

Recent Progress in Sagnac Interferometry: Ring lasers in Geodesy

Dr Bob Hurst

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UOC:

Jon-Paul Wells
Bob Hurst
Geoff Stedman
Rob Thirkettle
Nishanthan Rabeendran
John Holdaway
Clive Rowe
(Richard Graham)

TUM-BKG:

Ulli Schreiber
Thomas Klugel
Andre Gebauer
(Alex Velikoseltsev)

Associations with:

University of Pisa

Outline

- Theoretical basis
- (brief) History of the collaboration
- Current activities
- Future ambitions

Sagnac Effect

The fundamental effect:

For an optical system with a bi-directional path that encloses an area A , and rotating rigidly in inertial space at rate Ω , there is a **time difference** between two light signals travelling in opposite directions:

$$\Delta t = 4A \cdot \Omega / c^2$$

(True in both an ether-theoretic picture and according to Special Relativity.)

In a **passive** interferometer, the time difference appears as a **phase difference**:

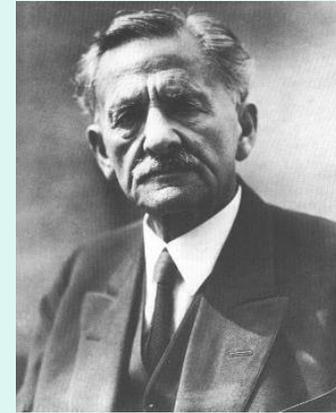
$$\Delta \phi = 8\pi A \cdot \Omega / (\lambda c)$$

Demonstrated in 1913 by Georges Sagnac, trying to show existence of ether.

Passive Sagnac Interferometry: Michelson-Gale experiment (1925)

(38 years after the more famous Michelson–Morley experiment.)

“Well, gentlemen, we will undertake this, although my conviction is strong that we shall prove only that the earth rotates on its axis, a conclusion which I think we may be said to be sure of already.”



- ◇ Motivated by speculations on ether-motion-related effects
 - ◇ Rectangular Sagnac interferometer, 612 m x 339 m
 - ◇ Built from 12-inch evacuated sewer pipe
 - ◇ Observed just the fringe shift expected from earth rotation
- *Astrophysical Journal*, **61**, pp137-145 (1925)

Active Sagnac interferometry

Build a **ring laser cavity** (may actually be triangular or square);

The phase difference now results in an **optical frequency difference** between the two directions:

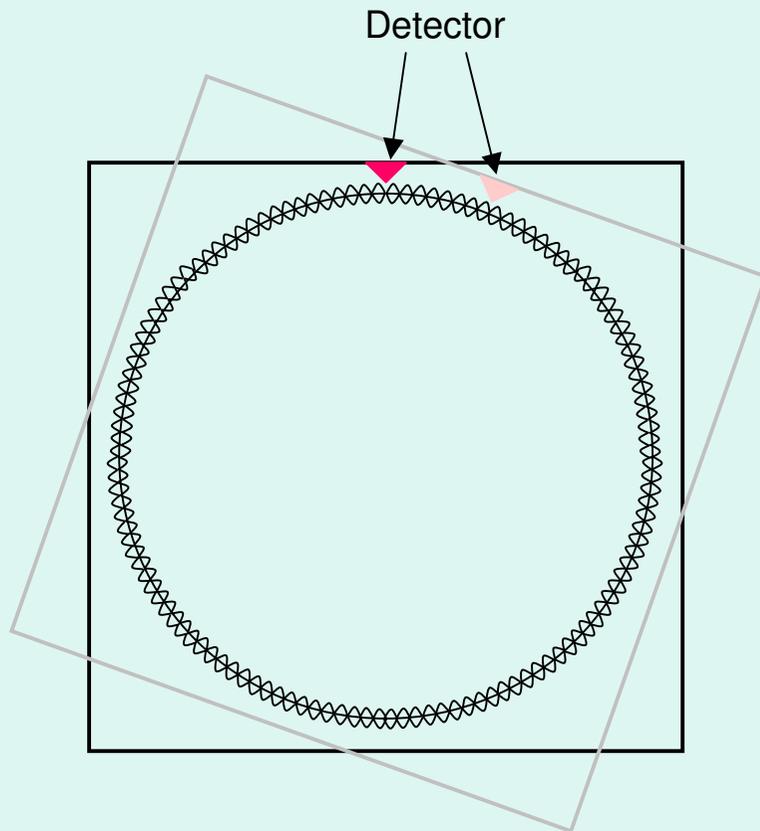
The diagram shows the equation for Sagnac frequency difference, $\delta f = \frac{4 A \Omega \cos \theta}{\lambda P}$. Callout boxes identify the variables: 'Area enclosed' points to A , '(Earth) rotation rate' points to Ω , 'Angle between rotation axis and gyro axis' points to θ , 'Sagnac frequency' points to δf , and 'Perimeter' points to P .

$$\delta f = \frac{4 A \Omega \cos \theta}{\lambda P}$$

We can measure this optical frequency difference as a beat frequency, by mixing the two beams at one of the corners.

Can measure variations in Ω or in $\cos \theta$

Ring Laser Gyros: 'Intuitive' description:

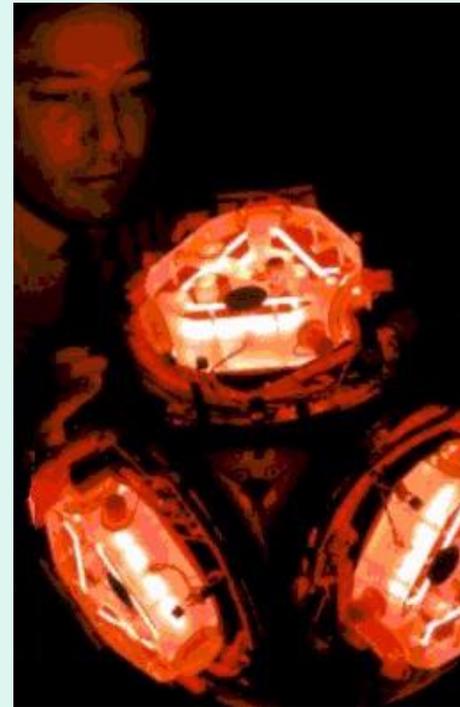
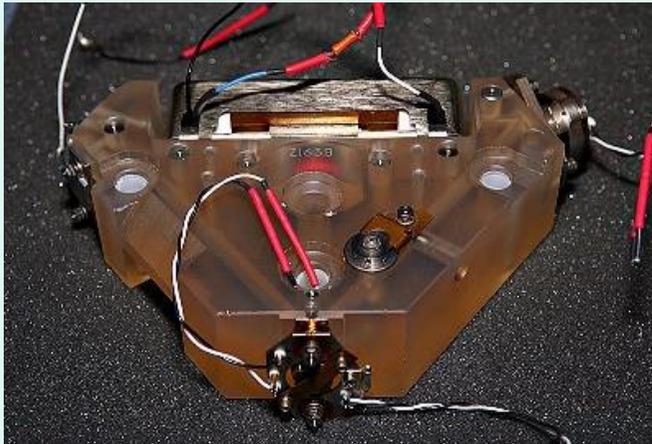


'Necklace' model:

- ◇ Imagine light following circular path in both directions;
- ◇ Creates a standing wave.
- ◇ In absence of rotation, standing wave is fixed in laboratory frame.
- ◇ When laboratory is rotated, standing wave remains fixed in inertial space.
- ◇ Sagnac signal detected as movement of detector relative to standing wave.

