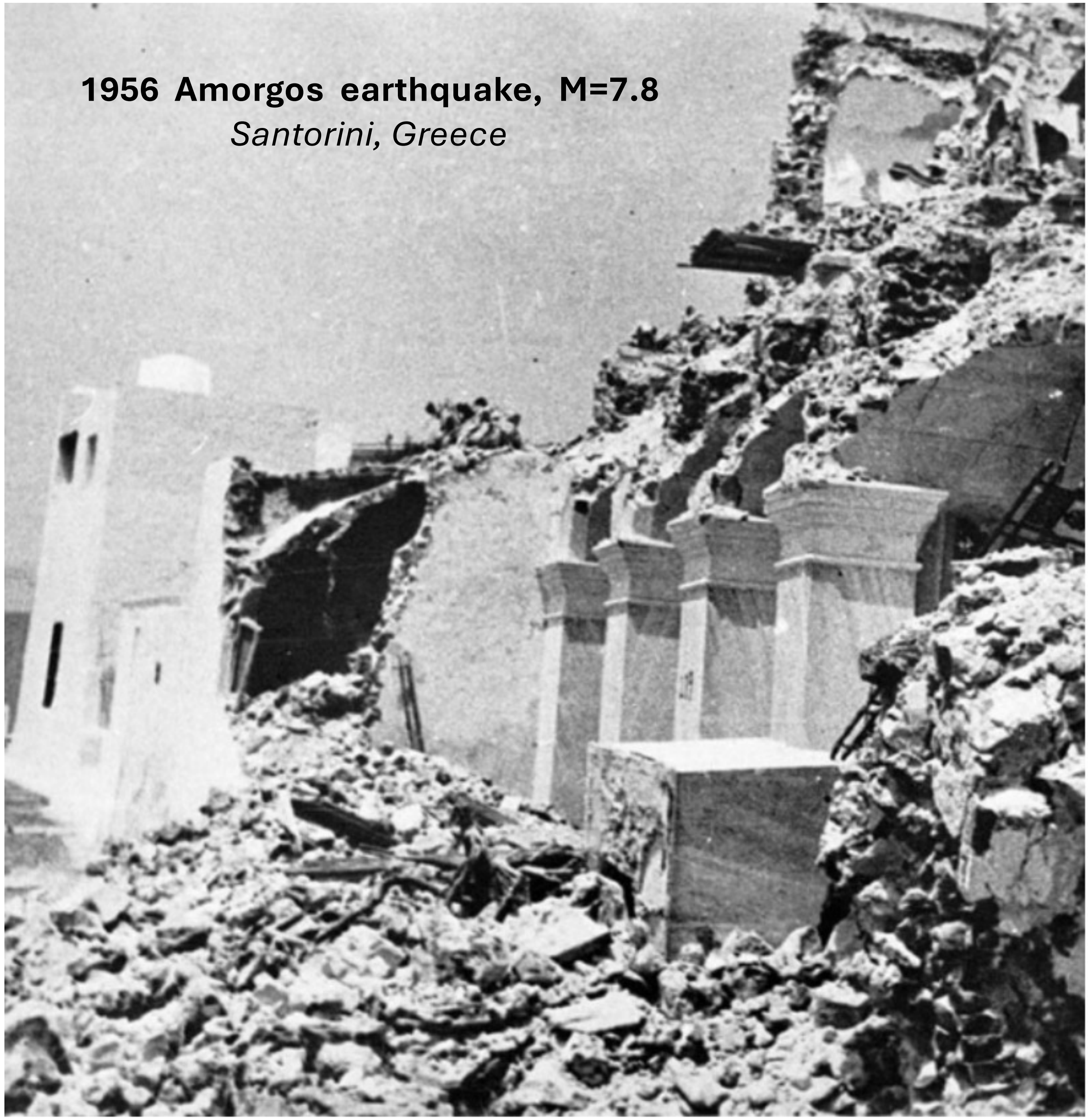


Gravity change by earthquake cycle processes expected from the MAGIC constellation

Shin-Chan Han and Jeanne Sauber

"… a mission targeting signals one order of magnitude smaller than currently possible enables a leap forward. MAGIC could provide information on the accumulation of mass along active tectonic zones, separation of fault plane models and monitoring of locked seismic zones." MAGIC MRD

Presented at GRACE-FO 2025 Science Team Meeting (online), 7-9 October 2025

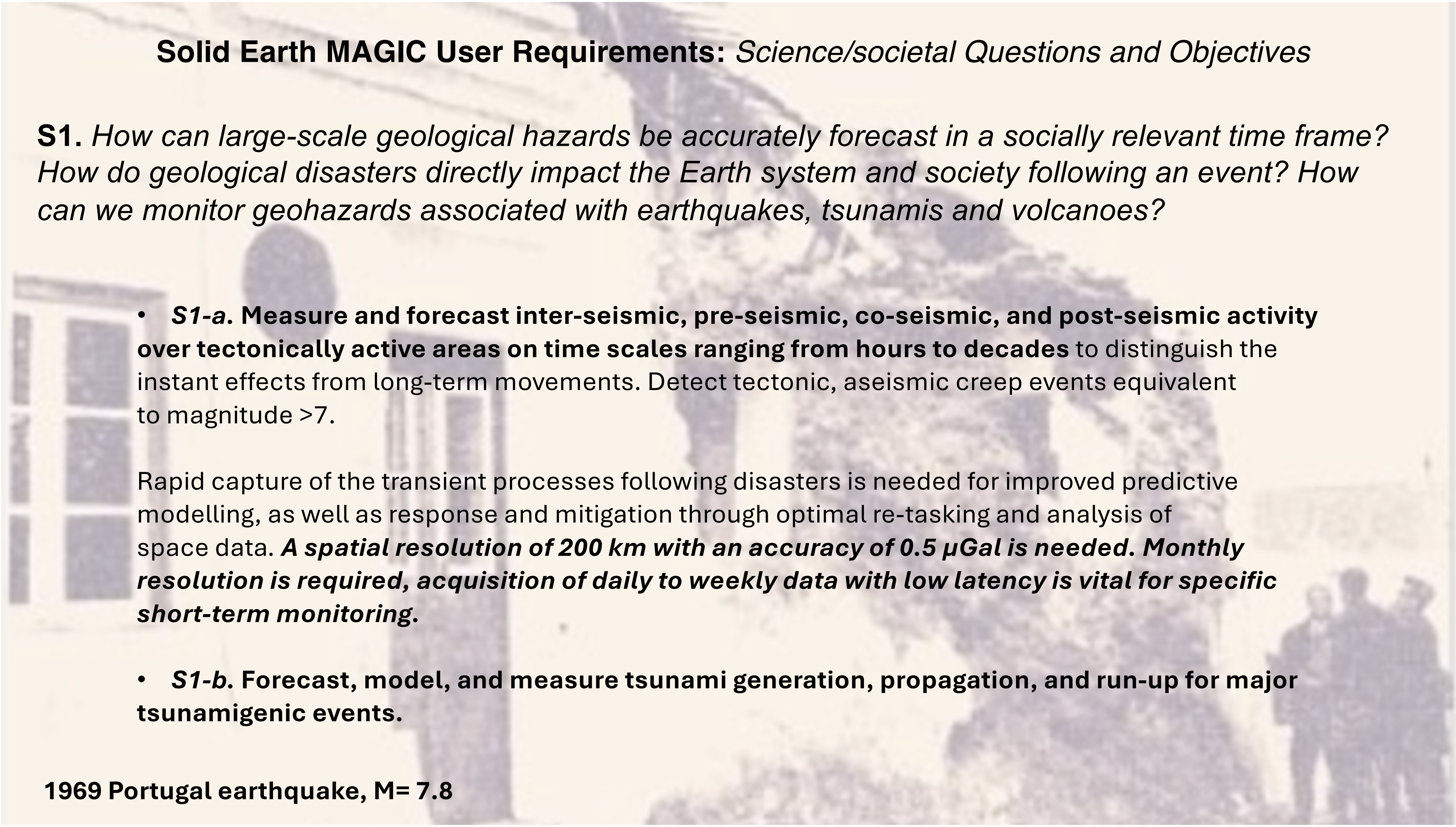
Solid Earth MAGIC User Requirements: *Science/societal Questions and Objectives*

S1. *How can large-scale geological hazards be accurately forecast in a socially relevant time frame? How do geological disasters directly impact the Earth system and society following an event? How can we monitor geohazards associated with earthquakes, tsunamis and volcanoes?*

- ***S1-a.* Measure and forecast inter-seismic, pre-seismic, co-seismic, and post-seismic activity over tectonically active areas on time scales ranging from hours to decades** to distinguish the instant effects from long-term movements. Detect tectonic, aseismic creep events equivalent to magnitude >7.

