16-12-2016

Status of GINGERino

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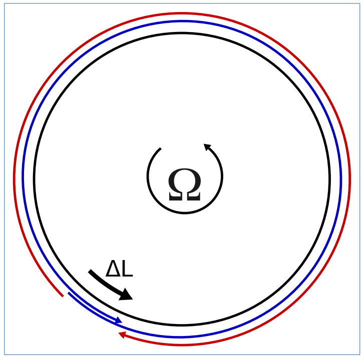
GINGER meeting @ DEI, 16-12-2016 Padova

Outline

- **Introduction**
  Sagnac interferometry & Ring Lasers Gyroscopes
- **Earth rotation (ER) measurements**
  ER in Geodesy
- **State of the art of Ring Laser Gyroscopes**
  ER in Relativity (GINGER idea)
- **Ongoing research at LNGS**

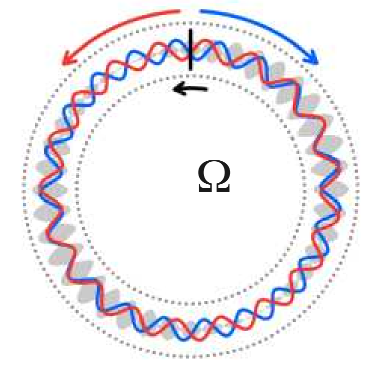
  Deep Underground rotations:
  GINGERino (underground seismology)
- **Conclusion**

Sagnac interferometry



Sagnac delay line

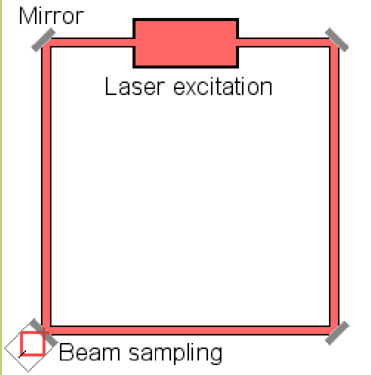
$$\Delta t_{Sagnac} = \frac{4A}{c^2}\vec{\Omega}\cdot\vec{n}$$



Resonant cavity

$$\Delta f_{Sagnac} = \frac{4A}{P\lambda}\vec{\Omega}\cdot\vec{n}$$

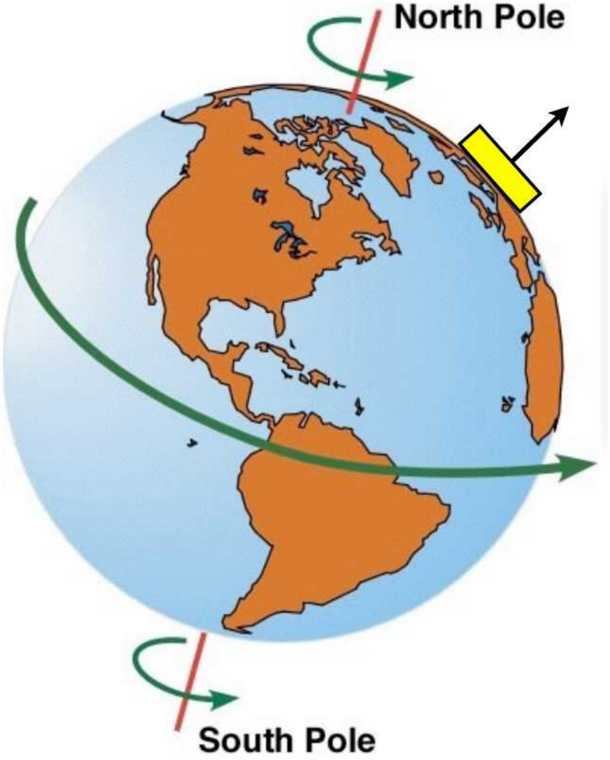
$$\text{Scale factor } K_S = \frac{4A}{P\lambda}$$



Ring laser

Internal generation,
<u>Simple detection:</u>
optical beat CW-CCW

- No moving masses
- No signal for a linearly accelerating reference-frame (and gravity)
- L > 1 m → Earth rotation is the bias!

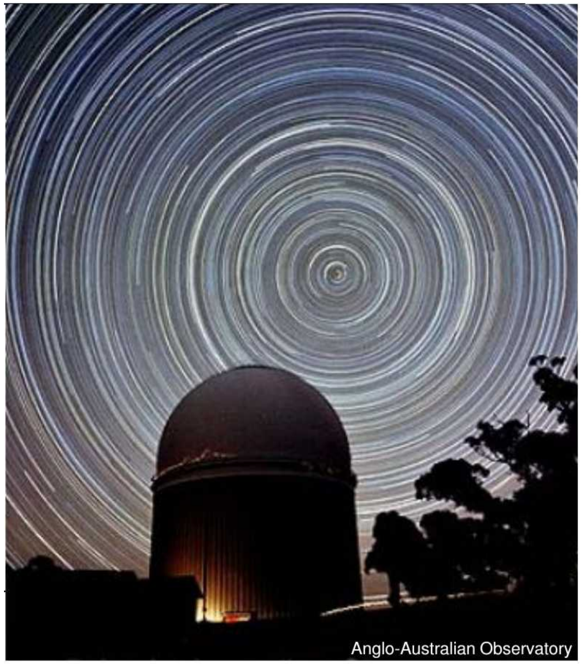


Ring Laser Gyroscopes
Pure frequency measurement
No need external space reference frame

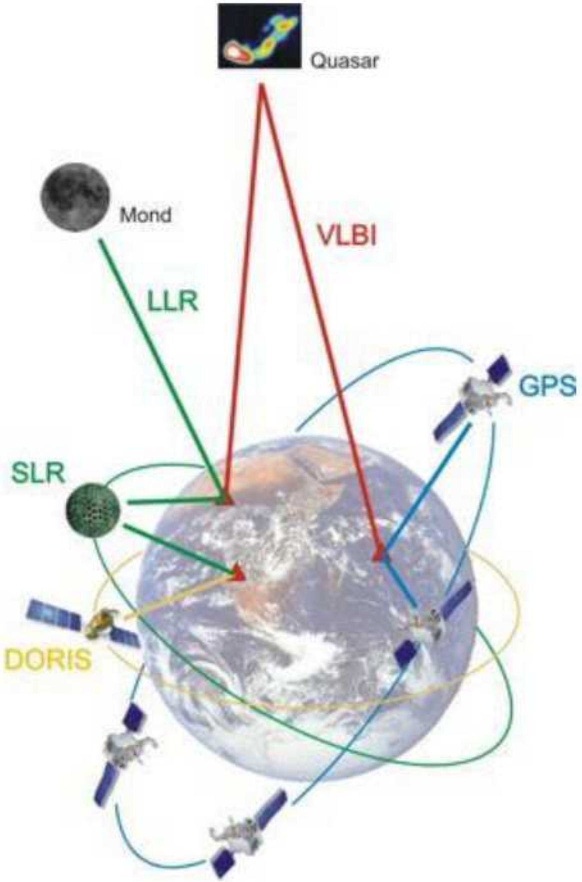
Earth rotation in Geodesy

Precise measurements of Earth rotation vector

- Link between **ICRF** (International Celestial Reference Frame)
  and **ITRF** (International Earth Reference Frame),
  → determination of the **EOP** (Earth Orientation Parameters)
- Earth's interior and atmospheric phenomena



Anglo-Australian Observatory



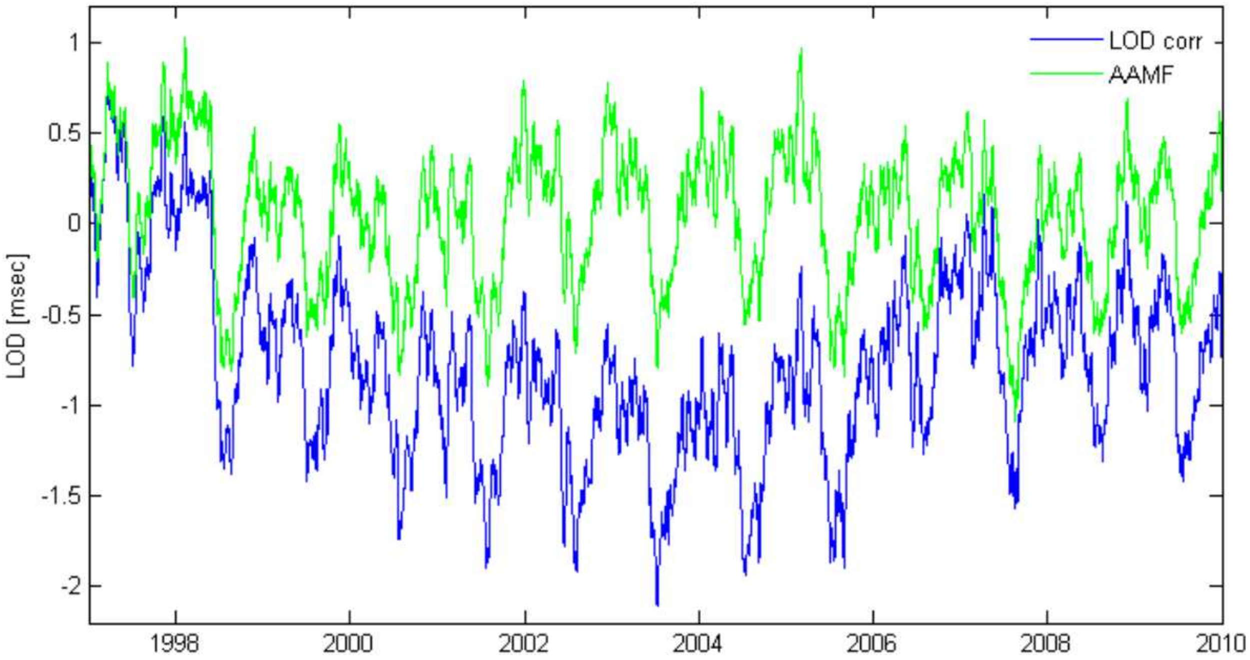
Typical Observation are based on "stellar methods"

Navigation (GNSS), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR),and Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radio-positioning Integrated by Satellite(DORIS)...

The measurement objects are defined in a **celestial frame of reference**, while the sensors are located on the Earth.

