Unravelling electrical structure of the mantle with ionospheric, magnetospheric and oceanic sources

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Electromagnetic Induction Workshop 2022, Review talk

Deep Electromagnetic sounding is a (very) old technique!

XV. *The Diurnal Variation of Terrestrial Magnetism.*

By Arthur Schuster, *F.R.S., Professor of Physics in Owens College. With an Appendix by* H. Lamb, *F.R.S., Professor of Mathematics in Owens College.*

Received March 20,—Read March 28, 1889.

believe to be of importance. The results of the calculation point not only to an external source, but to an additional internal source, standing in fixed relationship to the external cause. This we might have expected. A varying potential due to external causes must be accompanied by currents induced in the Earth's body, which, in turn, must affect the magnetic needle. The phase of these currents and their magnitude lead us to form definite conclusions on the average conducting power of the Earth, and it will be seen that there is strong evidence that the average conductivity is very small near the surface, but must be greater further down. In this part of the investigation I had much assistance from my colleague, Professor Lamb.

The first paper on GDS was published 133 years ago!

Long before any other EM/electric method was established or practiced.

Before plate tectonics was proposed or inner/outer core was discovered…

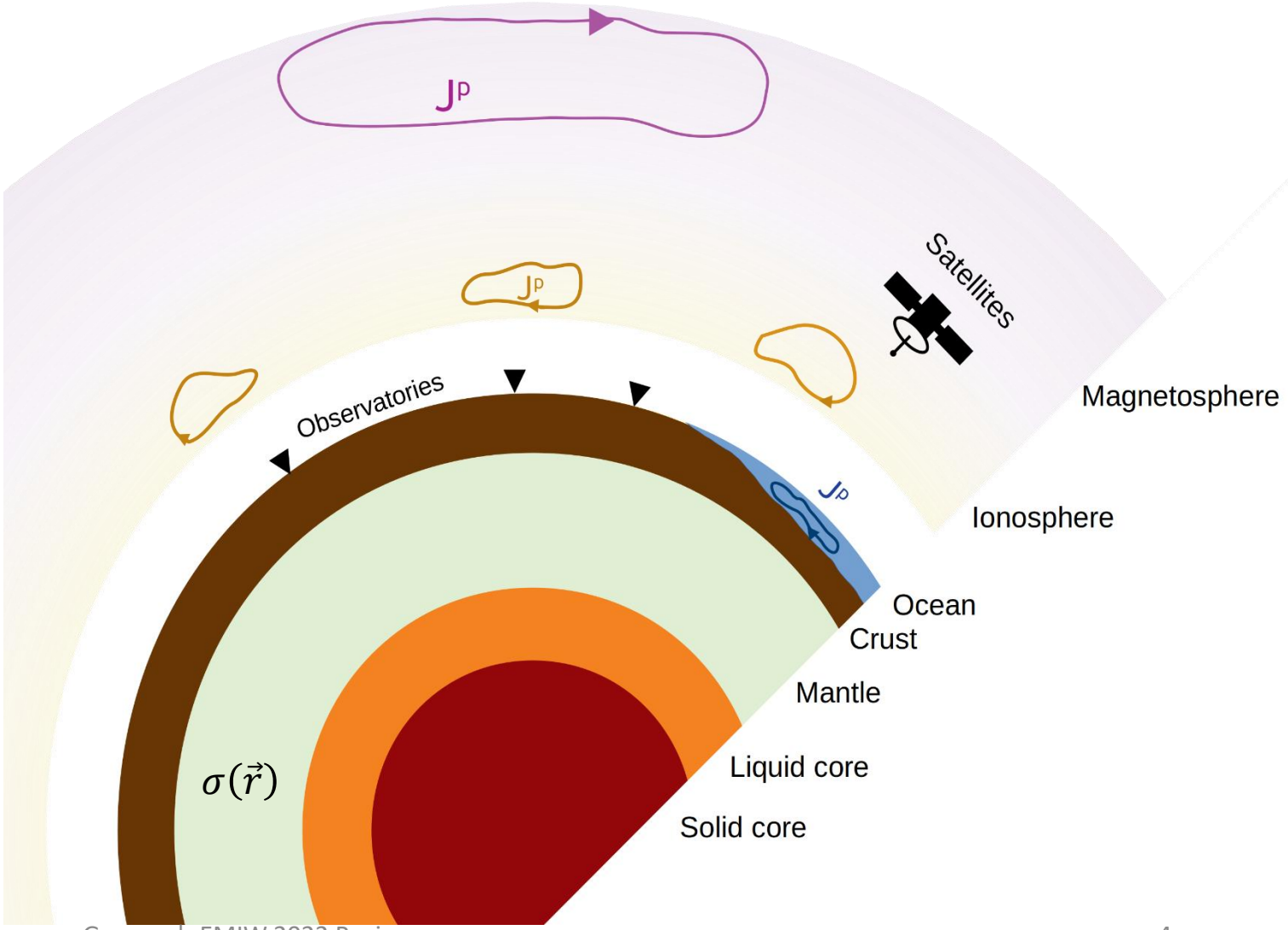
Scope and past reviews

Year of the review talk	Title	Reference
1972	Global electrical conductivity of the Earth	Rikitake (1973)
1972	The theory of geomagnetic induction	Price (1973)
1972	Global electromagnetic induction in the moon and planets	Dyal and Parkin (1973)
1972	Global geomagnetic sounding - methods and results	Bailey (1973)
1974	Morphology of slowly-varying geomagnetic external fields - A review	Matsushita (1975)
1974	On the inversion of global electromagnetic induction data	Anderssen (1975)
1974	Analytical solutions to global and local problems of electromagnetic induction in the Earth	Hobbs (1975)
1974	Solar-wind induction and lunar conductivity	Sonett (1975)
1978	The electrical conductivity of the moon	Vanyan (1980)
1984	Global electromagnetic induction	Roberts (1986)
1986	The global conductivity distribution	Parkinson (1988)
1998	Induction studies with satellite data	Olsen (1999)
2010	Deep electromagnetic studies from land, sea, and space: Progress status in the past 10 years	Kuvshinov (2012)
2022	Unravelling the Electrical Conductivity of Earth and Planets – A review	This paper

- *This review will cover years from 2012 to present*
- *Spatial scales from 10^3 km to the global*
- *Space weather / GICs won't be covered*
- *Planetary studies will not be included (next review?)*

Electromagnetic (EM) induction methods

- EM methods measure the Earth response to a *time-varying* EM source field.
- The EM response depends on subsurface *conductivity* structure
- J^p – primary electric currents
- B^p – primary magnetic field
- J^s – secondary electric currents
- B^s – secondary magnetic field



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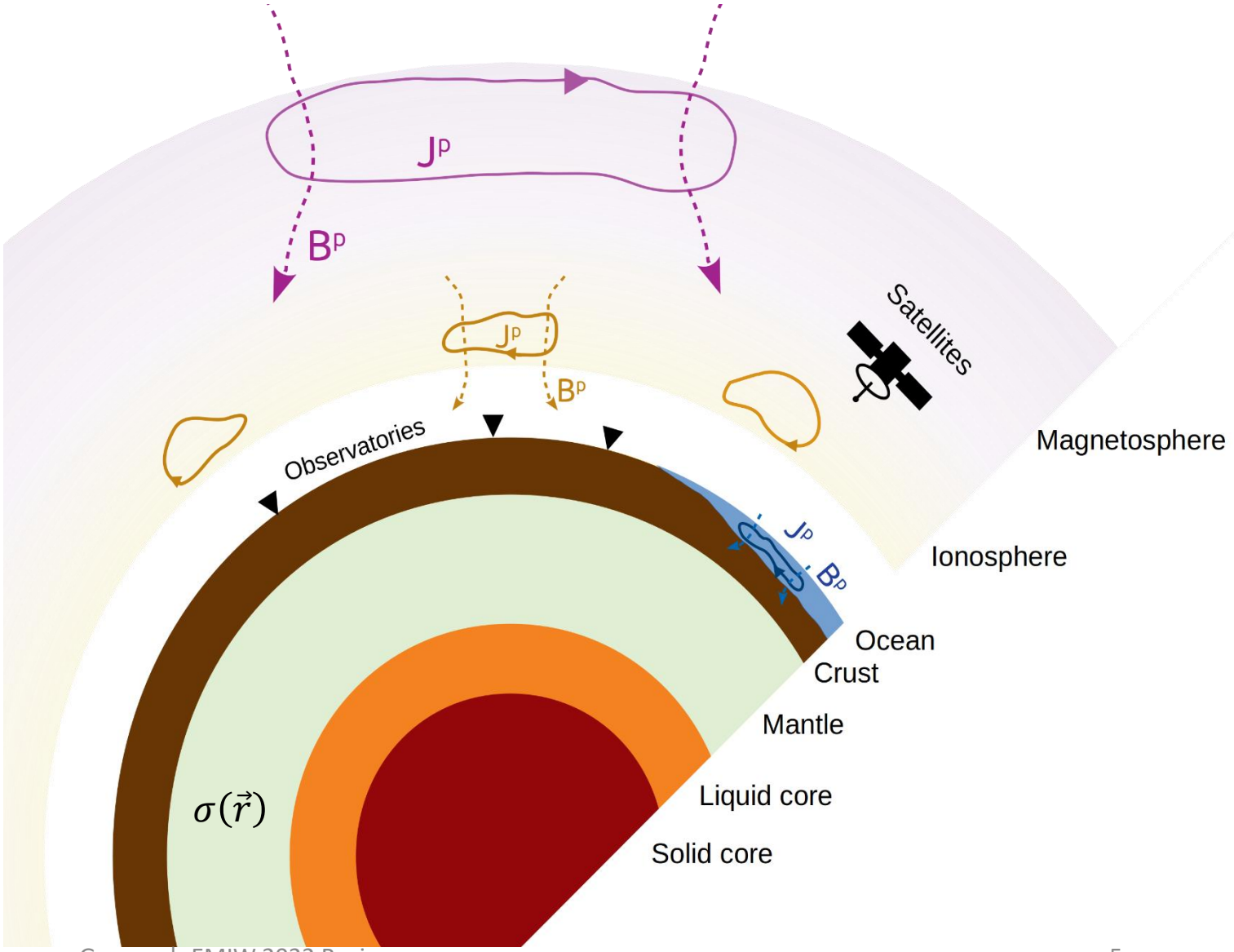

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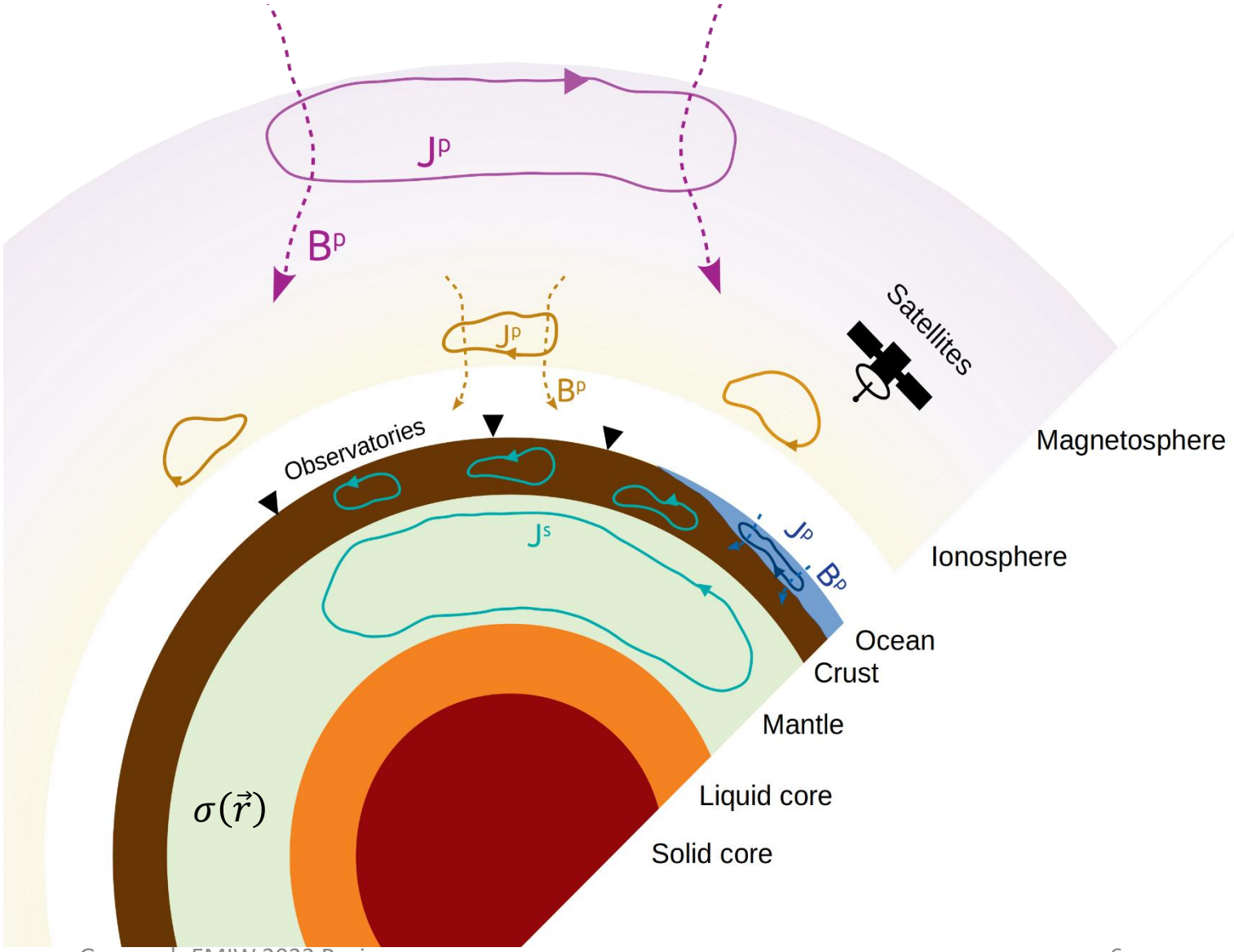