  Rapid capture of the transient processes following disasters is needed for improved predictive modelling, as well as response and mitigation through optimal re-tasking and analysis of space data. ***A spatial resolution of 200 km with an accuracy of 0.5 μGal is needed. Monthly resolution is required, acquisition of daily to weekly data with low latency is vital for specific short-term monitoring.***

- ***S1-b.* Forecast, model, and measure tsunami generation, propagation, and run-up for major tsunamigenic events.**



1969 Portugal earthquake, M= 7.8

Earthquakes analysed and modelled with GRACE-GRACE-FO data

Table 1. A list of "GEQ" earthquakes with their GCMT information on magnitude, general location, depth and mechanism type

Year	M_w	Name	Depth [km]	Location	Note
2004	8.1	Mcquarie Is.	< 60km	South of New Zealand	SS, S
2004	9.2	Sumatra	< 60km	Aceh, Indonesian	TH, S
2005	8.6	Nias Is.	< 60km	South of Aceh	TH, S
2006/2007	8.3	Kuril Is.	< 60km	North east of Japan	TH/NF, S
2007	8.5	Bengkulu	< 60km	South Sumatra	TH, S
2009	8.1	Samoa	< 60km	Polynesian Is.	TH/NF, S
2010	8.8	Maule	< 60km	Chile	TH, S
2011	9.1	Tohoku-Oki	< 60km	Japan	TH, S
2012	8.6	Wharton basin	< 60km	Indian Ocean	SS, S
2013	8.3	Okhotsk	600 km	Sea of Okhotsk	D
2016/2017	7.9/7.9	East Papua NG	100-150 km	Papua New Guinea	TH/NF, ID
2019	8.0*	Peru	100-150 km	western Peru	NF, ID

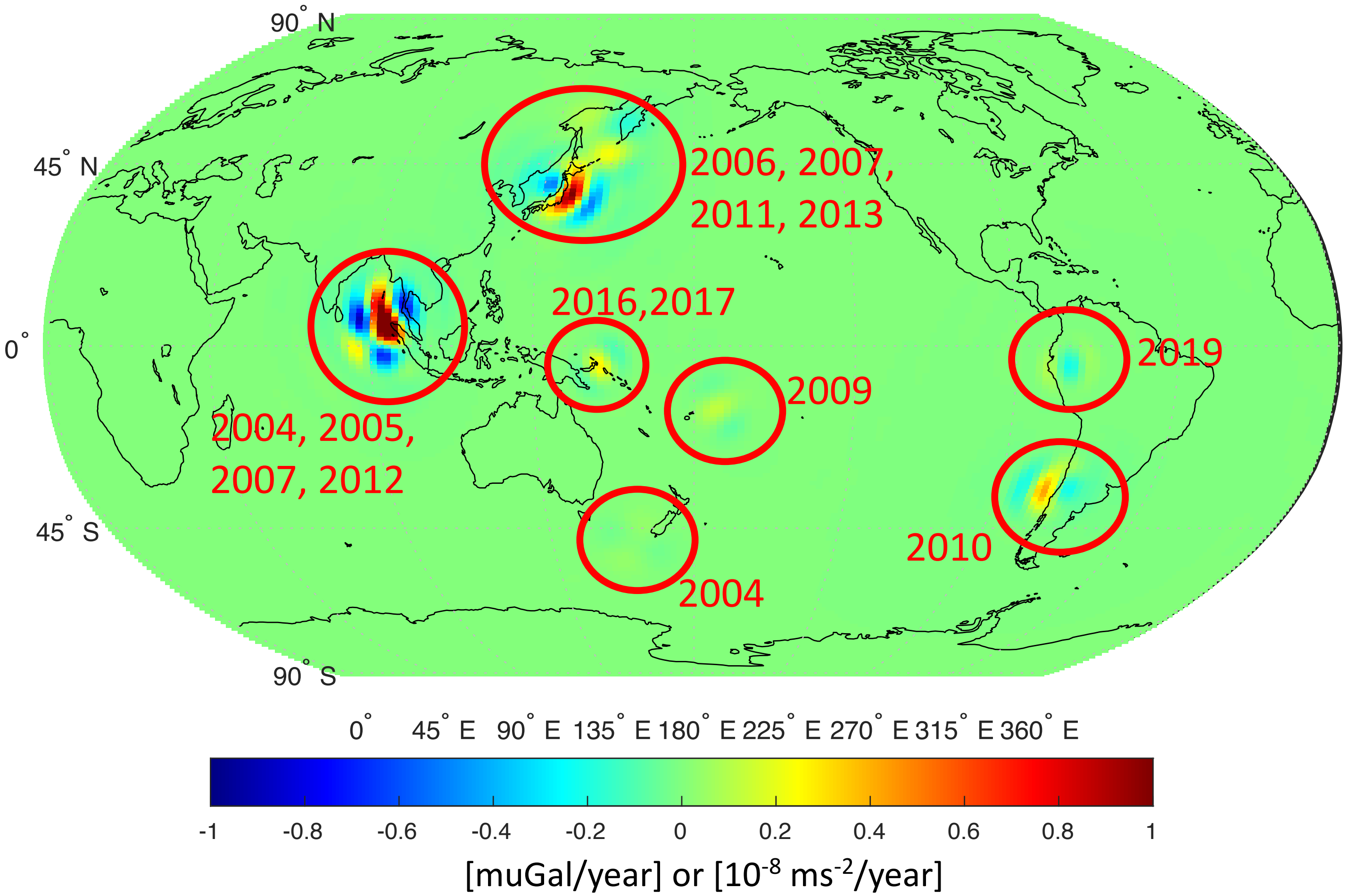
Note: the events are classified in terms of focal mechanisms; Thrust (TH), Strike-slip event (SS), and Normal faulting (NF), and of depths; Shallow (S), Intermediate-depth (ID), and Deep (D) events.

Studies of three additional recent events are ongoing:
2021 M_w 8.1 Kermadec trench
2021 M_w 8.2 South Sandwich Is.
2021 M_w 8.2 Chignik, Alaska.

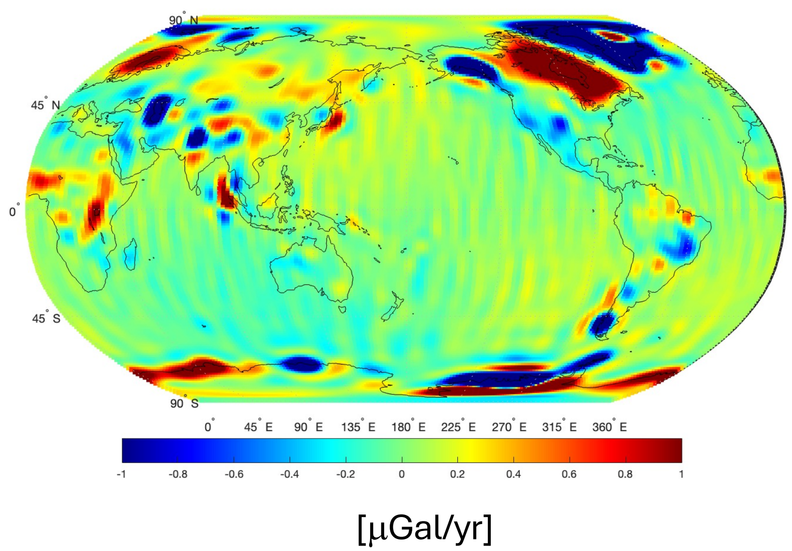
For all of these earthquakes , a signal was detected by the GRACE-GRACE-FO gravity measurements. For events with Mw <8.5, the coseismic signal was not significant but the post-seismic signal measured over multiple years was.