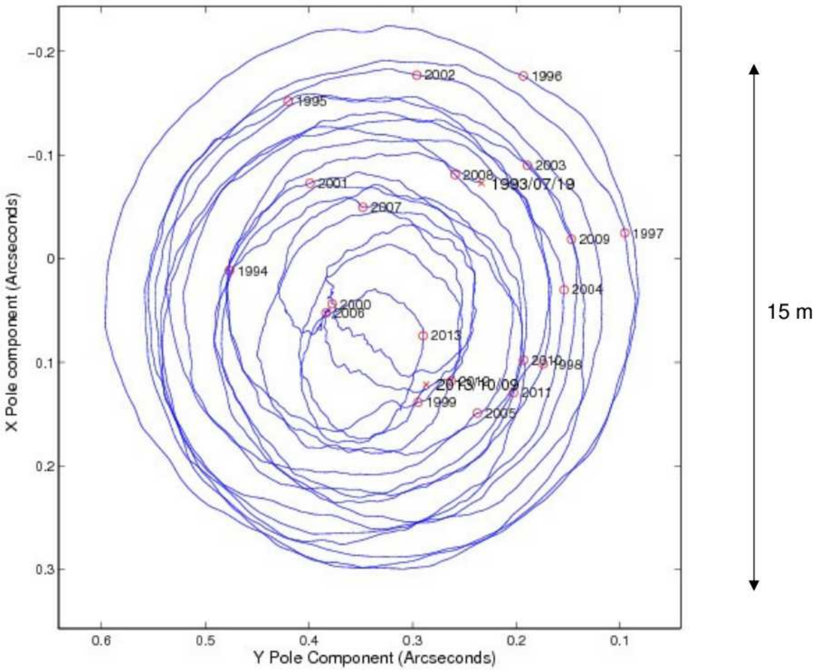
Earth rotation in Geodesy

Modulus variations (Length Of Day)



Measured LOD and Atmospheric Angular Momentum from Weather Model

Direction variations



Polar Motion, moon and sun torque, free oscillation, geodynamics

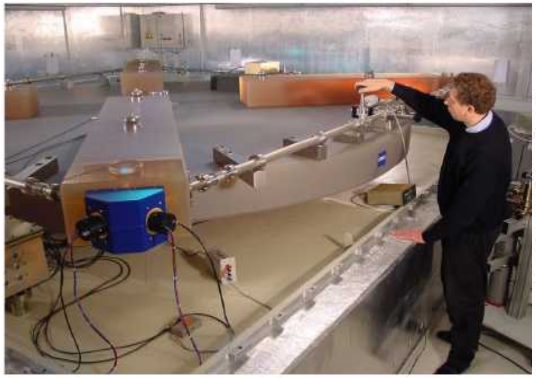
Sub daily time scale?

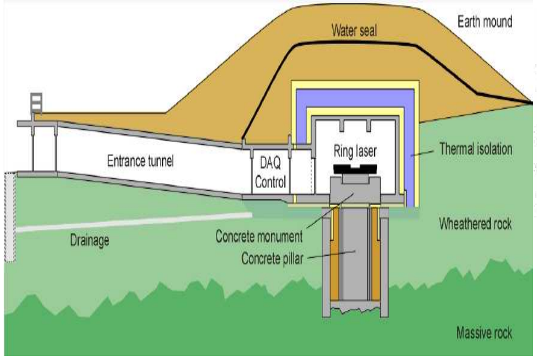
- “Stellar” methods have typically lower time resolution
- Need to link: Earth based reference frame <--> Celestial reference frame

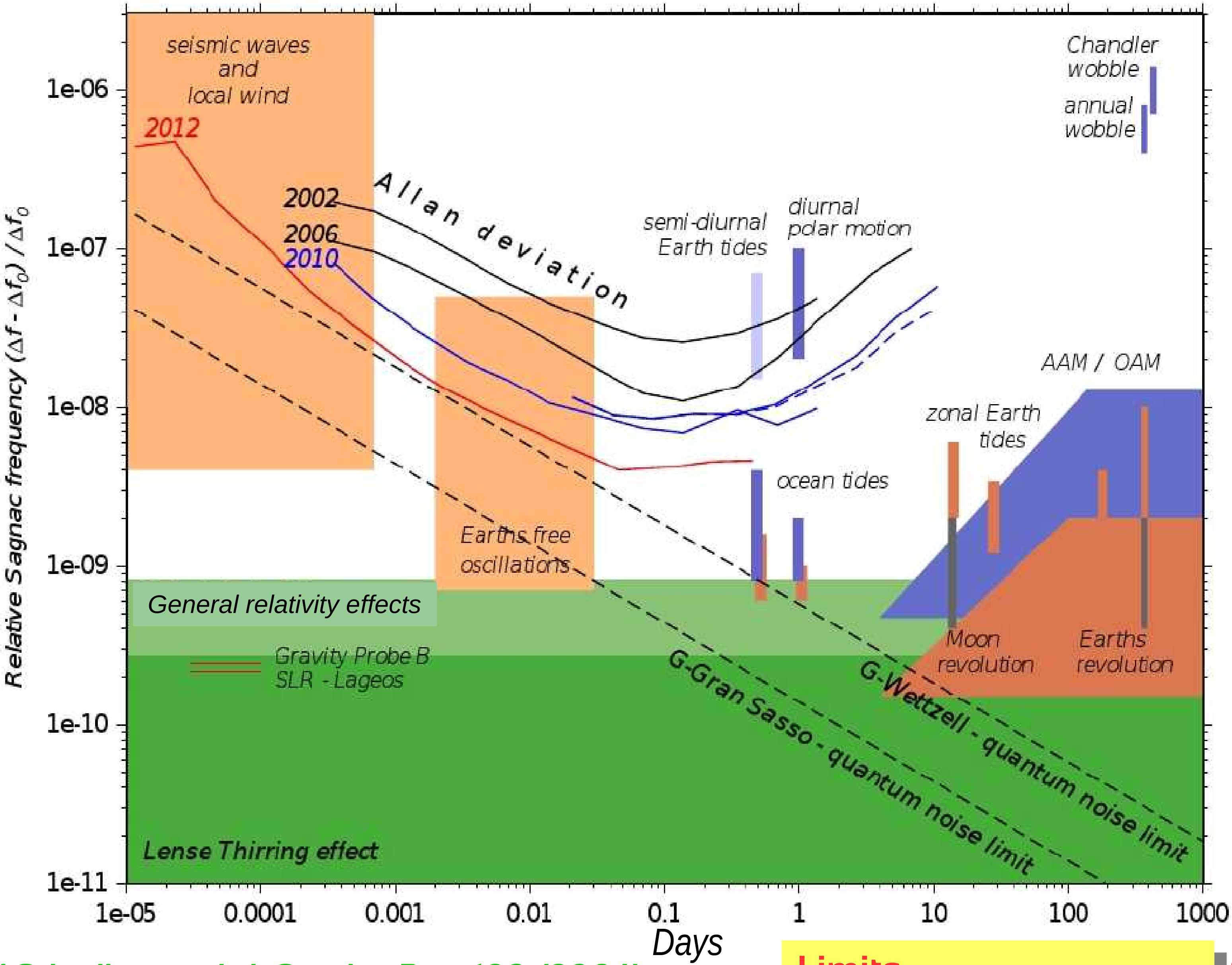
Ring Laser Gyroscopes can play this role [target resolution $10^{-9}\ \Omega_E$]

State of the art: "G" ring laser at Wettzell (Germany)

Monolithic (L=4m)
+ perimeter stab. (comb)







GEODESY

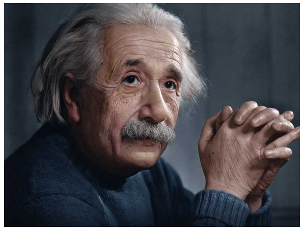
- Diurnal (Oppolzer) *K.U.Schreiber, et al., J. Geophy. Res.. 109, (2004)*
- Annual (circular)+Chandler (elliptical) Wobble T=432 s.d.

K.U.Schreiber, et al.,PRL. 107, 173904 (2011)

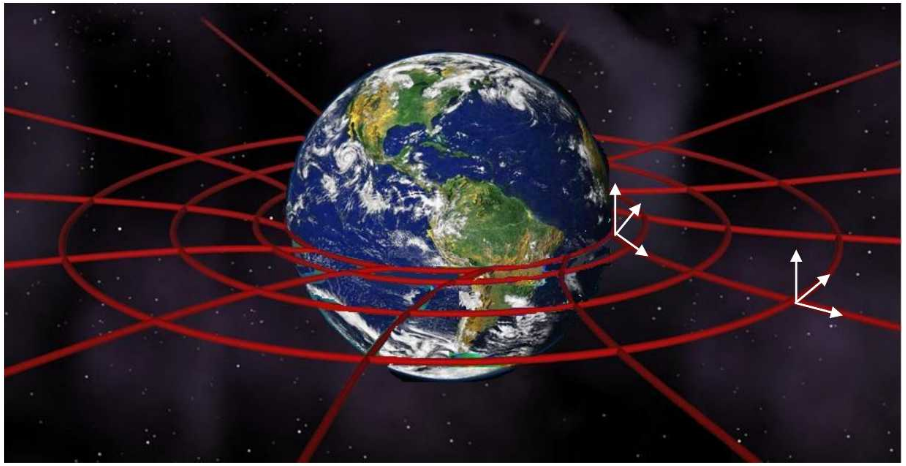
Limits

- Surface noise
- Ring Laser Dynamics

Earth rotation and General Relativity



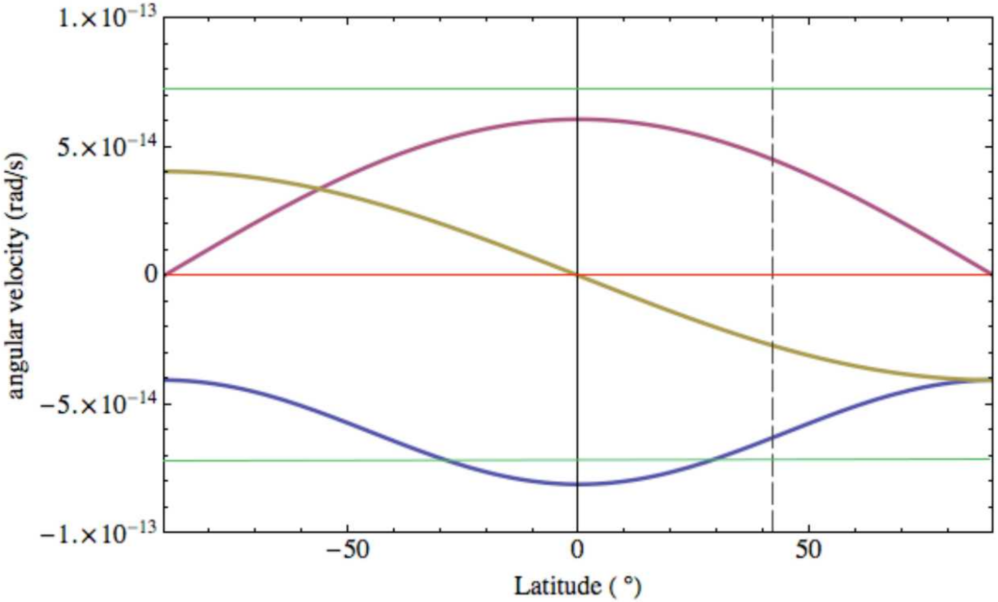
"The axis of a ***gyroscope*** will *precess following the curvature of the* ***local*** *space-time due to:* ***Earth's Mass*** *(Geodetic precession) and* ***Earth's Rotation*** *(Lense-Thirring or Frame Dragging)"*



Results in Space : Lageos+GRACE & Lares, Gravity Probe B

..on ground with a laser Gyroscope

$$\delta\vec{\Omega} \simeq \boxed{\underbrace{\frac{GM}{c^2 R}\Omega_E \sin\theta\, \hat{e}_\theta}_{6.98\, 10^{-10}\,\Omega_E}} + \boxed{\underbrace{\frac{G}{c^2 R^3} J_E \Omega_E [\hat{j}_E - 3(\hat{j}_E \cdot \hat{u}_r)\hat{e}_r]}_{2.31\cdot 10^{-10}\,\Omega_E}}$$



Relativistic corrections are on the meridian plane and depend on the latitude of the laboratory