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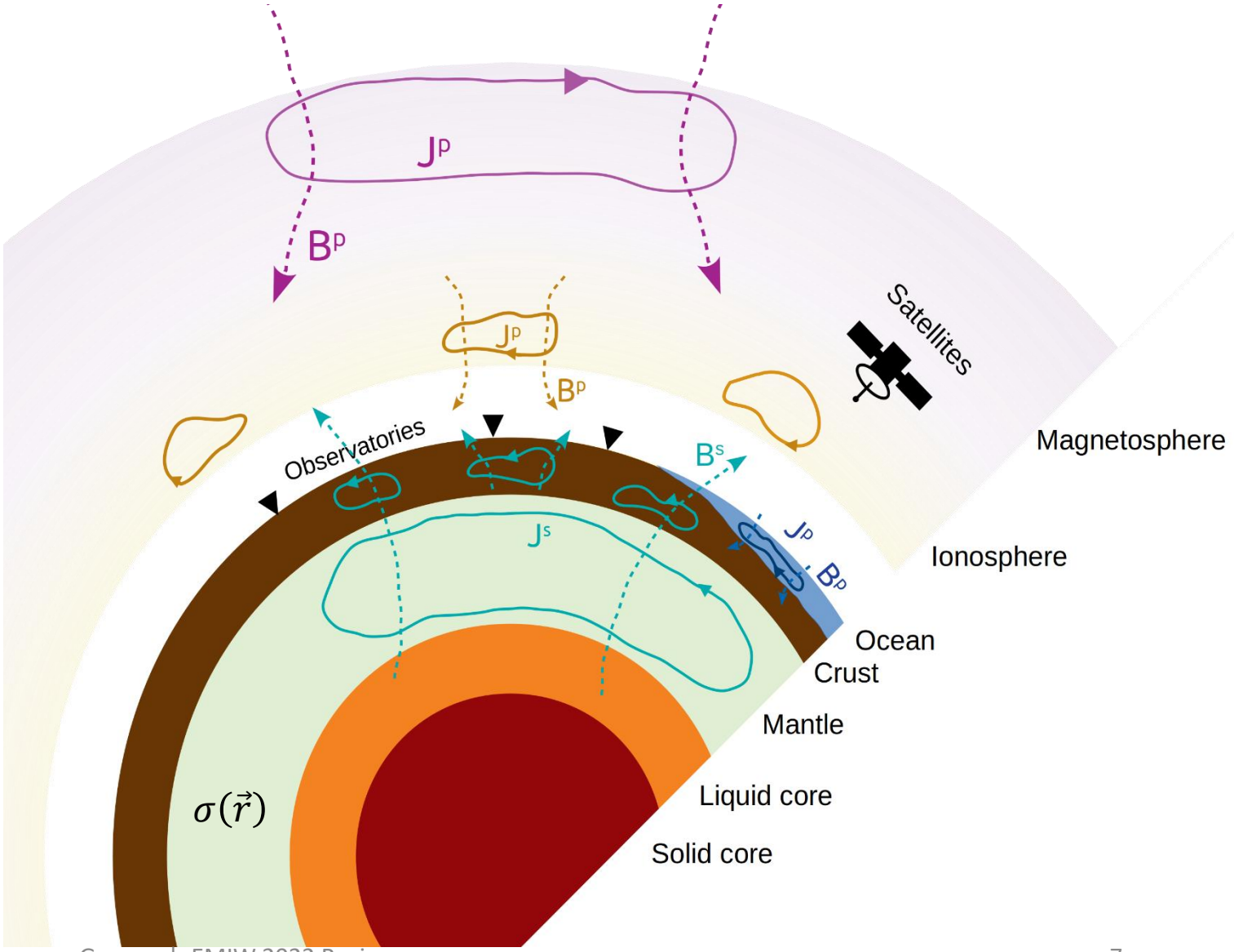
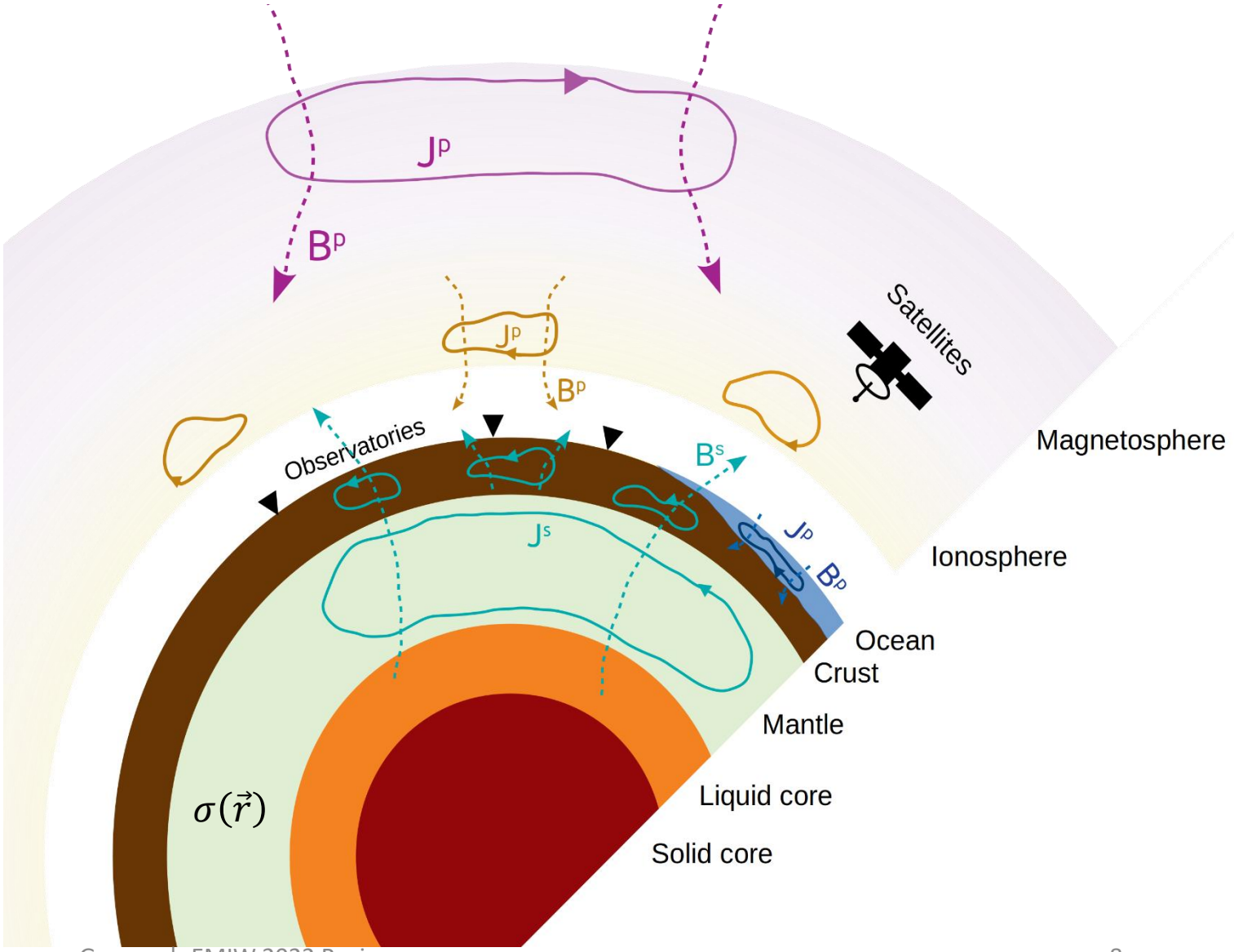


Electromagnetic (EM) induction methods

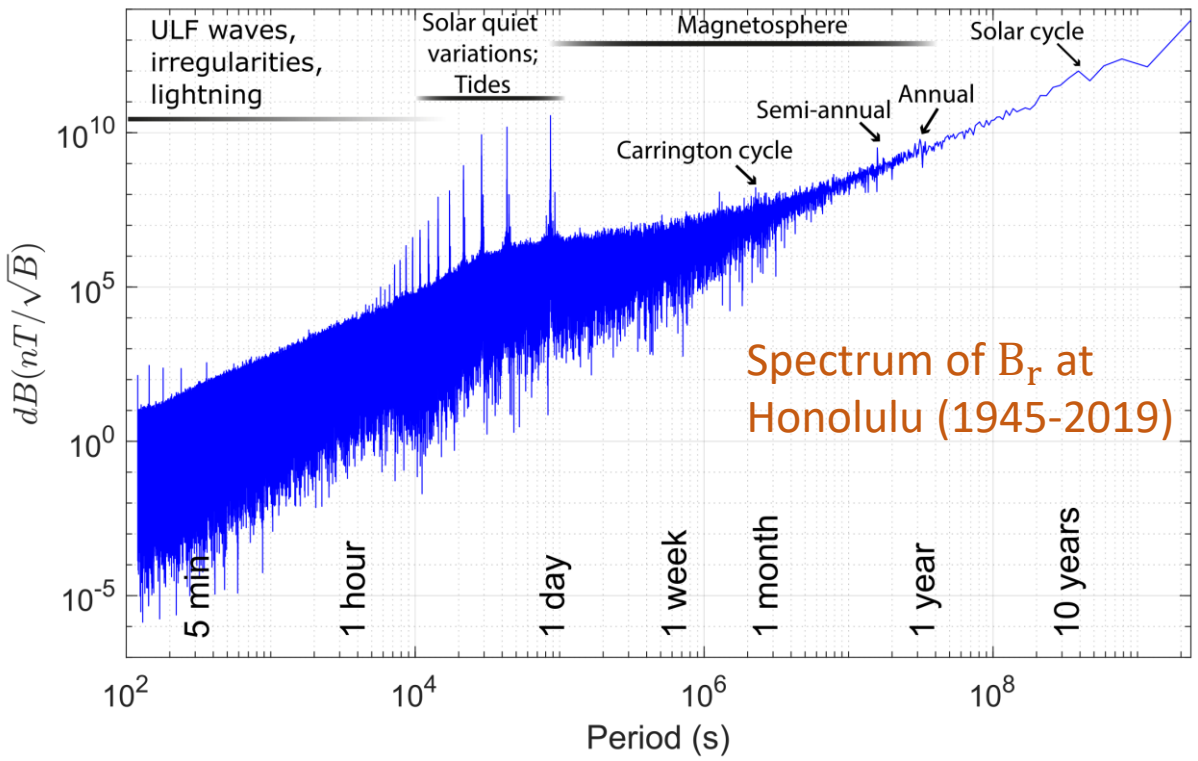
- EM methods measure the Earth response to a *time-varying* EM source field.
- The EM response depends on Earth's conductivity structure
- Governing equations:

$$\mu^{-1}\nabla \times \vec{B} = \sigma\vec{E} + \vec{j}^{p}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$



Earth's electromagnetic environment



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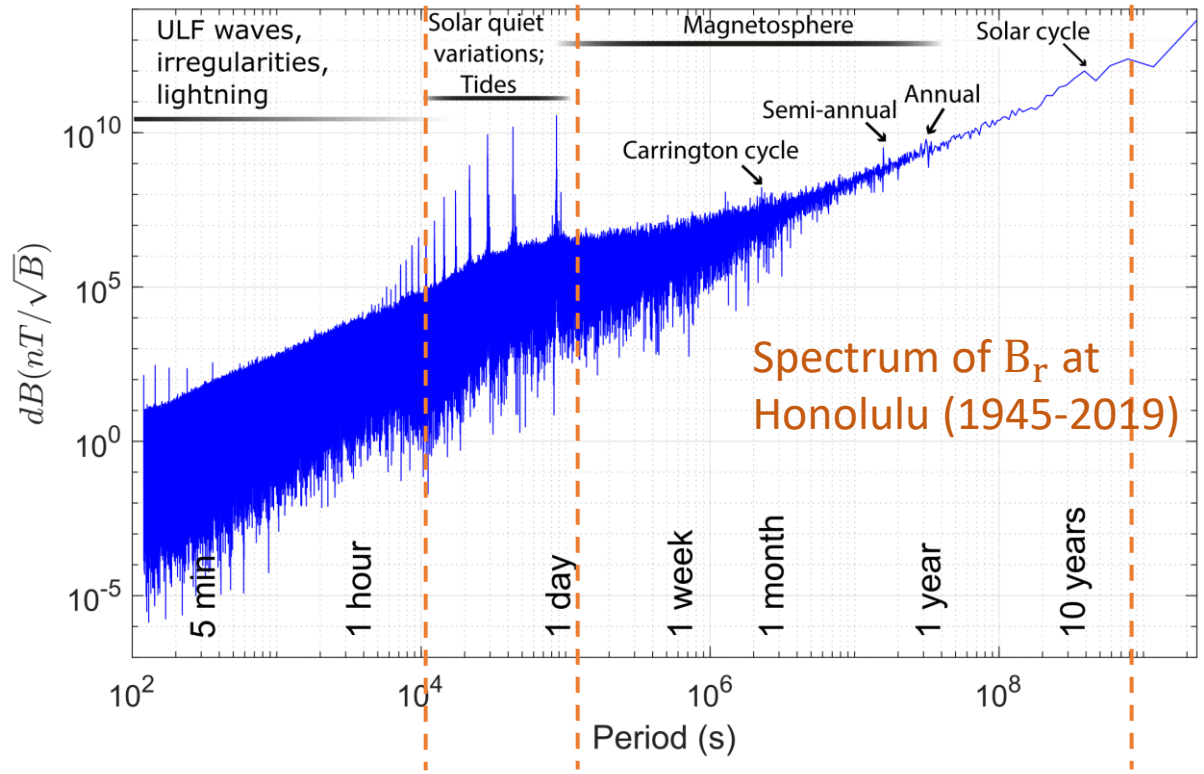
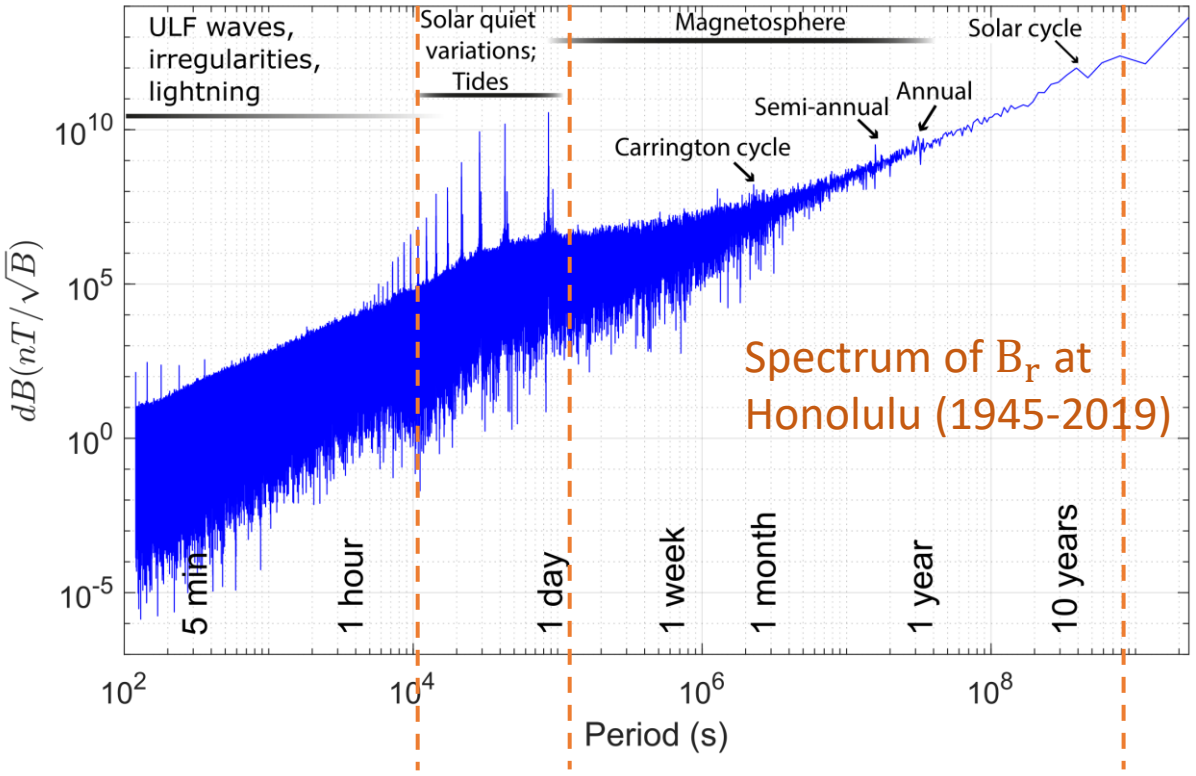


Band:	"Plane wave"	"Daily"	"Magnetospheric"
Depth (km):	< 350	200-600	> 400 (down to CMB)

- Depth of sounding is proportional to the period.
- Simple "plane wave" source assumption at shorter periods.
- Complex and heterogeneous sources at longer periods. Source structure is generally not known.