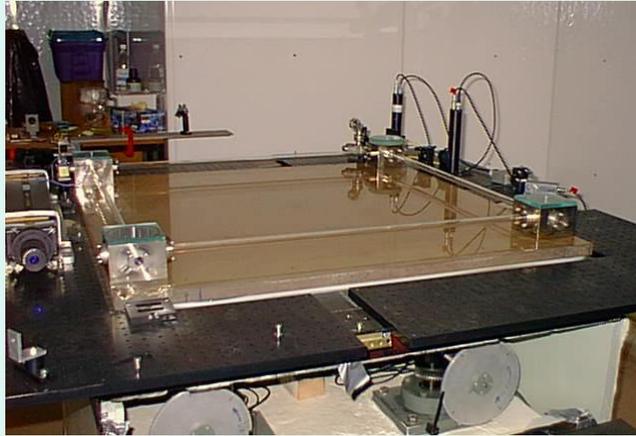
Ring Laser Gyros for navigation systems

- Developed very promptly after demo of first rotation-sensing ring laser by Macek and Davis (1963)
- First uses were military, by now used in many modern airliners



Big Ring Lasers for Earth-rotation measurements:

Early development work at University of Canterbury, New Zealand:



C-I laser (~1992) 0.85 m square

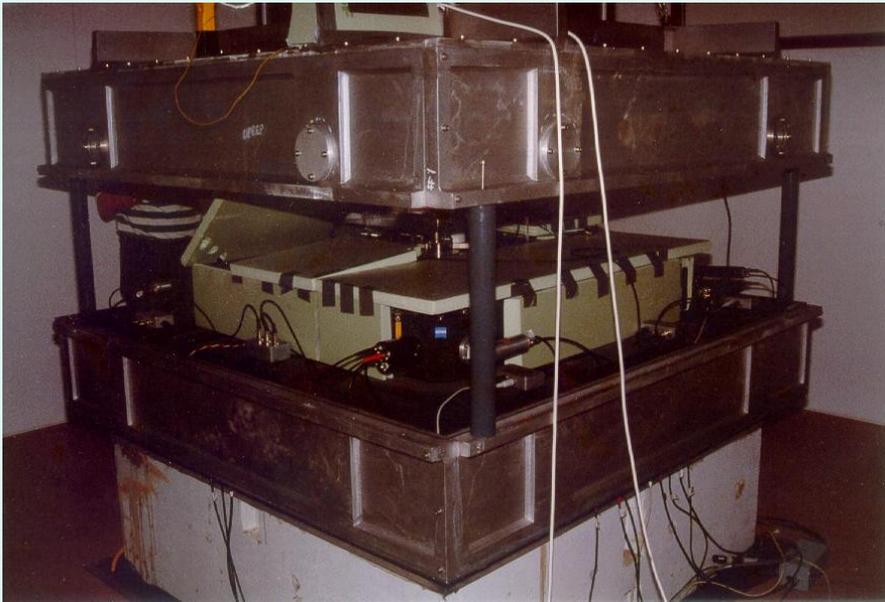
Operated in department building, then transferred to Cashmere Cavern

Early photos in Cashmere cavern

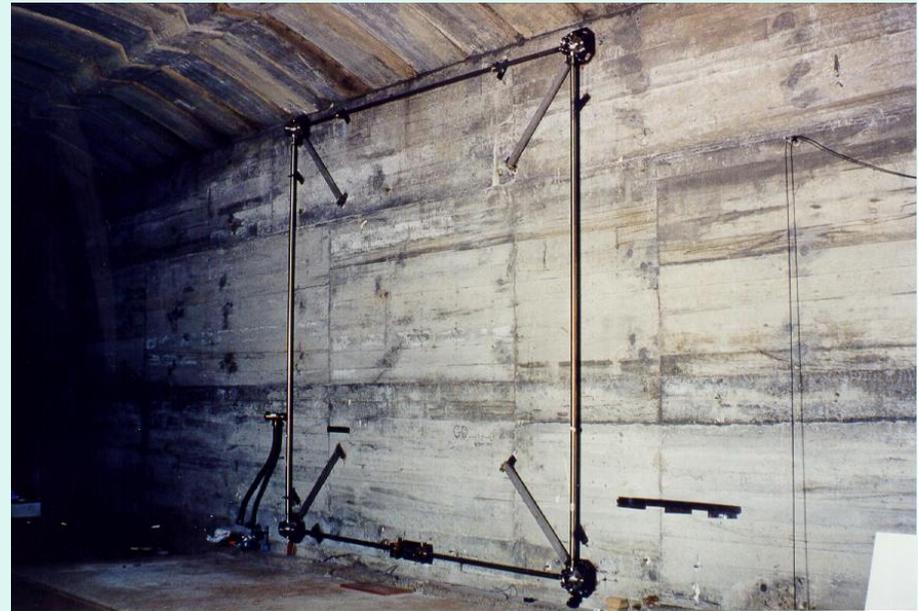


Following C-I, increasingly large ring lasers were built in reasonably quick succession.

C-II 1997, 1 m x 1 m



G-0 1999, 3.5.m square



(Intended as engineering prototype for "G" laser in Germany.)

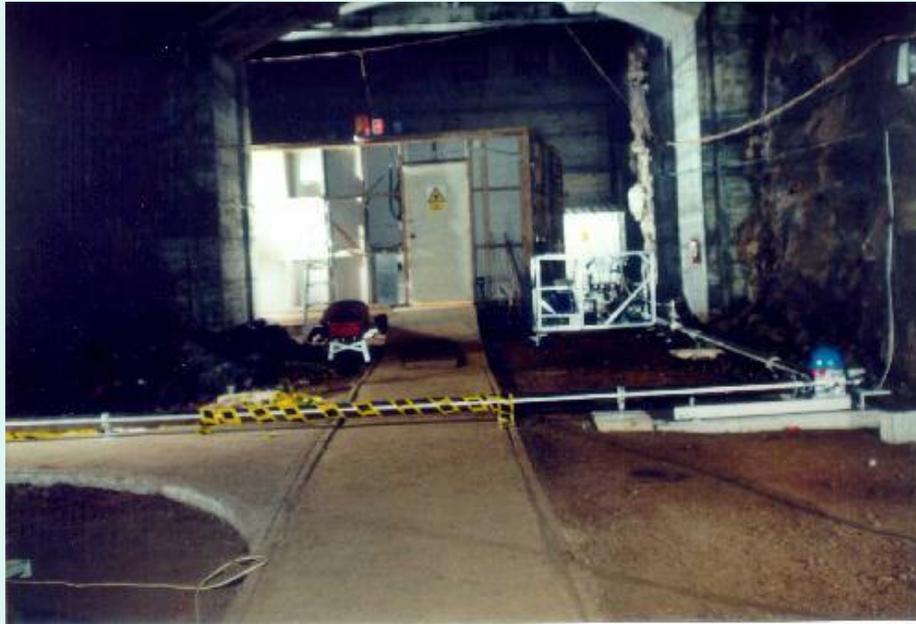
'G' (Grossring)

(Wettzell) 2001 4 m square.