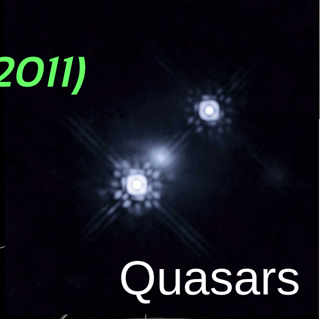
🟪 $\delta\vec{\Omega}\cdot\vec{u}_r$ (radial)

🟦 $\delta\vec{\Omega}\cdot\vec{u}_E$ (Earth axis)

🟨 $\delta\vec{\Omega}\cdot\vec{u}_{NS}$ (north-south)

GINGER motivation

F. Bosi et al., Phys. Rev. D 84, (2011)

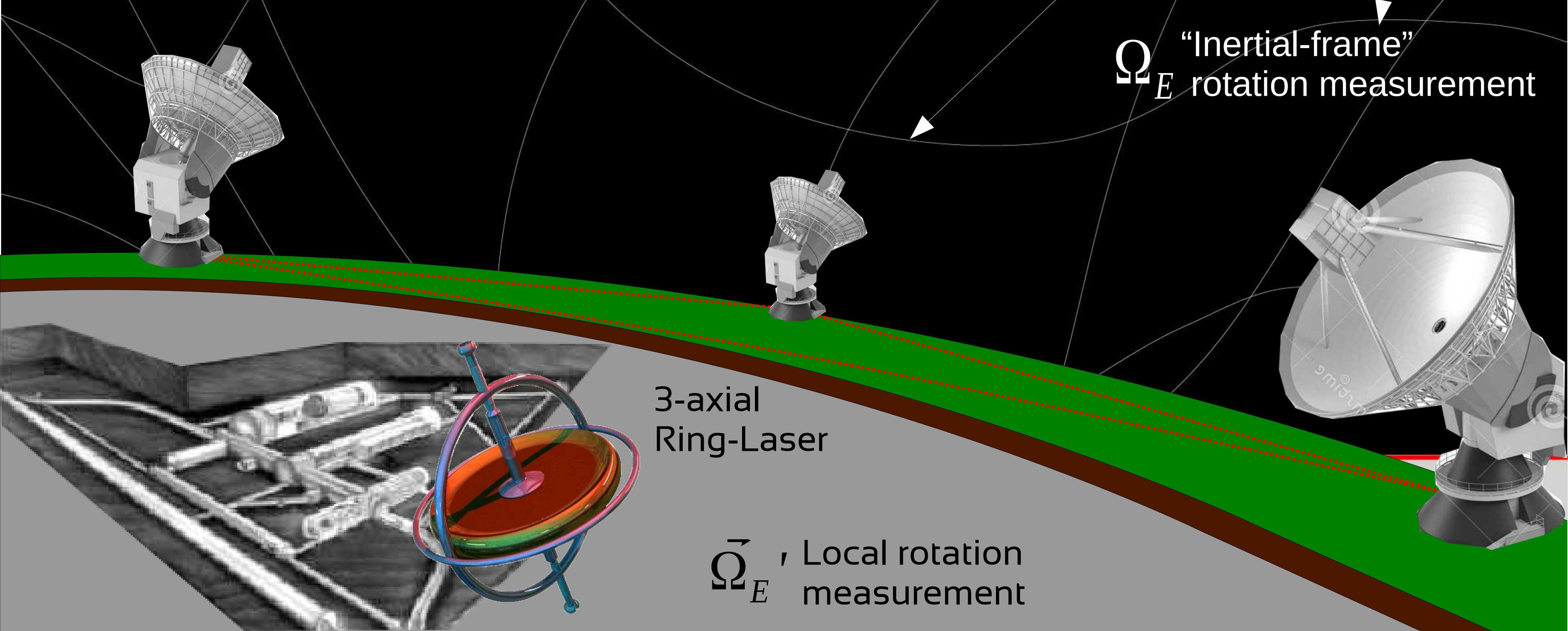


Satellites are in geodetic motion (free fall),
while in ground laboratory the observer is in a non inertial motion

Metric is tested on different length scales (planetary → meter-scale)

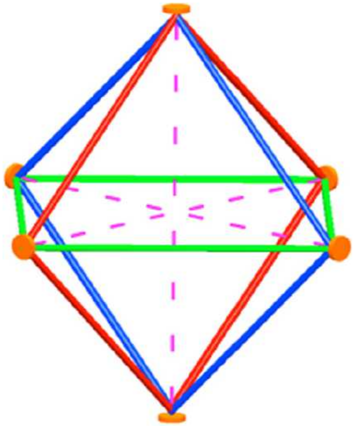
The apparatus is more accessible in a terrestrial laboratory
(the experiment can be repeated)

Different interpretation, no need of gravitational field models



GINGER key-points

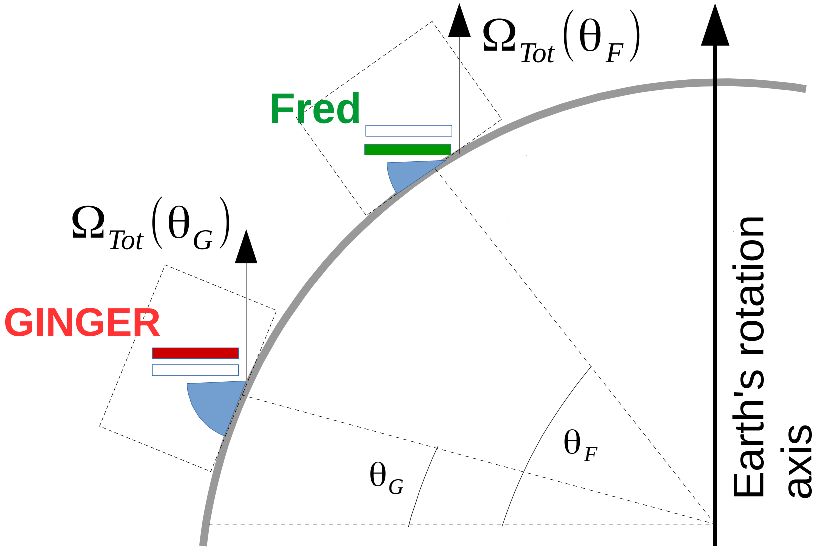
Multi axial approach



- **Measure vector modulus + direct comparison with IERS**
- Use one shared-mirrors octahedral array
- Minimize laser dynamics non-reciprocal effects (L>6m)+**modeling**

Multi site approach

- Exploit the dependence of GR terms on the **latitude (differential measurement)**
- Use **2 TWIN RINGS** oriented at the maximum signal at different latitudes
- **Calibrate the 2 TWIN RINGS** when located at the same latitude (only mirrors defects)



Requirements

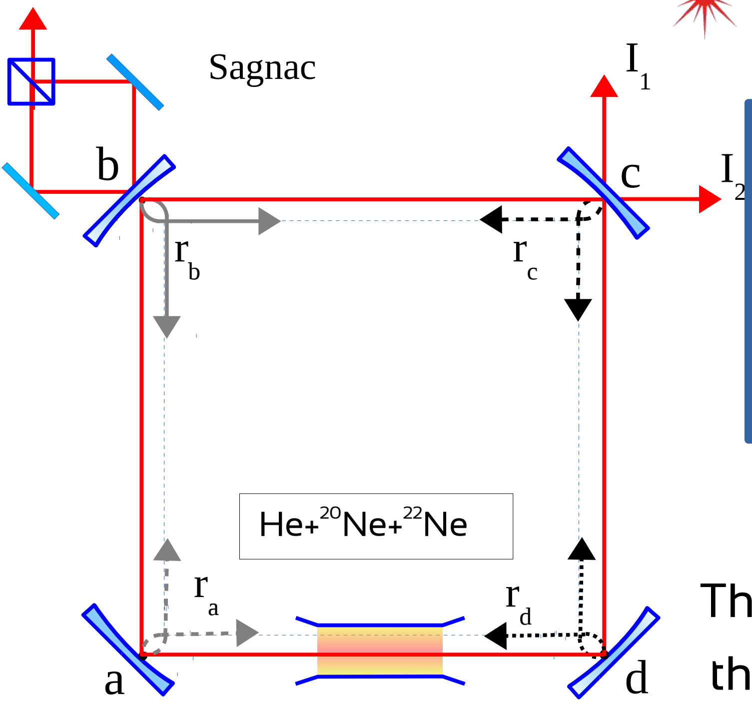
$$f_{Si}=\boxed{\frac{4A_i}{P_i\lambda_i}}_{\text{Si}}\vec{\Omega}\cdot\hat{n}_i+syst.\qquad\frac{|\delta f_{Si}|}{|f_i|}<10^{-10}$$

Systematics are diluted if L>6 m

Strong requirements on GEOMETRY

Underground laboratory → low rotational noise

Ring Laser dynamics



Opposite beams coupled dynamics

$$\dot I_1 = \alpha_1 I_1 - \beta I_1^2 - \theta_2 I_2 I_1 + r_2\sqrt{I_1 I_2}\cos(\psi-\epsilon_1)\ ,$$

$$\dot I_2 = \alpha_2 I_2 - \beta I_2^2 - \theta_1 I_2 I_1 + r_1\sqrt{I_1 I_2}\cos(\psi+\epsilon_2)\ ,$$

$$\dot\psi = \omega_s + \underbrace{\tau_1 I_1 - \tau_2 I_2}_{\text{Non reciprocal dispersion}} \underbrace{- r_2\sqrt{\frac{I_2}{I_1}}\sin(\psi-\epsilon_2) - r_1\sqrt{\frac{I_1}{I_2}}\sin(\psi+\epsilon_1)}_{\text{Backscattering}}$$

The backscattering parameters $r_1, r_2, \epsilon_1, \epsilon_2$ depend on the **interference of back scattered waves** (amplitude and phases)