Earth's electromagnetic environment

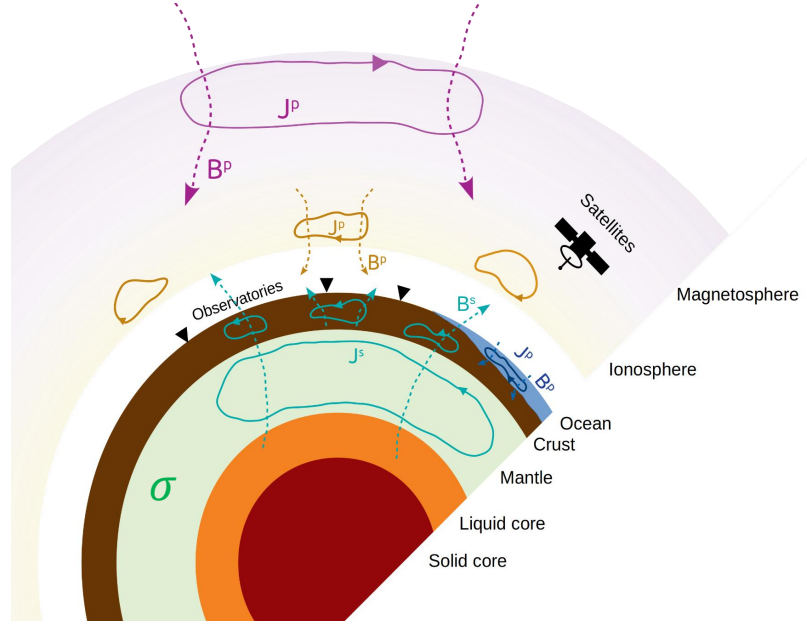


Magnetotelluric / Oceanic tidal sources:

(1) $$\min_{\sigma} \|d - F(\sigma)\|_2^2 + R(\sigma)$$

Long-period Ionospheric / Magnetospheric sources:

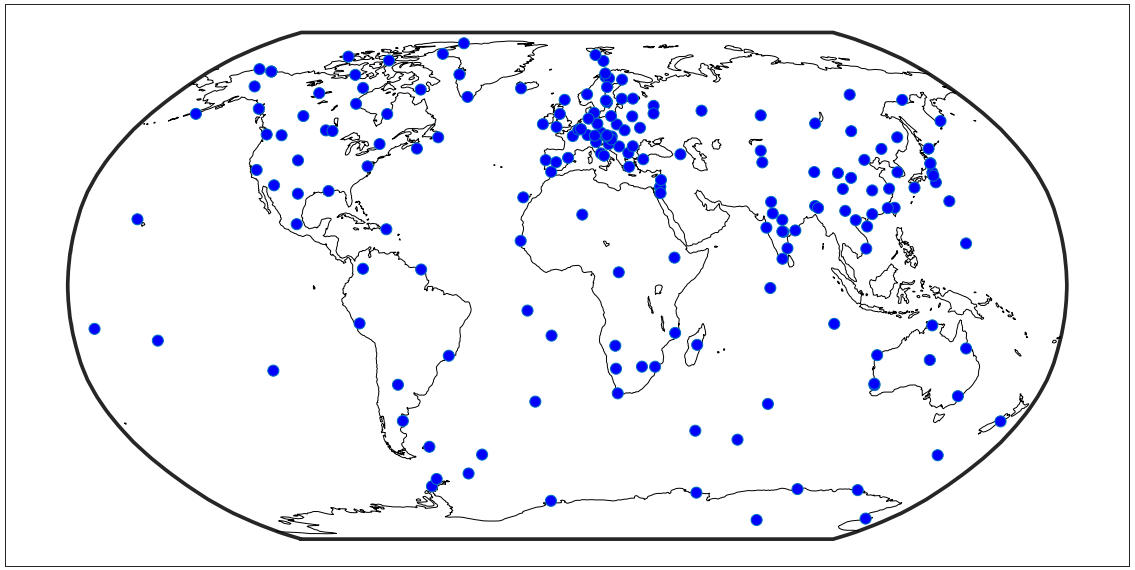
(2) $$\min_{\sigma, j^p} \|d - F(\sigma) j^p\|_2^2 + R(\sigma, j^p)$$

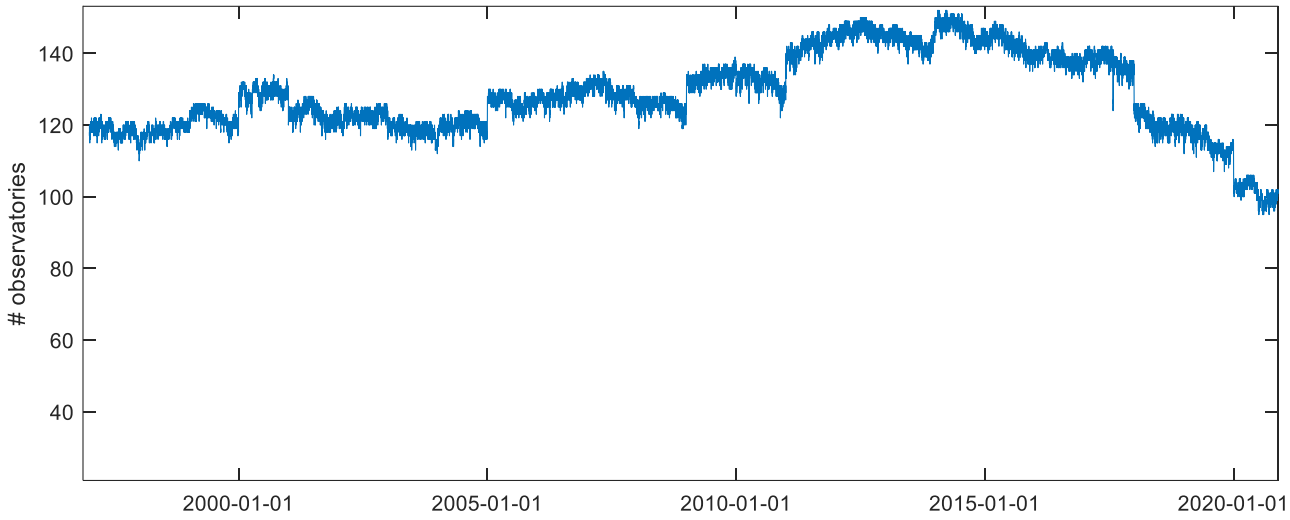


Band:	"Plane wave"	"Daily"	"Magnetospheric"
Depth (km):	< 350	200-600	> 400 (down to CMB)
Inversion strategy:	(1)	(1), (2)	(2)

Data

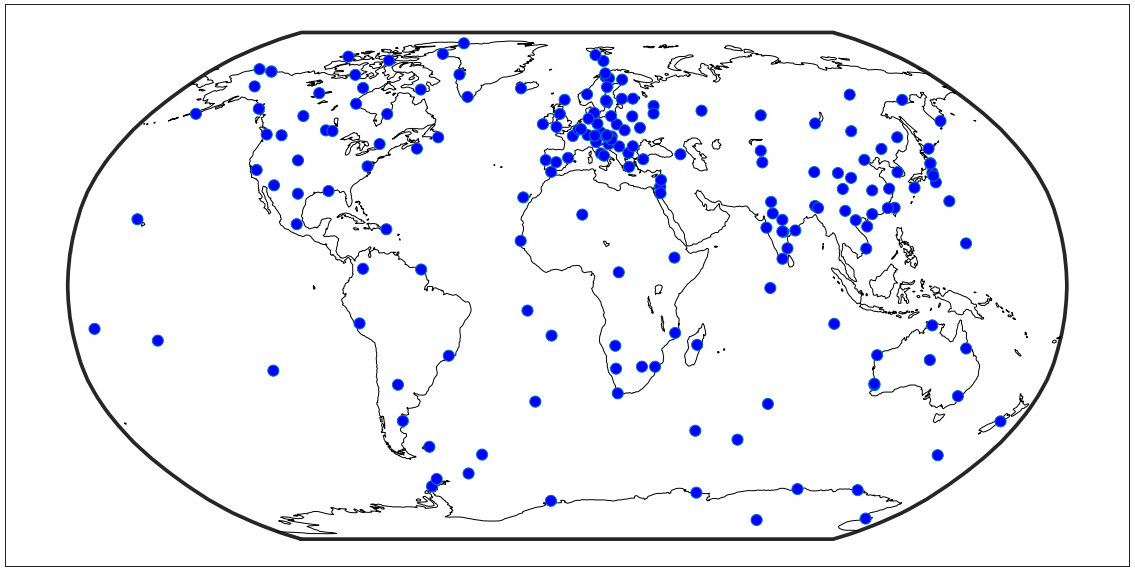
Data: geomagnetic observatories





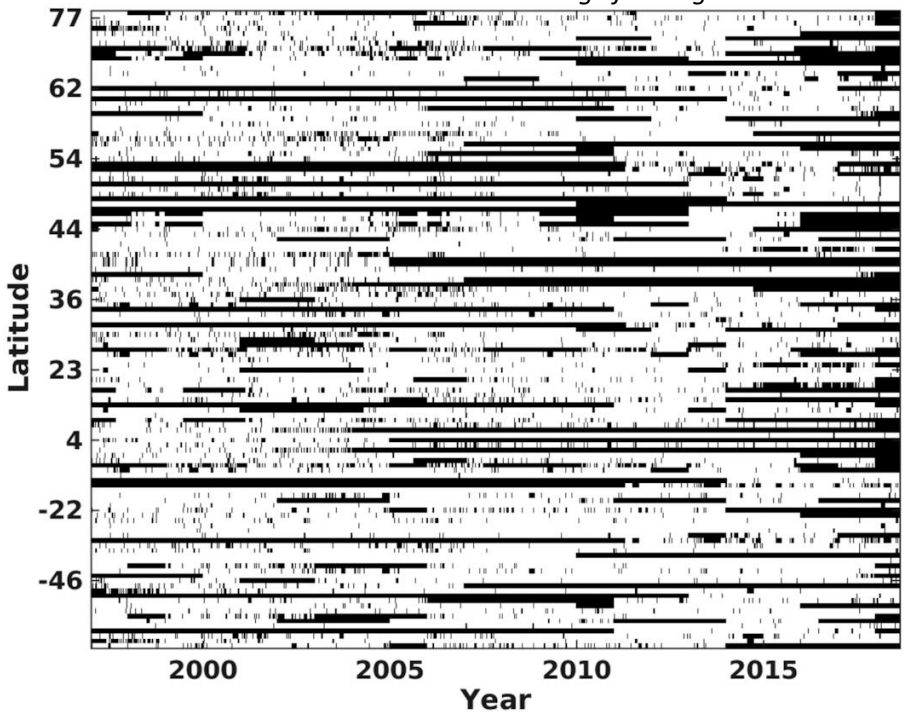
MacMillan and Olsen 2013: maintained BGS product (hourly, minute, second data) based on INTERMAGNET and other sources

Data: geomagnetic observatories



Black indicates gaps

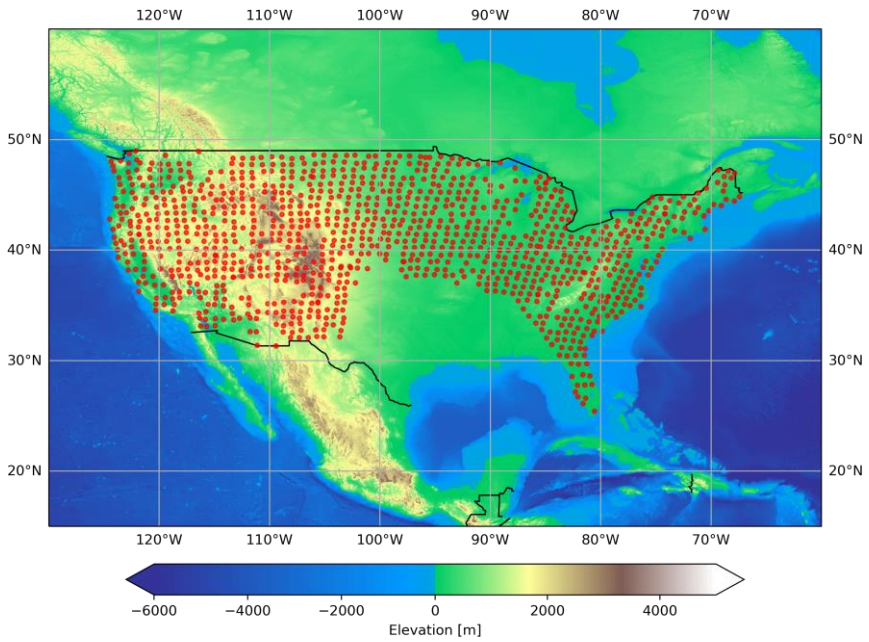
Image from Egbert et al 2021



MacMillan and Olsen 2013: maintained BGS product (hourly, minute, second data) based on INTERMAGNET and other sources

