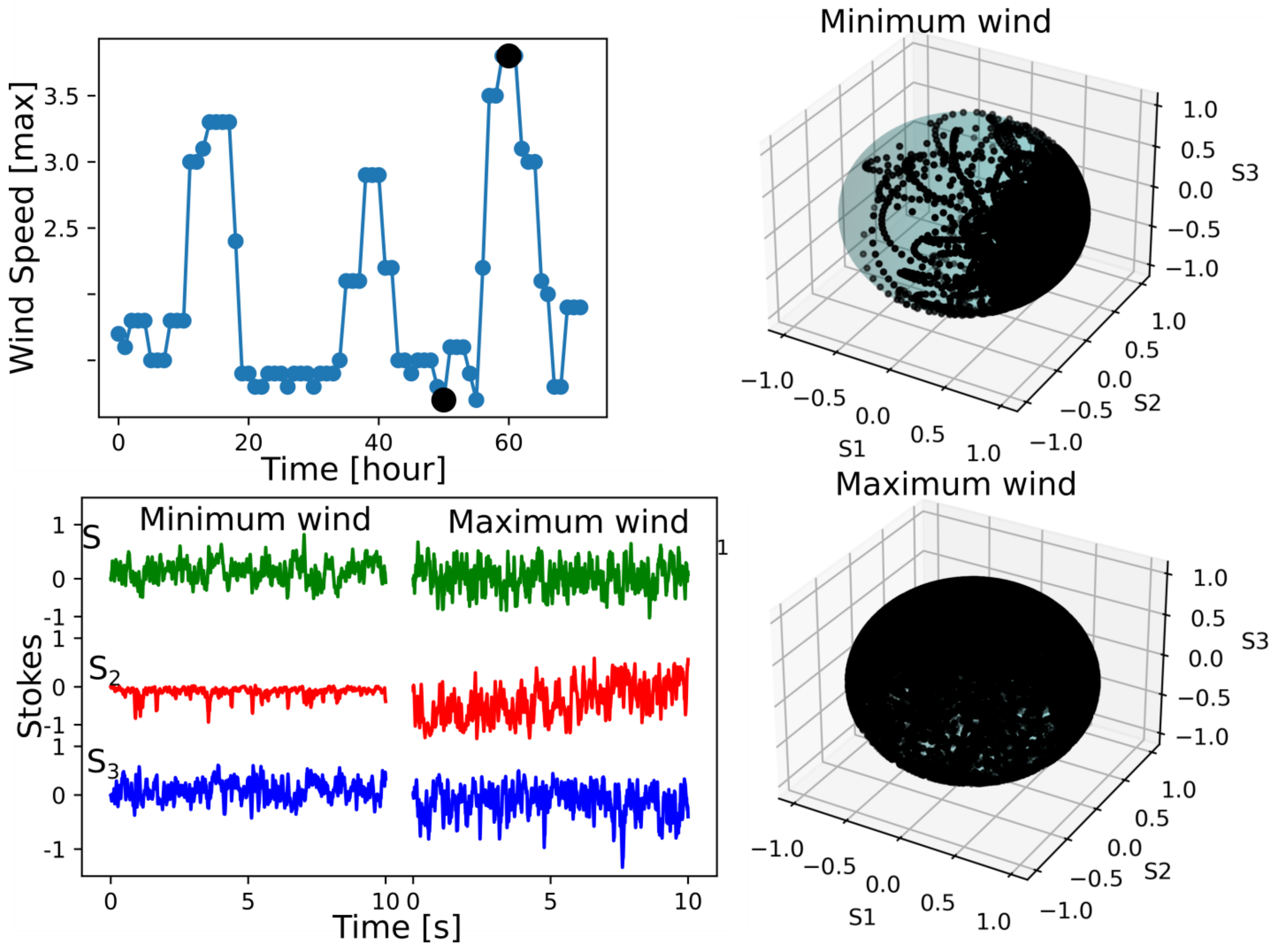
Results – State of Polarization

Is environmental sensing still possible?