The size of the detected coseismic gravimetric change was up to -20 μGal and poseismic change of up to 2 μGal/yr.

GEQ predicted gravity anomaly rate



Gravity trend map: GRACE/GRFO L2



CSR L2 RL06.2, Lmax=60, a linear trend of gravity changes (April 2002 - May 2024)

The GEQ product has been processed in a self-consistent way.

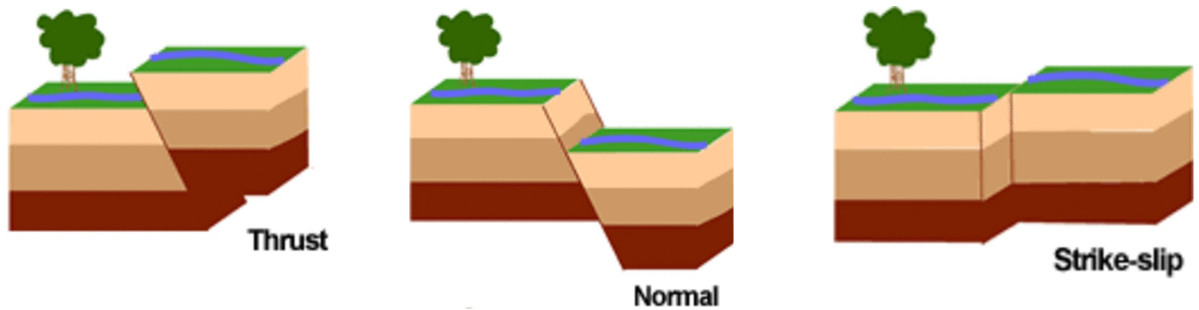
GEQ model results are available: https://zenodo.org/records/17064329

MAGIC L2 gravity simulation solutions applied to earthquakes

1. We use MAGIC L2a errors and “GEQ” modeling results to quantify signal-to-noise ratio expected in the MAGIC L2 time series.

2. We examined earthquakes of three distinct faulting types featured with the lowest moment magnitudes detected by GRACE – GRACE-FO:

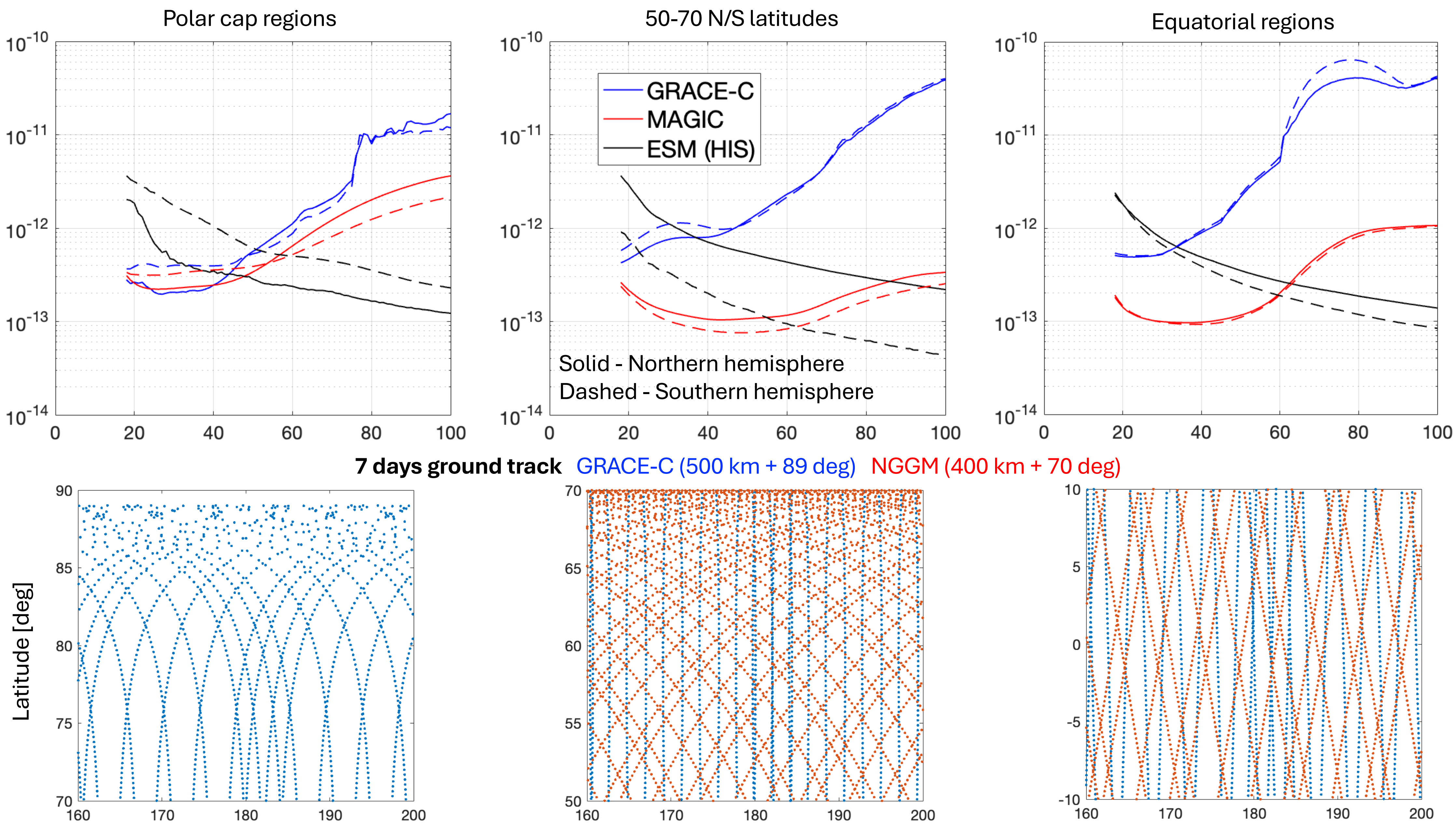
Thrust	2021 Mw 8.2 Chignik, Alaska
Normal faulting	2019 Mw 8.0 Peru
Strike slip	2004 Mw 8.1 Macquarie island, South Pacific