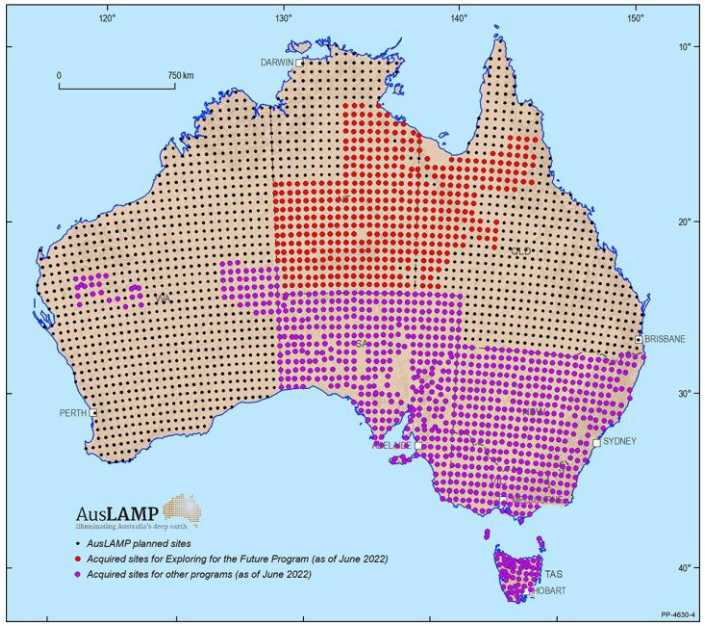
Data: large-scale arrays

USArray



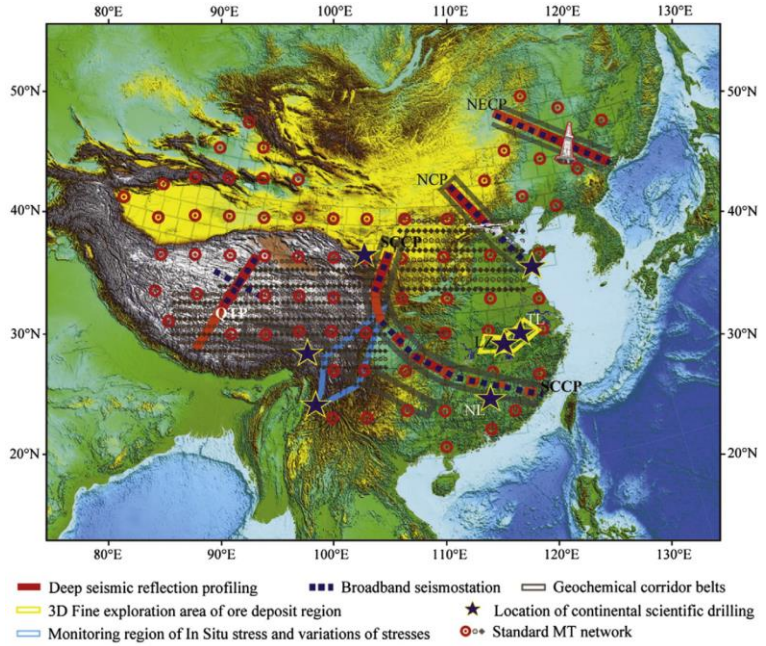
Schultz et al. 2006 – 2022, OSU, USGS

AusLAMP



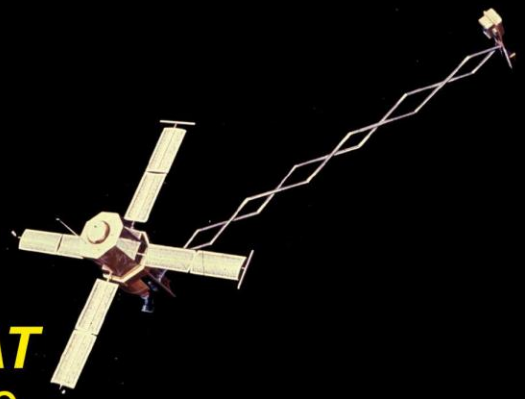
Geoscience Australia, 2022

SinoProbe



Dong et al., 2022

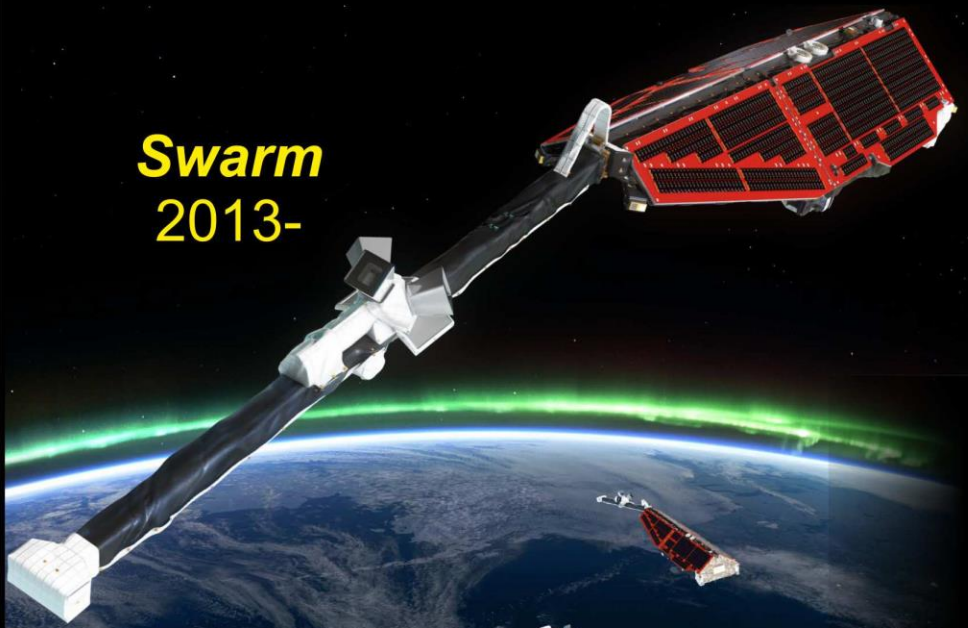
POGO
1965-70



MAGSAT
1979-80

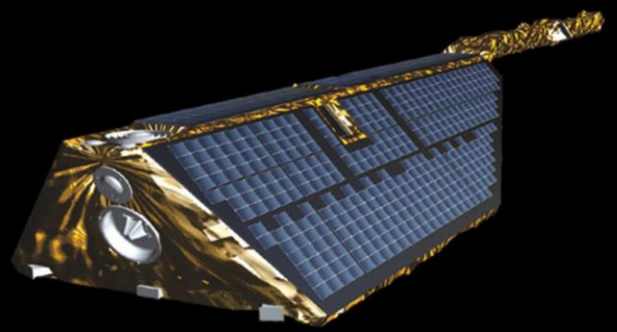
Ørsted
1999-2014

SAC-C
2000-2005



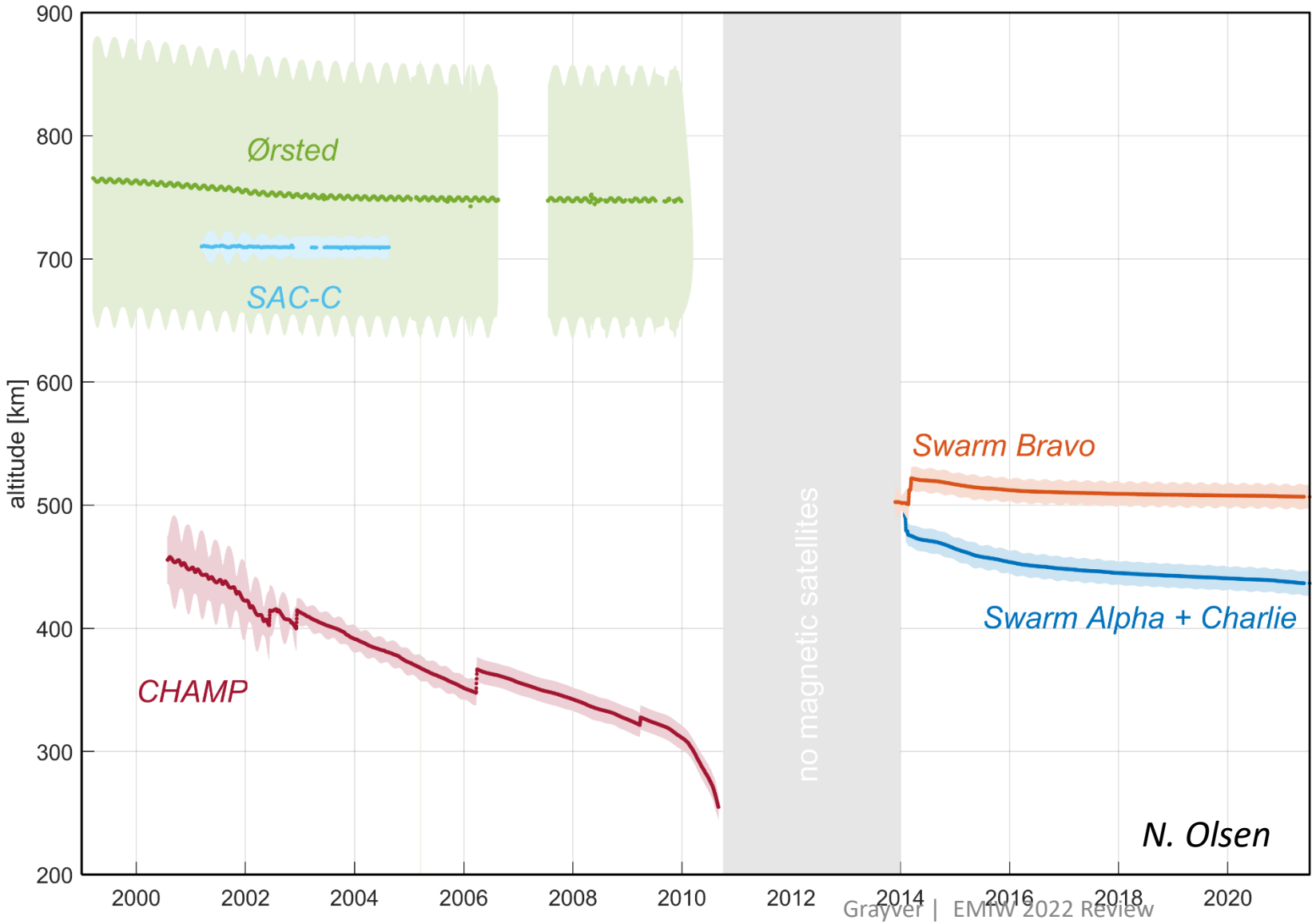
Swarm
2013-

CHAMP
2000-2010



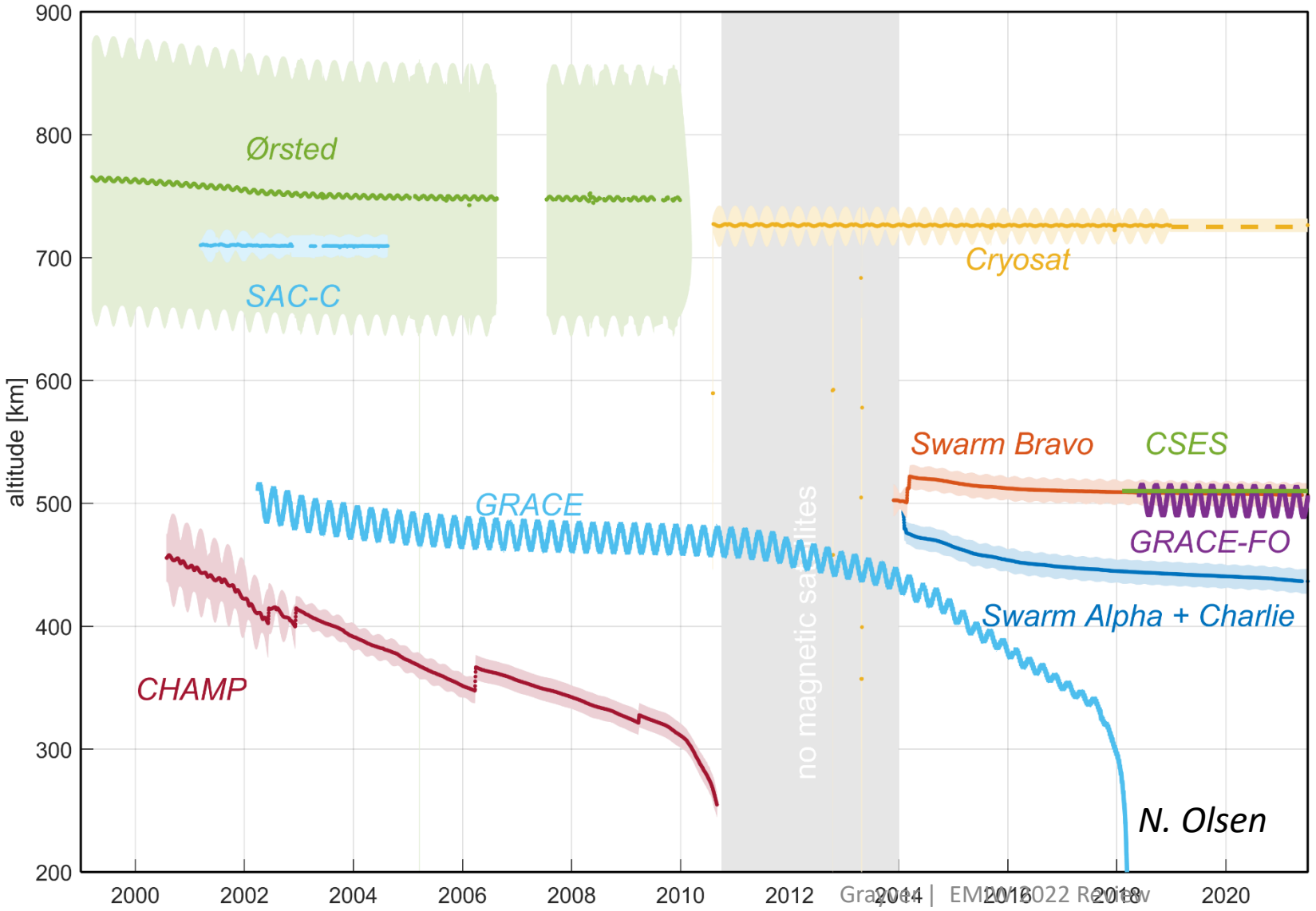
Courtesy of N. Olsen

Data: Dedicated Science Satellites



No high-precision magnetic field data are available in the gap between CHAMP and Swarm
(Oct 2010 and Nov 2013)

Data: Dedicated Science Satellites + Platform Magnetometers

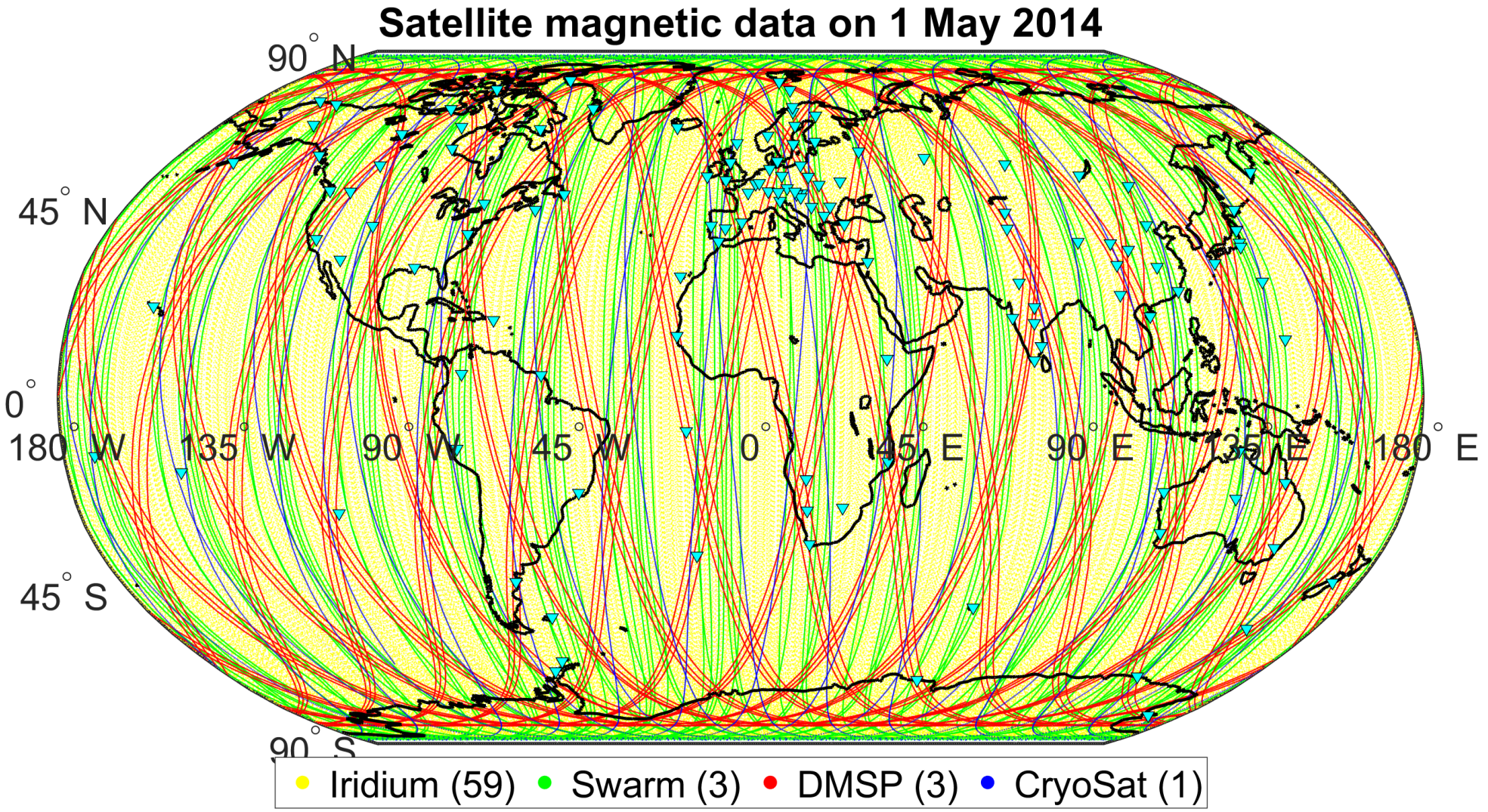


No high-precision magnetic field data are available in the gap between CHAMP and Swarm (Oct 2010 and Nov 2013)

Swarm, GRACE-FO and CryoSat-2 provide simultaneous data for improved time-space separation of external sources

Swarm: Olsen et al. 2013
CSES: Shen et al. 2018
CryoSat-2: Olsen et al. 2020
GRACE-FO: Stolle et al. 2021

Data: Dedicated Science Satellites + Platform Magnetometers



Data: summary

- **Geomagnetic observatories**
  - Pros: long quality-controlled time series
  - Cons: uneven sparse coverage

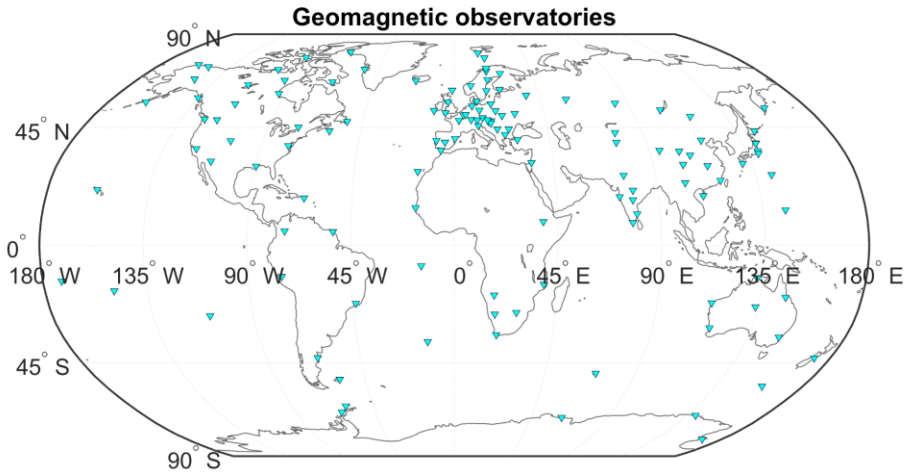


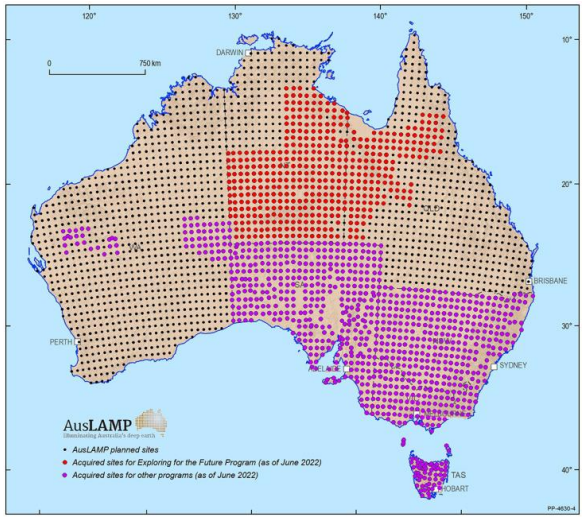
Image: GFZ

Temporary stations (arrays)