Critical! 1) position and shape of the **laser finger-print on the mirror** ☹

2) **interdistances** between the scattering centers ☹

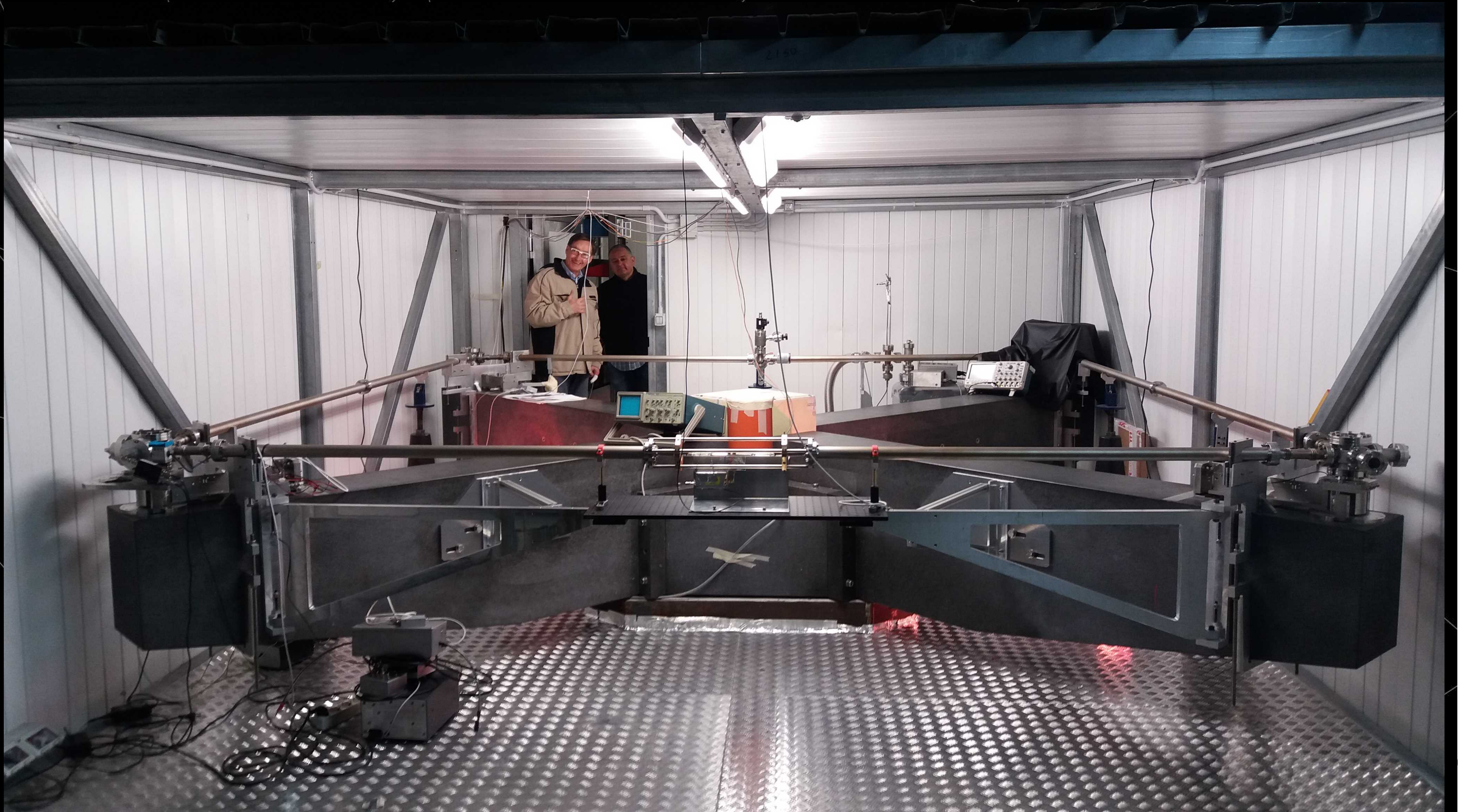
BUT

- In small rings, backscattering can be estimated (and subtracted)! ☺
- In large rings (L>4m and excellent mirrors) cavities (linewidth<f_s) backscattering is out of resonance ☺

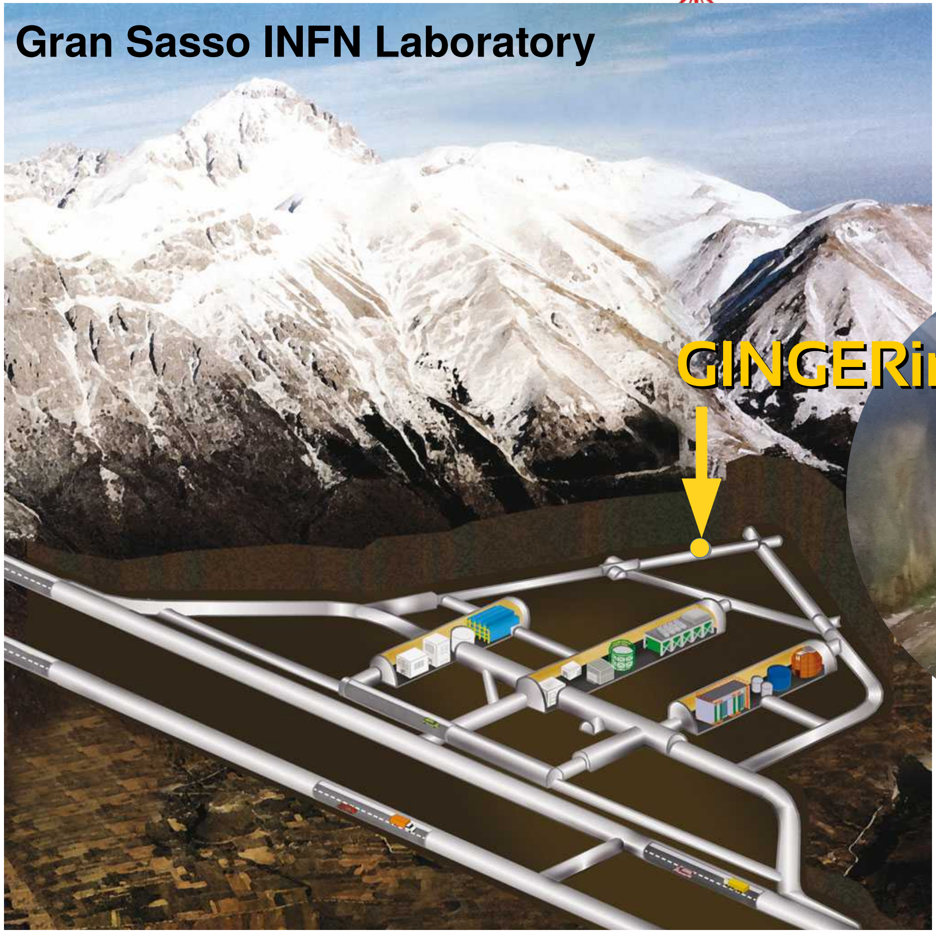
Beam path geometry is the ultimate limit to stability

GINGERino: deep underground ring laser

He-Ne laser at 633 nm
Square cavity, L=3.6 m, Mirrors r.o.c= 4 m
Earth rotation Sagnac bias: **fs=280.4 Hz**



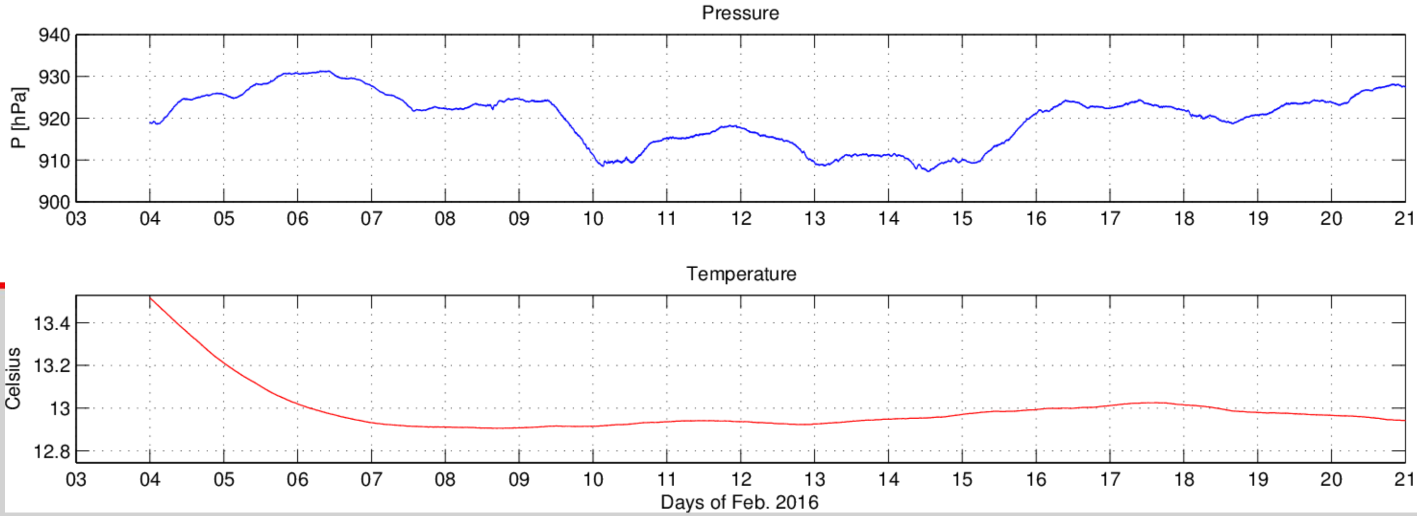
Installation site

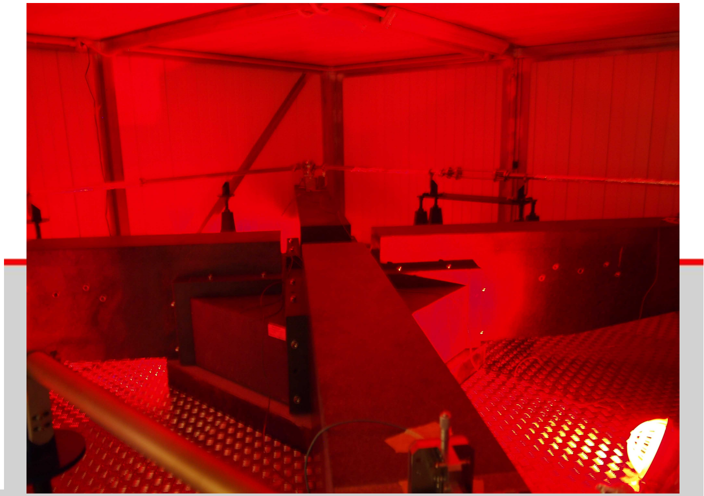


- The laboratory is located beneath **1 km of rock**, Isolated from the other experiments

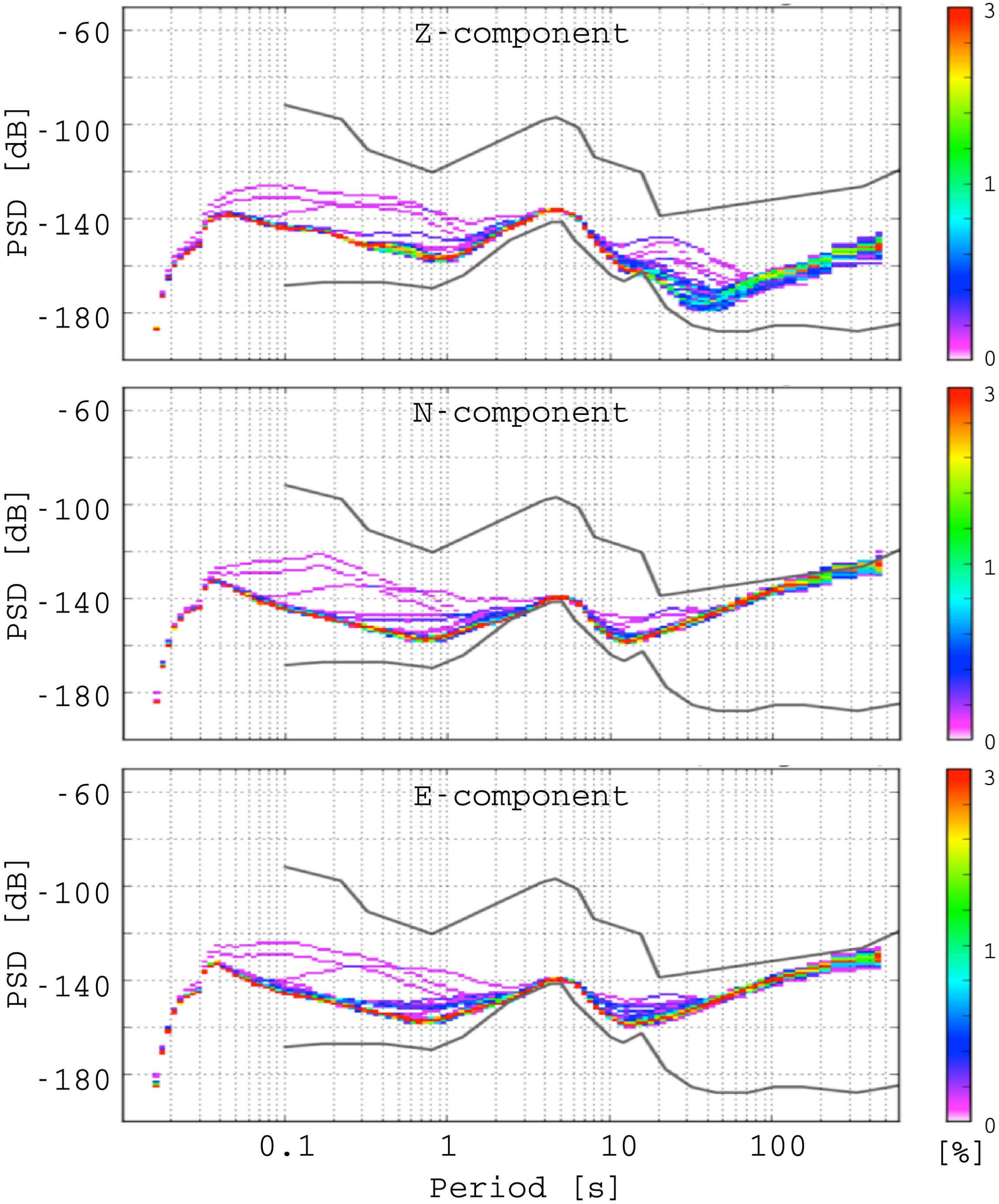
- Natural conditions:
T=8 °C, Relative humidity>90%