UG-1-2-3

(Cashmere)



UG-1: 2001, 17.5 m x 21 m

UG-2: 2004, 21 m x 39.7 m

UG-3: 2009, 17.5 m x 21 m

UG-3 is to our knowledge the world's largest operating ring laser.



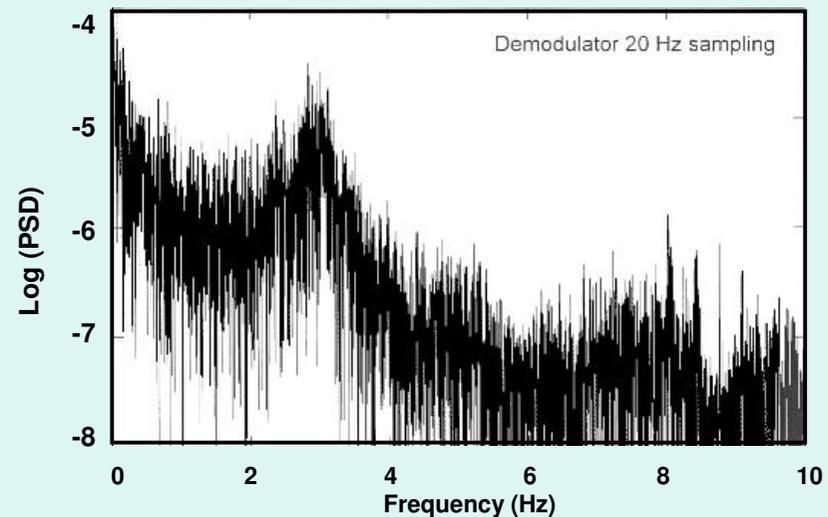
'Family' of 3 GEOSENSOR lasers:

University of Canterbury
Pinon Flat (California)
University of Pisa

Smaller (1.6.m square), versatile configuration, for miscellaneous studies



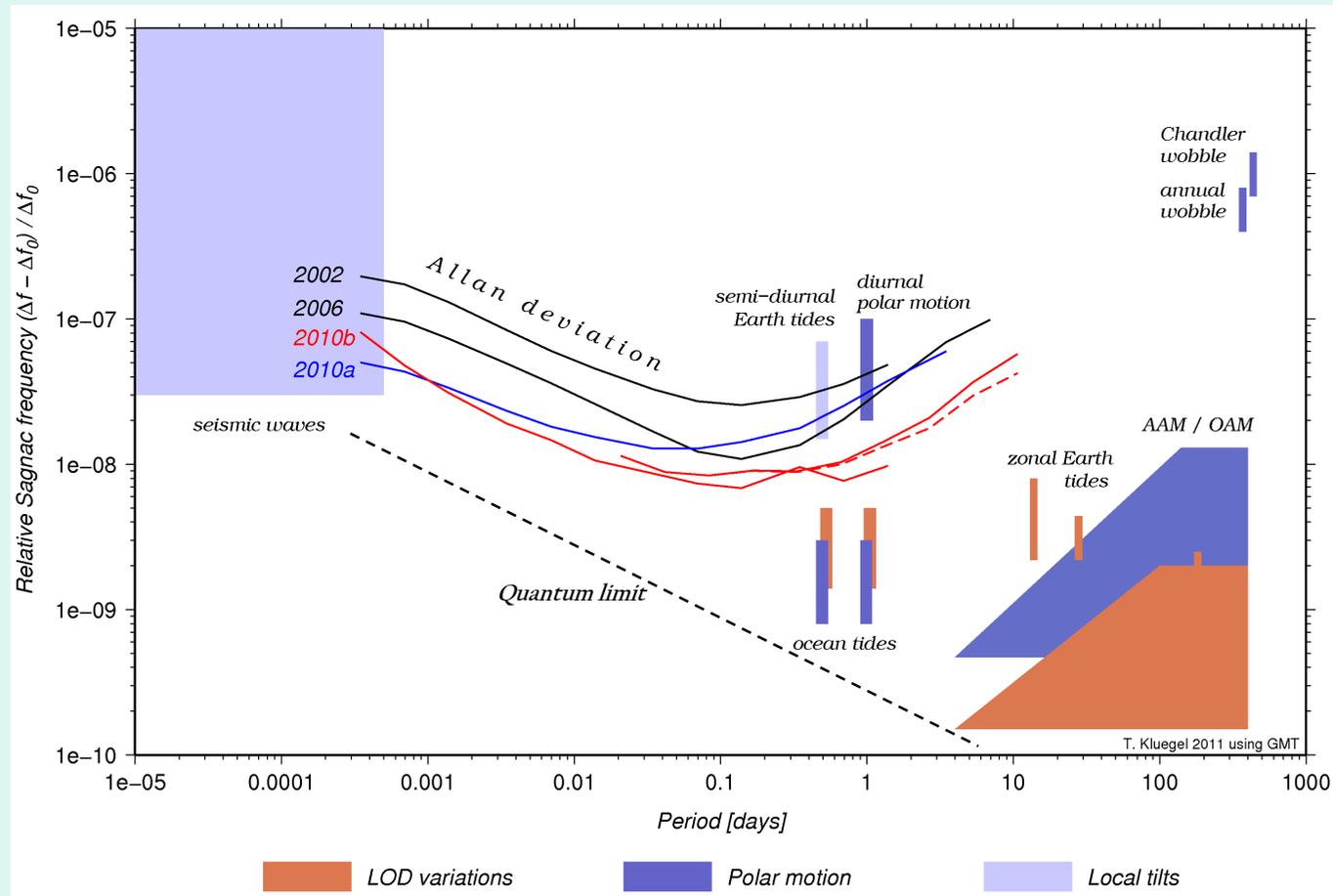
Building resonance shown by the PR-1
GEOSensor in Physics Department,
University of Canterbury



Summary of progress: 'G'