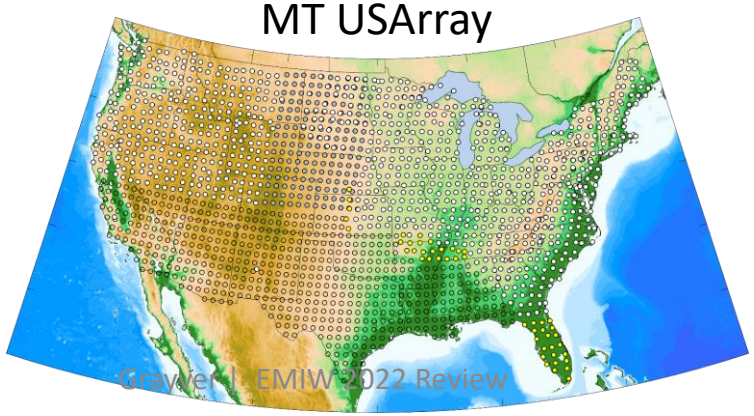
Pros: improved local resolution

Cons: short time series

AusLAMP



MT USArray



Satellites (CHAMP 2000-2010, Swarm 2013 - present)

Pros: accuracy, coverage

Cons: space-time aliasing

ESA Swarm satellites

New: satellite platform magnetometers (potentially hundreds of satellites, e.g. CryoSat-2, GRACE-FO)

Pros: unprecedented resolution

Cons: lower accuracy (1x – 100x nT)

Modelling and Inversion

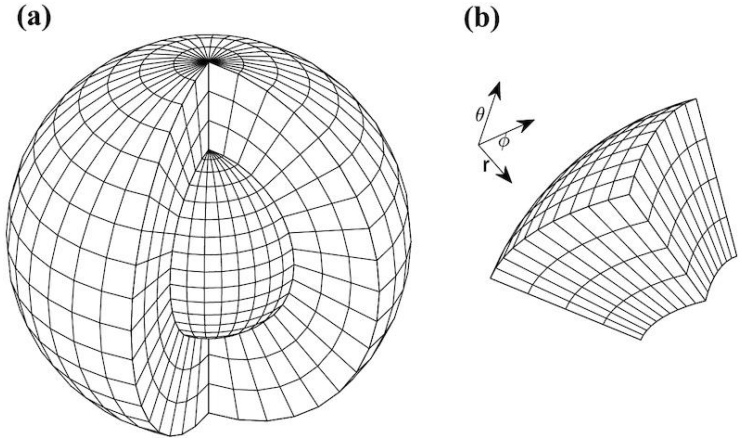
Modelling and inversion

- Modelling benchmark study by Kelbert et al. 2014:
  - Tested 7 codes
  - Many new codes since then…
- FD: Zhang et al. 2019 (ModEM-based)
- FE: Grayver et al. (2019); Yao et al. (2022)
- IE: Chen et al. 2021; Kruglyakov and Kuvshinov 2022
- Spectral-FE: Velimsky et al. 2018 (frequency domain), Velimsky et al. 2019 (TD)

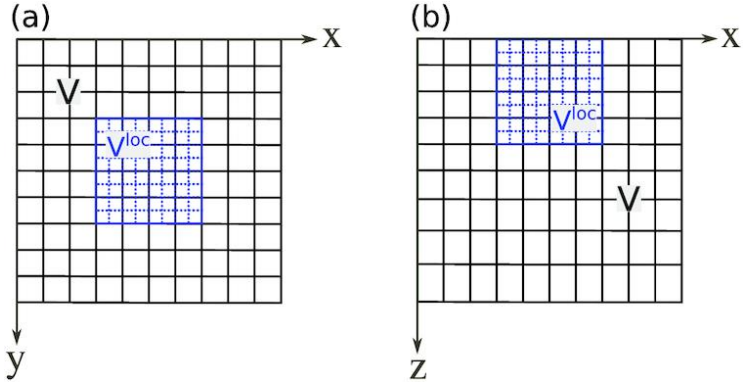
- Derivation of general adjoint operators (essential for 3-D inversion):
  - Egbert and Kelbert 2012
  - Pankratov and Kuvshinov 2010, 2014

Multi-scale grids and regional modelling

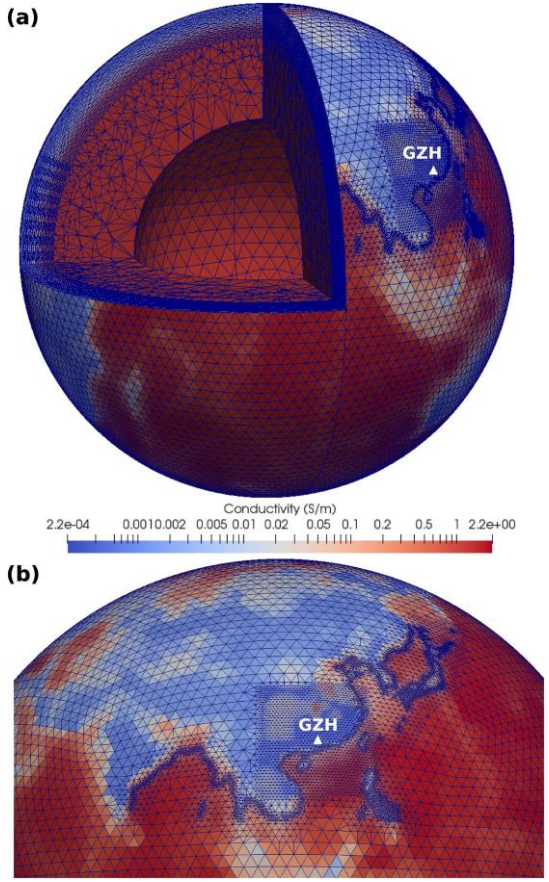
Zhang et al. 2019 (ModEM)



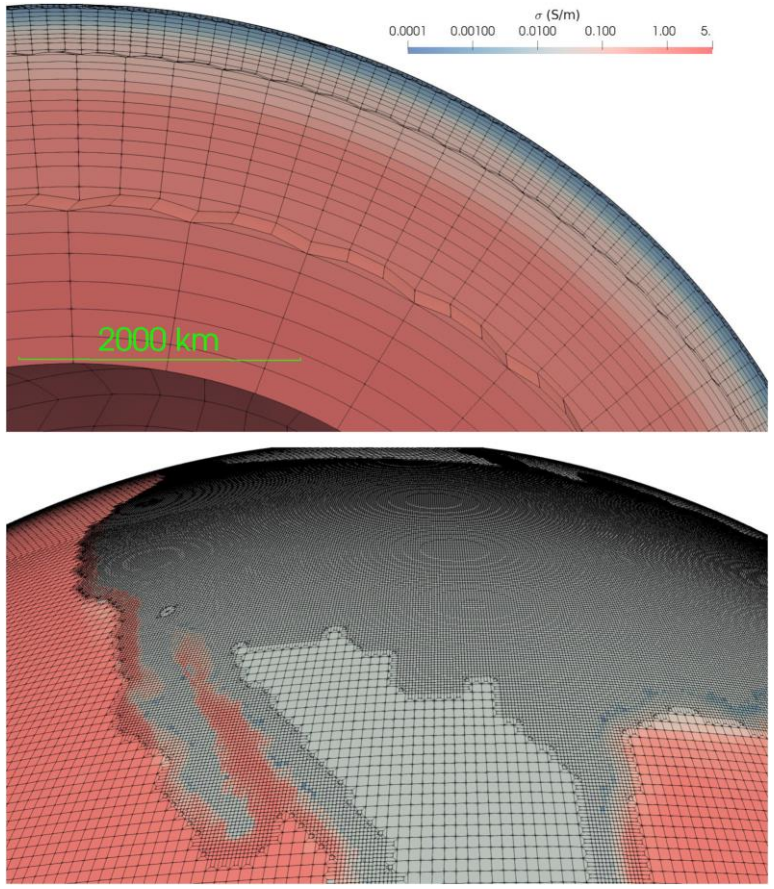
Chen et al. 2022 (Nested-IE)



Yao et al. 2022



Grayver et al. 2019

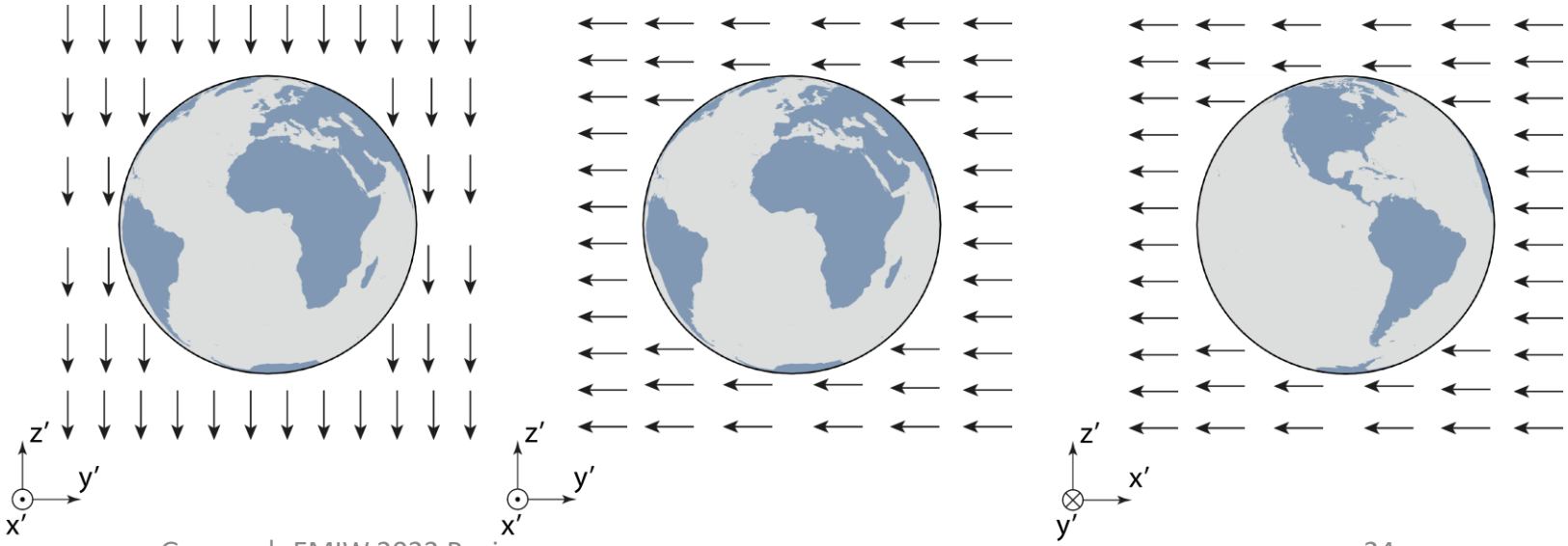


3-D MT modelling in a sphere

- Uniform planetary fields (Fainberg et al. 1983).
- Described by degree 1 Spherical Harmonic functions.
- Reproduces plane wave impedance in a relevant period range.
- No tippers due to non-zero B_r.

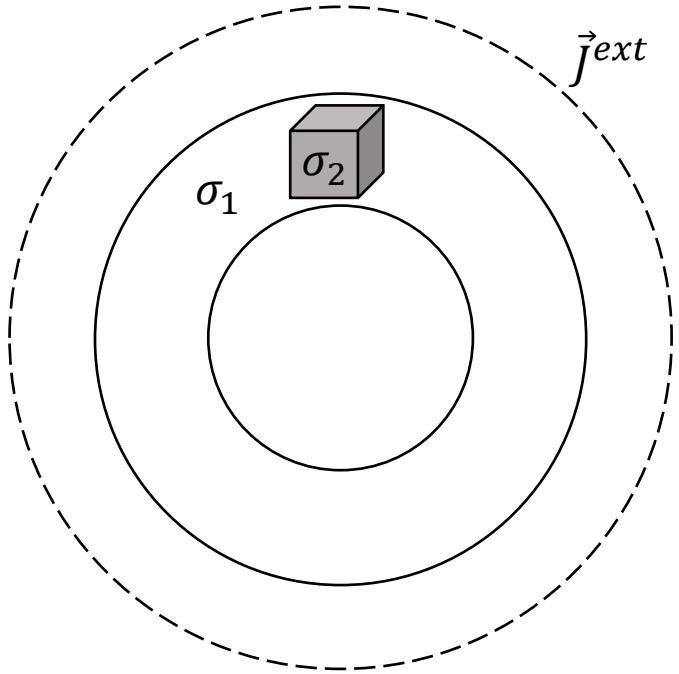
$$\begin{bmatrix} -E_\theta^1 & -E_\theta^2 & -E_\theta^3 \\ E_\phi^1 & E_\phi^2 & E_\phi^3 \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} -H_\theta^1 & -H_\theta^2 & -H_\theta^3 \\ H_\phi^1 & H_\phi^2 & H_\phi^3 \end{bmatrix}$$

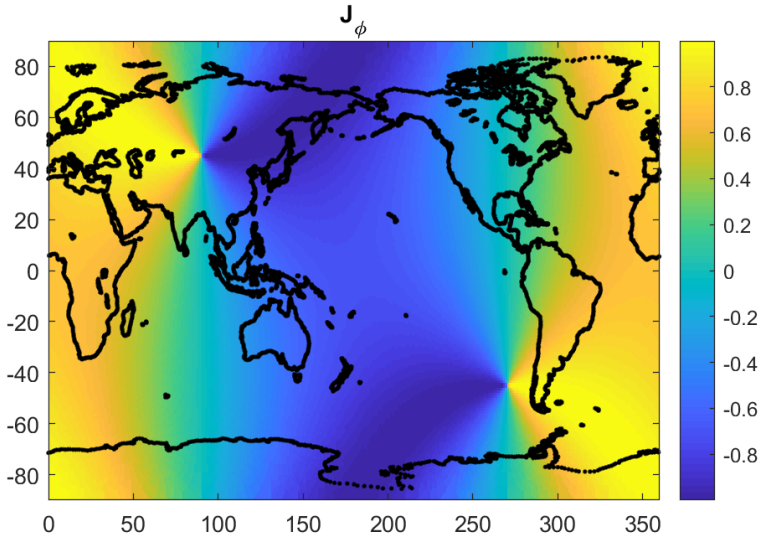
Grayver et al. 2019

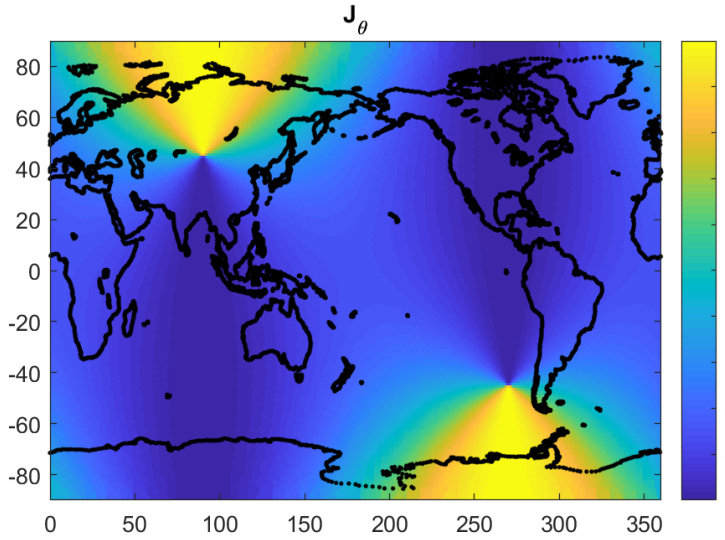


3-D MT modelling in a sphere

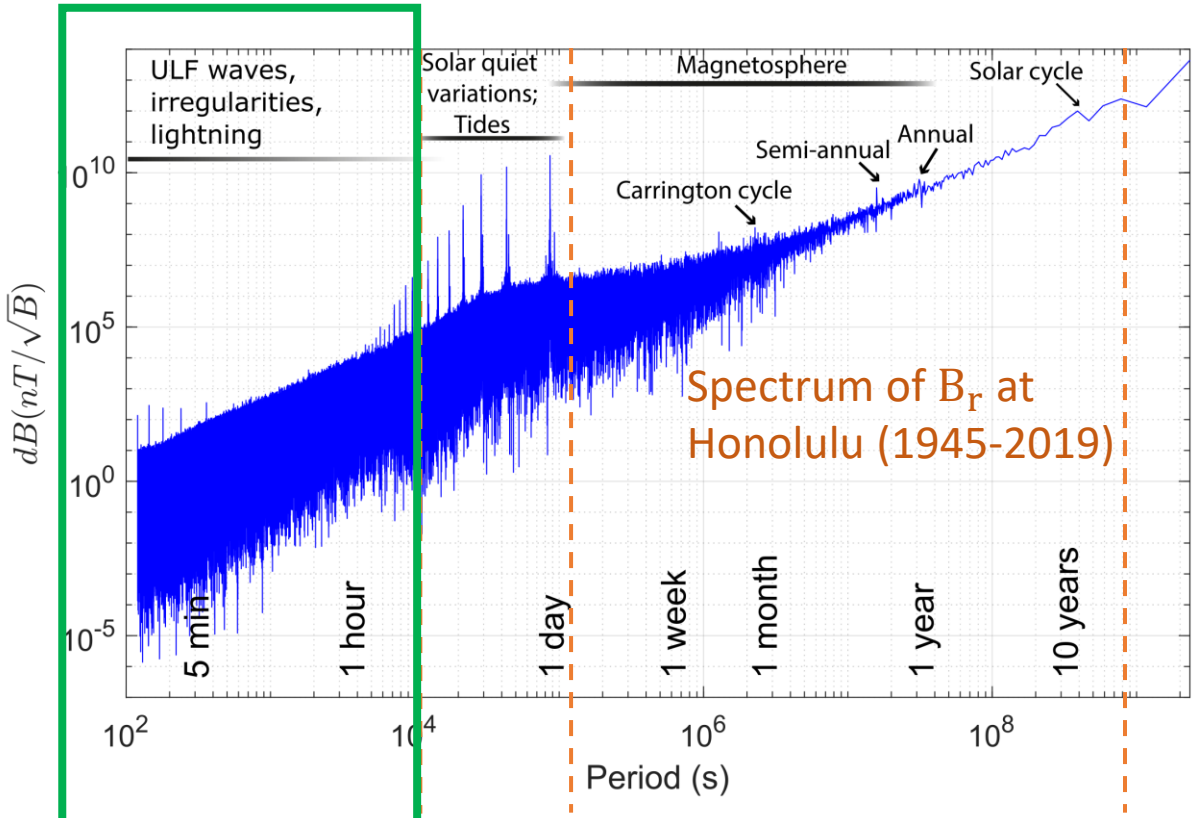
- Alternative source model based on a sheet current $\vec{J}^{ext}$ flowing in ϑ-direction placed above the Earth's surface + plus two rotated orthogonal polarizations (Kruglyakov and Kuvshinov, 2022).
- Radial (vertical) field is zero for any 1-D model, thus it can be used to compute tippers.