- **TEMPERATURE** increased by IR-lamps
Tint:--> 13°C, relative humidity--> 60%



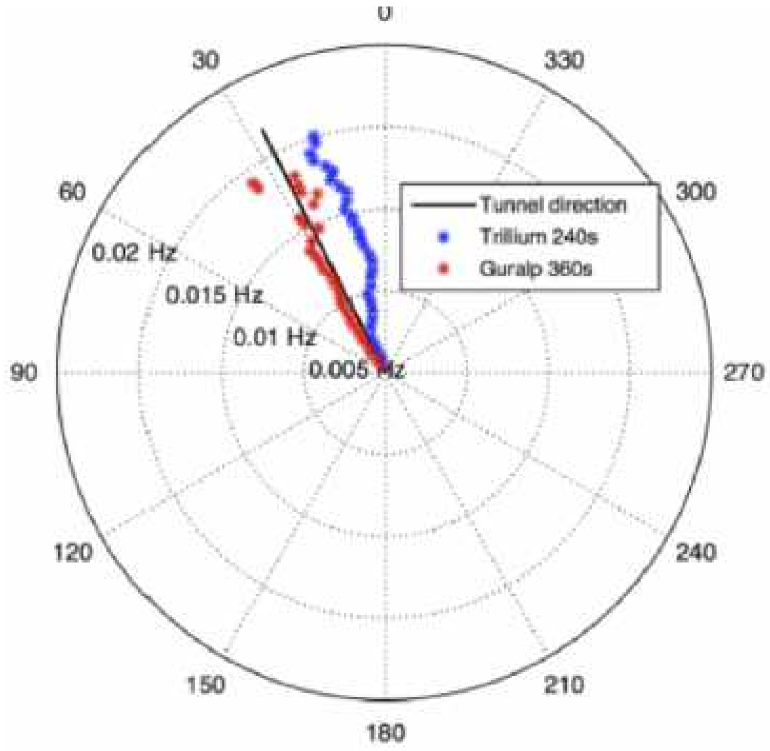


Seismic noise

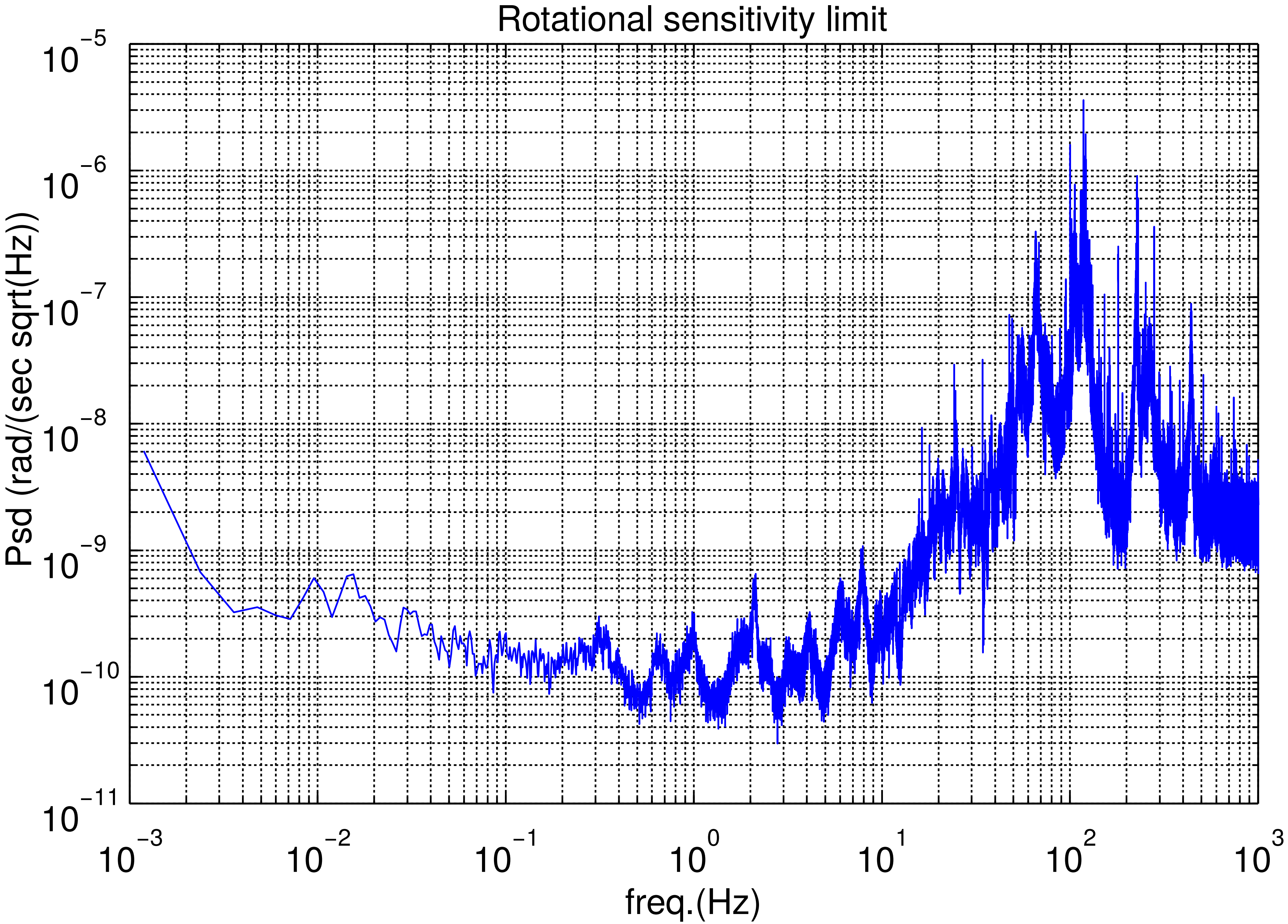


Flicker noise at long periods (east and north):

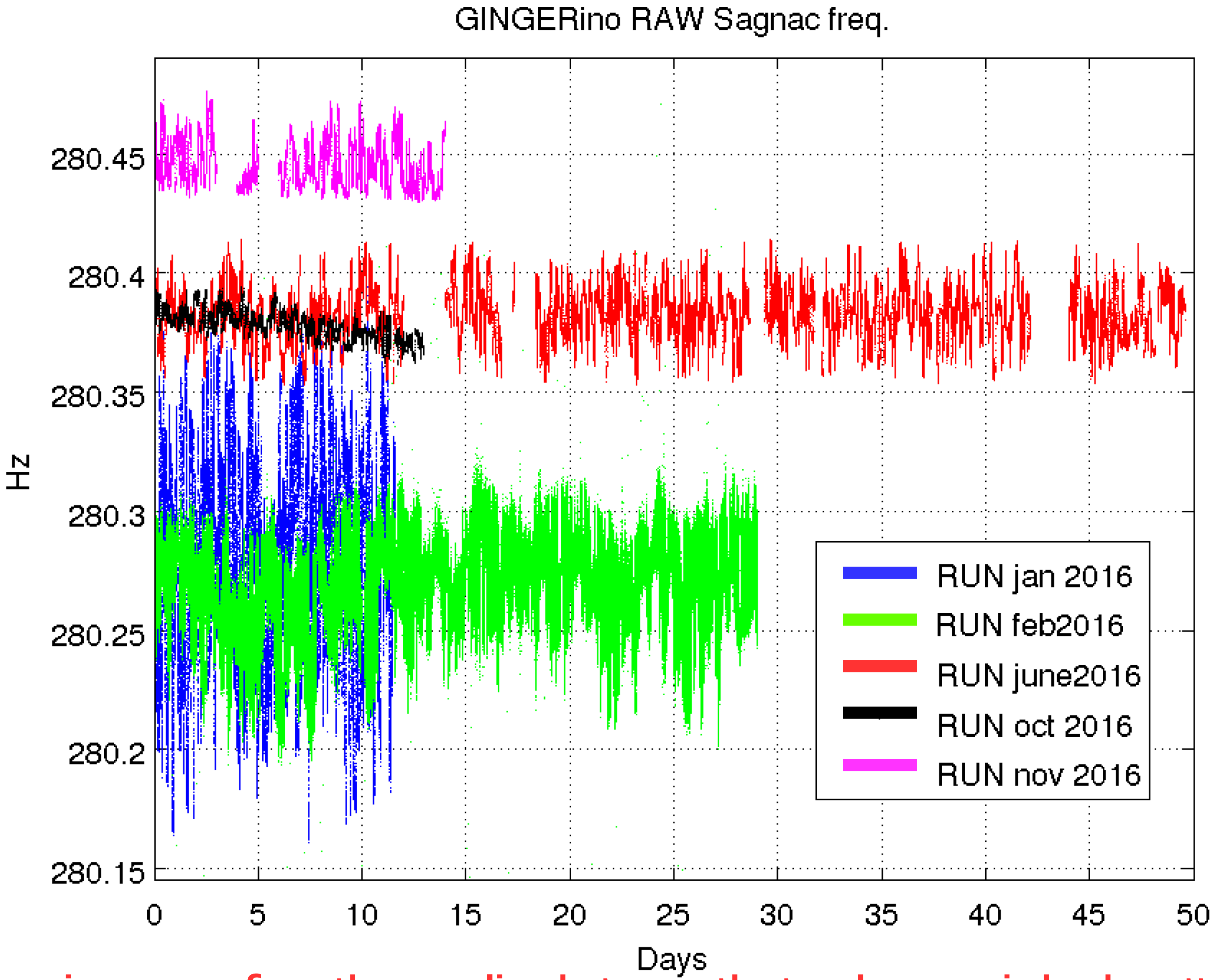
- Propagates along the tunnel direction
- Possibly related to strong pressure variations.
- Better isolation from the experimental halls will help. Pressure tight doors.



