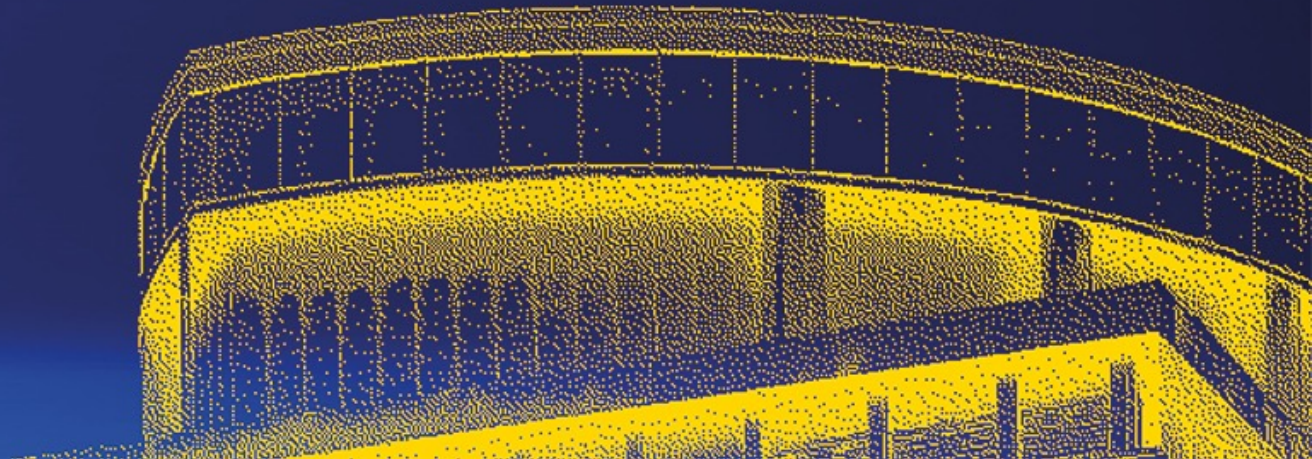


SWEDISH **BIG SCIENCE FORUM**



FREQUENCY AND TIME SYNCHRONISATION



**Sven-Christian
Ebenhag**

Senior Researcher/
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Harri Hellgren

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Norbert Hubi

Technology Development
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SKA

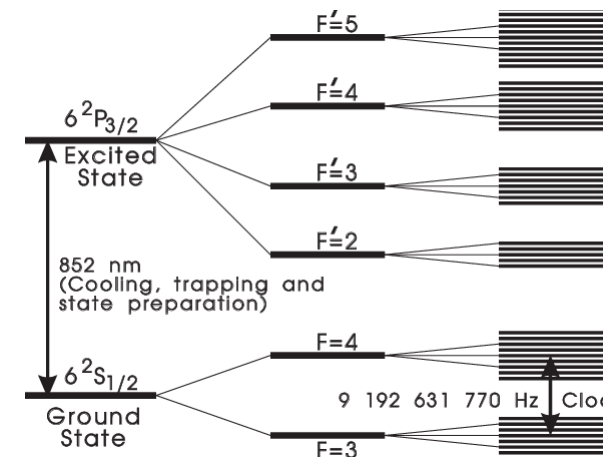


Time and Frequency

Swedish Big Science Forum 2024-02-01

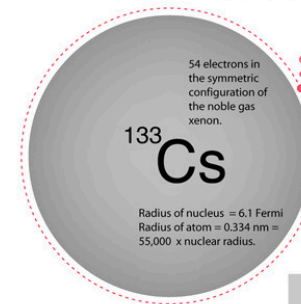
How long is a Second?

- 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

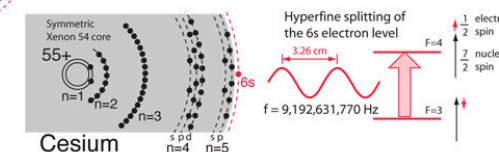


Cesium Atomic Clock

1 second = 9,192,631,770 cycles of the standard Cs-133 transition



The lone electron outside the 54-electron symmetric core is at a distance of about 55,000 x the nuclear size. It has a splitting of energy levels about 1/100,000 the ionization energy and even 1000 times smaller than the thermal kinetic energy of the atom. But the exceptional precision of that tiny energy splitting allows us to measure time with a precision of 1 second in 1.4 million years!



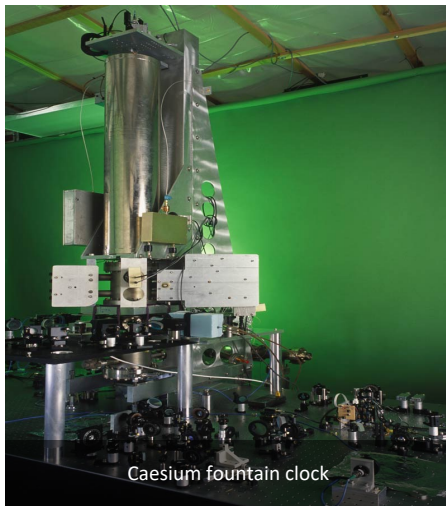
Atomic clocks



Commercial Caesium clock



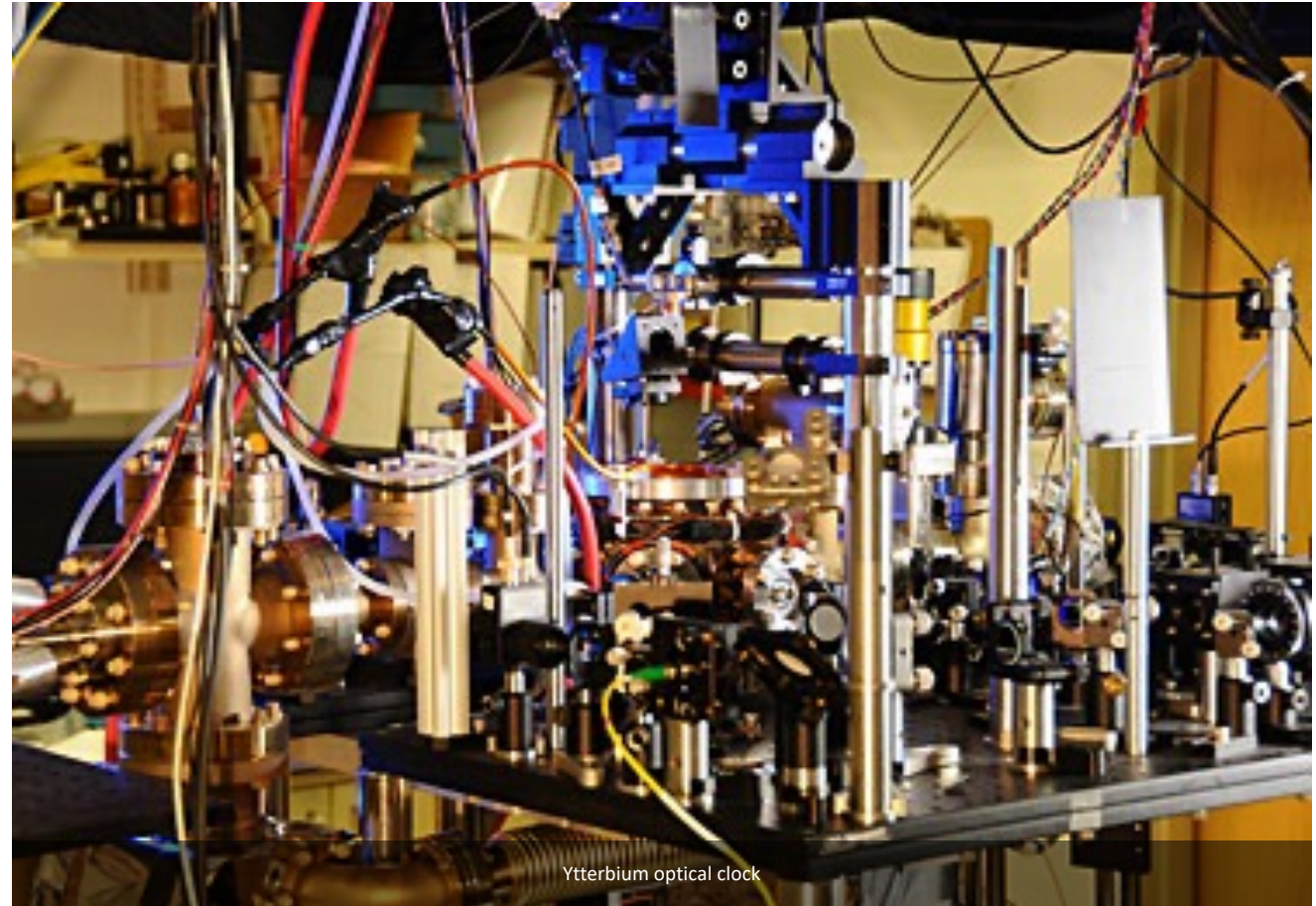
Commercial Hydrogen maser



Caesium fountain clock

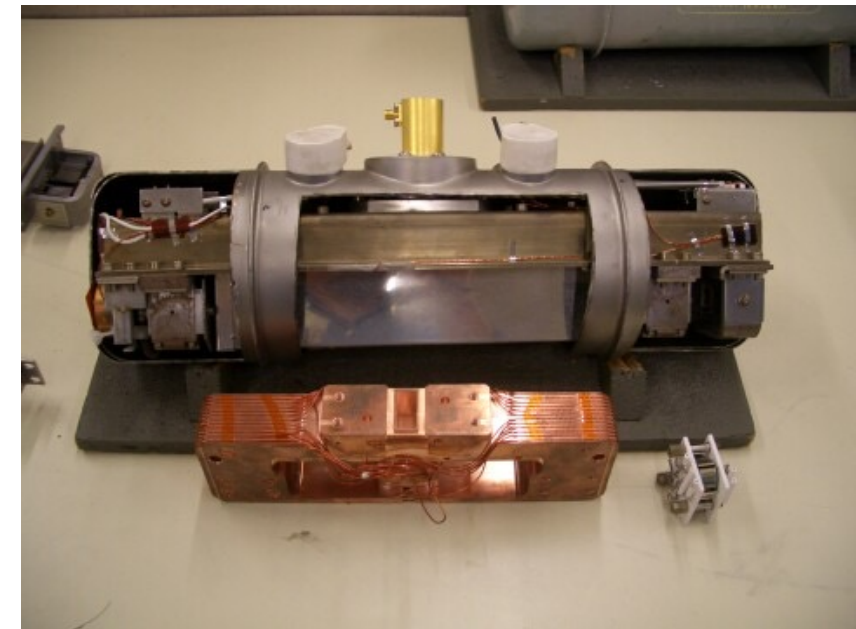
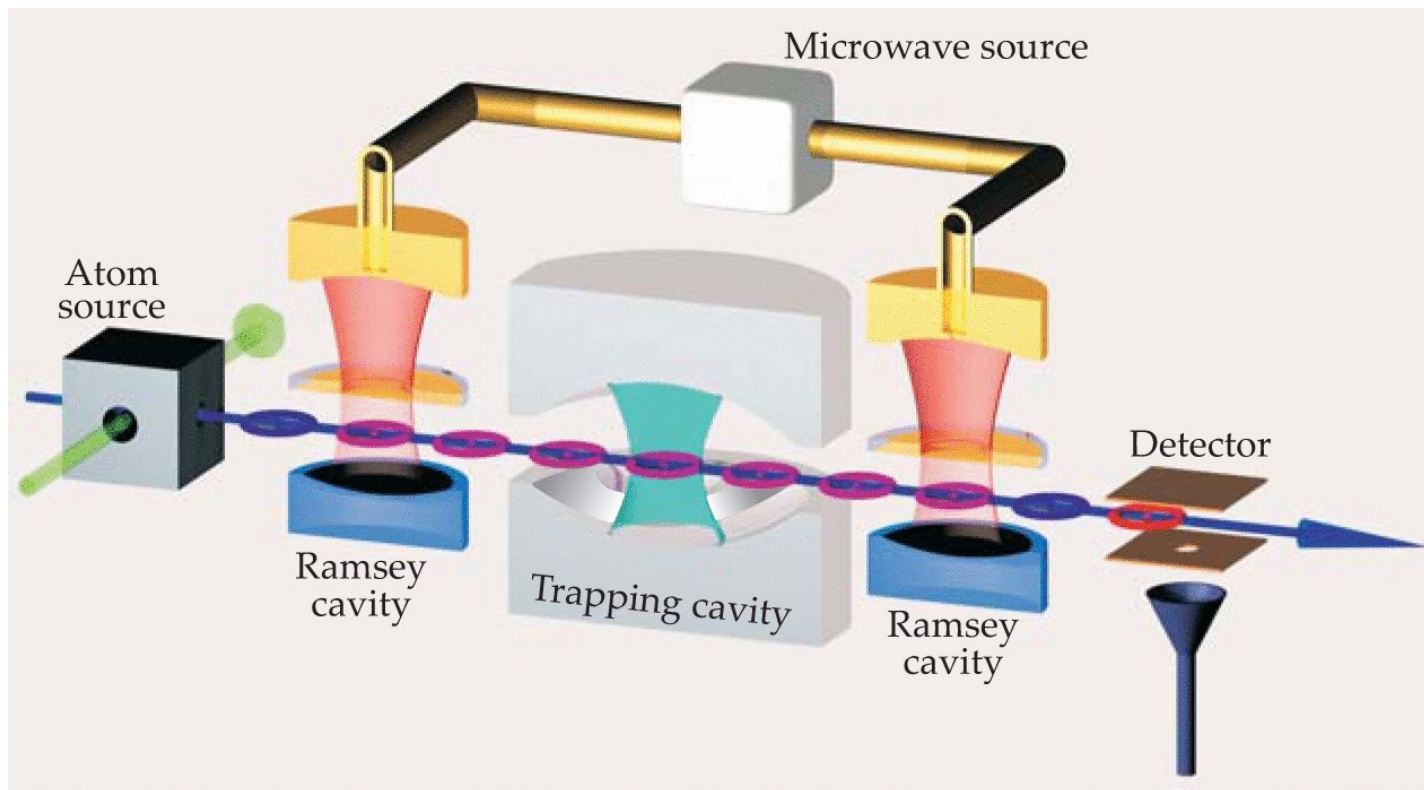