3. Both coseismic (elastic) and postseismic (viscoelastic) geopotential changes were calculated.

4. Examined instantaneous range-rate perturbation by earthquakes and tsunamis for MAGIC (i.e., GRACE-C and NGGM orbits).

MAGIC L2a “localized” degree amplitude spectra at different latitude bands

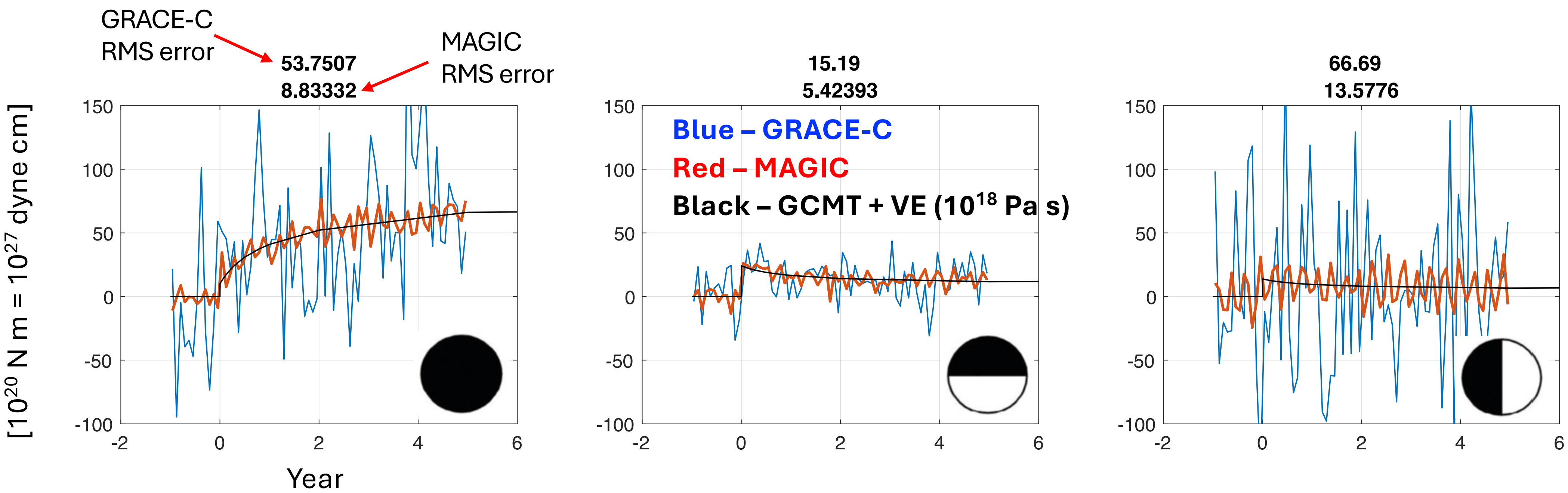


Modelling of gravity changes by earthquakes

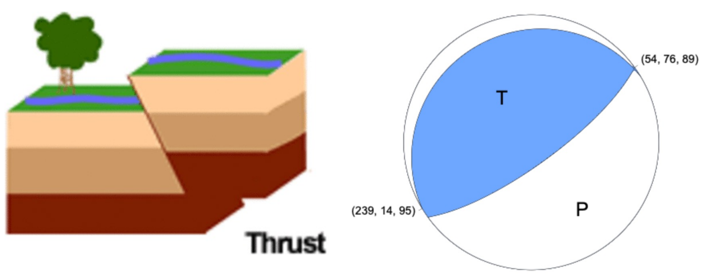
$$g(\theta,\varphi,t) = \left(\frac{-M_{rr}}{2}\right) g_{rr}(\theta,\varphi,t) + M_{r\theta} g_{r\theta}(\theta,\varphi,t) + M_{r\varphi} g_{r\varphi}(\theta,\varphi,t) + \left(\frac{M_{\theta\theta}-M_{\lambda\lambda}}{2}\right) g_{\theta\theta,\lambda\lambda}(\theta,\varphi,t) + M_{\theta\varphi} g_{\theta\varphi}(\theta,\varphi,t)$$

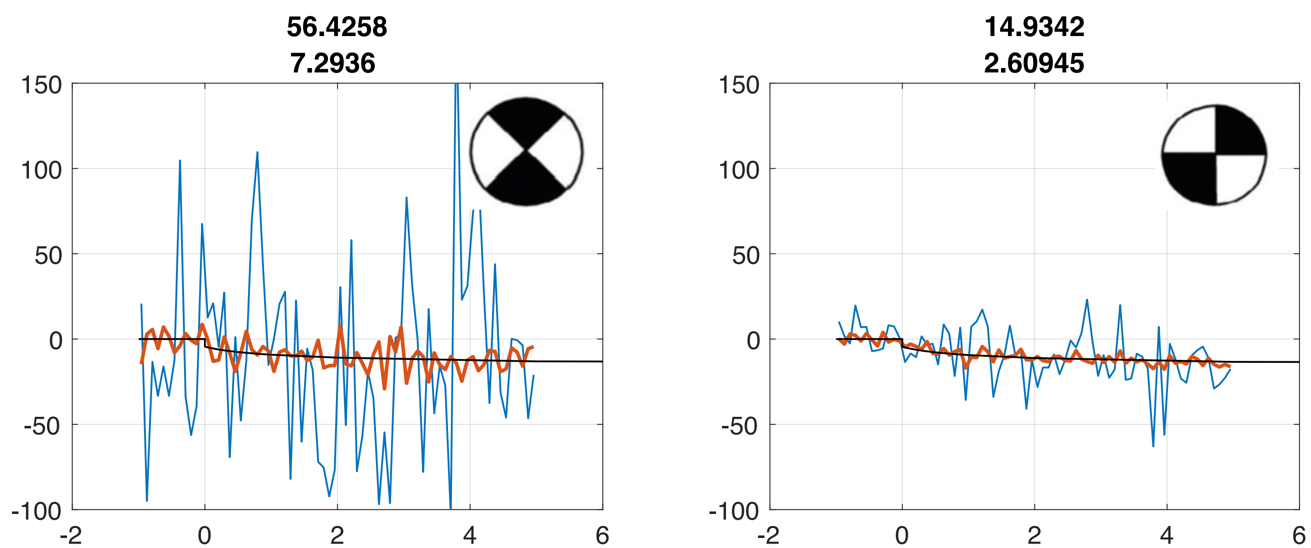
	Five response (Green's) functions	Five EQ source parameters	Spherical harmonic coefficients
	$g_{rr}(\theta,\varphi,t)$	M_{rr}	m=0, monopole
	$g_{r\theta}(\theta,\varphi,t)$	$M_{r\theta}$	m=1, dipole, sensitive
	$g_{r\varphi}(\theta,\varphi,t)$	$M_{r\varphi}$	m=1, dipole, ***less sensitive by high-inclination orbit***
	$g_{\theta\theta,\lambda\lambda}(\theta,\varphi,t)$	$M_{\theta\theta} - M_{\lambda\lambda}$	m=2, quadrupole, ***less sensitive by high-inclination orbit***
	$g_{\theta\varphi}(\theta,\varphi,t)$	$M_{\theta\varphi}$	m=2, quadrupole, sensitive

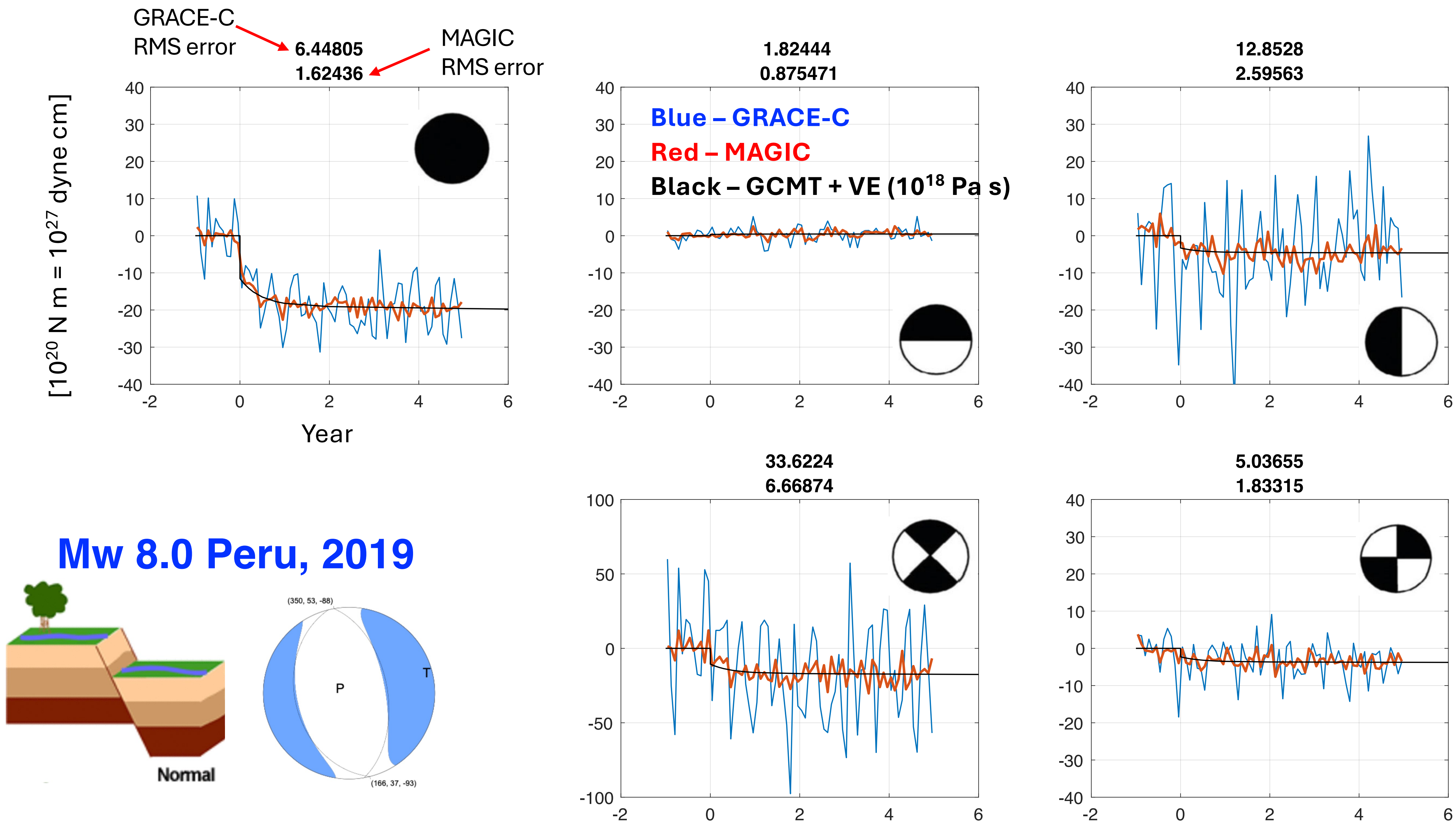
- They are computed in terms of spherical harmonics (orders 0, 1, and 2 + all degrees)
- Consistent with global seismological formulation and analysis (e.g. Global Centroid Moment Tensor, GCMT)
- The post-seismic Green's functions are dependent primarily on <u>two parameters</u> (lithosphere thickness and asthenosphere viscosity)