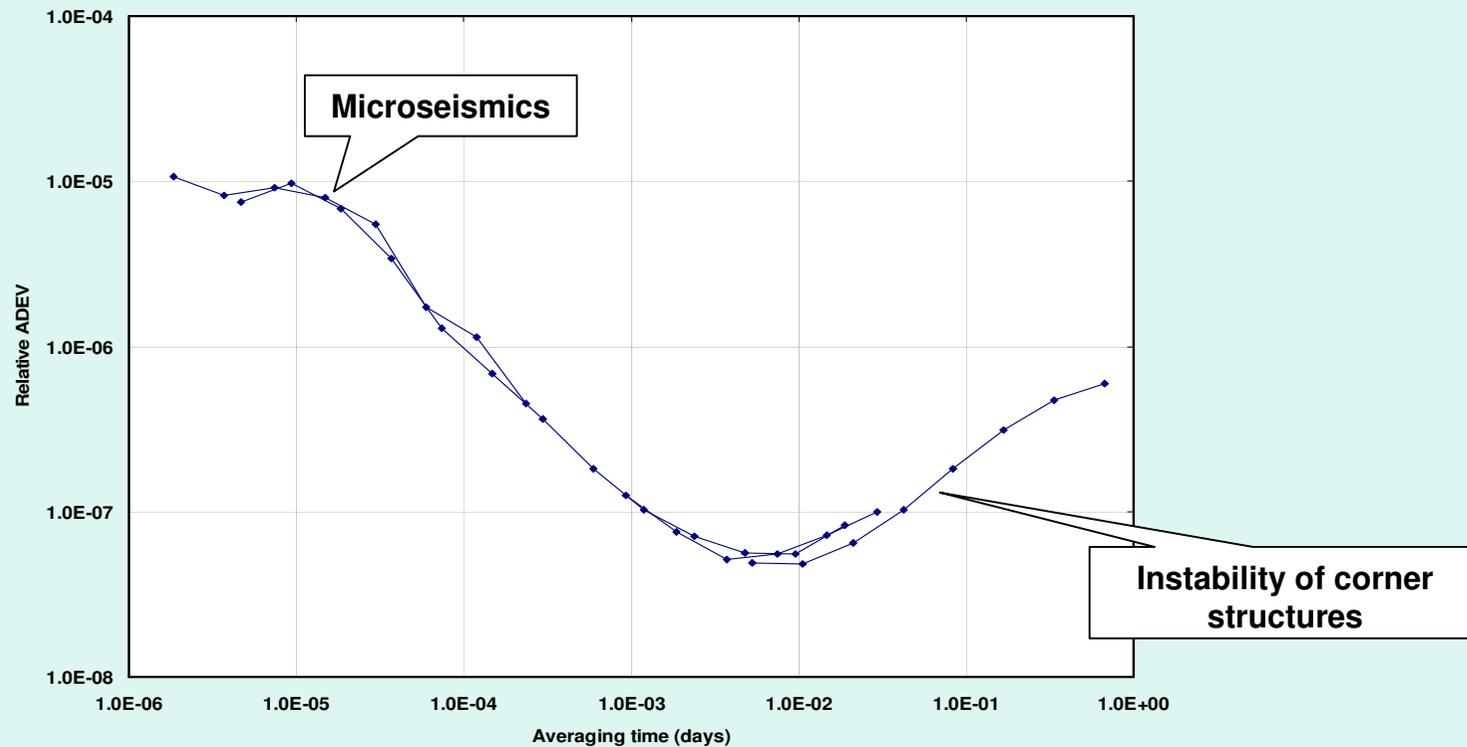
Improvements over the years:

- ◇ Installation of better mirrors (lower loss, lower scatter)
- ◇ Improved beam power control
- ◇ Installation of 'getters' to prevent gas deterioration
- ◇ Barometric pressure, optical frequency control



UG stability:

- ◇UG is not monolithic, therefore corners move independently to some extent
- ◇Causes effective latitude instability on time scales \sim hours
- ◇At short times, strongly affected by microseismic activity



Current areas of interest:

Geodetic effects:

Kinematics of whole earth:

Polar motion (Oppolzer modes)

Chandler wobble

Atmosphere and ocean angular momentum

Tidal effects, ocean loading

Seismic effects:

S-wave phase velocity

Coseismic rotations

Fundamental physical effects

Frame-dragging and other relativistic precessions

Relating celestial and terrestrial reference frames :

Think of a Ring Laser Gyro as a component of an **Inertial Navigation System** for 'Spaceship Earth'....



Key question:

Why is an inertial system for angular measurement useful, when we already have a system that can use external reference points (VLBI, quasars)?