Small Rubidium clock



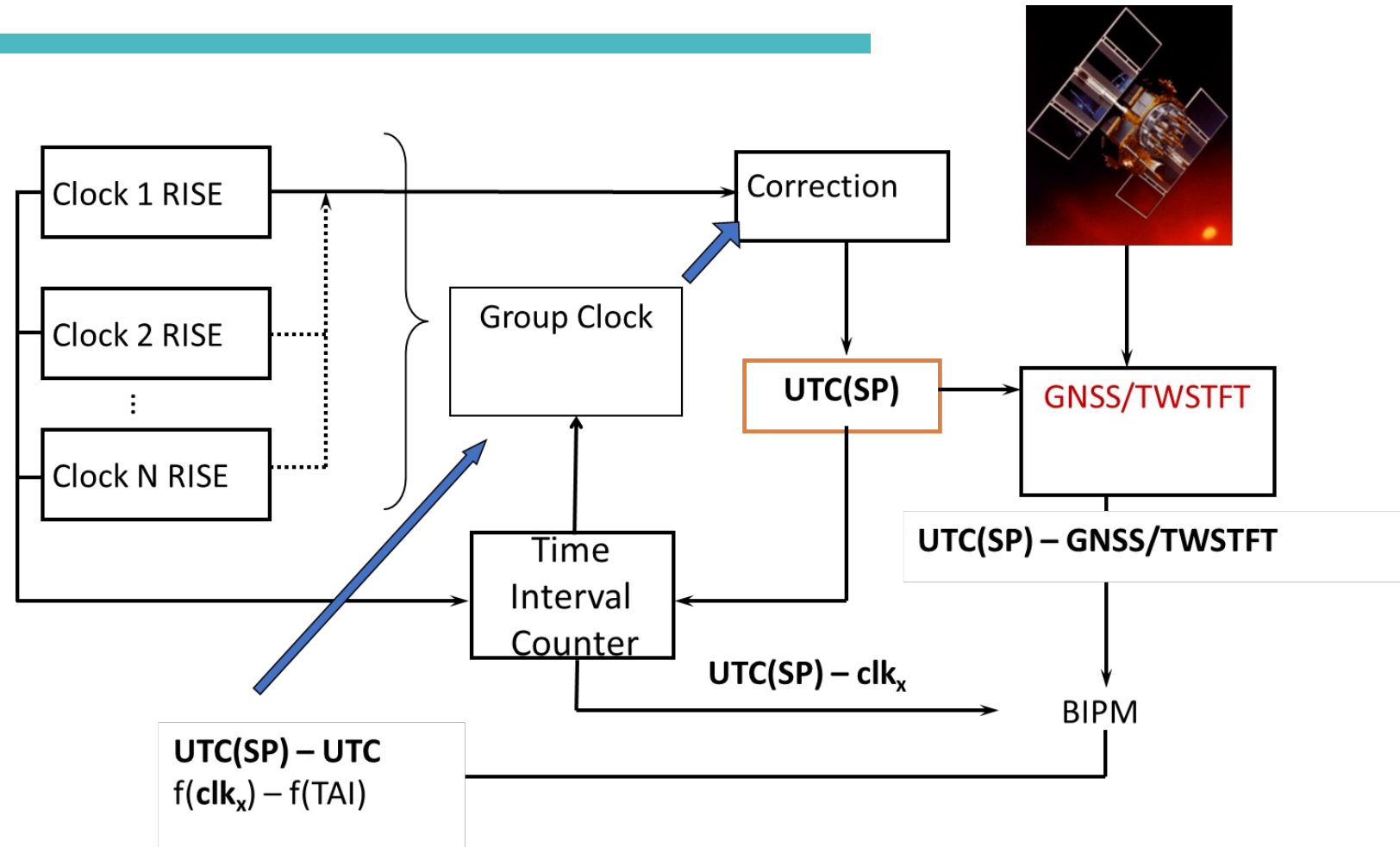
Ytterbium optical clock

Cesium beam tube



CREDIT
Microchip

Swedish National Time Scale UTC(SP)

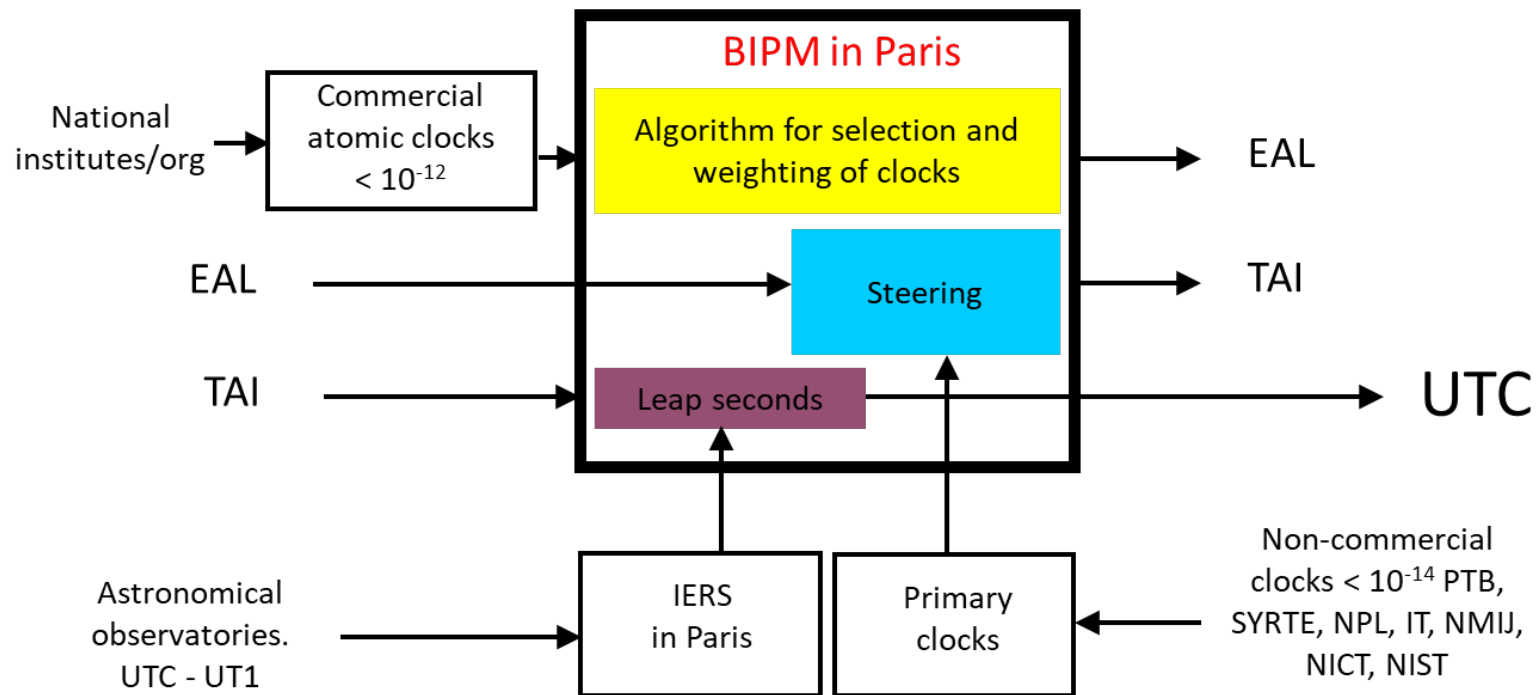


UTC(SP) an important part of UTC!

- 80 lab, >500 clocks.
- Comparisons and monthly reports to BIPM.
- The Atomic time Scale (TAI) comprise from the weighted average of all clocks
- UTC is created to adjust to the Earths rotation, and that is done by adding leap seconds to TAI