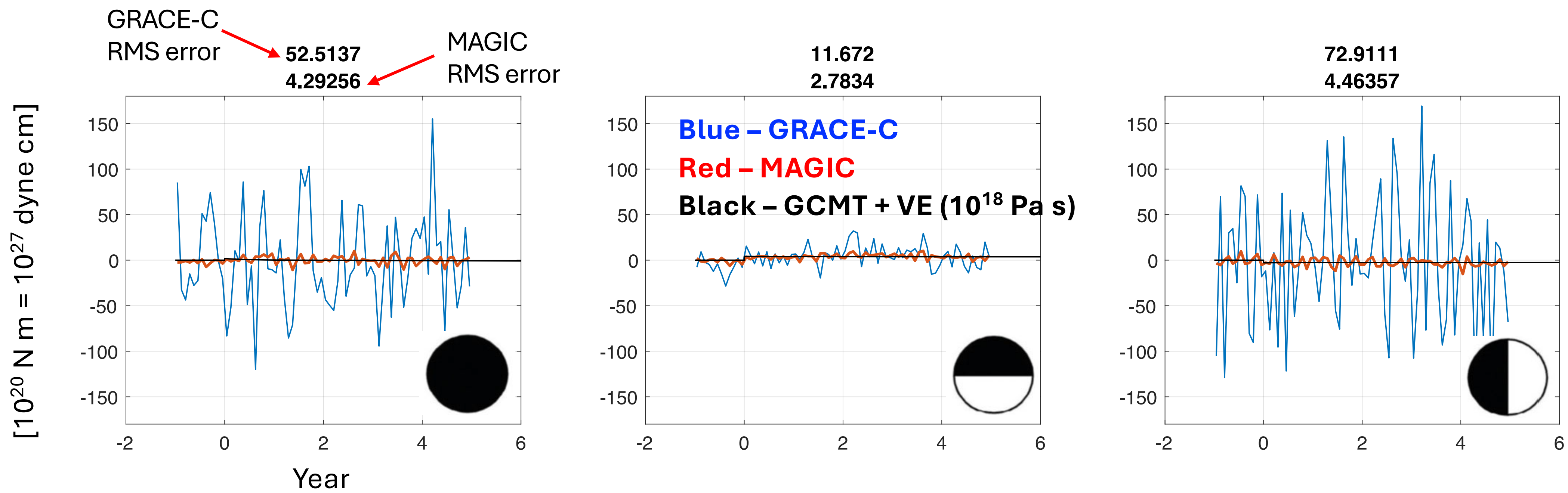


Mw 8.2 Chignik, Alaska, 2021

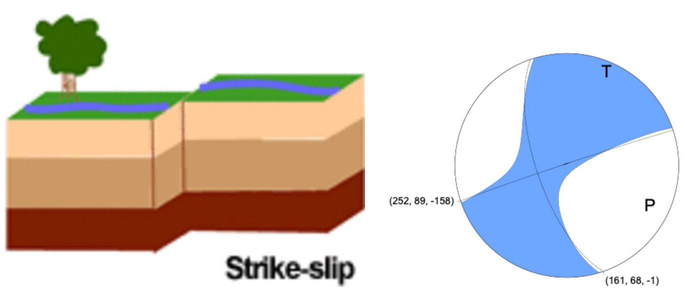


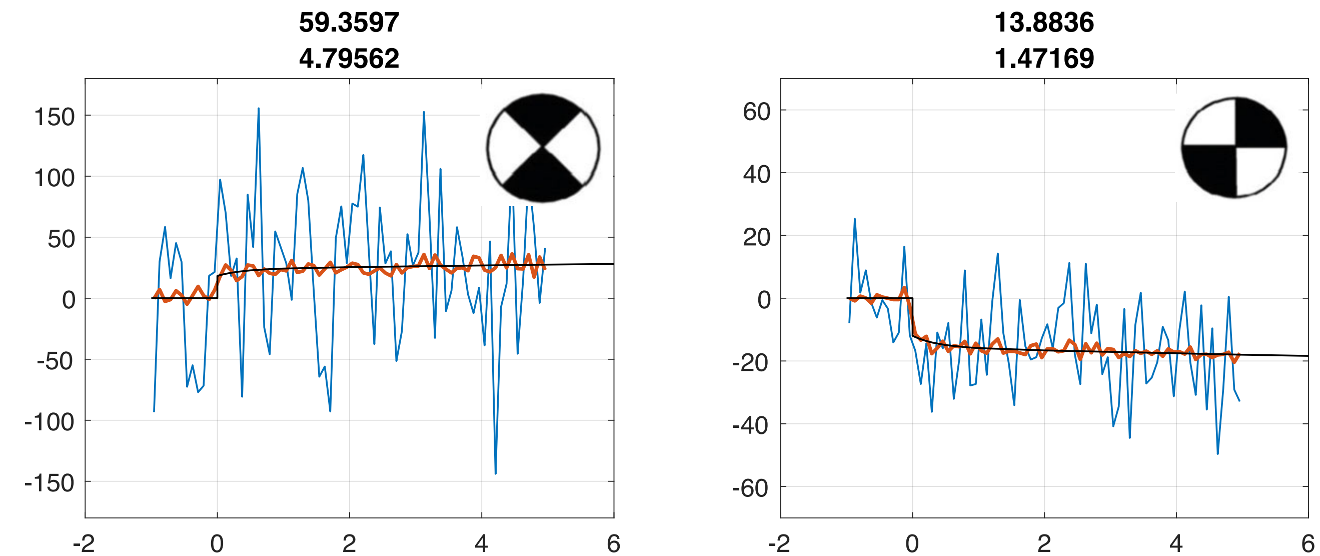



GRACE-C RMS error
MAGIC RMS error
6.44805
1.62436
1.82444
0.875471
12.8528
2.59563
33.6224
6.66874
5.03655
1.83315
Blue – GRACE-C
Red – MAGIC
Black – GCMT + VE (10^{18} Pa s)
[10^{20} N m = 10^{27} dyne cm]
Year
Mw 8.0 Peru, 2019
Normal
(350, 53, -88)
(166, 37, -93)
P
T