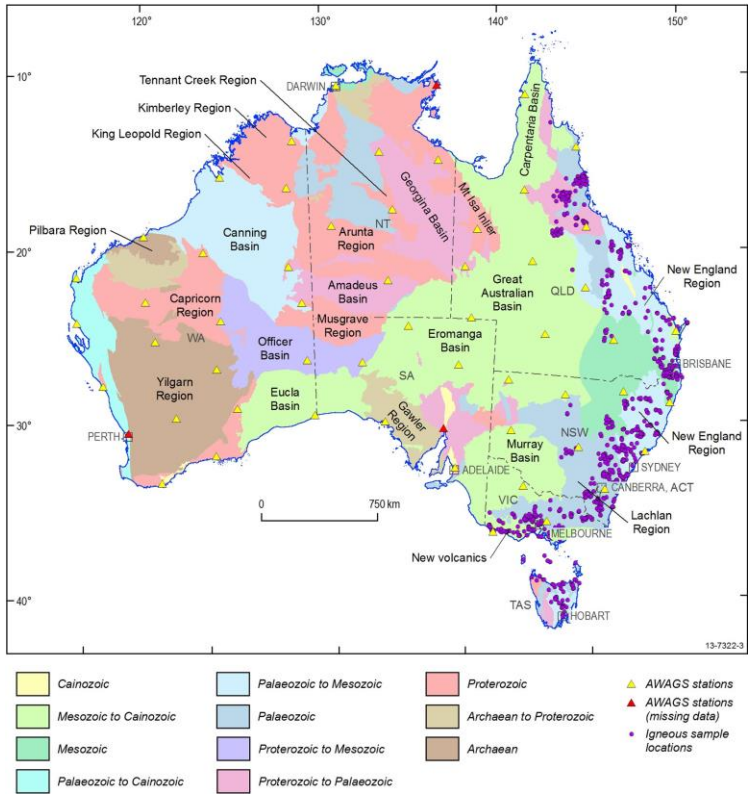


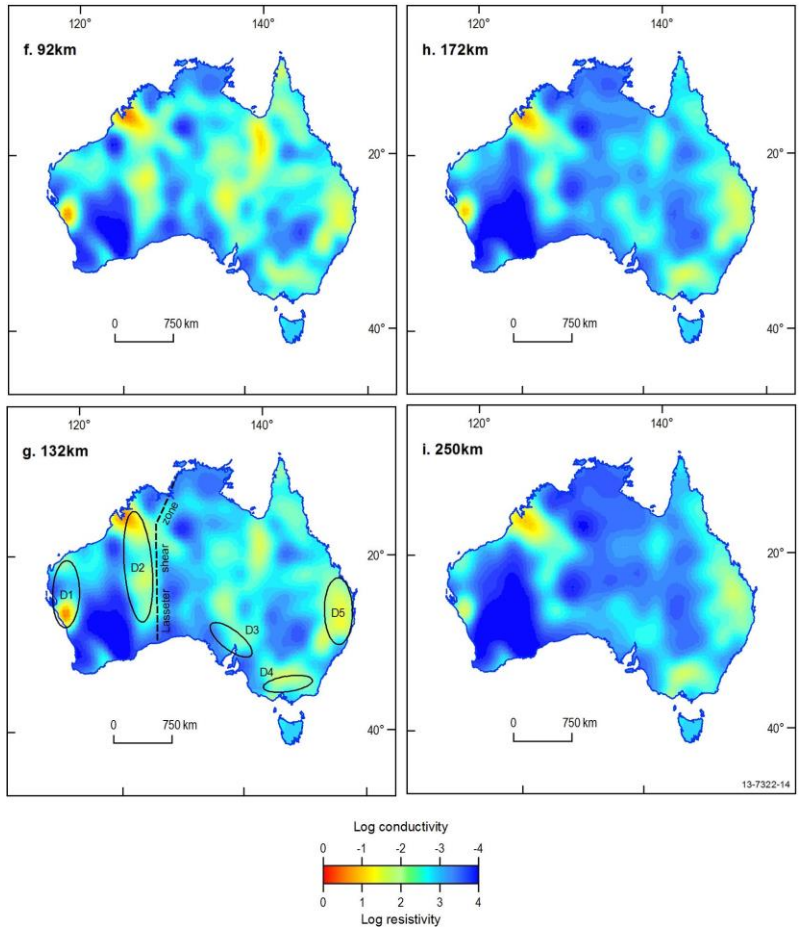
Large-scale MT / GDS



Band:	“Plane wave”	“Daily”	“Magnetospheric”
Sounding depth (km):	< 350	200-500	> 400