BIPM calculates UTC

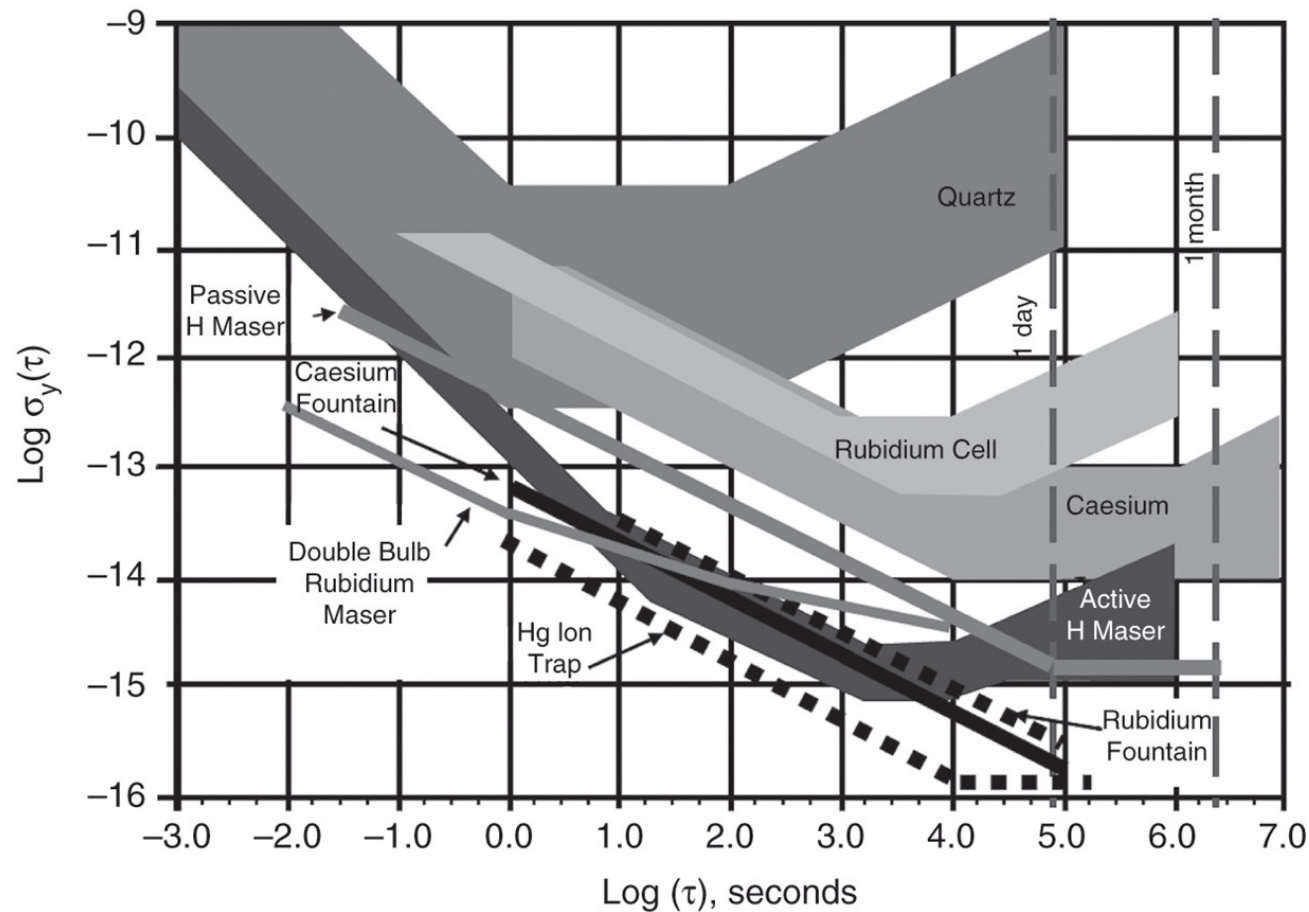


BIPM is the International Bureau of Weights and Measures

IERS is the International Earth Rotation and Reference System Service

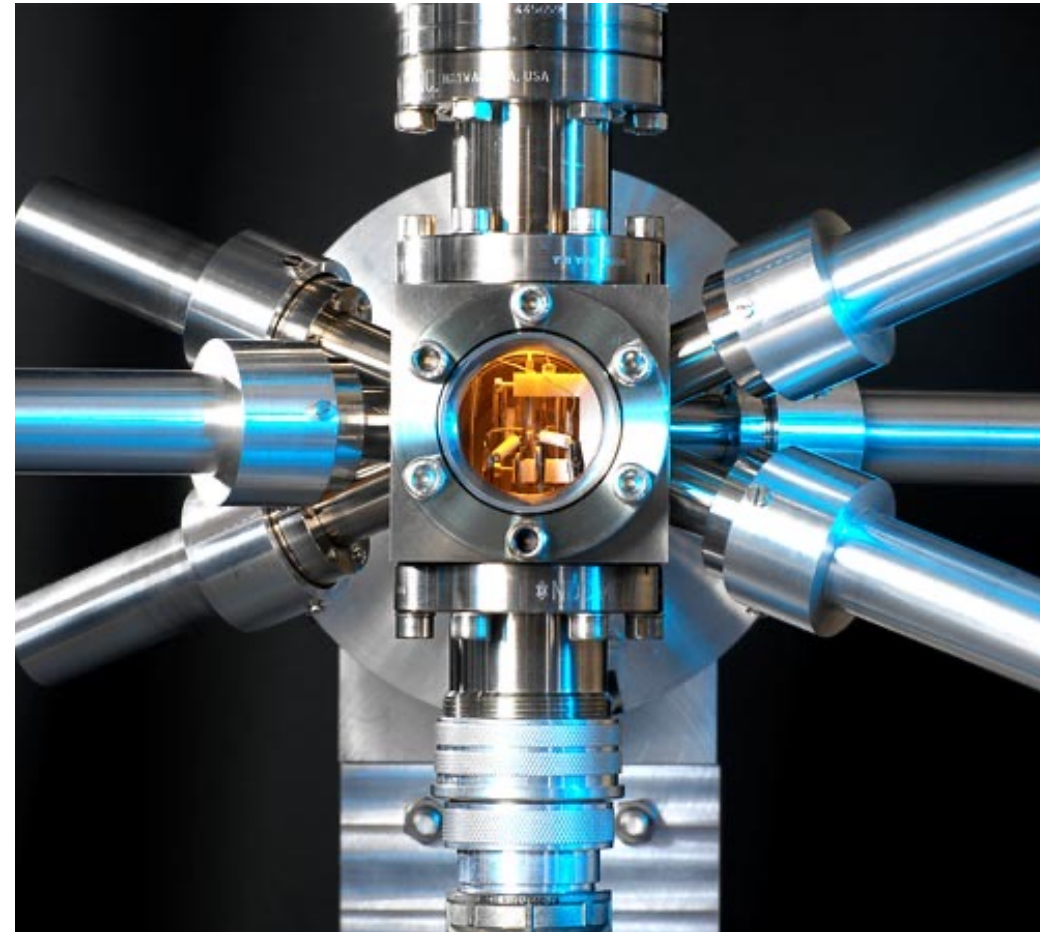
EAL (Échelle Atomique Libre, free atomic time scale)

Frequency stability of common atomic clocks



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



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**System Integration
Engineer**

EISCAT Association

Current Associates



Forskningsrådet,
Norway



Suomen Akatemia,
Finland



Vetenskapsrådet, Sweden



CRIRP, PRC



NIPR, Japan



NERC
UKRI, U.K.

Affiliates



KOPRI & KASI,
S. Korea



DLR-SO, Germany

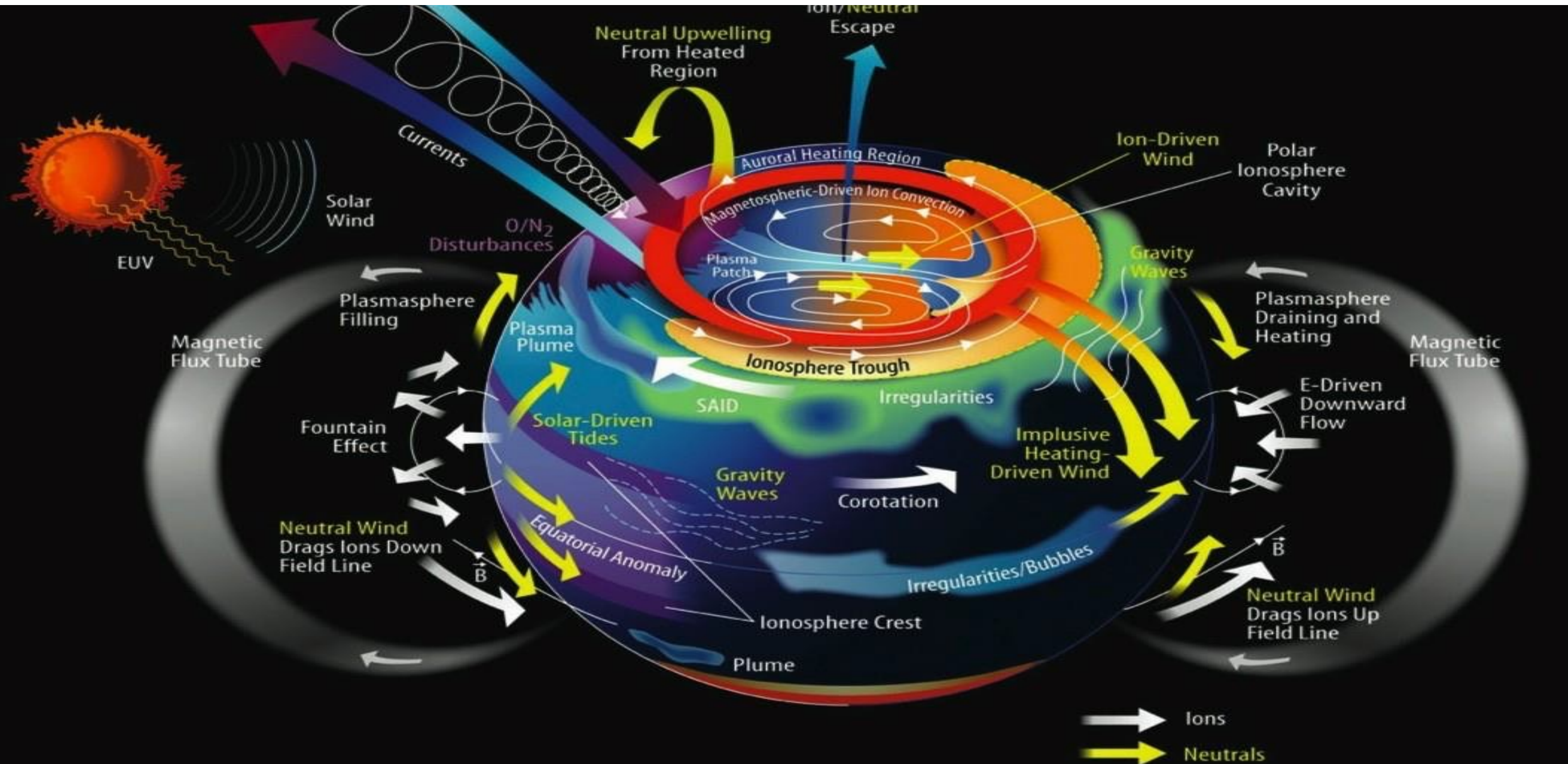


IRA, Ukraine



METI Int, U.S.