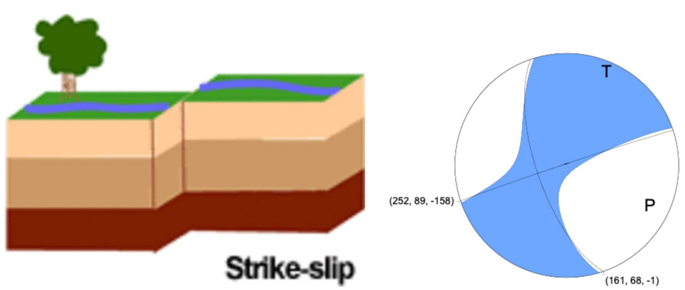


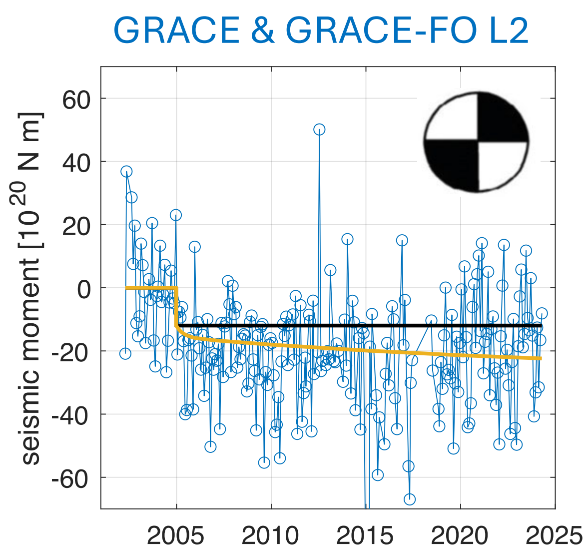
Mw 8.1 Macquarie island, South Pacific, 2004

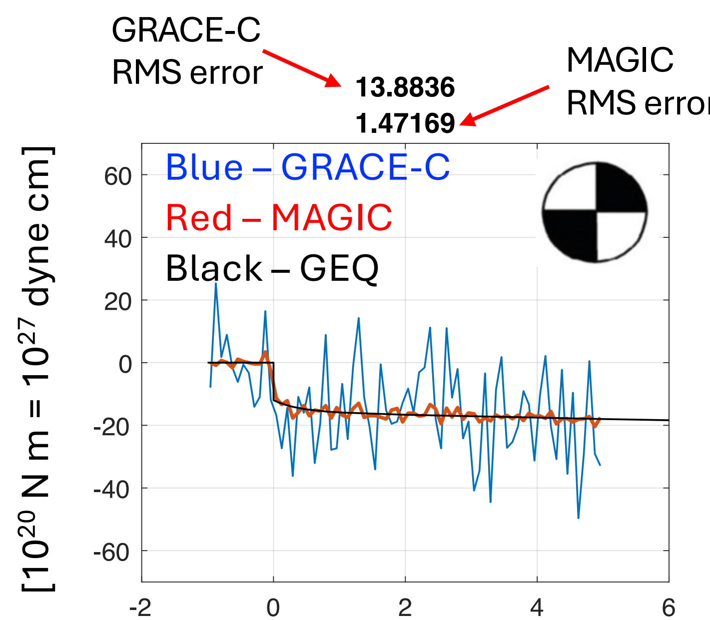




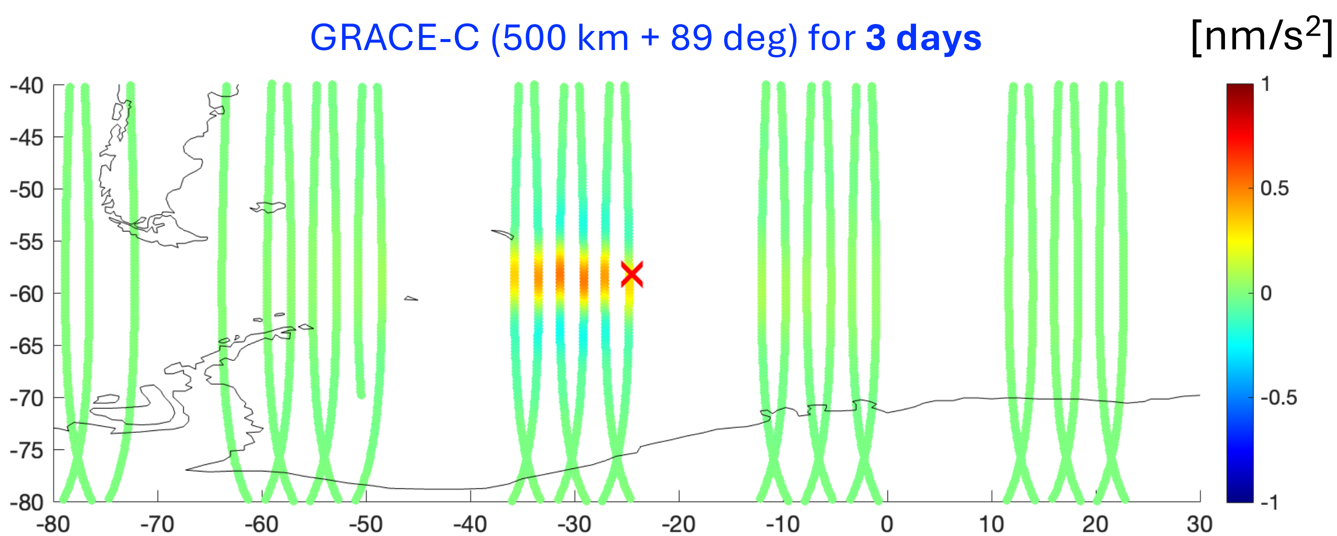
Mw 8.1 Macquarie island, South Pacific, 2004