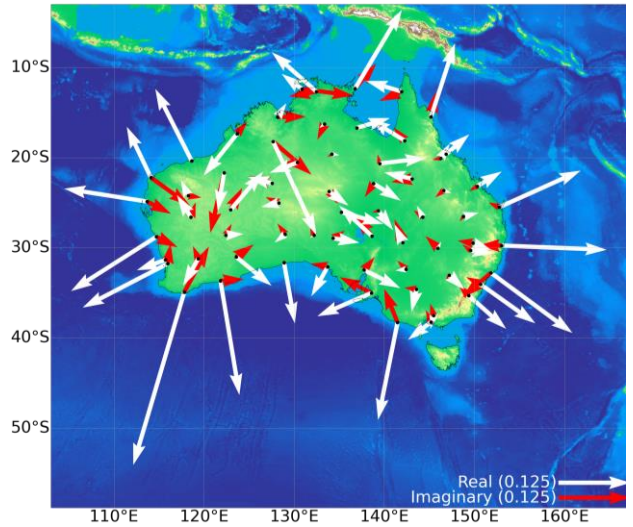
Inversion of tippers from AWAGS data



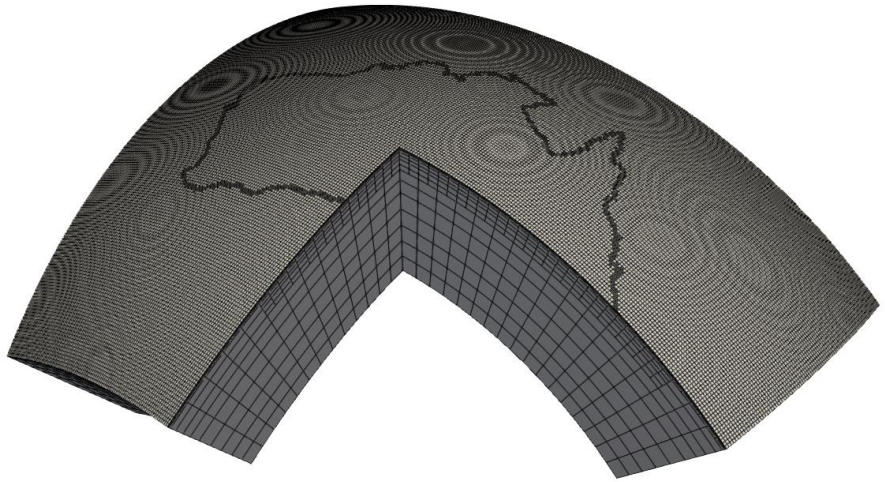


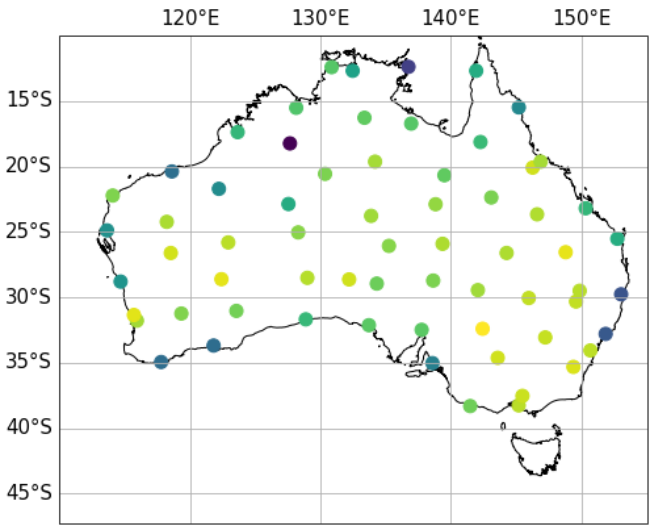
Wang et al. 2014

Inversion of tippers from AWAGS data

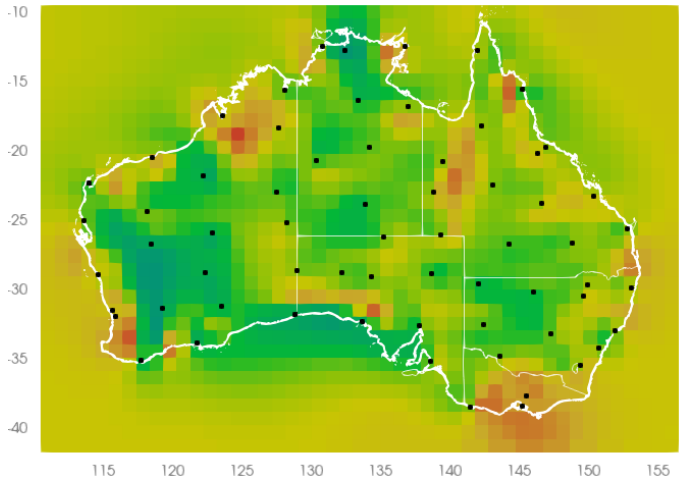


Cicchetti, Grayver et al. 2022

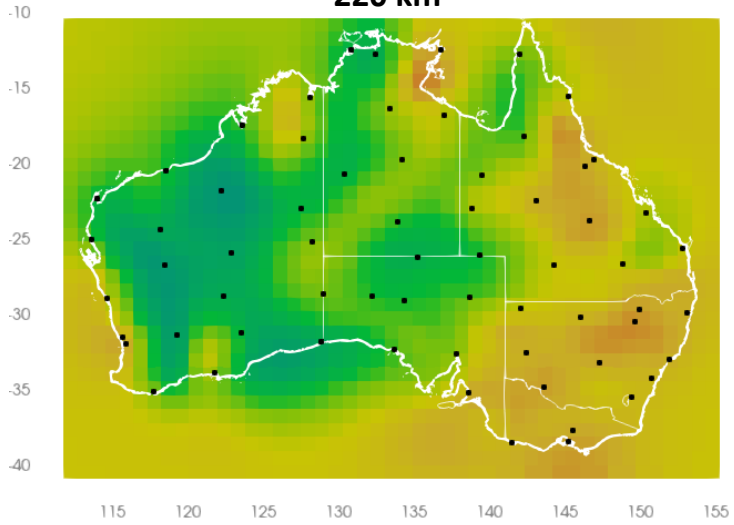




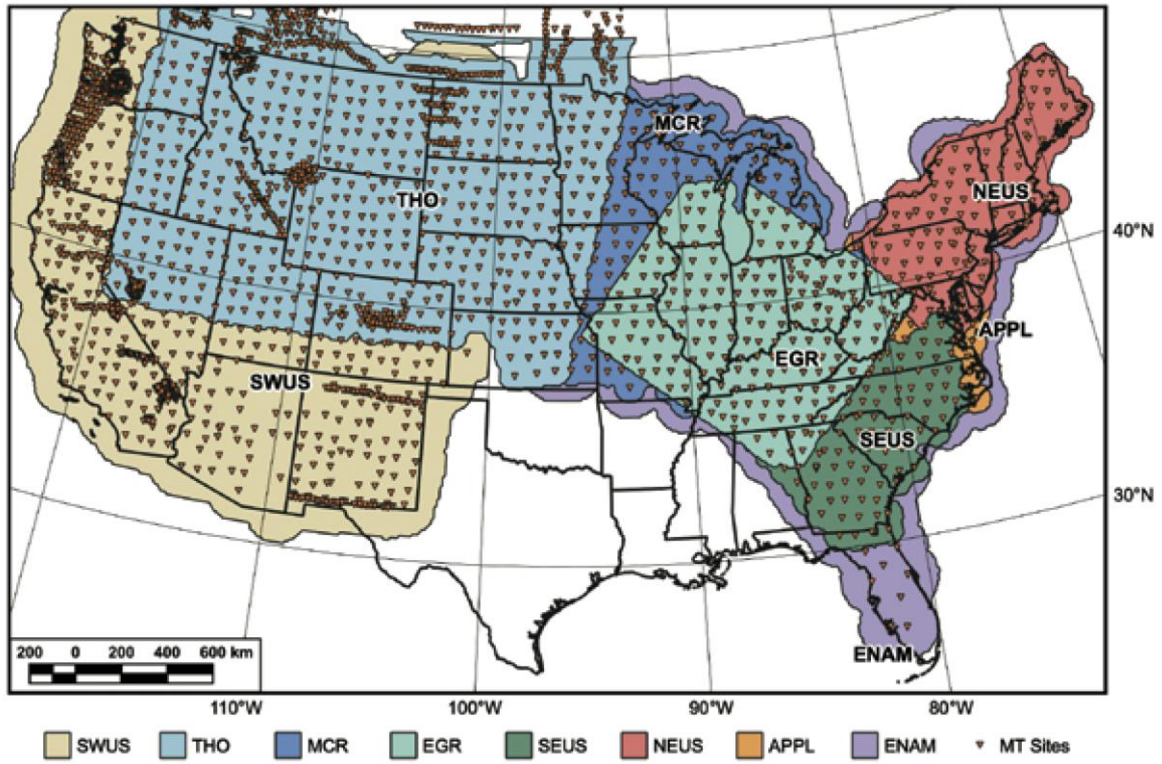
70 km

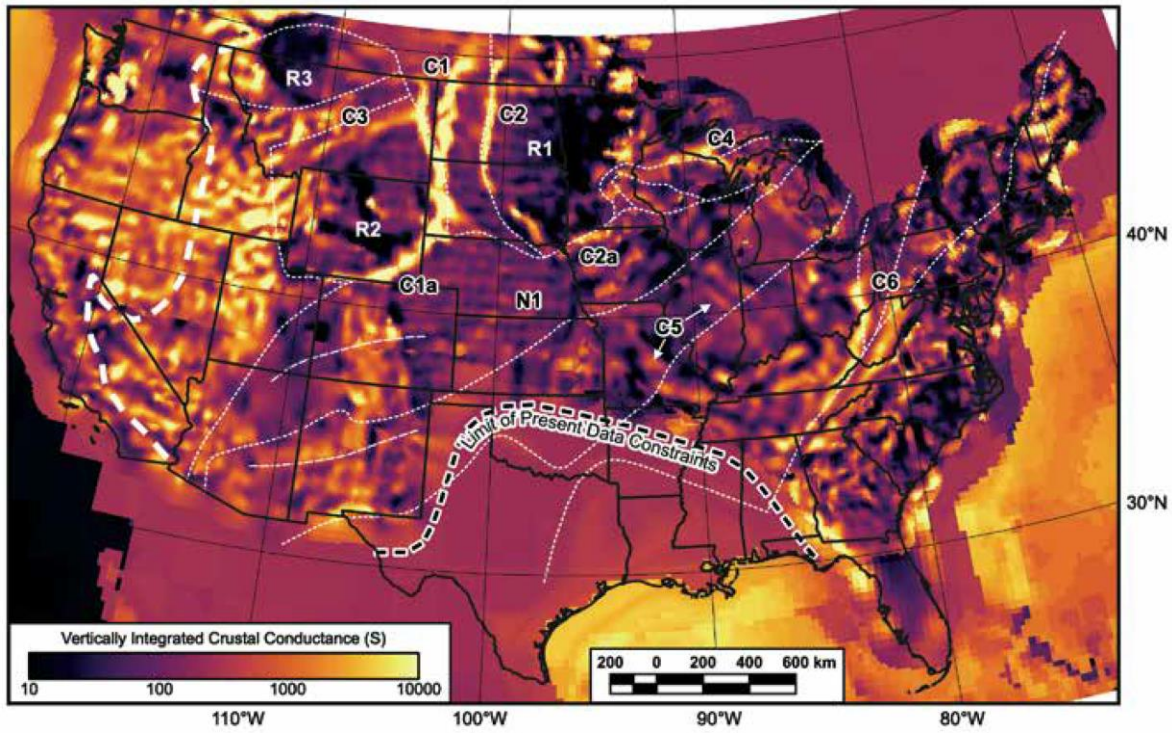


220 km



Inversion of USArray





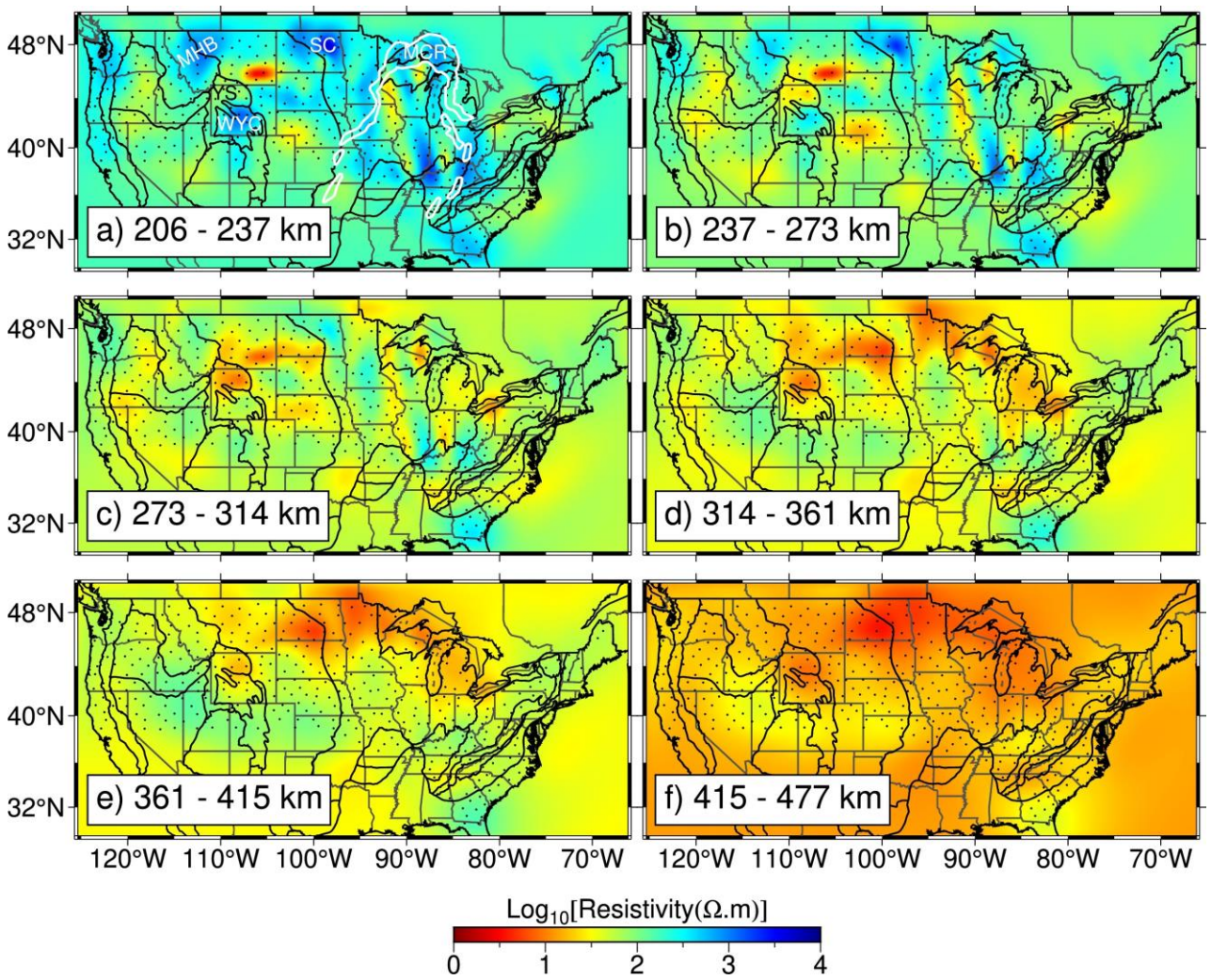
Murphy et al. 2023; Kelbert et al. 2019

> 1500 stations in total, regional Cartesian models, merged posteriori

Inversion of USArray

Yang and Egbert 2021

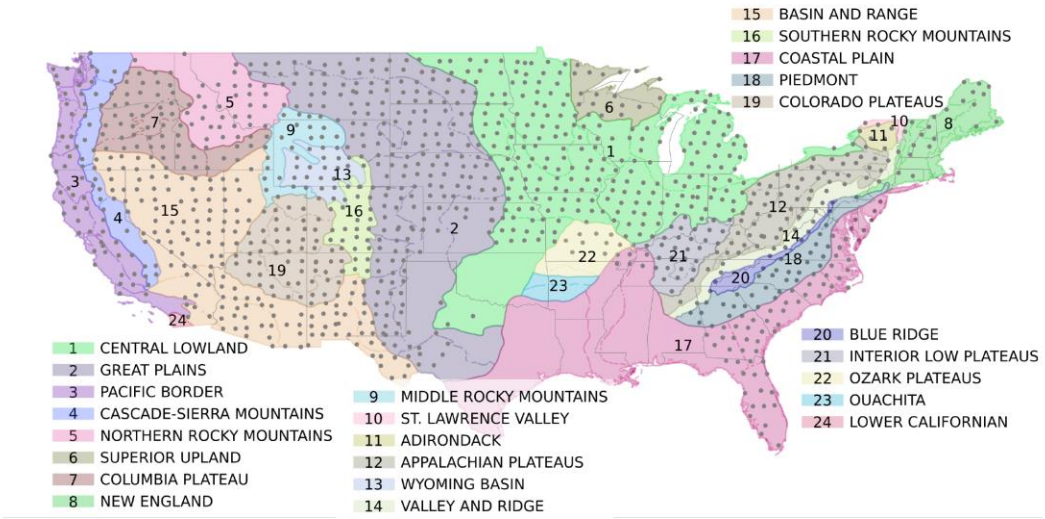
~500 stations, decimated array, Cartesian

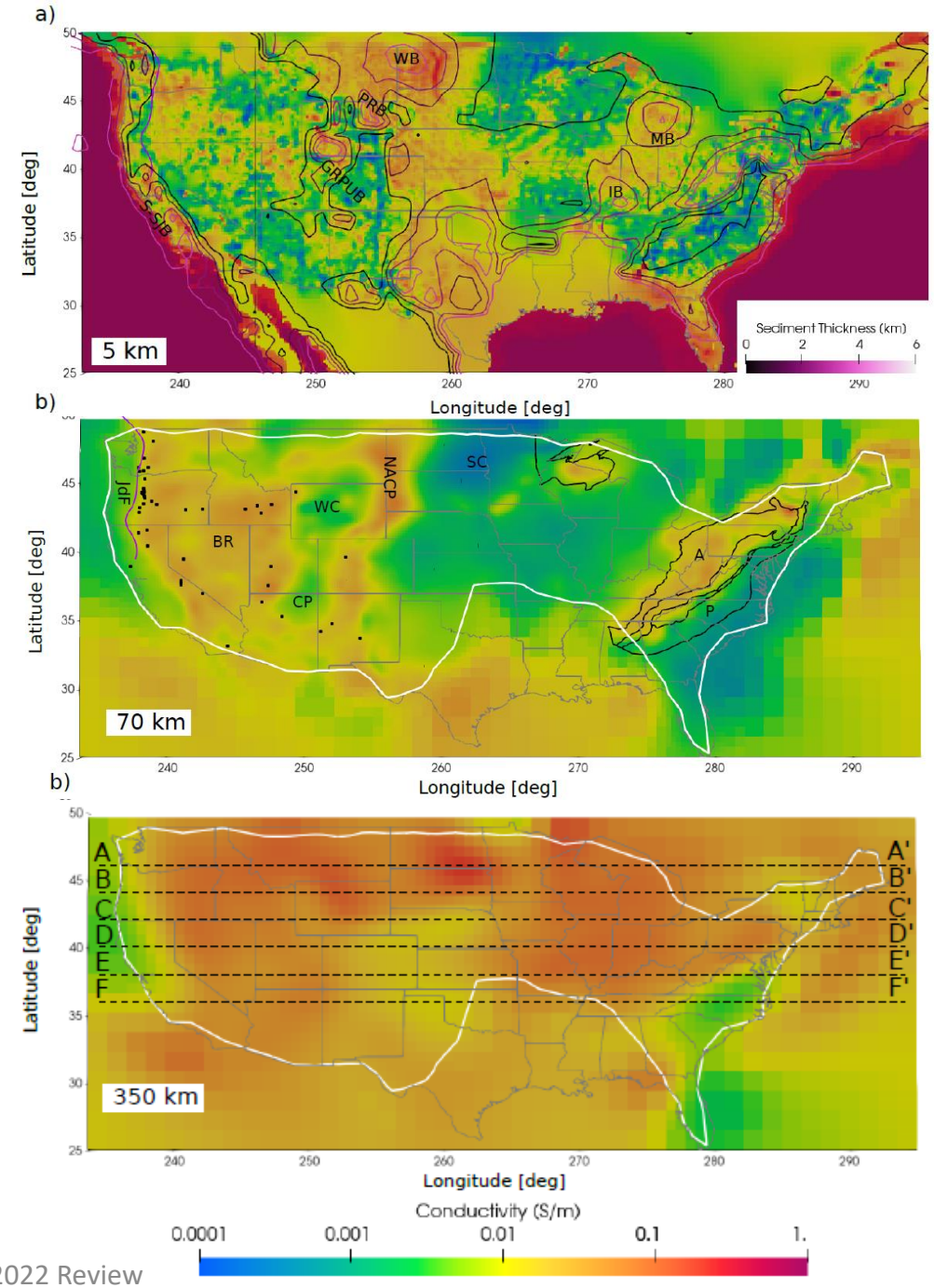


Inversion of USArray

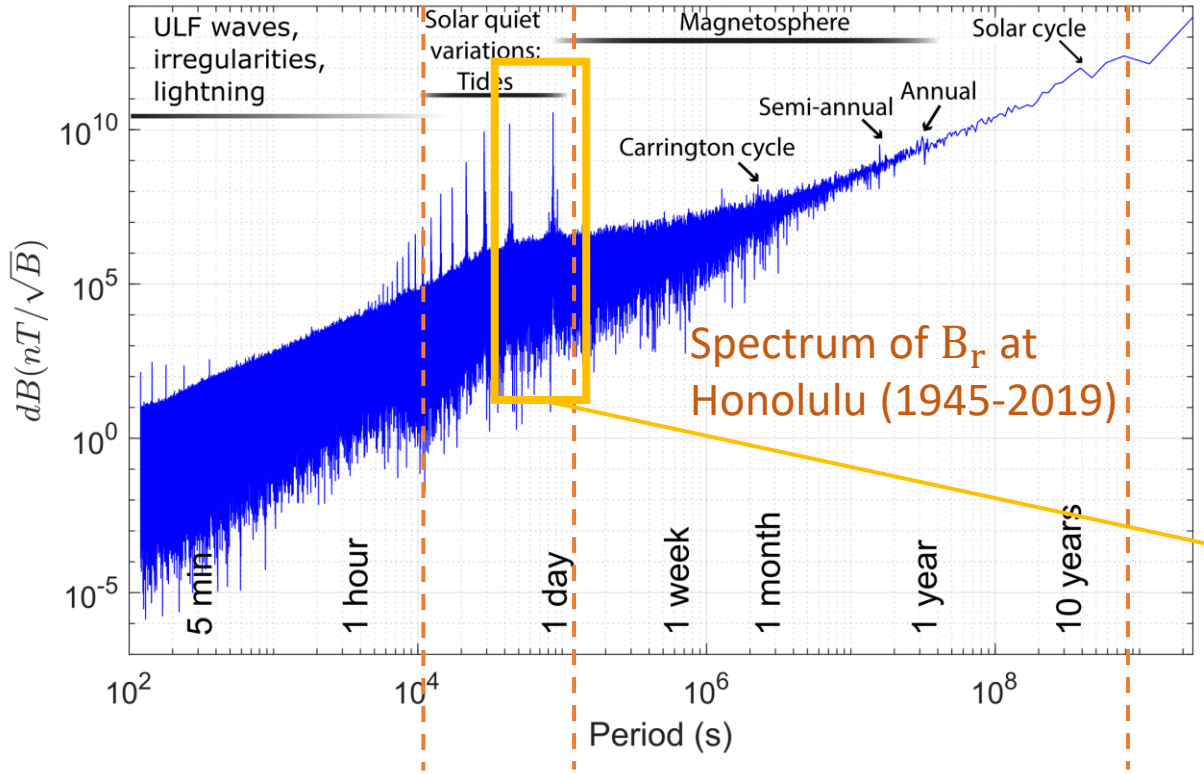
Munch and Grayver 2023, EPSL

1300 stations, nominal array resolution, Spherical

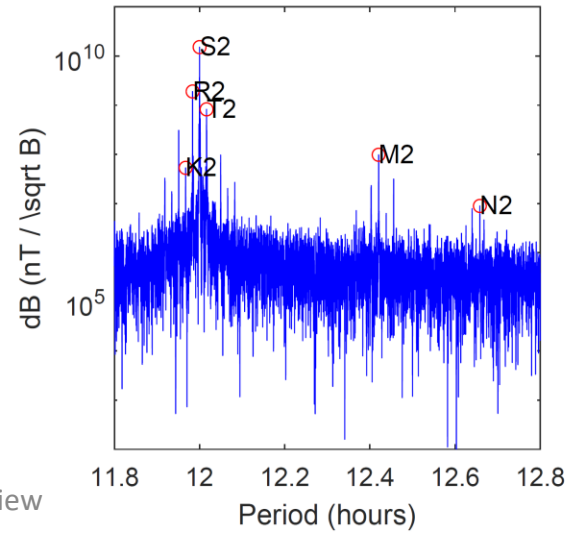


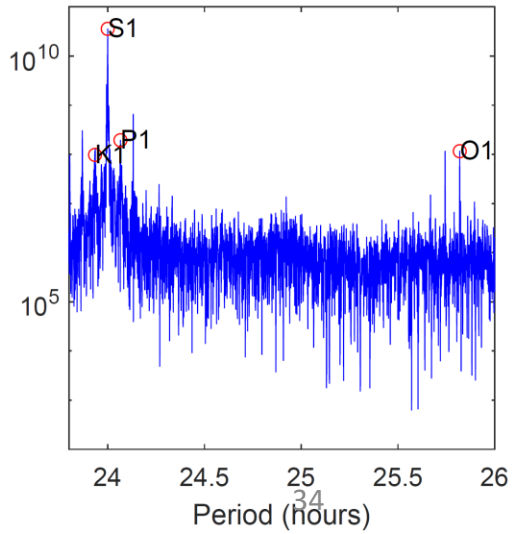


Oceanic sources



Spectrum of B_r at Honolulu (1945-2019)





Band:	“Plane wave”	“Daily”	“Magnetospheric”
Sounding depth (km):	< 350	200-500	> 400

Oceanic sources: motivation

- Upper mantle below oceans is a key to understanding many geodynamic processes: MOR and subduction, plumes, etc…
- Marine MT is possible, but very expensive.
- Satellite-detected tidal magnetic signals appear the only source for global sounding of sub-oceanic mantle.