Science



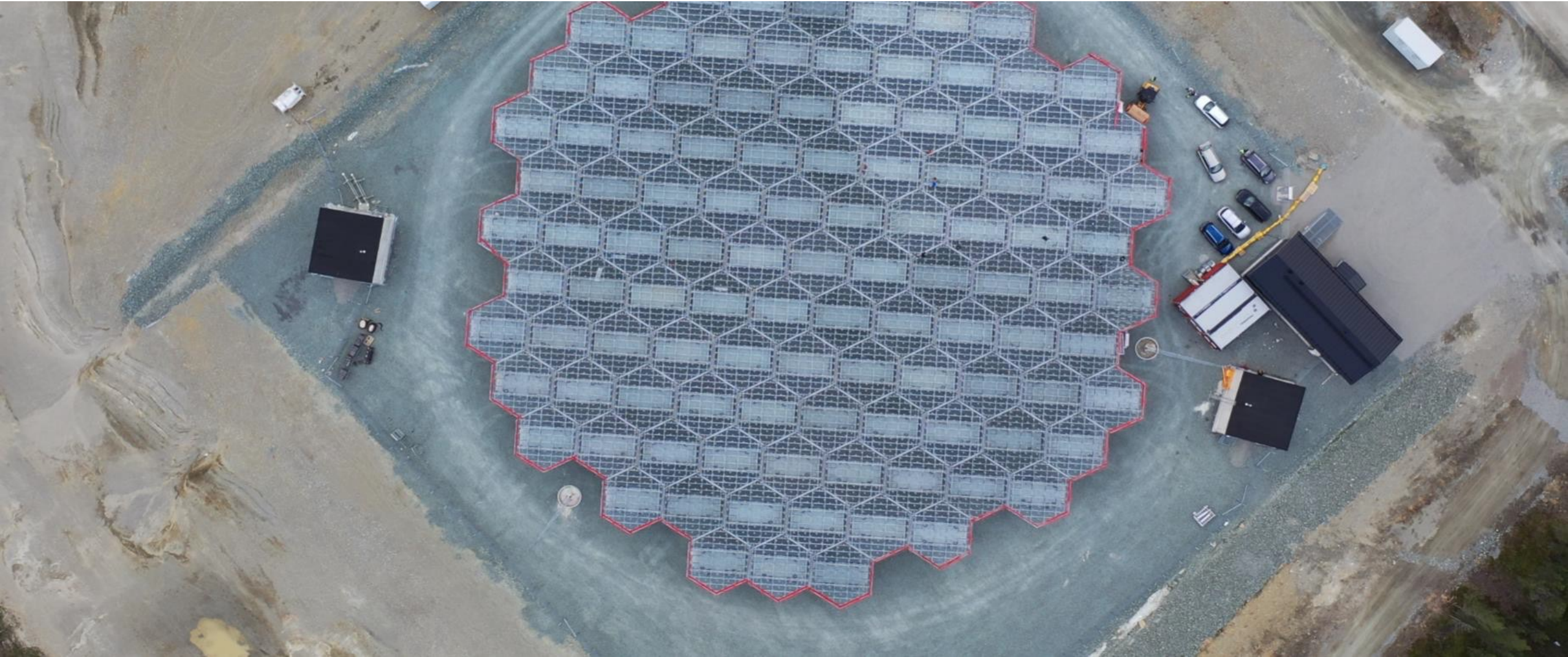
Old



Skibotn, Norway



Skibotn, Norway



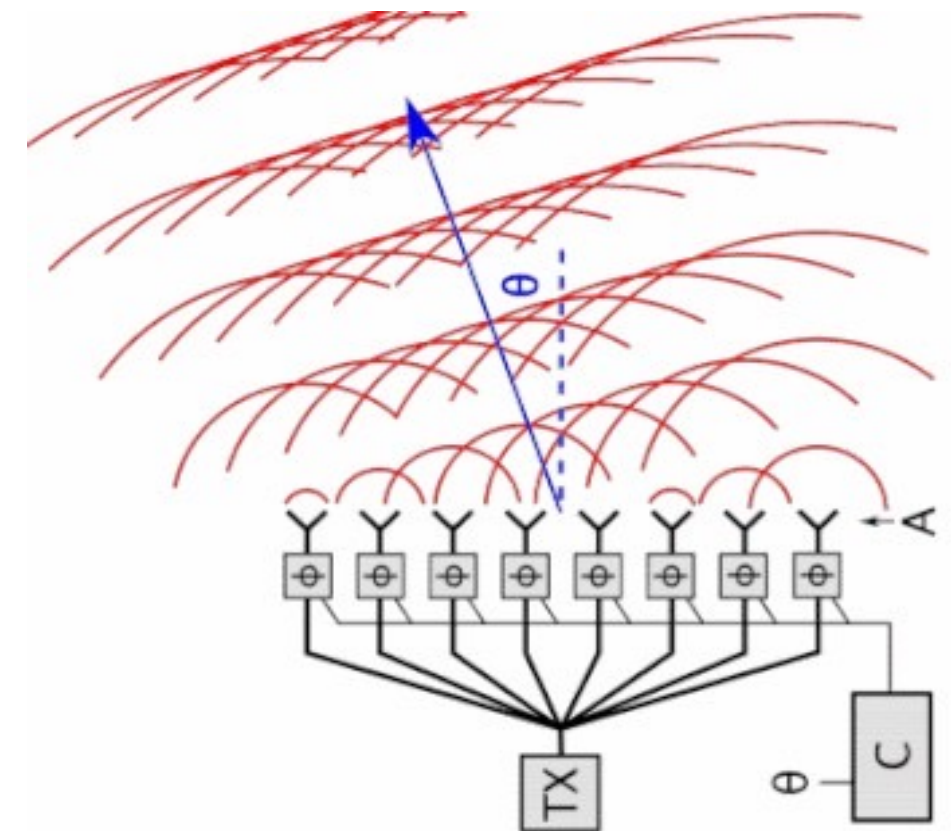
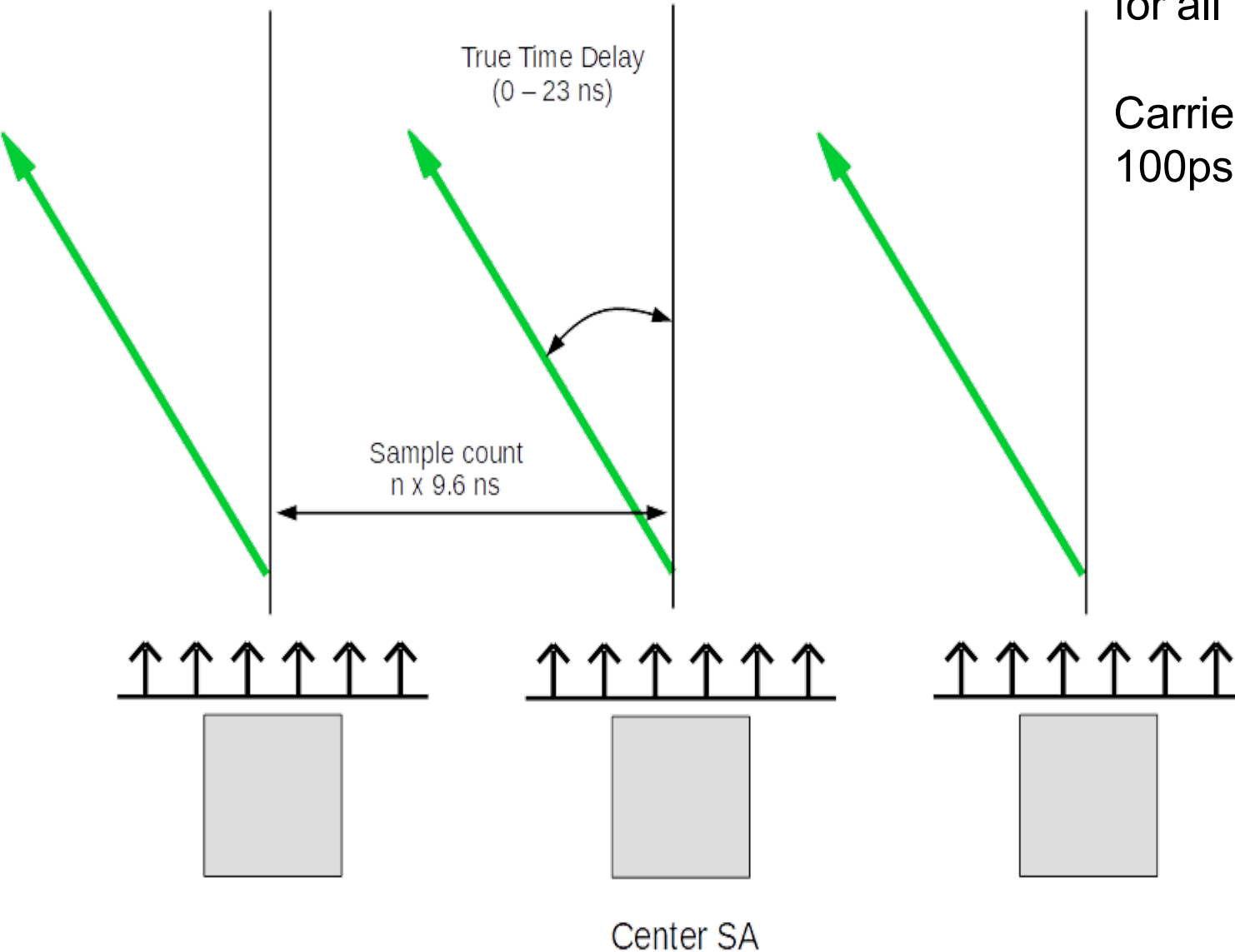
Karesuvanto, Finland



Beamforming

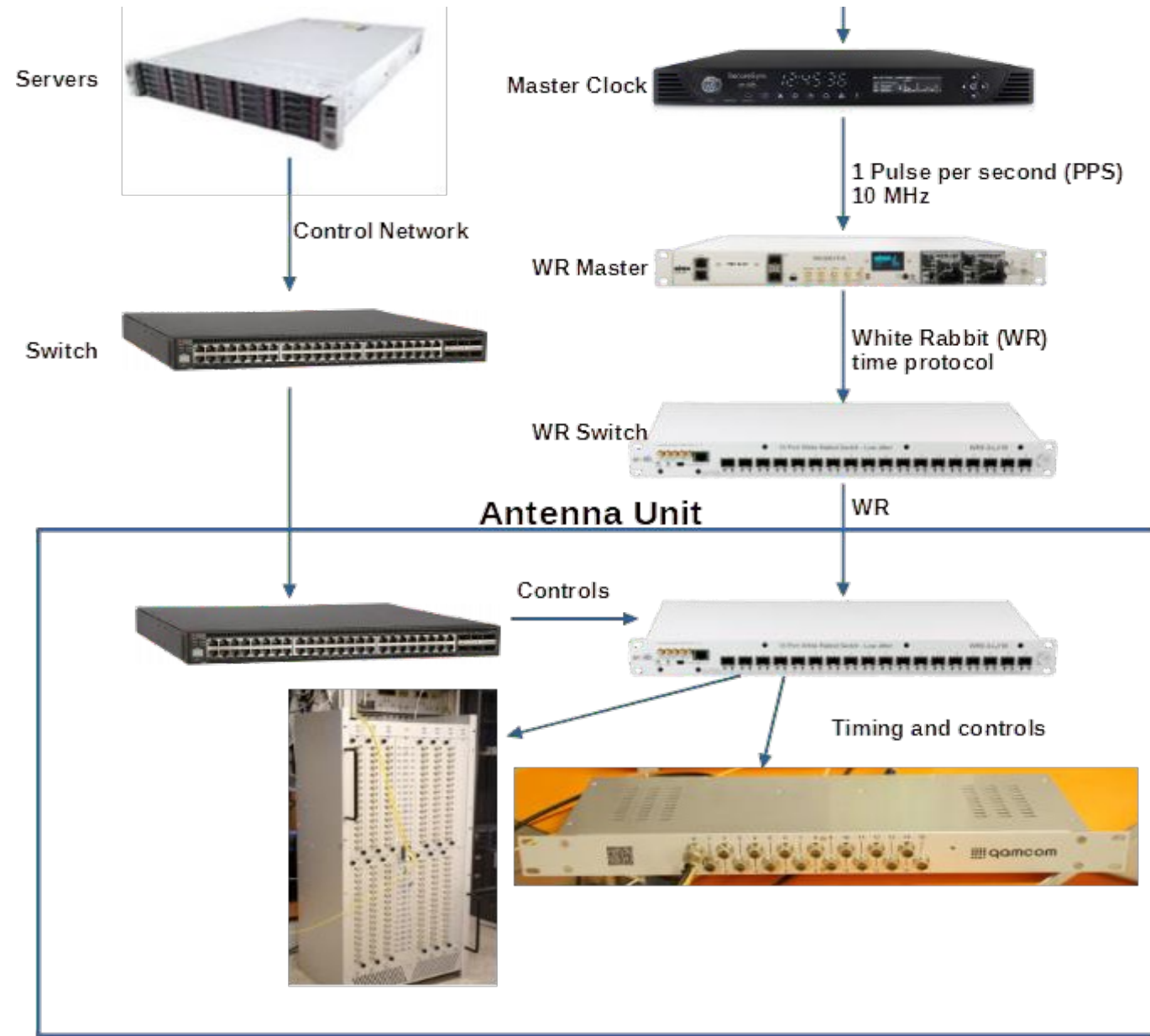
Each antenna in subarray has specific delay value for all pointing directions.