- Nature is typically well behaved
  - No distinct frequency tones
  - Broadband, low-frequency response
  - Ranges of interest can be filtered out
- Extracting wind contributions
  - Focusing on frequencies below 45Hz
  - High sampling rate avoids aliasing
  - Filtering and decimation can be done in HW
- Difference in wind conditions observed
  - Amount of SOPR clearly correlates
  - Aerial fiber, highly affected
  - Frequencies of interest very different



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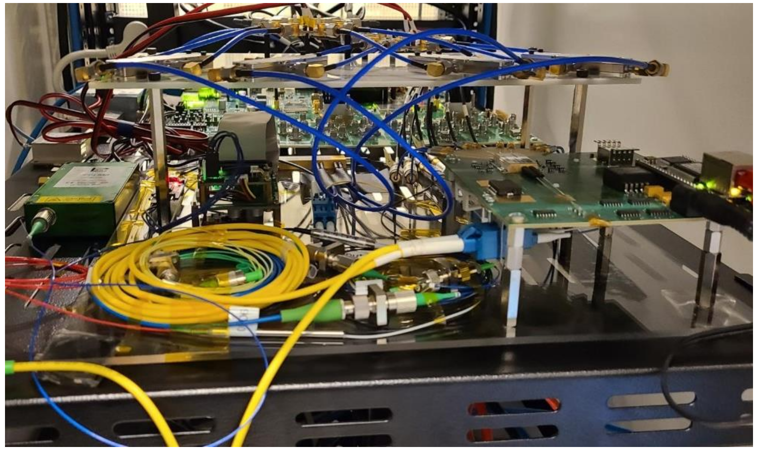
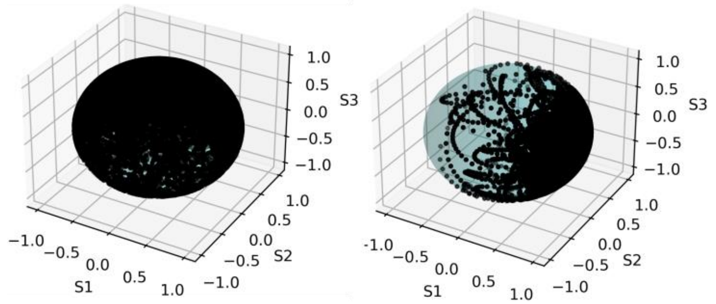
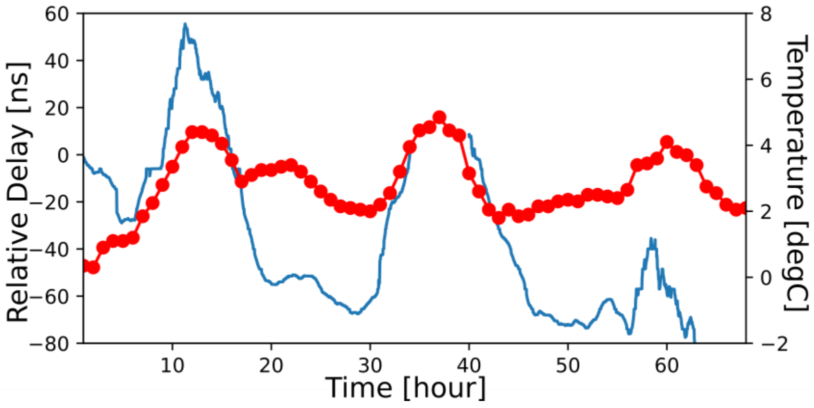
Conclusions

Transceiver-based sensing over aerial fibers

- Coherent transceiver as sensors
  - Full-field detector → Polarization and phase interferometer
  - DSP continously track environmental fiber distortions
  - Might be hard to get to but the information is there!
- Field trial over 524km of aerial fiber
  - Fiber wound around high voltage cables
  - Polarization rotations dominated by n*50Hz
  - Can be filtered out with sufficient sampling rate to avoid aliasing!
- Environmental sensing
  - Demonstrated equalizer-based time-of-flight measurements
  - Good qualitative agreement with temperature observations
  - Showed SOP-based monitoring of wind conditions