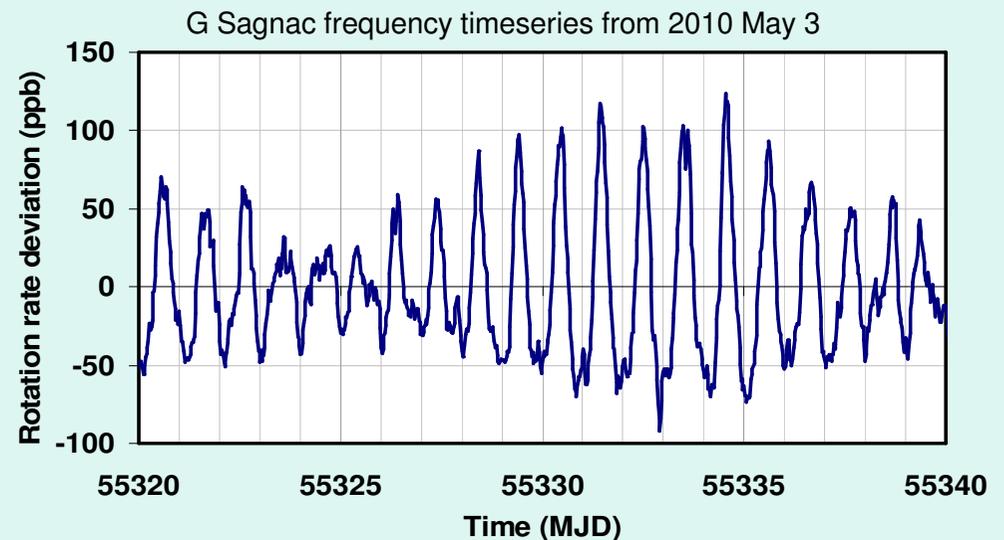
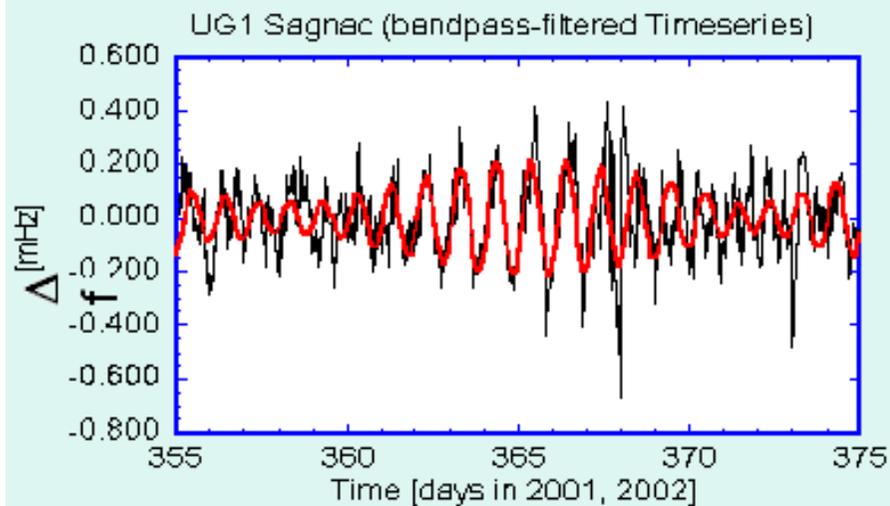
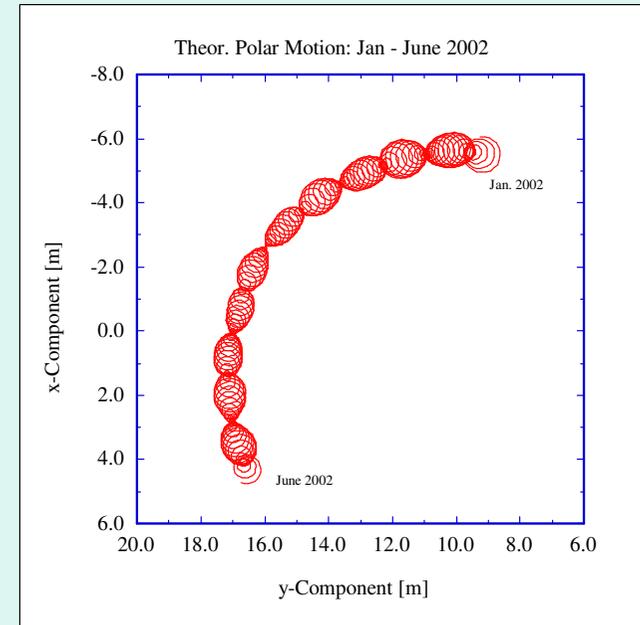
(Some) answers:

- ◊ Ring laser gyro can measure relatively local effects e.g, seismic, weather-related
- ◊ Continuous operation, high time resolution with in principle no latency
- ◊ Fundamental physical effects (e.g. Lense-Thirring effect)

Earth Polar motion

Components on time scales from <1 day, to >1 year

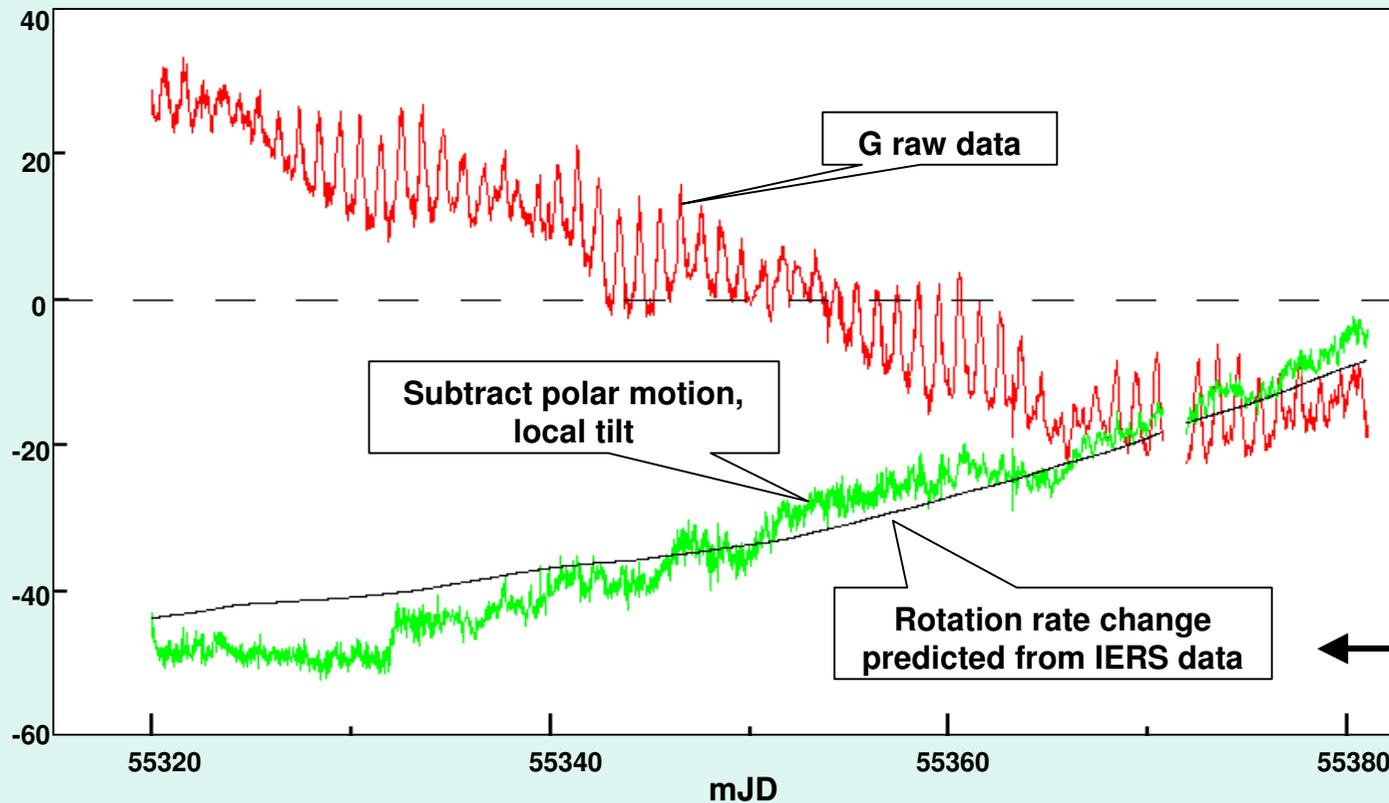
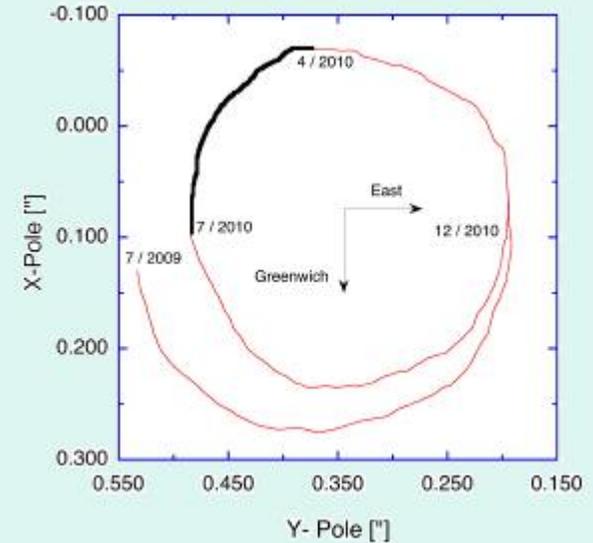
Diurnal polar motion: Interaction of 'precession of the equinoxes' with Earth rotation, period 1 (sidereal) day, typically 40-60 cm at poles; highly complex structure