Carrier 233 MHz phase difference $< 10^\circ \rightarrow 100\text{ps}$

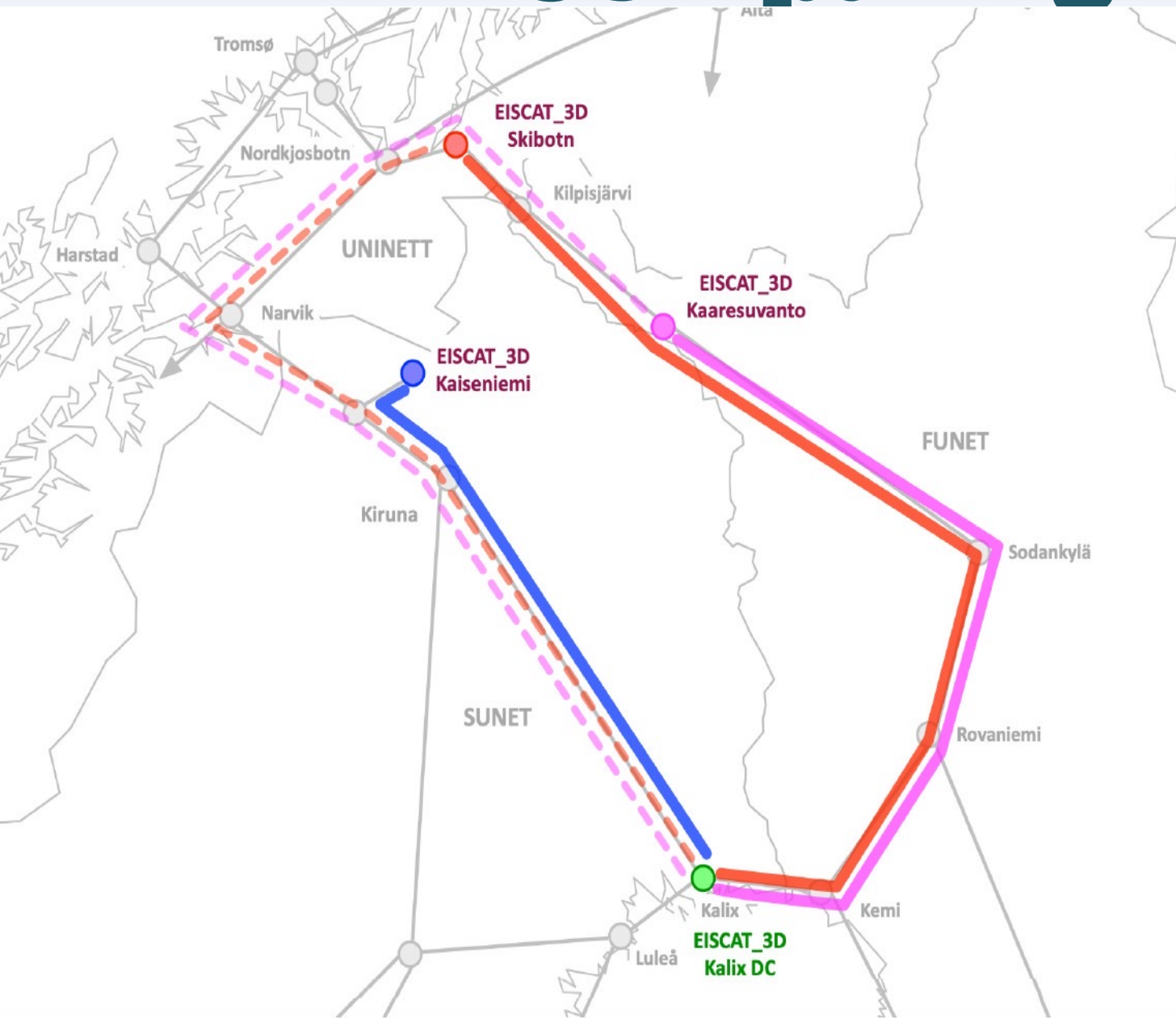


Control and Timing networks

- Data bandwidth is limited through the WR switches
- Control data is separated until the last layer of WR switches



Computing network



4 Tbit/s from each site the Data Center.

Network can be equipped with filters so that White Rabbit signal can transfer through network.

Now GNSS clocks at each site but future maybe synchronize to external White Rabbit source.

Future Developments

Extend Sweden and Finland sites from 55 subarray to full 109

- White Rabbit (or other) time over fiber system for $<100\text{ps}$ timing uncertainty
- 55 receiver devices connected with fiber

Timing calibration

- Phased array transmitter and receiver calibration
- Can be done using calibration masts or e.g., drones

Site to site synchronization

- White Rabbit or other sub nanosecond synchronization method to synchronize sites.

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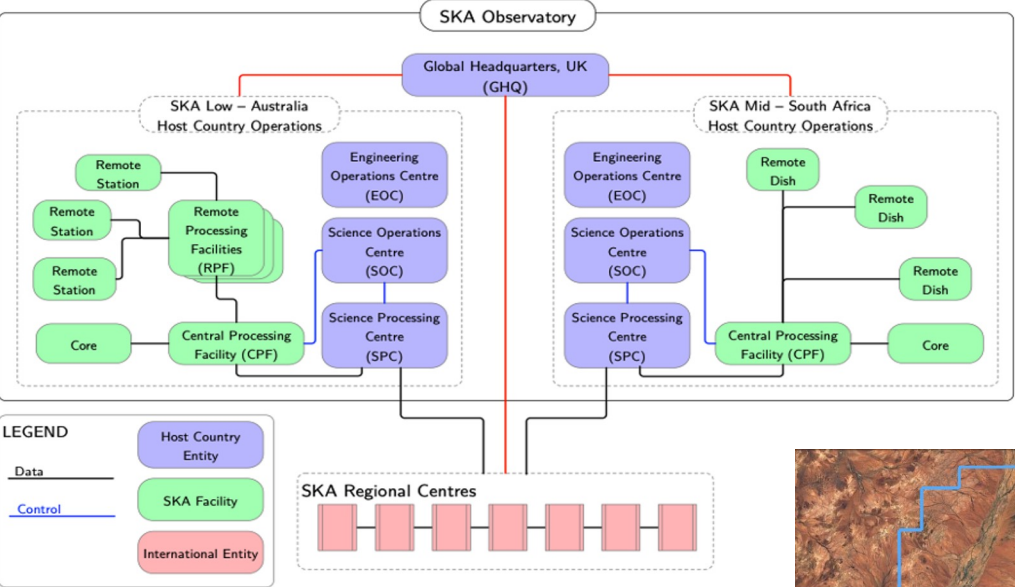
Synchronisation and Timing (SAT) System

Alice Pellegrini
RF & Antenna Engineer & Team Lead
On behalf of Aniket Hendre – T&F engineer

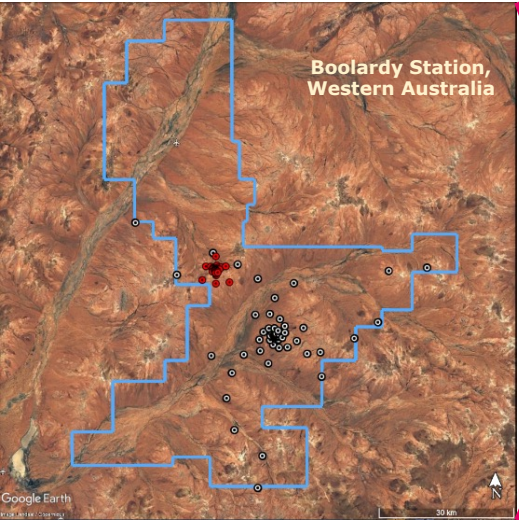
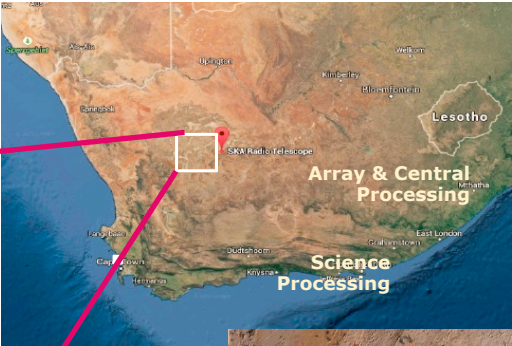
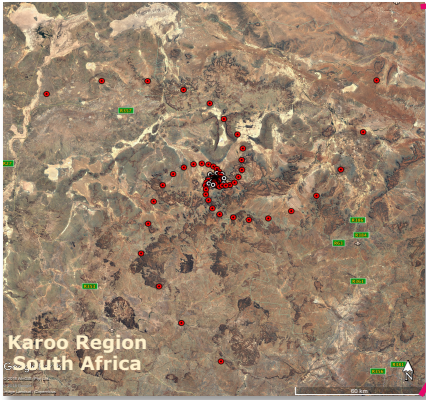
31 January 2024



Overview: SKA Observatory



1 Observatory
2 Telescopes
3 Host countries
SKAO Headquarters in Jodrell Bank (UK)



SKAO Mission

"The SKAO's mission is to build and operate cutting-edge radio telescopes to transform our understanding of the Universe and deliver benefits to society through global collaboration and innovation."



Importance of Synchronisation and Timing (SAT)

- **Why we need SAT system?**

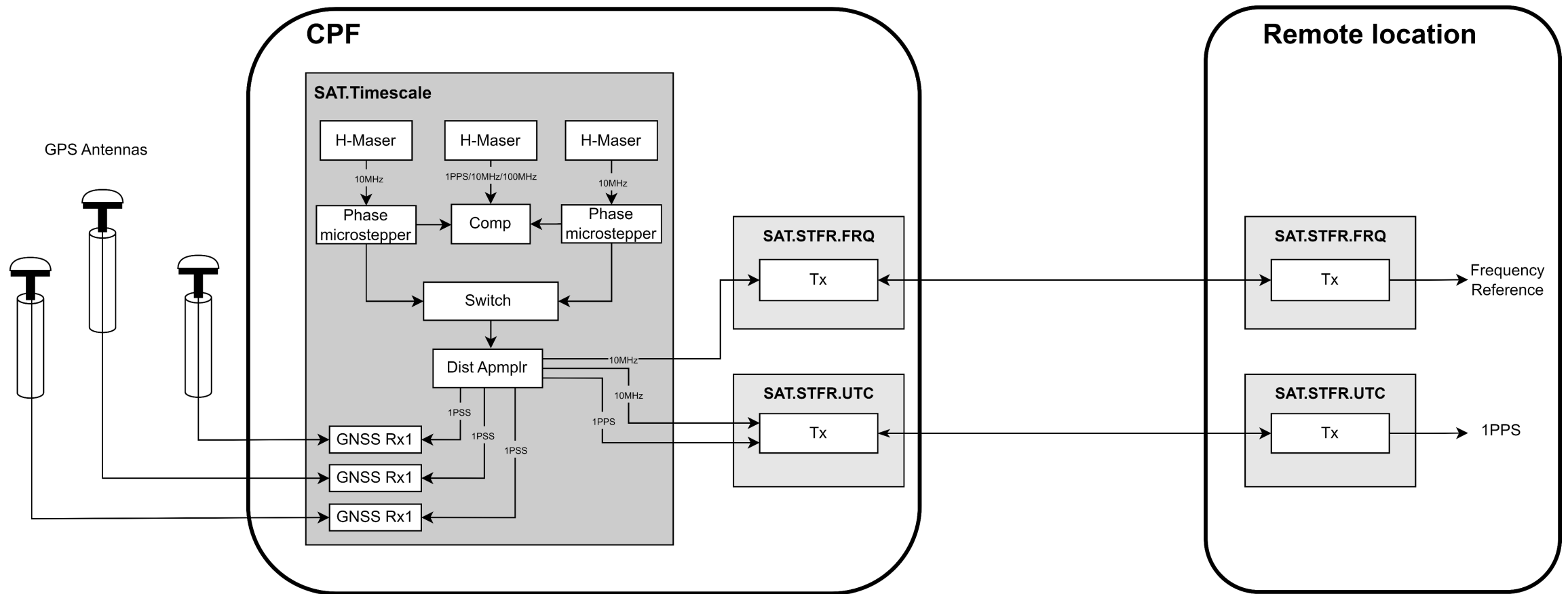
All interferometer systems like the SKA telescopes must be able to combine the signals from different antennas coherently.