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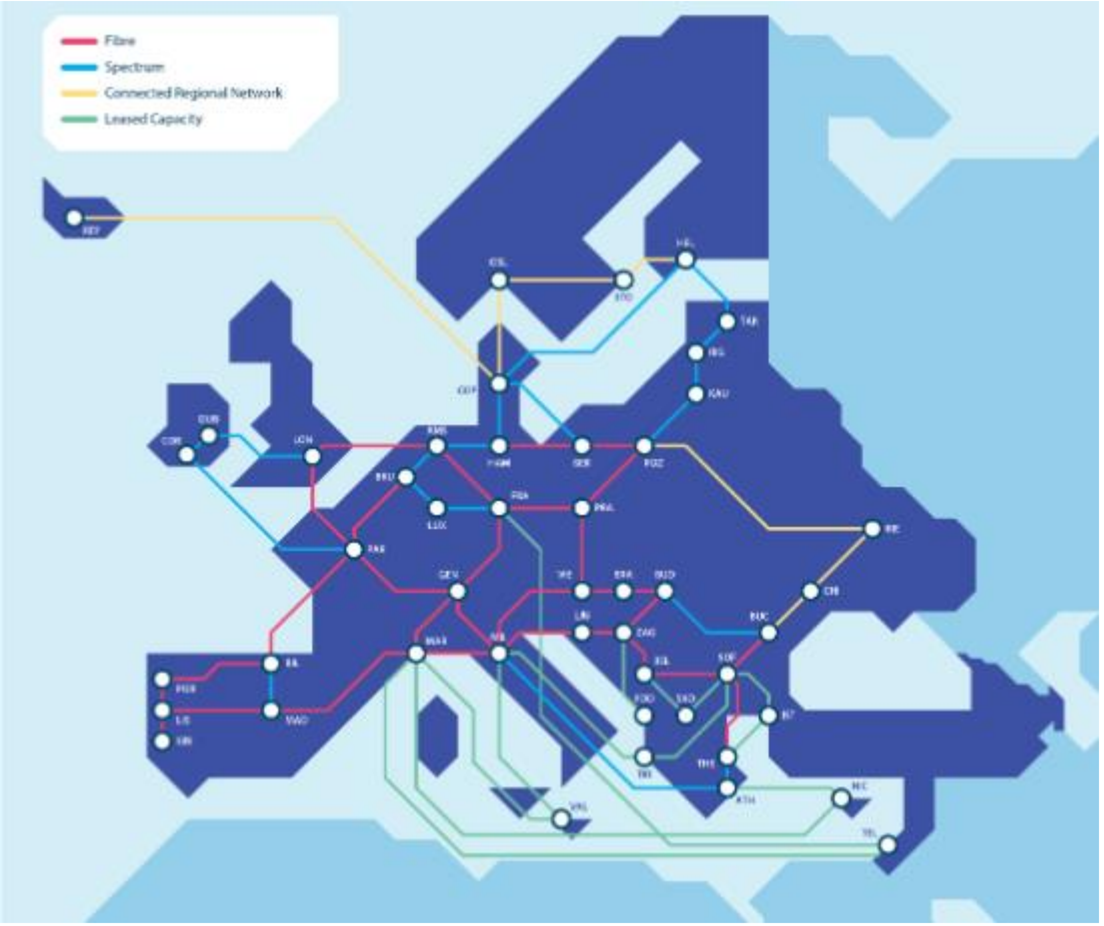
So far

Initial aim specifications

- 100GBit compatible
- 1pps
- Frequency 1 to 200 MHz
- 19 inch rack
- Bi-direct and duplex
- Sub ns
- PTP, WR or custom format
- Redundant power
- FPGA



THANK YOU FOR YOUR ATTENTION

Sven-Christian Ebenhag

Research Institutes of Sweden

Safety and Transport
Measurement Science and Technology