Detection of Chandler wobble

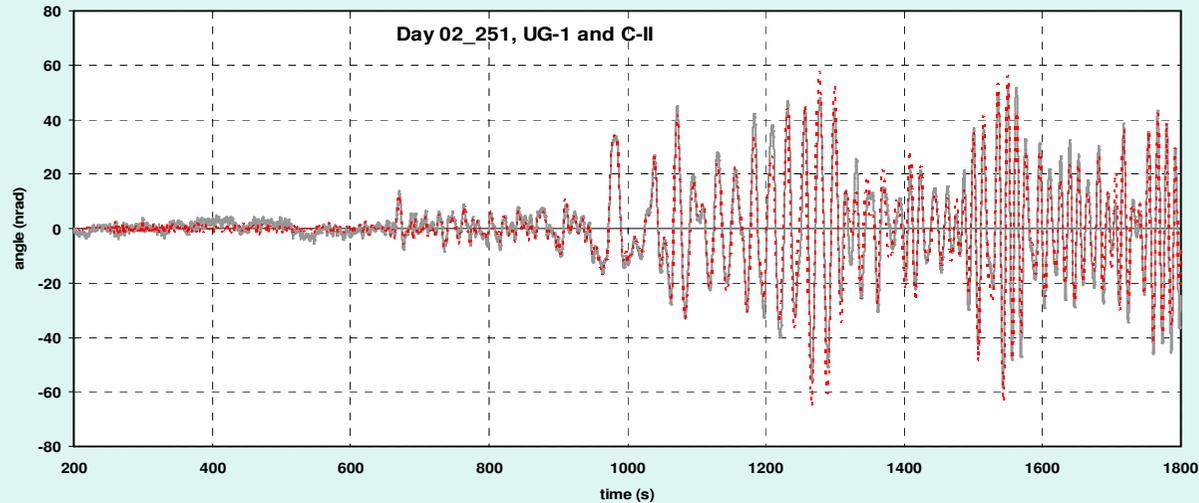
(A 'Eulerian' wobble, amplitude several metres, period ~435 days)

With recently improved stability, and ability to subtract short-term geophysical effects, G record now shows Chandler wobble.



Seismic phenomena

Observation of earthquakes with the ring lasers is by now routine.



Approach to analysis:

Look for effects that cannot be measured with conventional seismometers:

- Transient rotations (rather than translations)
- 'Step-function' coseismic rotation caused by relaxation of strain (elastic rebound) around earthquake epicentre.

Studies of Rotational components of Seismic waves

From seismic wave theory, a relationship emerges between transverse acceleration and rotation rate about a vertical axis:

$$\frac{a_T}{\Omega_z} = \frac{-k^2 c^2 A \sin(kx - kct)}{\frac{1}{2} k^2 c A \sin(kx - kct)} = -2c$$

This implies that from instruments **at a single location**, transverse wave velocity can be estimated.

By cross-correlating the rotation rate against transverse accelerations at different azimuths, **direction of arrival** can be deduced.

Normally these determinations would require an array of seismometers.

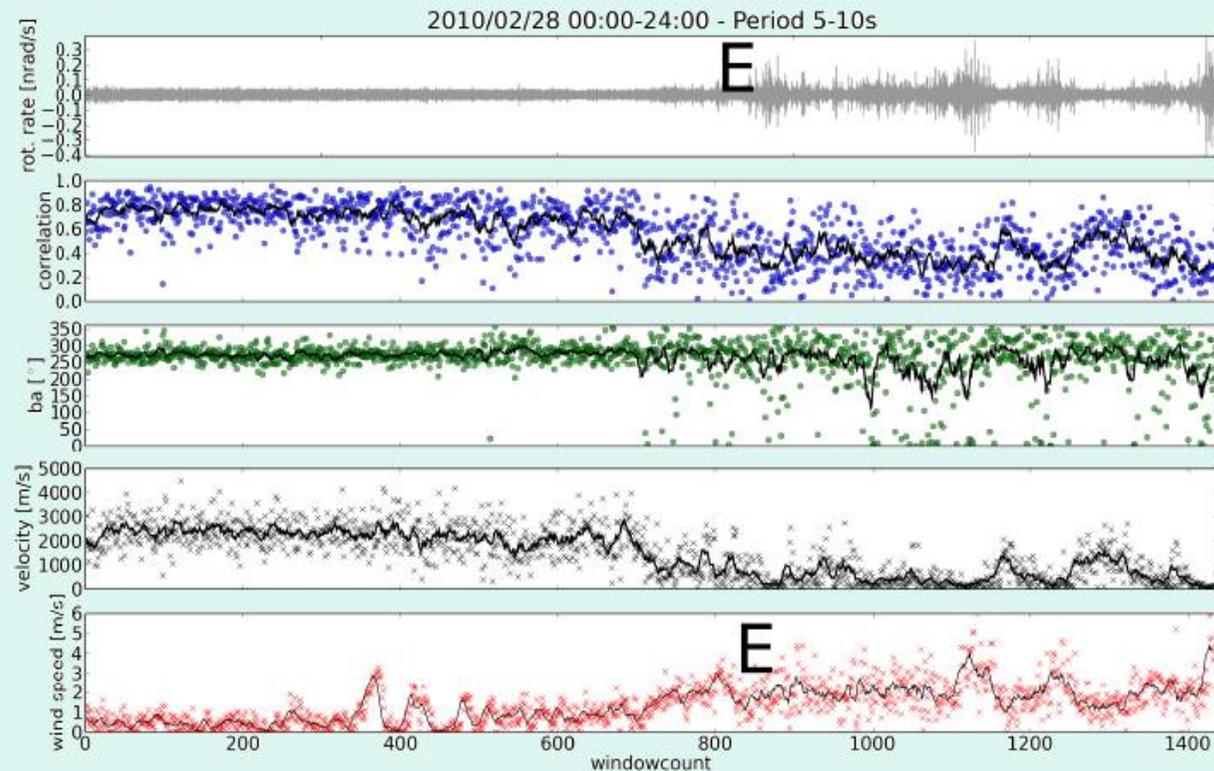
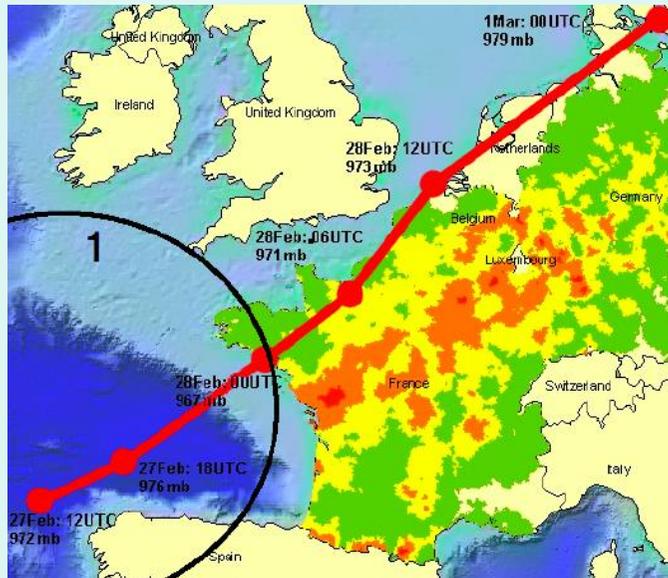
Example: Xynthia windstorm 2010