The SAT system provides frequency and time signals:

- To maintain coherence within the antenna array
- To maintain time and frequency standards locally [UTC(k)] for **each site** (SKA1-Low in AU and SKA1-Mid in SA)
- **Distribute** references to each digitiser (dish: SKA1-Mid and RPF: SKA1-Low) with **minimal phase fluctuations** to maintain **high degree of coherence** and **accurate time**
- To time stamp science data at the signal chain source with high precision
- To synchronise all instrumentation across the telescope network



Overview of SAT



SAT: Synchronisation and Timing

STFR: System for Time and Frequency Reference

SAT.STFR.FRQ: Reference Frequency distribution sub-system

SAT.STFR.UTC: Reference Time distribution sub-system

SAT.Timescale: Observatory clock sub-system



Importance of any SAT- Why we need it?

- Being the world's largest telescope, SKAO has challenging requirements on a parameter such as **sensitivity**, angular resolution, field of view, frequency coverage, bandwidth, etc
- Unpresented **Sensitivity** (capacity to detect weak radio signals) plays an important role in achieving greater **image fidelity**
- The sensitivity of the telescope depends on (among other factors), the short-term **frequency stability (1-100s)** of the reference clock used at the very beginning of the digital signal chain (at the input of all digitisers)
- High-frequency **stability** yields a high degree of **coherence** and hence **high sensitivity**
- Timing accuracy is needed to do precise **time stamping** of the astronomical signal (needed for Pulsar and VLBI science)



SAT Timescale overview

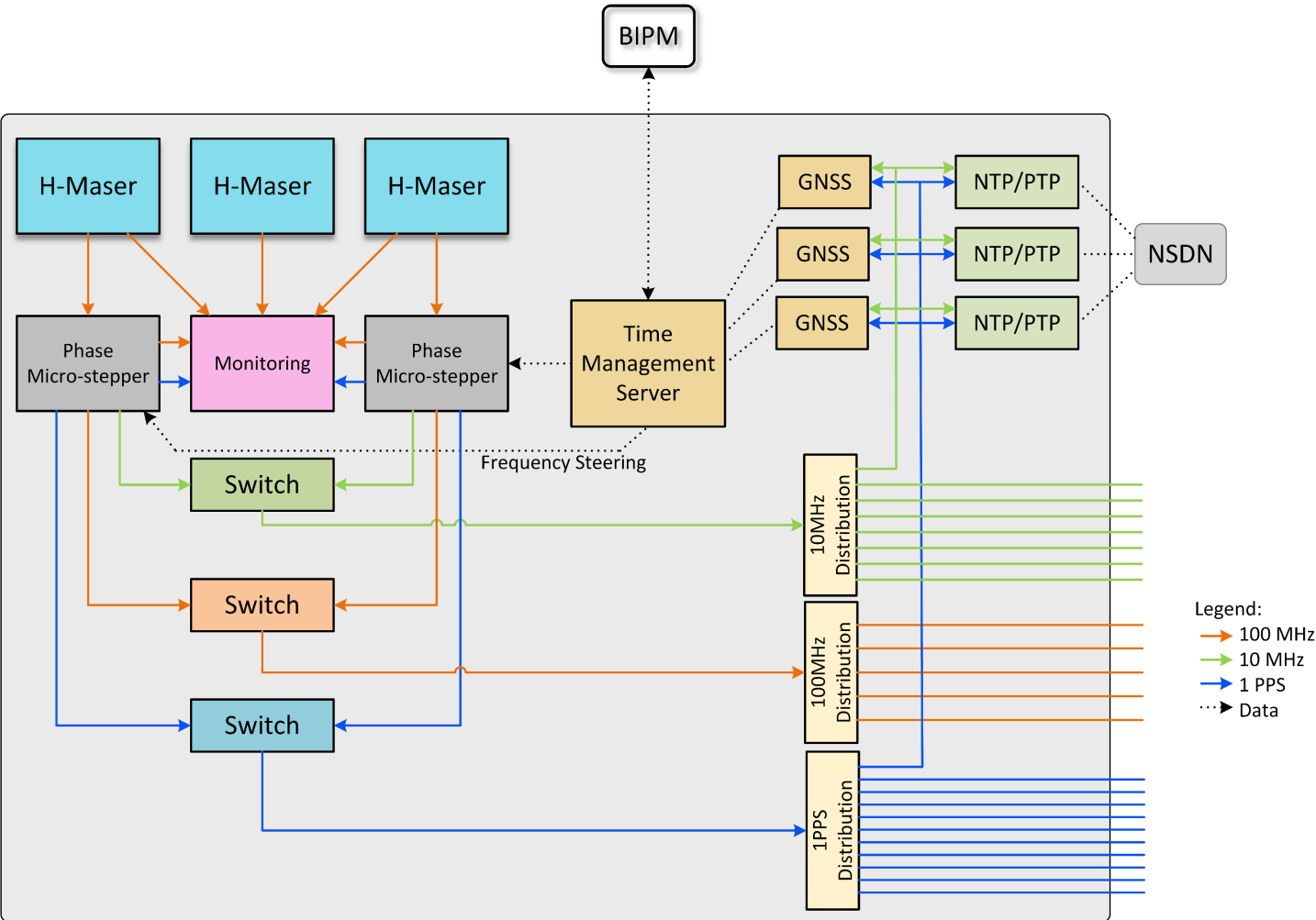


SKAO's Timescales

- Two Timescales
 - One for **SKA1-Mid** in Karoo Desert (South Africa)
 - One for **SKA1-Low** in Murchison Shire (Australia)
- Functioning at remote areas (away from towns or cities) and gives accurate **timing** as well as accurate **positioning** information
- **Reliability** is a key requirement
- Convenient to adopts international standards like IGS, way of meeting SKAO's requirements



Block diagram



- Ensemble of **three** Active H-Masers
- **Three cornered hat** configuration for redundancy and early fault detection
- Phase micro steppers are used to avoid frequent steering of H-Masers
- GNSS Common view technique or PPP can be used for UTC traceability.
- Implement **UTC(k)** for both AU and SA site
- Incorporate IGS to operate **CoRS**
- Supplies NTP/PTP to SKAO auxiliary services (Servers and PCs)

Courtesy: National Physical Laboratory (NPL) UK, Detailed Designed Documents for SKA1-Mid and SKA1-Low Timescale.



Key performance requirements of Timescales

Reference frequency stability

Averaging Time (s)	Desired stability
1	2.0×10^{-13}
10	5.0×10^{-14}
100	1.3×10^{-14}
1000	3.2×10^{-15}
Floor up to 10^5	3.0×10^{-15}

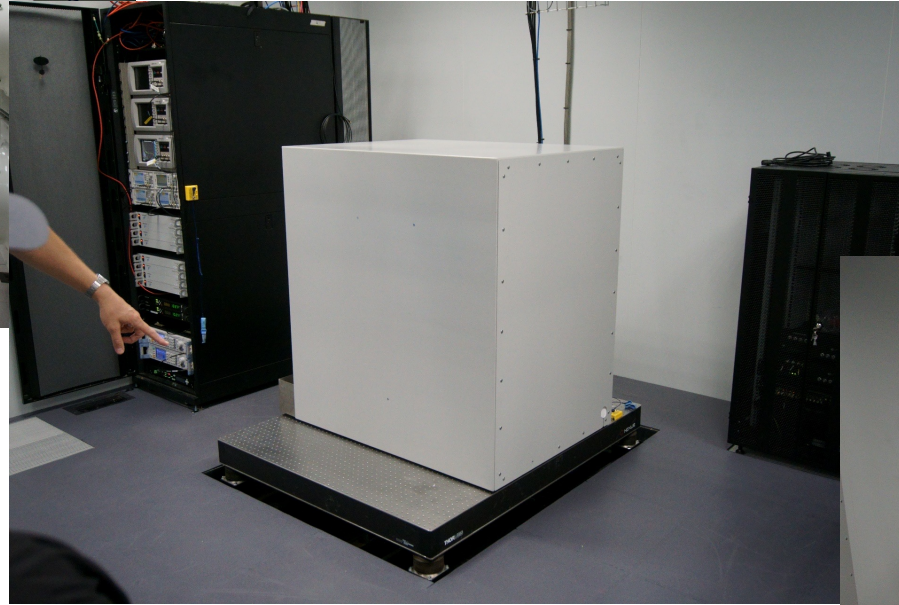
Desired reference frequency stability in terms of Allan deviation for SKA1-Mid and SKA1-Low

Time uncertainty from the UTC

- **SKA1-Mid** Less than **5ns** (1-sigma) at least for 10 years
- **SKA1-Low** Less than **9ns** (1-sigma) at least for 10 years



Hardware deployed at site



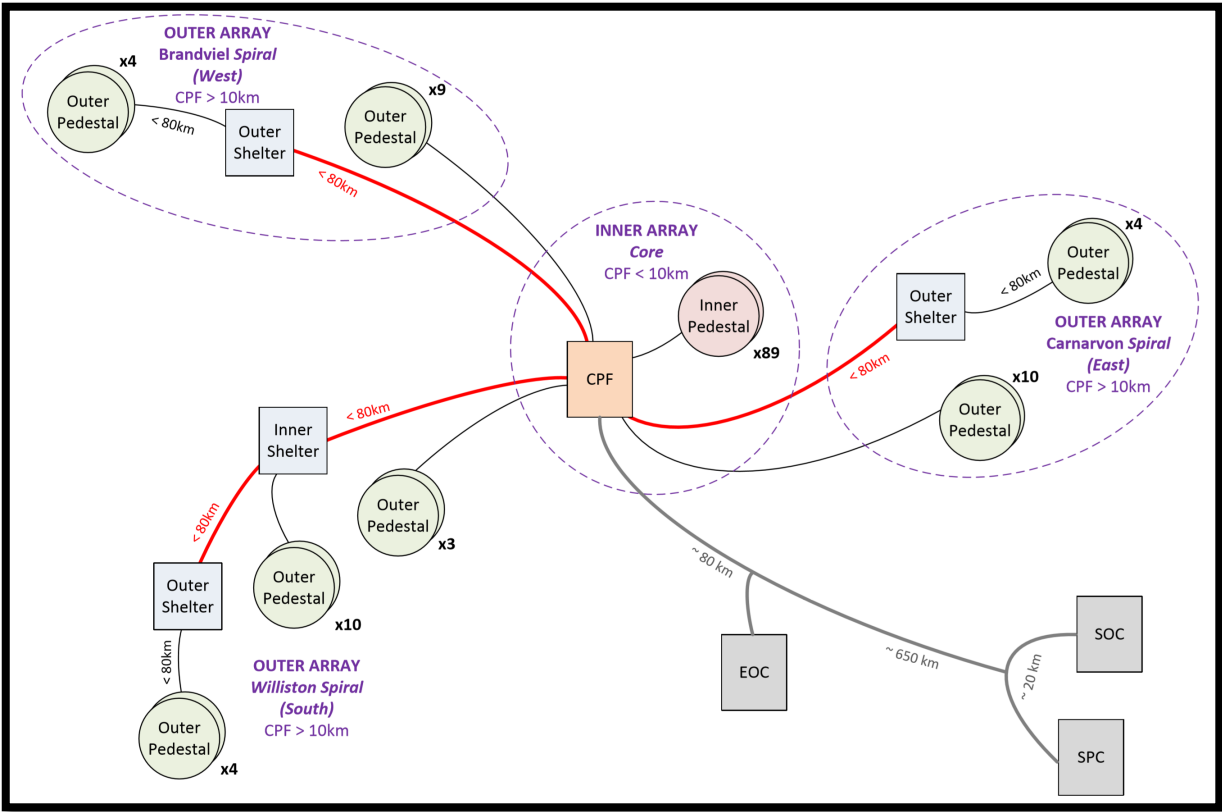
SKA1-Mid SAT.Timescale will
integrate and replace MeerKAT
Timescale