Rotational noise (raw data)



GINGERino raw data



Excess noise comes from the coupling between the two beams via backscattering/losses

Present Shot-noise limit: $\Omega_{SN} = 4 \cdot 10^{-10} \, rad/(s\sqrt{Hz})$

[Expected: <u>tenfold</u> improvement with best quality supermirrors]

Data processing

Acquired optical signals (5 kS/s)

S(n) =	Sagnac
I1(n) =	CCW monobeam
I2(n)=	CW monobeam
G(n) =	Excitation level

Power Control

Analog PI circuit
stabilizes the I2 (t >1 s)

Backscattering correction

Identified parameters

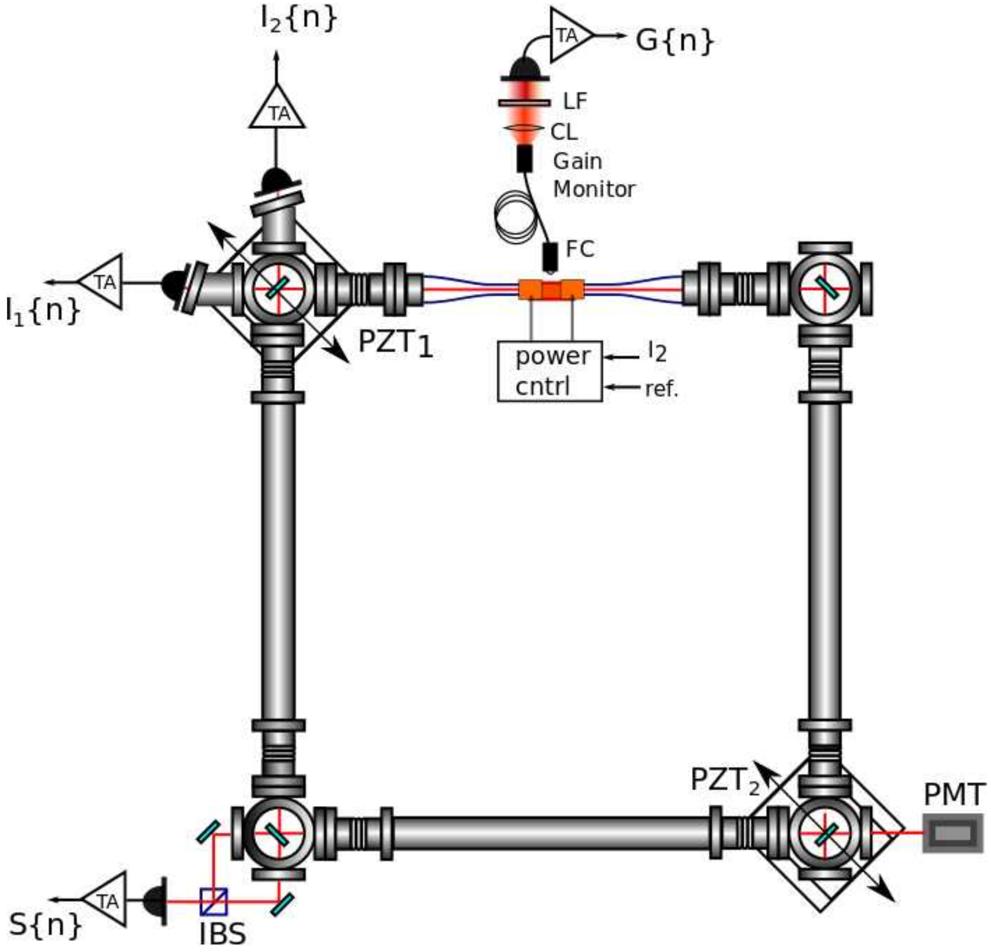
$$\widehat{r_1} = \frac{i_2\omega}{2(c/L)\sqrt{I_1 I_2}}$$

$$\widehat{r_2} = \frac{i_1\omega}{2(c/L)\sqrt{I_1 I_2}}$$

$$\widehat{\varepsilon} = \frac{\phi_1 - \phi_2}{2}$$

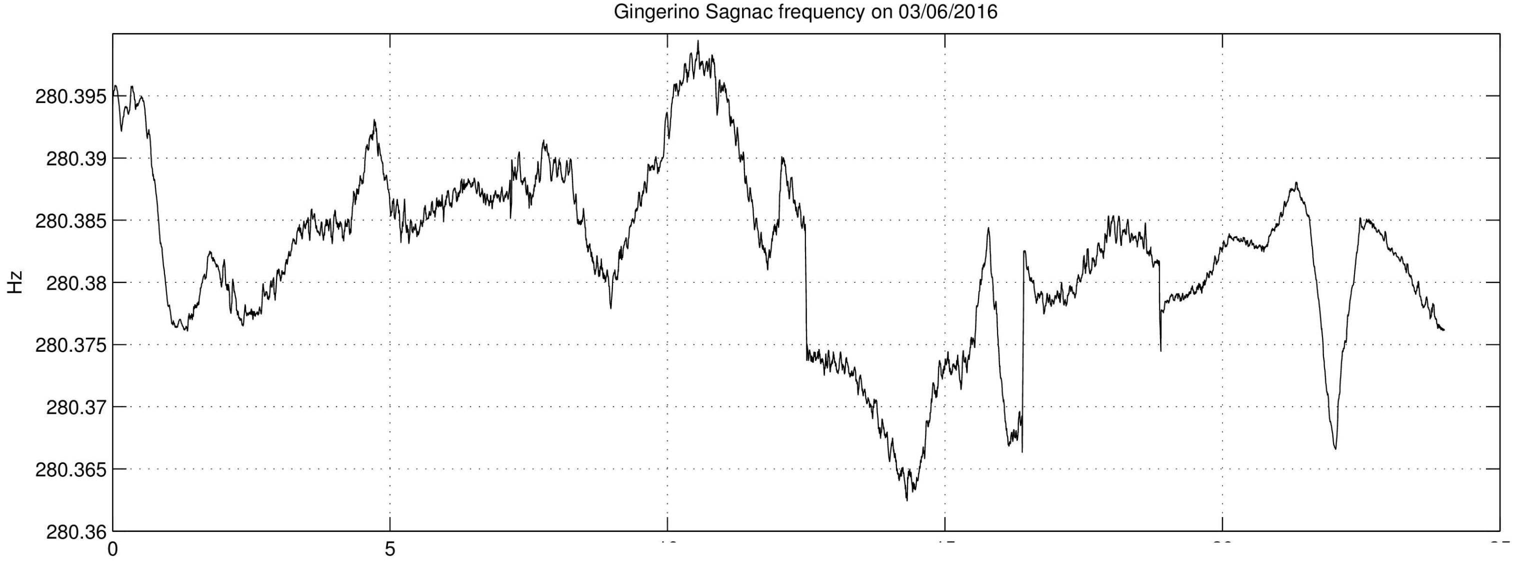
A. Beghi et al. Applied Optics 51, 31 (2012)

D. Cuccato et al. Metrologia 51, 97, (2014)



$$\begin{cases} \mathcal{I}_1(t) \simeq \frac{\alpha_1}{\beta} + 2r_2\sqrt{\alpha_1\alpha_2}\frac{\alpha_1\cos(\varepsilon+\omega_s t) + (\frac{\omega_s}{c/L})\sin(\varepsilon+\omega_s t)}{\beta\left(\alpha_1^2 + (\frac{\omega_s}{c/L})^2\right)} - 2\frac{r_1 r_2 (c/L)}{\beta\omega_s}\sin(2\varepsilon) \\ \mathcal{I}_2(t) \simeq \frac{\alpha_2}{\beta} + 2r_1\sqrt{\alpha_1\alpha_2}\frac{\alpha_2\cos(\varepsilon-\omega_s t) - (\frac{\omega_s}{c/L})\sin(\varepsilon-\omega_s t)}{\beta\left(\alpha_1^2 + (\frac{\omega_s}{c/L})^2\right)} + 2\frac{r_1 r_2 (c/L)}{\beta\omega_s}\sin(2\varepsilon) \\ \Psi(t) \simeq (\omega_s - \frac{2r_1 r_2 (c/L)^2\cos(2\varepsilon)}{\omega_s})t + (c/L)\frac{r_1\sqrt{\frac{\alpha_1}{\alpha_2}}\cos(\varepsilon-\omega_s t) + r_2\sqrt{\frac{\alpha_2}{\alpha_1}}\cos(\varepsilon+\omega_s t)}{\omega_s} \end{cases}$$