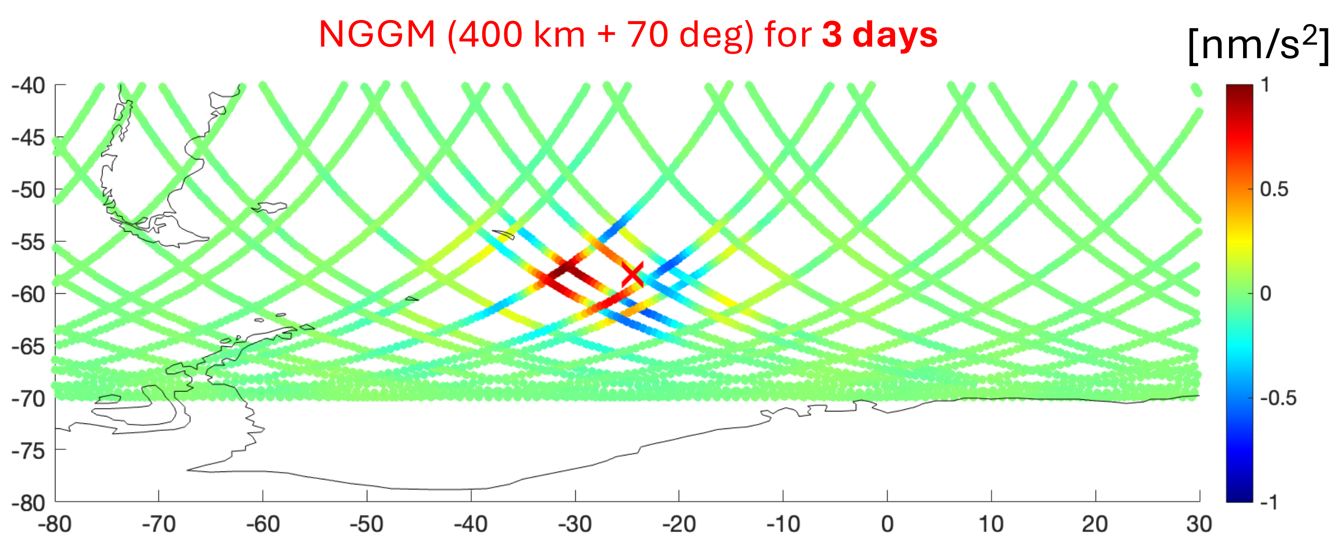


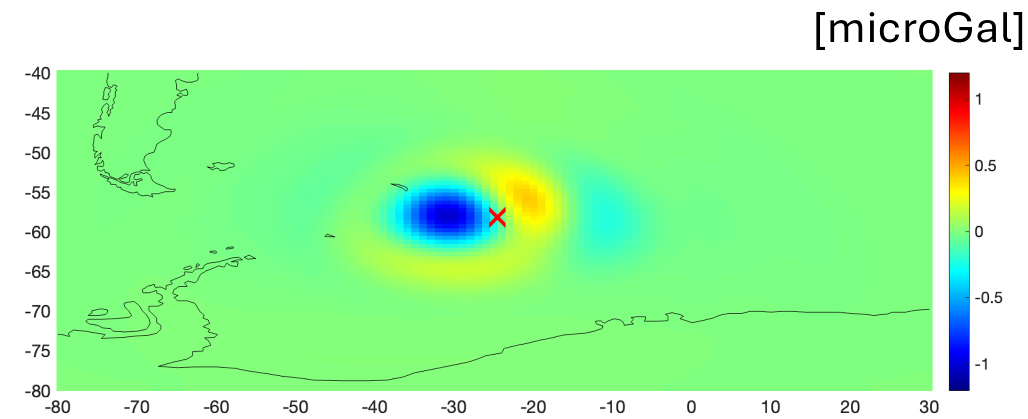




MAGIC L1B measurements of gravity change by *earthquake*







2021 South Sandwich Island Earthquake

Range acceleration perturbation is as large as

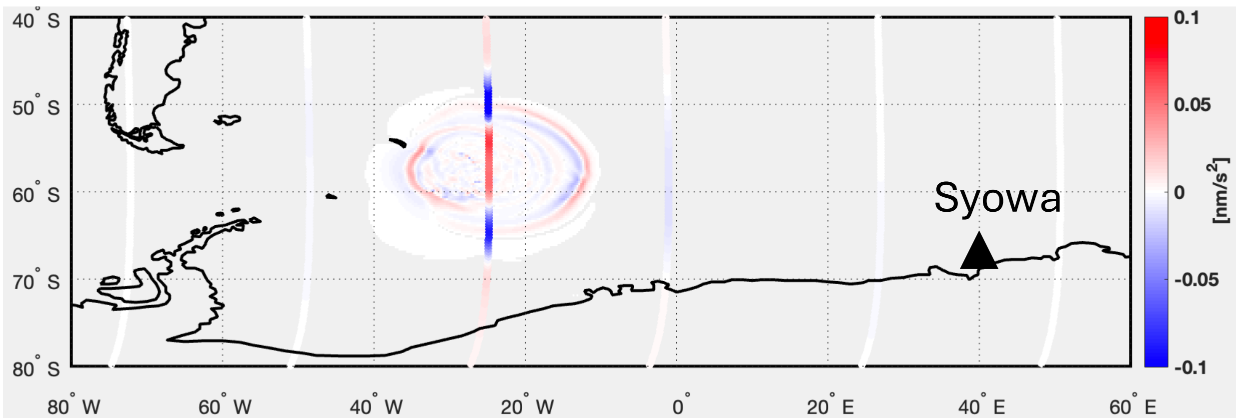
0.4 nm/s^2 for GRACE-C
1.2 nm/s^2 for NGGM

NGGM =>
Larger signals (from lower altitude) +
Richer samplings (from lower inclination)

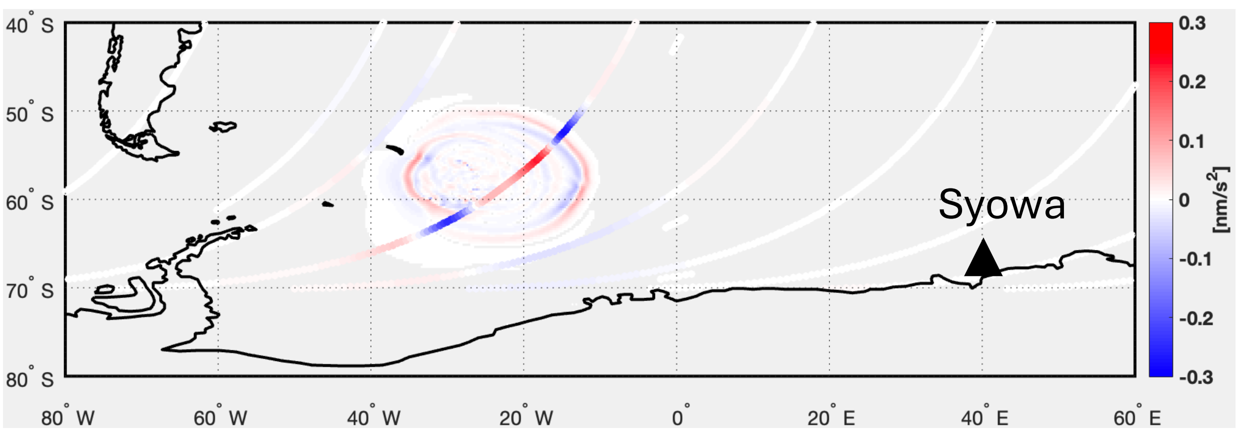
Acknowledgement. Thomas Papanikolaou

MAGIC L1B measurements of gravity change by *tsunami*

GRACE-C (500 km + 89 deg) for **1 day ascending** [nm/s^2]



NGGM (400 km + 70 deg) for **1 day ascending** [nm/s^2]



3x amplified signals + denser ground tracks

2021 South Sandwich Island Tsunami

10-20 cm tsunami (<200 km wavelength) recorded at Syowa tide gauge, East Antarctica

Range acceleration perturbation is as large as

0.1 nm/s^2 for GRACE-C
0.3 nm/s^2 for NGGM

NGGM =>
Increased possibility to detect more (smaller) events

Acknowledgement. Jean Roger & Daeha Lee

Summary: MAGIC Simulations for Improved Geohazard Products

Based on our assessment of the ESA's SING simulated "L2a" (unfiltered/raw) data products, we found the following for MAGIC's applications to geohazards:

1. MAGIC will reduce a detection threshold of earthquake gravity change by *a factor of 2-20*, depending on focal mechanism and epicenter latitude.

2. We found MAGIC sensitivity down to *2×10^{20} N m (eqv. Mw 7.5)* for the strike-slip component.

3. *Lower altitude* NGGM will observe earthquakes and tsunamis *3x larger in L1B* intersatellite ranging perturbation than GRACE-C .

4. *Lower inclination* NGGM will bring *improved sensitivity in E-W* particular at latitudes 50-70° N/S and make L2 gravity solution error *more isotropic*.

We will provide coseismic finite-slip faulting and post-seismic relaxation models with the geopotential change expanded out to d/o 180 for >14 earthquakes that could be used as input to the next generation Earth System Models (ESM-3, *Dobslaw et al.*, 2025).

Thank you for your Attention!

SING "L2/L3" simulation Data Acknowledgement: Pail et al. 2025, MAGIC WG

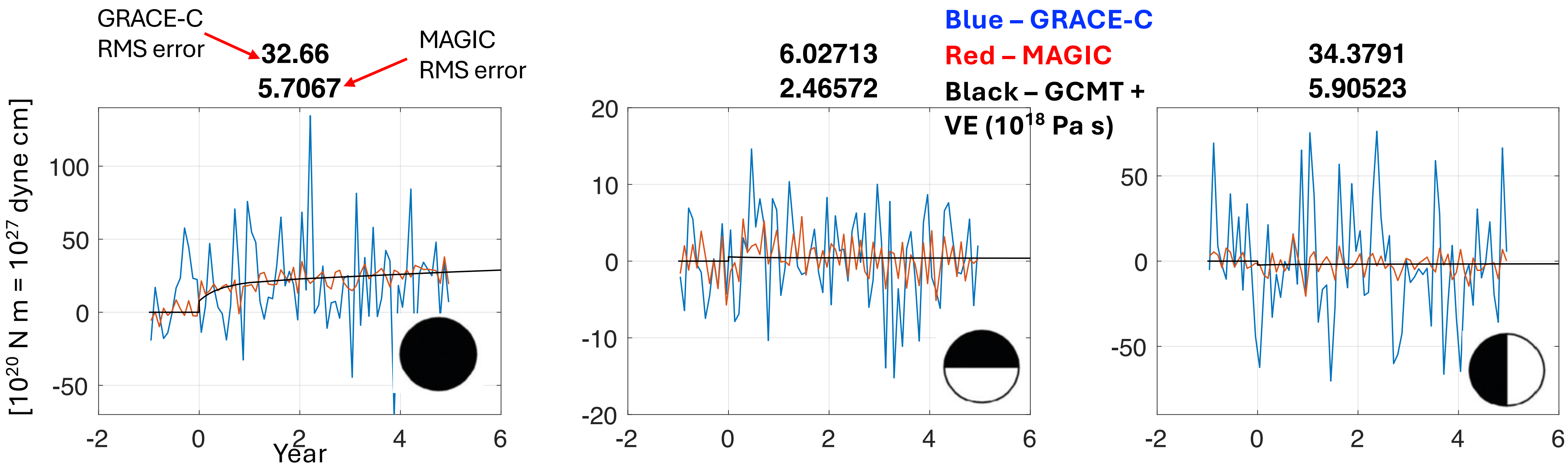
SING "HIS" simulation Data Acknowledgement, ESM: Dobslaw et al., 2015, 2025