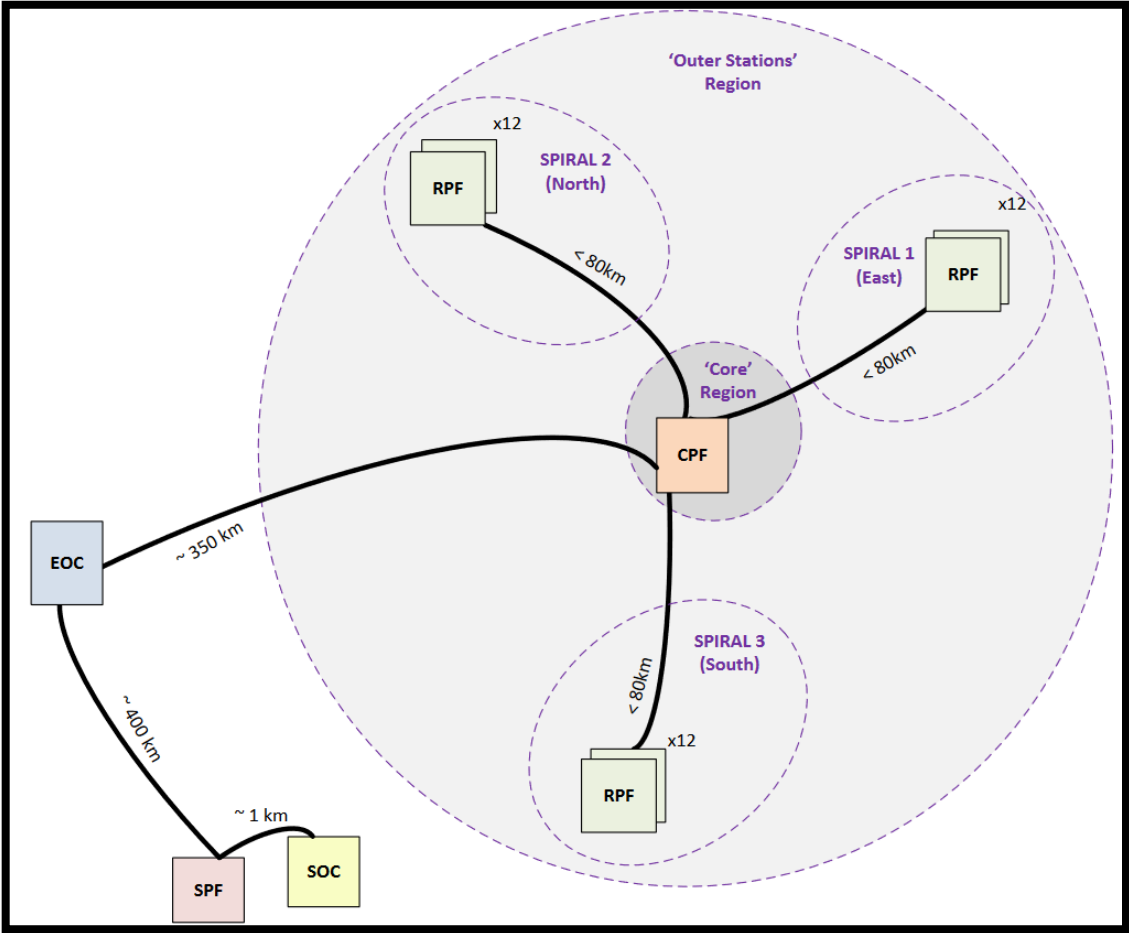
Reference Frequency Distribution



Distribution Network



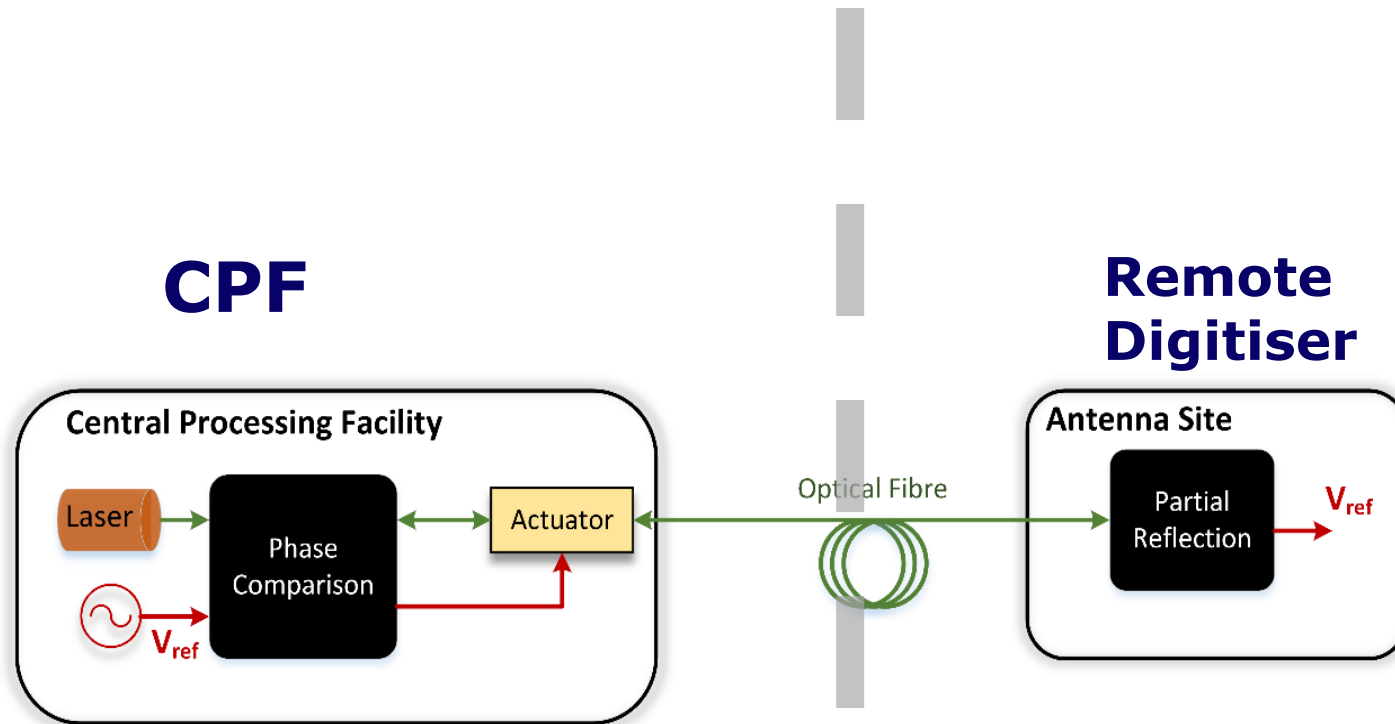
SKA1-Mid (over-head)



SKA1-Low (buried)



Block diagram



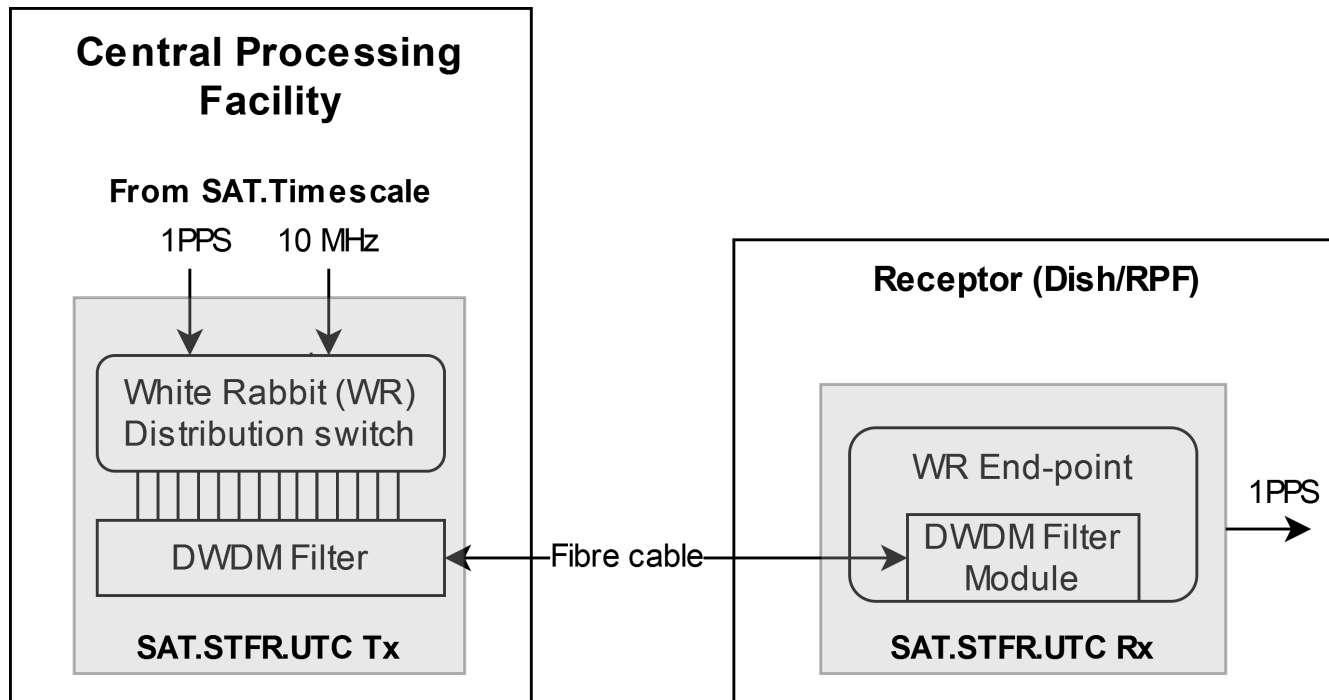
- Round trip closed-loop feedback control system based on optical phase sensing and actuation
- Track the delay changes through the fibres and counteracts to minimise the impact on the stability of the reference frequency
- Maintains $\sim 99\%$ coherence in the baseline
- Clean-up oscillator to minimise short term jitters (fluctuations withing round trip time)



Reference Time Distribution



Block diagram (Mid Example)



- WR based system (1ns over 10km)
- Long distance + instability of the laser wavelength + fibre dispersion = Timing uncertainty
- It uses SFPs suitable for DWDM network (internal temperature control)
- The accuracy for long distances is achieved by using long reach SFPs and optical amplifiers.
- Time accuracy requirements:
2ns (RMS) over 175km
reference to SAT.Timescale