Example: 24 h backscattering correction


Gingerino Sagnac frequency on 03/06/2016

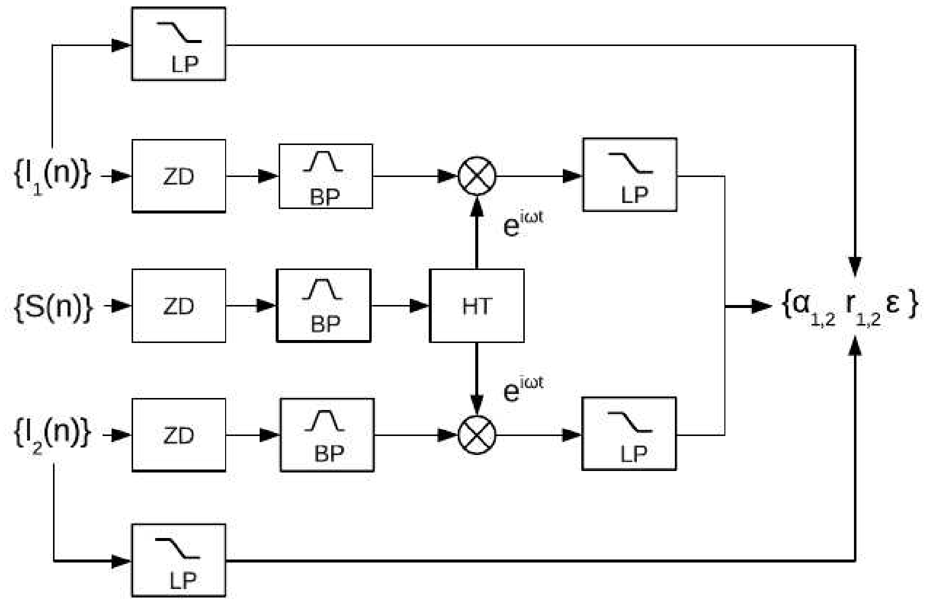
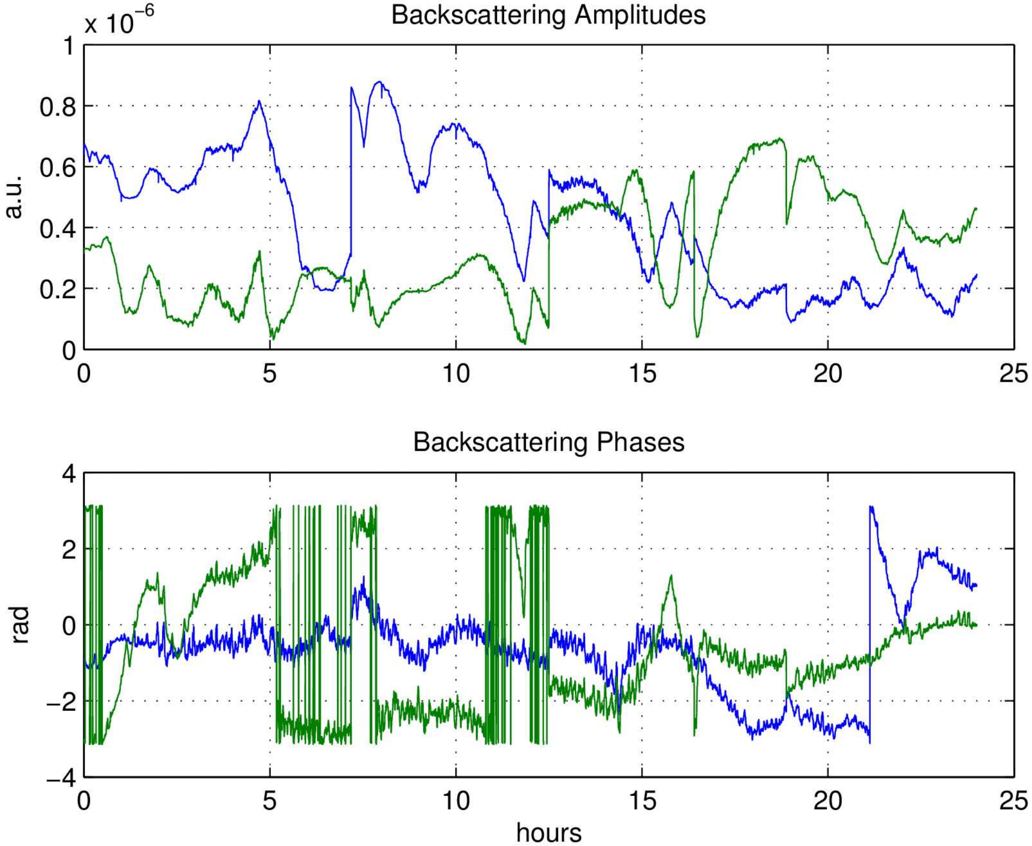
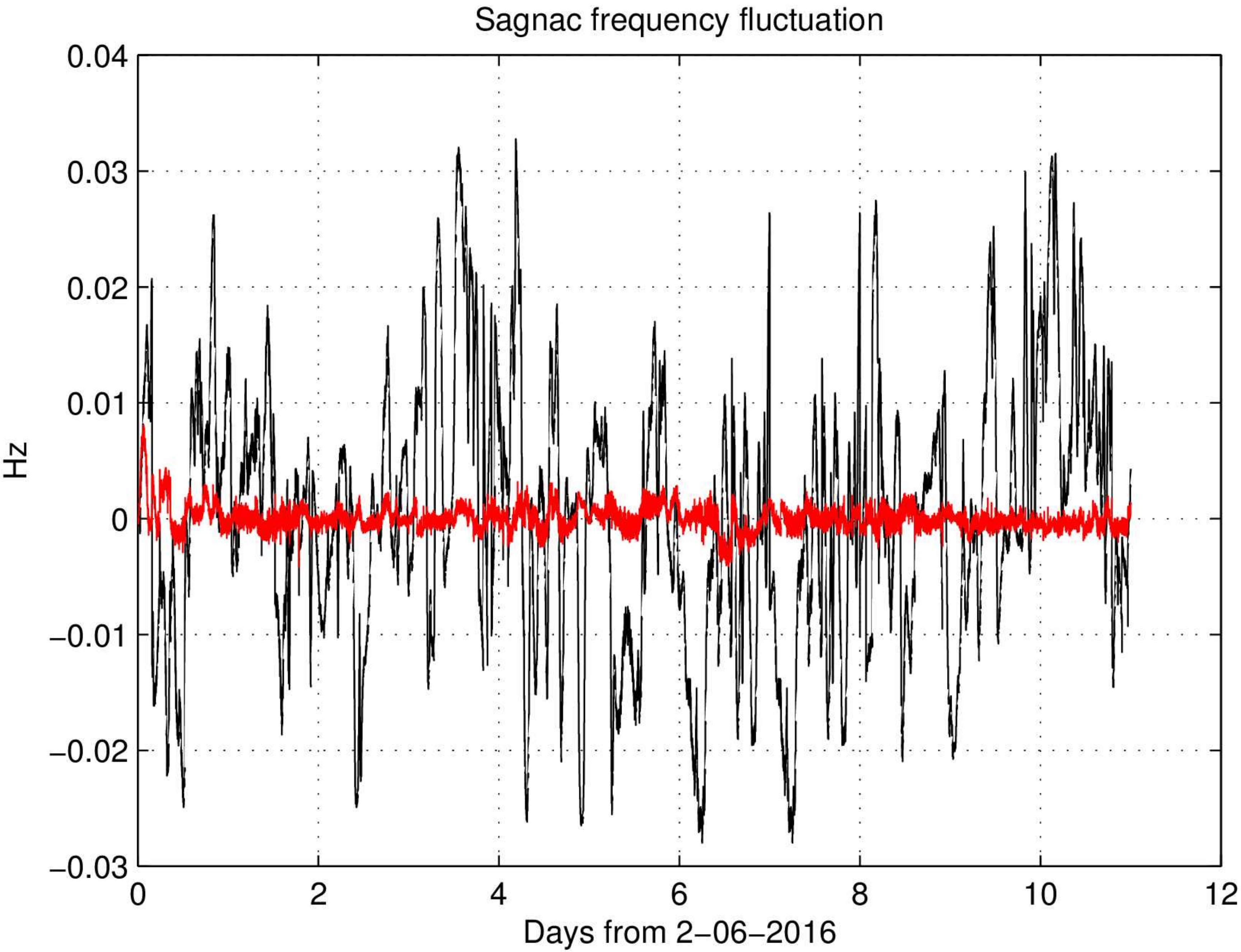


Fig. 3. Schematic of the parameter estimation procedure. LP, lowpass Butterworth filter; BP, bandpass Butterworth filter; ZD, zoom and decimation routine; HT, Hilbert transform (see text).