ESA Funding for "NGGM and MAGIC Science and Applications Impact Study"

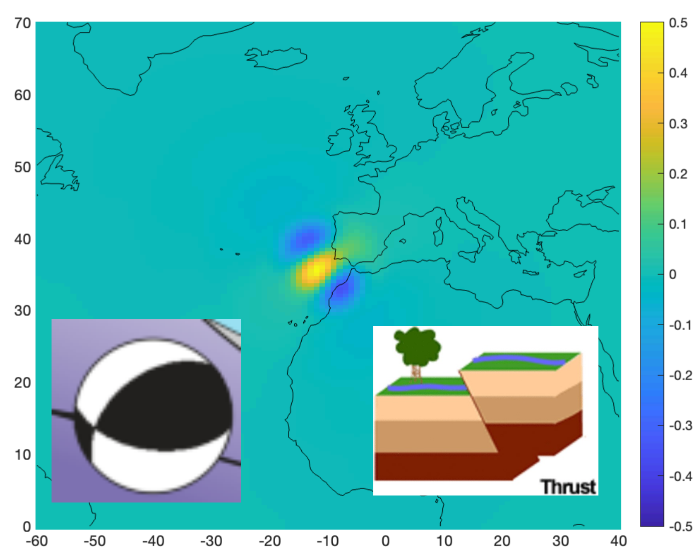
Earthquake simulations: S-C Han and J. Sauber

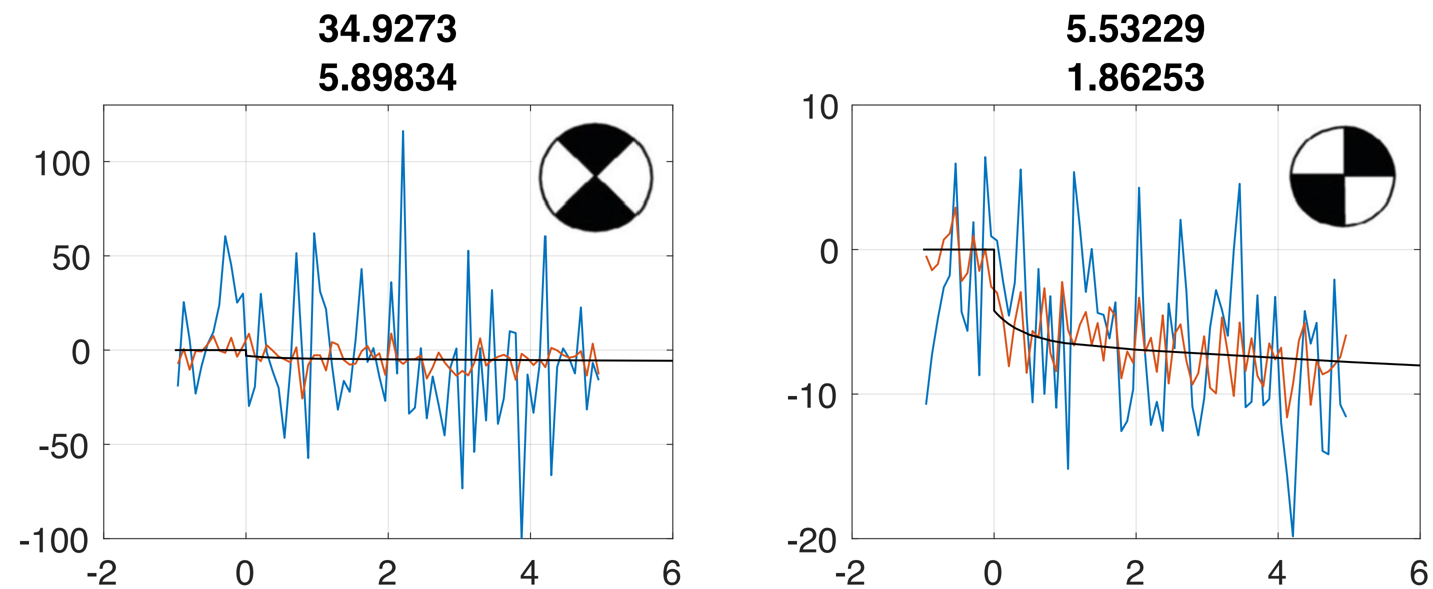
NASA GRACE-Follow-On Science Team and MAGIC Working Group

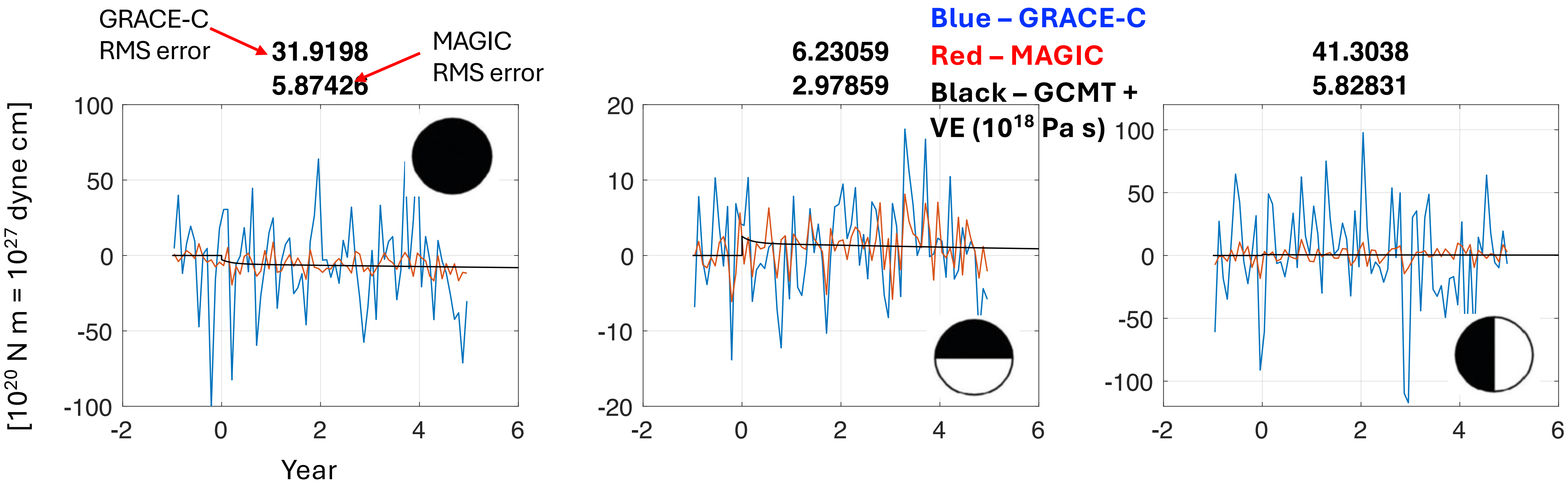
1953 Cefalonia Island, M=7.2, western Greece



Mw 7.8 Portugal 1969







Mw 7.5 Amorgos 1956