Reproduced from:

"Phase velocity and source direction estimation using collocated measurements of rotational and translational motions from ambient seismic noise"

Peter Gaebler

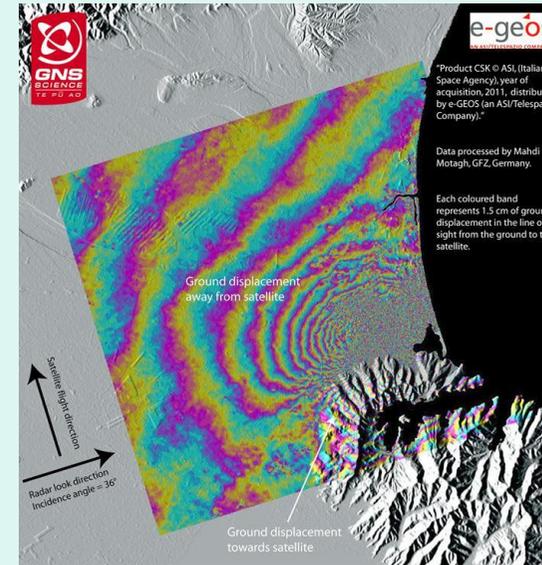
Ludwig-Maximilians-University Munich
Munich, July 2010



Earthquake co-seismic slip, co-seismic rotation



Fault trace of m7.1 earthquake ~30 km from Christchurch, Sept 2010

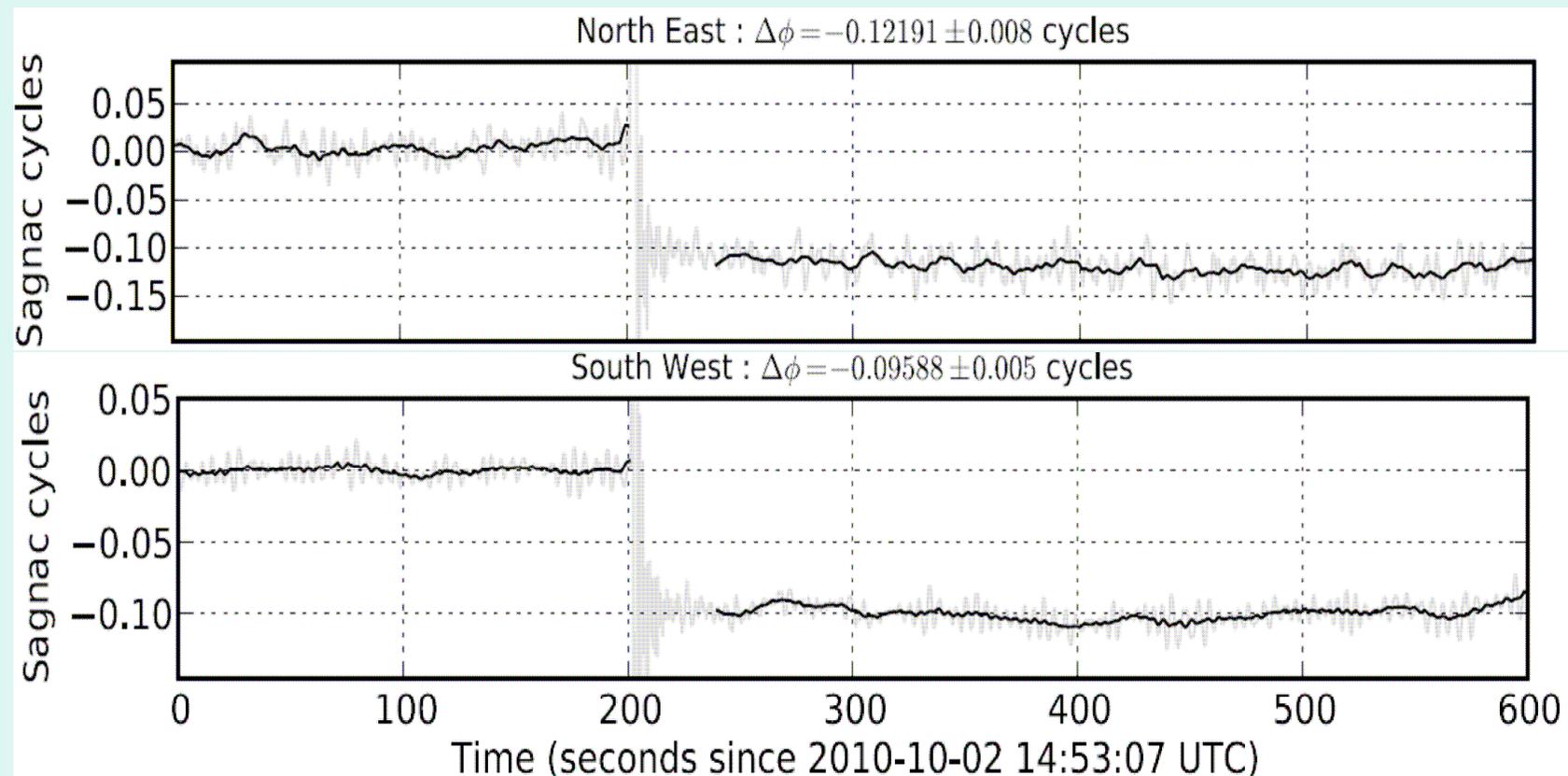


It is *expected* that release of regional elastic strain during an earthquake event should cause small permanent residual rotations in the 'near field' close to the epicentre.