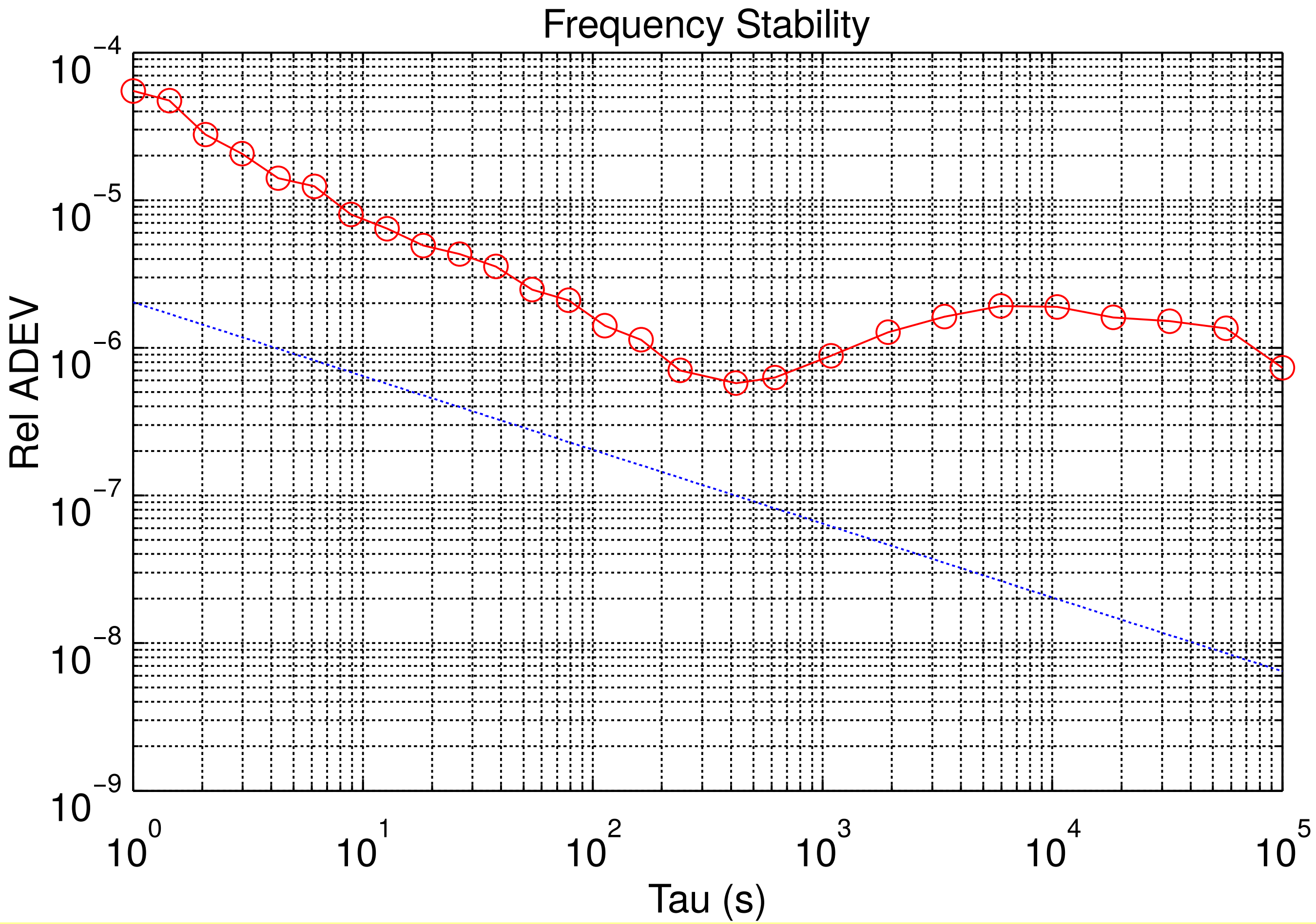

Backscattering Amplitudes

Backscattering Phases

Long period observations 2-13 june 2016



Long period observations 2-13 june 2016



Maximum resolution: 0.6 ppm at 500 s of integration time → **30 p rad/s**

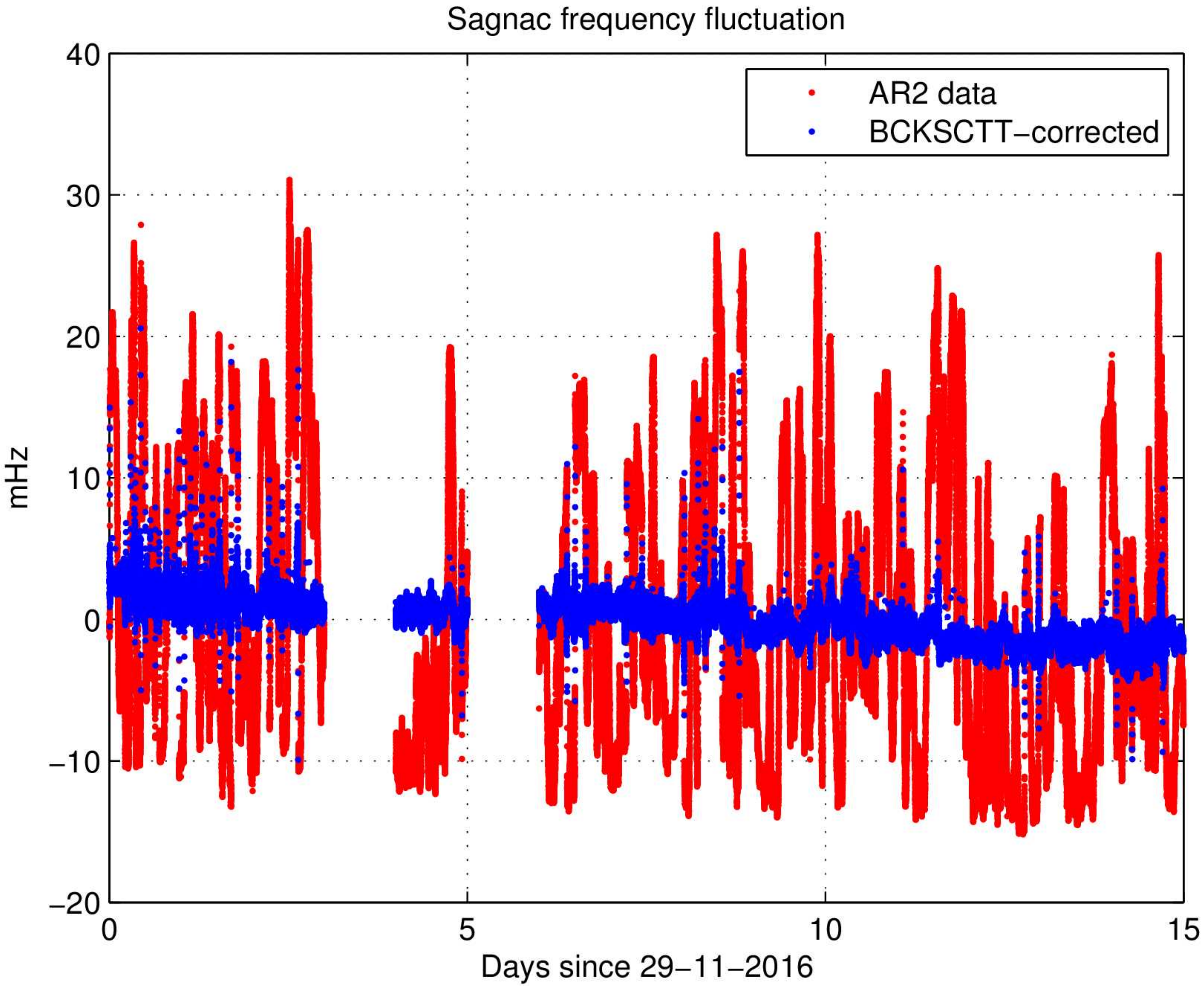
Noise limits:

-Laser optical frequency fluctuations

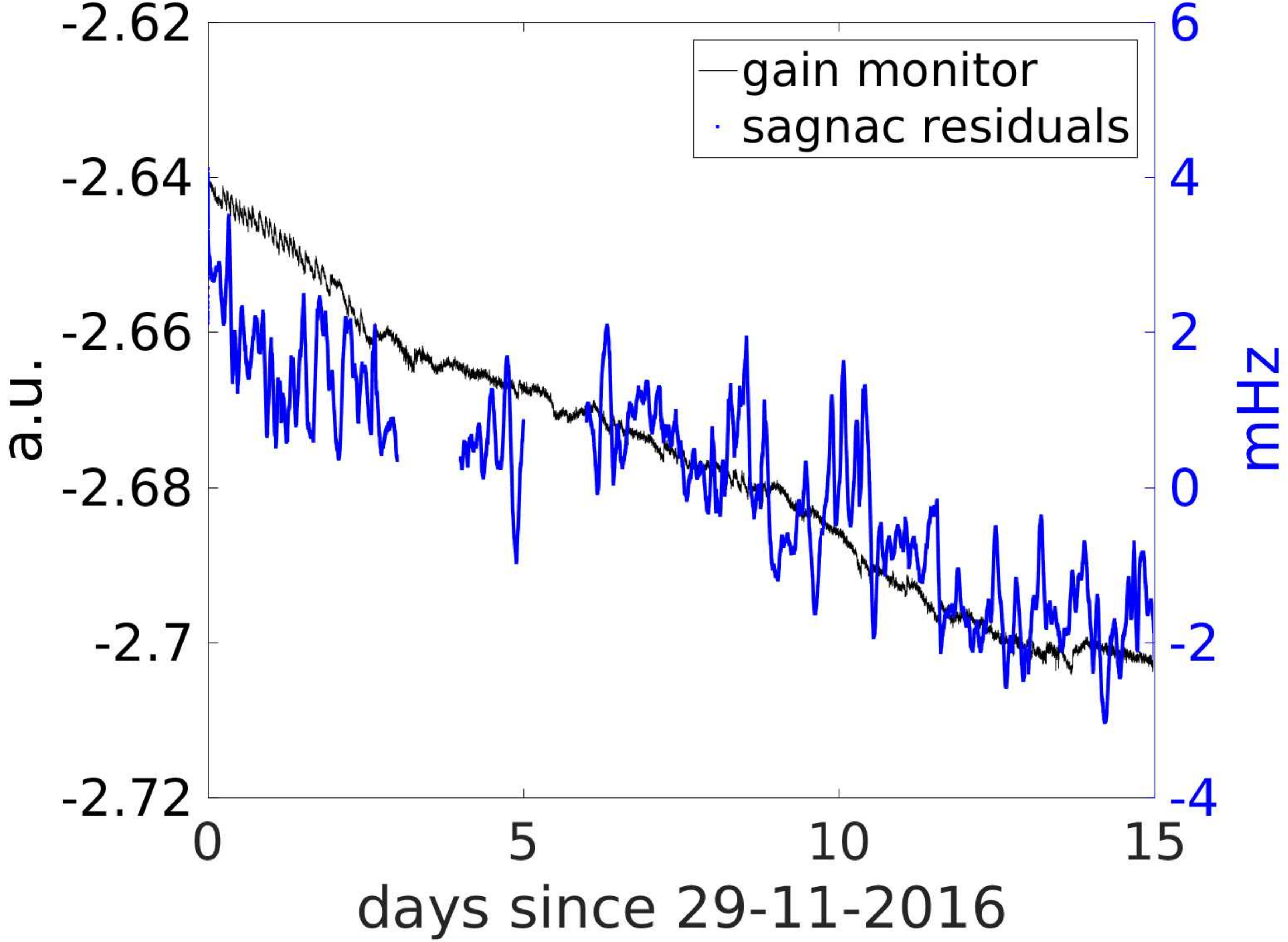
-Residual fluctuation in the ambient temperature and pressure

-Local Tilts (to be investigated)

Preliminary analysis of the November 2016 RUN



Losses monitor and Sagnac residuals

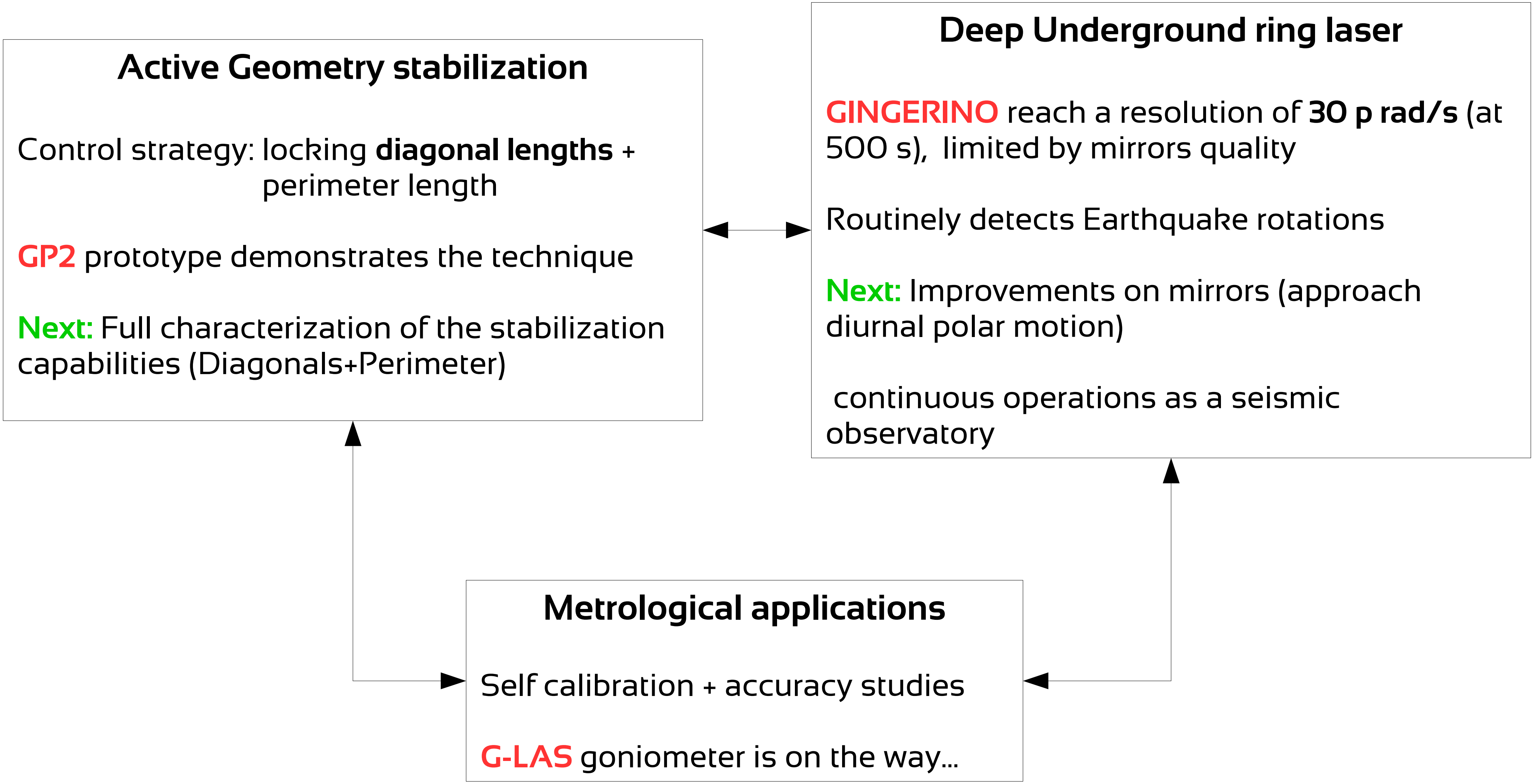


Present stability determination is in progress…

Conclusion

RING laser gyros are approaching the resolution of **$10^{-9}\Omega_E$** (impact on GEODESY)

Ground based Tests of GR are under study
(**Multi axial / Multi-site** approach are considered)



Active Geometry stabilization

Control strategy: locking **diagonal lengths** + perimeter length

GP2 prototype demonstrates the technique

Next: Full characterization of the stabilization capabilities (Diagonals+Perimeter)

Deep Underground ring laser

GINGERINO reach a resolution of **30 p rad/s** (at 500 s), limited by mirrors quality

Routinely detects Earthquake rotations

Next: Improvements on mirrors (approach diurnal polar motion)

continuous operations as a seismic observatory

Metrological applications

Self calibration + accuracy studies

G-LAS goniometer is on the way…