Composition

WR-Z16 Switch



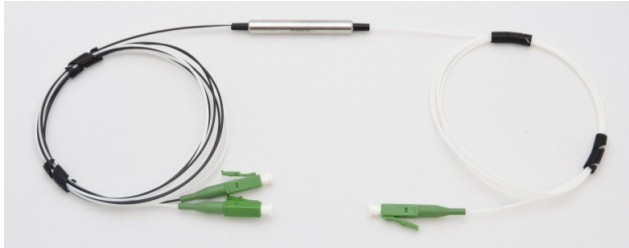
DWDM SFP



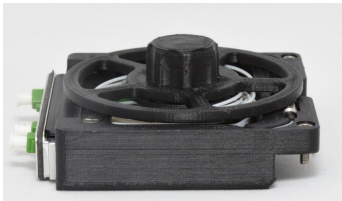
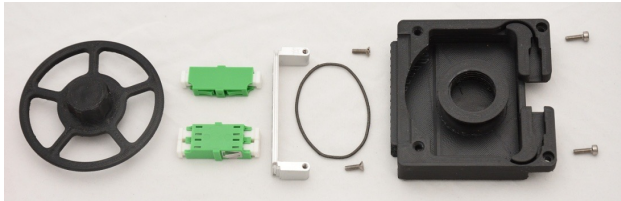
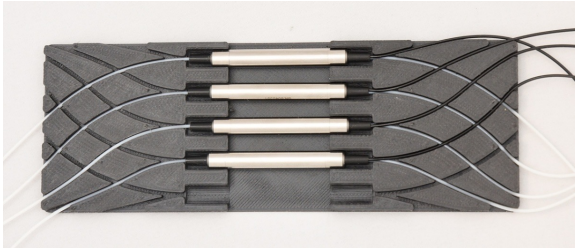
WR ZEN TP-FL



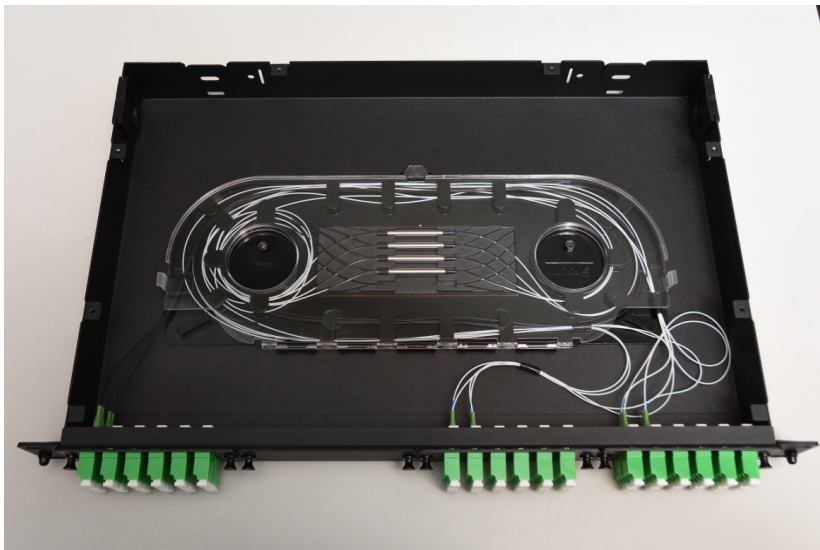
DWDM Filter



Filter cable assembly



DWDM Filter Box



Construction update

- Mid and Low Time distribution system: SAFRAN, Spain
- Mid Frequency distribution system: University of Western Australia
- Mid and Low Timescale: Contractor from UK has been identified
- H-Masers: T4 Science, Switzerland



*We recognise and acknowledge the
Indigenous peoples and cultures that have
traditionally lived on the lands on which
our facilities are located.*



www.skao.int

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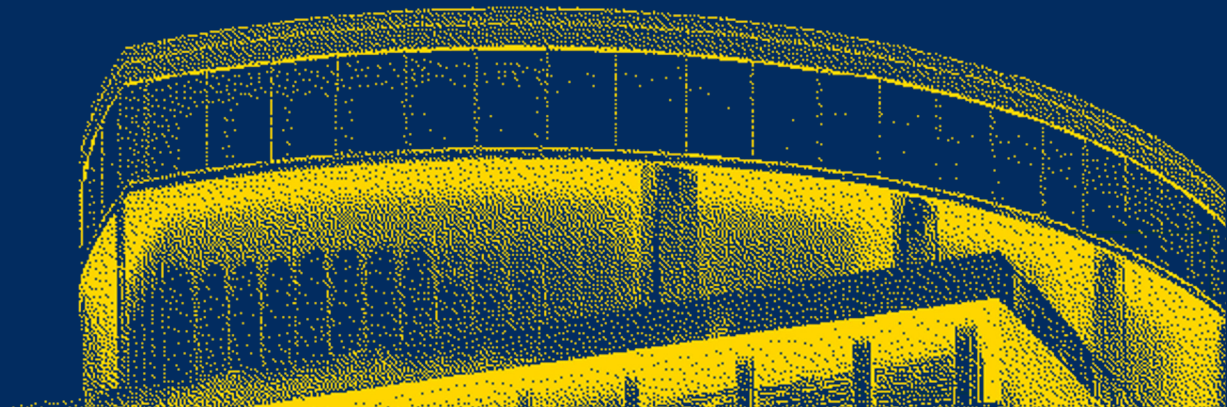
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Technology Development at the European Southern Observatory

Norbert Hubin (ESO)



THE EUROPEAN SOUTHERN OBSERVATORY

Intergovernmental treaty-level organization

- 16 Member States plus host State Chile and strategic partner (Australia)
- ~30% of the world's astronomers
- Created in 1962 by 5 MS with a goal to build a large telescope in the southern hemisphere



Mission

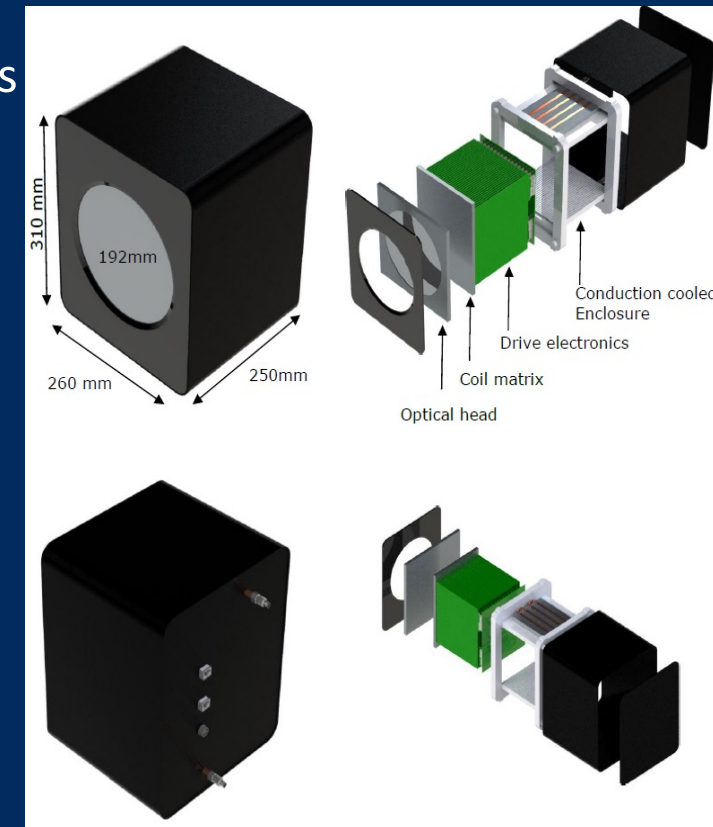
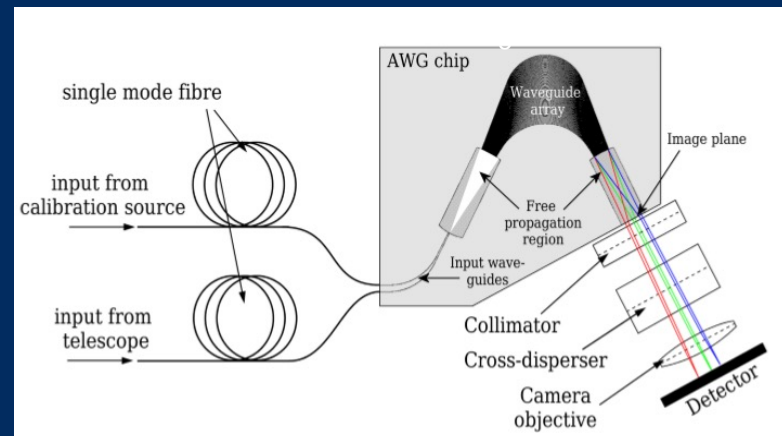
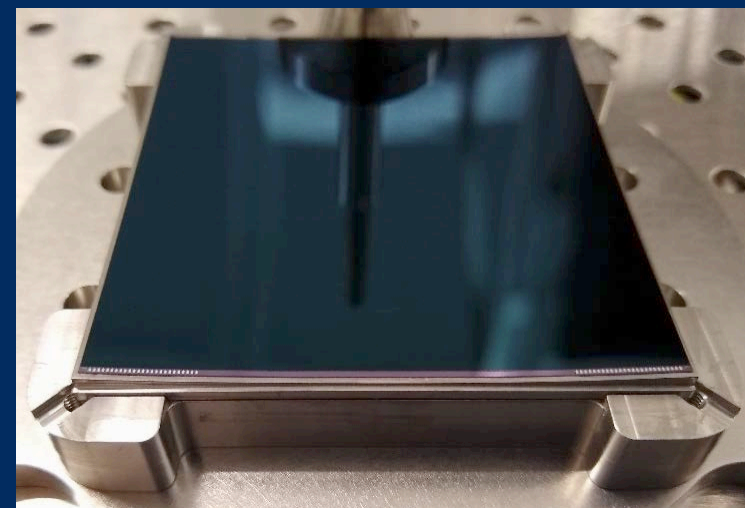
- Design, build, and operate advanced ground-based observatories
- Foster international collaboration for astronomy
- Develop state-of-the-art instruments in collaboration with institutes & industry
- Secure new technologies for future projects for all our infrastructures
- Operates the VLT, La Silla & ALMA telescopes in Chile
- Building the 39.3m ELT (~1.5 BEUR)

HQ in Garching near Munich
~750 Staffs (Garching + Chile)



Technology Development programme & interests I

- Technologies for optical-infrared instrumentation:
 - Large, low noise, High QE detectors from infrared to blue visible, CMOS, CCD, APD ($2\text{-}4\text{-}6\text{-}9\text{k}^2$)
 - Smaller, low noise, fast readout detectors/cameras in IR & visible for wavefront control, fringe tracking & adaptive optics (256^2 , 512^2 , 700^2); 1-2-3 kHz frame rate
 - High performance detector controllers for science and "engineering" detectors
 - Curved CMOS & CCD detectors with radius of 500mm 6Kx6K pixels ←
 - Deformable mirrors for Adaptive Optics with 1, 2, 12000 actuators at 2-3 kHz
 - Astrophotonics for spectrographs with array waveguide chips ←
 - Innovative wavefront sensors for high contrast imaging (exoplanets) ←



Technology Development programme & futur interests II

- Technologies for Optical/Infrared telescopes:
 - accelerometer systems with noise level better than $\sim 10 \text{ ng}/\sqrt{\text{Hz}}$ in the 1 Hz $\sim$ 1kHz frequency range, providing acceleration measurements in real-time for inclusion in a control loop ← critical for ultimate performance of our VLT interferometer and probably of interest for the currently built ELT
 - Reinforcement learning for wavefront control, focal plane high contrast imaging and fringe tracking interferometry ←
 - Exploring photonics lanterns for large mirror phasing (petaling) ←
 - Large segmented mirror in-situ cleaning solution for the ELT (ionized air knife, special optics brushes, laser cleaning,...) ← demonstration followed by practical implementation at the observatory
 - Machine learning for complex telescope/instrument operation, trouble shooting and maintenance assistance ← exploratory
 - Remotely controlled sensors and actuators (without cabling) ← exploratory
 - Integrated control electronics for science detectors (i.e ASICS) in view of the potential future WST project ←
 - Large format Volume Phase Holographic gratings for high resolution spectrographs

Thank you!

Norbert Hubin
ESO technology Development Programme
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@esoastronomy



@ESO



european-southern-observatory



@ESOobservatory



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BREAK

***Swedish fika – refreshments with opportunities
for informal networking and 1-to-1 meetings***