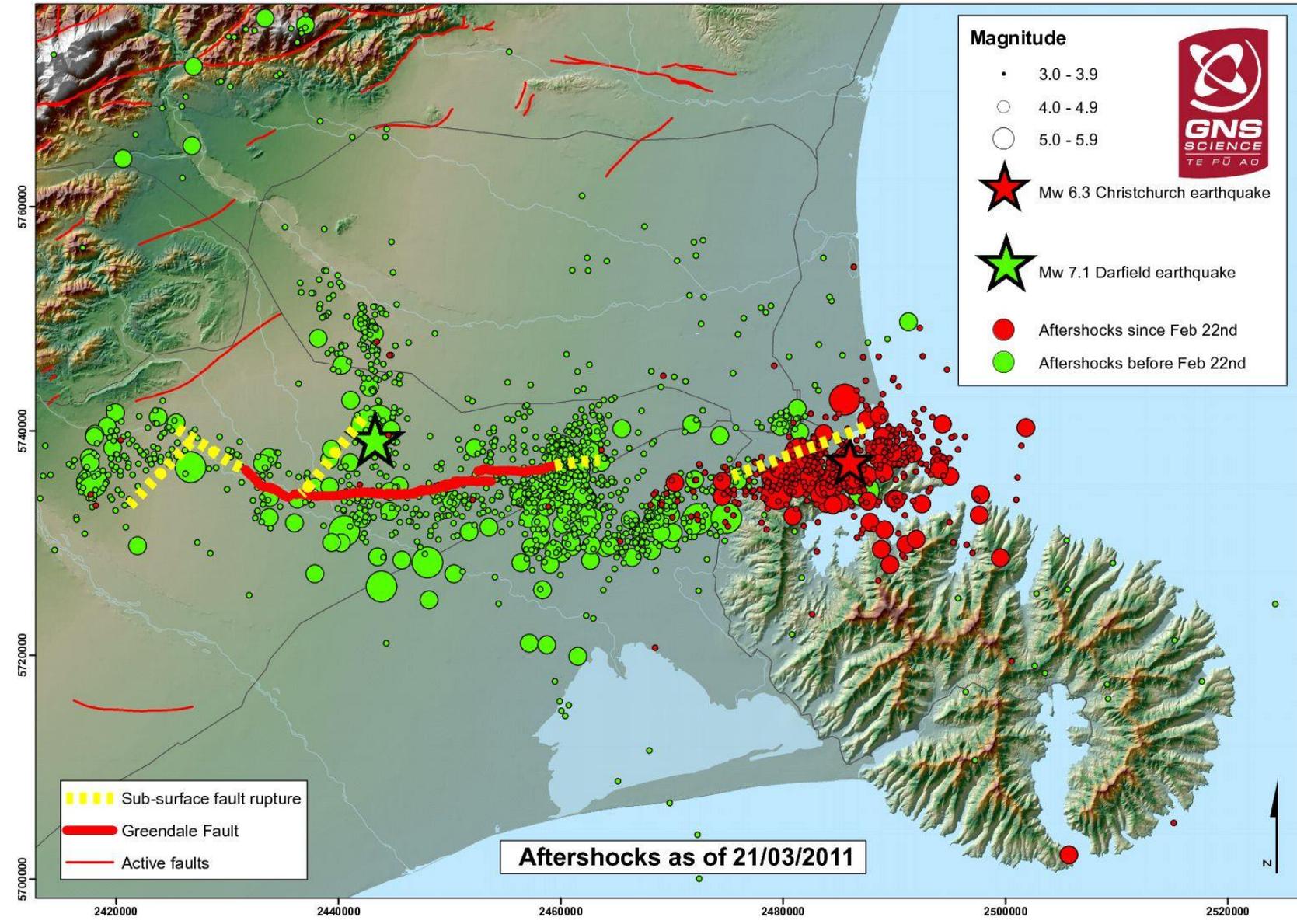
Measurements of size of these effects should assist in modelling earthquake source mechanisms.

Example of a measured co-seismic rotation

Magnitude 3.04, Distance 2.2 km, azimuth 80.5 deg, depth 5 km



(Rotation: 3.6 nrad anticlockwise)



Future Directions.....

Continue with improvement program for G:

- Backscatter corrections, possible backscatter cancellation
- Push toward 10^{-9} (1 ppb) stability

Will we ever build more ultra-large ring lasers?

- Maybe, but would require an improvement in mirror technology

Improved absolute accuracy (toward 1 ppb, see next slides)

Future Directions.....

Move toward measuring *absolute* rotation rates

$$\delta f = \frac{4A\Omega \cos \theta}{\lambda P}$$

For a ring laser in the shape of an equilateral triangle, and with $\theta = 0$, the Sagnac equation becomes,

$$\delta f = N\Omega/12 \sqrt{3}$$

where N is the (whole-ish) number of wavelengths around the perimeter i.e. **the sensitivity is quantized.**

N (with its fractional part included) can be determined to better than 1 ppb accuracy!

Applications for absolute rotation rate measurements:

1 Length of day (LOD)

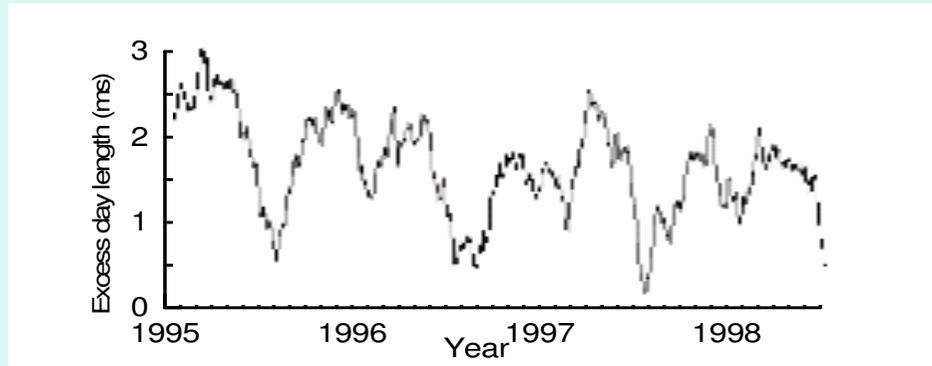


Figure 1: LOD variations as determined by VLBI and GPS measurements.
(*International Earth Rotation Service*)

2 Relativistic precessions of the rotating Earth:

-Lense-Thirring effect: $\Omega'/\Omega = 2GI/(c^2R^3)$

-de Sitter (Geodetic) precession due to solar orbit: $\Omega'/\Omega = 3v^2/2c^2$

-Geodetic-like precession due to Earth rotation

(Typical size of these effects: < 1 ppb)

Conclusions:

After ~20 years of development, ring laser gyros have reached a level of stability and resolution where they can make a contribution to Geodesy, Seismology, and measurement of local geophysical perturbations;

The process of improvement has not stopped:

- An extra order of magnitude stability is likely possible from G
- New lasers, designed to measure LOD are planned
- Relativistic precessions may be within reach.