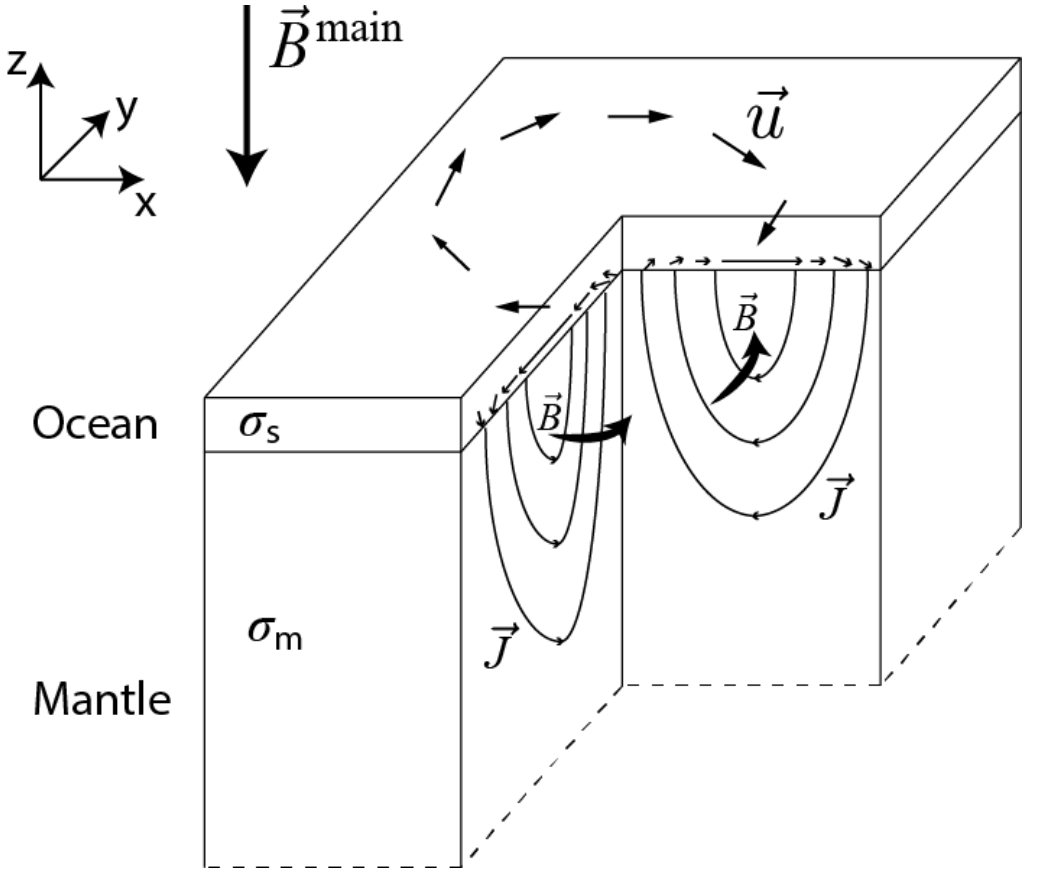
Motional induction

- pre-Maxwell's equations (in frequency domain):

$$\nabla \times \vec{E} = -i\omega\mu\vec{H}$$
$$\nabla \times \vec{H} = \vec{J}$$

- The current term consists of conduction and extraneous terms:

$$\vec{J} = \sigma\vec{E} + \underbrace{\sigma(\vec{u} \times \vec{B}^{main})}_{\text{current induced by the flow}}$$

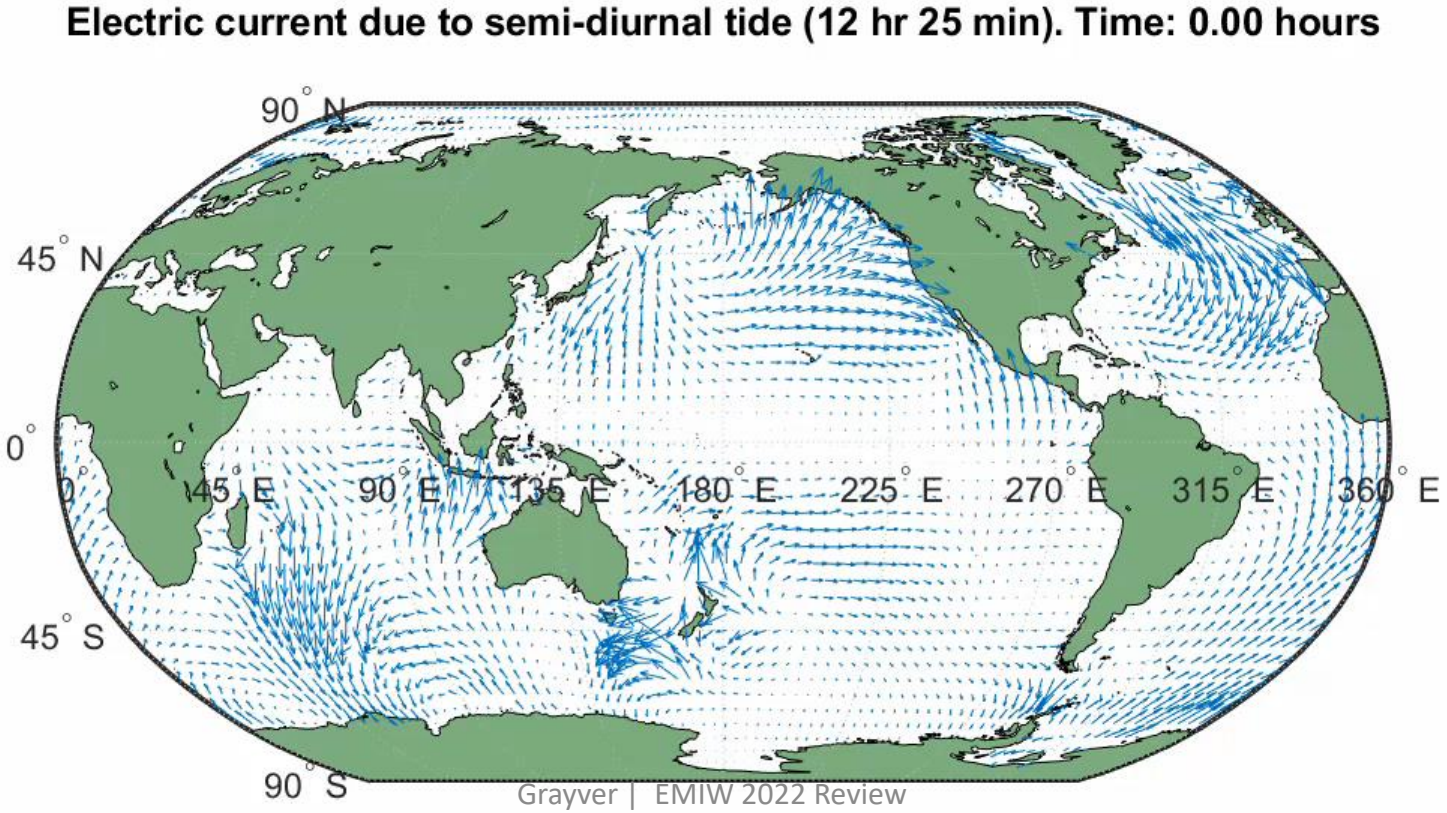


Reworked after Tyler 1997

Example: electric current due to M2 tide

- This animation shows electric currents induced by the M2 semi-diurnal lunar tide (as given by the TPXO model of G. Egbert) calculated as:

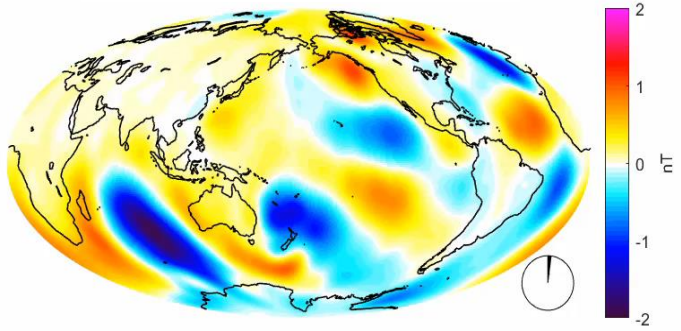
$$\vec{J}^{ext}(\vec{r}, \omega_{M2}) = \sigma_s(\vec{r}) \left[\vec{u}_{M2}(\vec{r}, \omega_{M2}) \times \vec{B}^{\text{main}}(\vec{r}) \right]$$



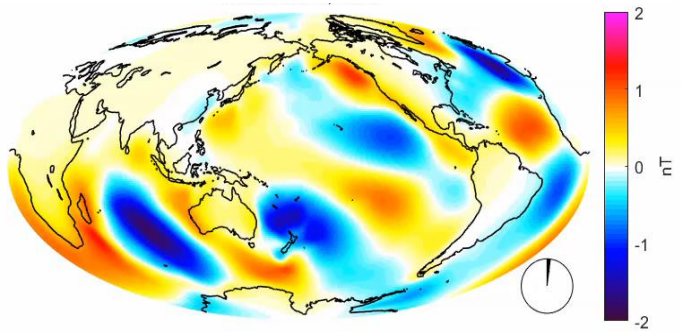
Sounding upper mantle below the oceans with tides

- Principal lunar semidiurnal M_2 (Period = 12.42 hours)

Observed B_r



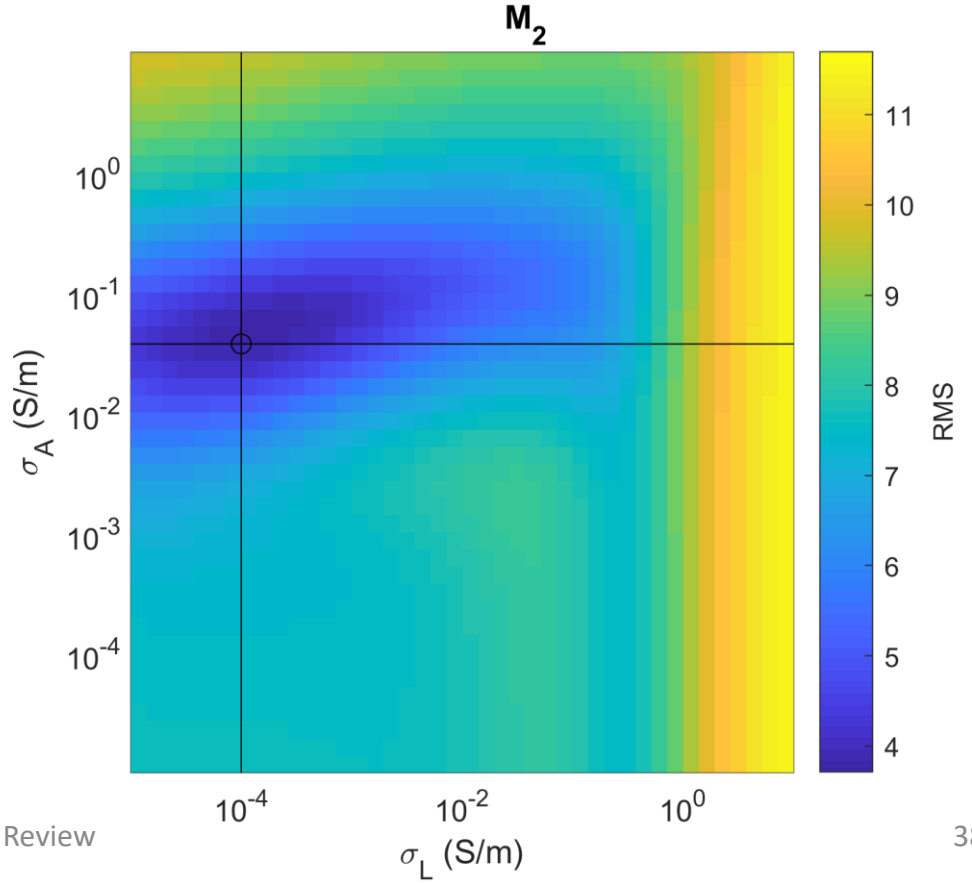
Simulated B_r for lowest RMS model



Grayver and Olsen, GRL, 2019

Grayver and Olsen 2019

- Sensitivity to the conductivity of lithosphere (σ_L) and asthenosphere (σ_A) (LAB thickness is fixed to 70 km)



Use of tidal signals for conductivity imaging

Studies on mantle conductivity with tidal signals:

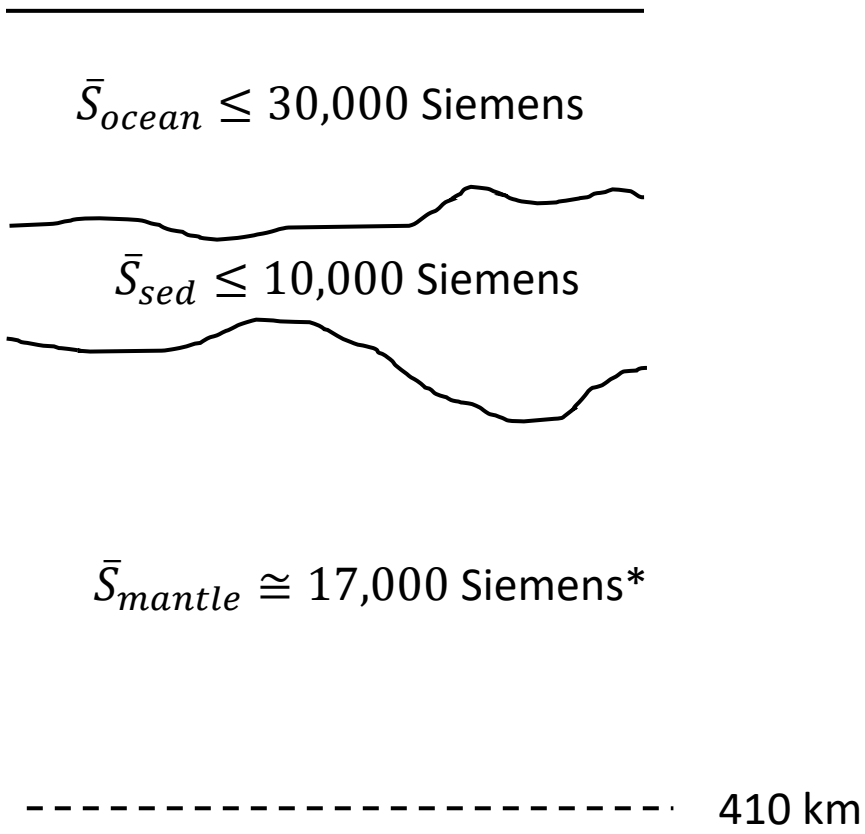
- Schnepf et al. 2015: sensitivity study to the upper mantle conductivity.
- Grayver et al. 2016: global ocean mantle conductivity profile from satellite M2 magnetic signals
- Grayver et al. 2017: Joint inversion of tidal and magnetospheric sources.
- Zhang et al. 2019: constraints on pacific LAB from observed seafloor tidal signals.
- Martinec et al. 2021: 3-D modelling study with real-data validation.
- Sachl et al. 2022: 3-D inversion of tidal magnetic signals (synthetic study).

Mapping global tidal signals:

- Sabaka et al. 2015: mapped satellite magnetic signals due to the M2 tide globally (CI approach).
- Gayver and Olsen 2019: Extraction of M2, O1 and N2 constituents (sequential approach).
- Sabaka et al. 2020: M2, O1, N2 mapped (CI approach)
- Saynisch-Wagner et al. 2021: mapped several constituents using Kalman-filter approach

Conductivity models of the ocean and sediments

- Average conductance of the ocean and marine sediments is equivalent to that of the entire upper mantle.
- Complex non-linear effect due to ocean and marine sediments in a wide range of periods.



Conductivity models of the ocean and sediments

From Grayver 2021, G3

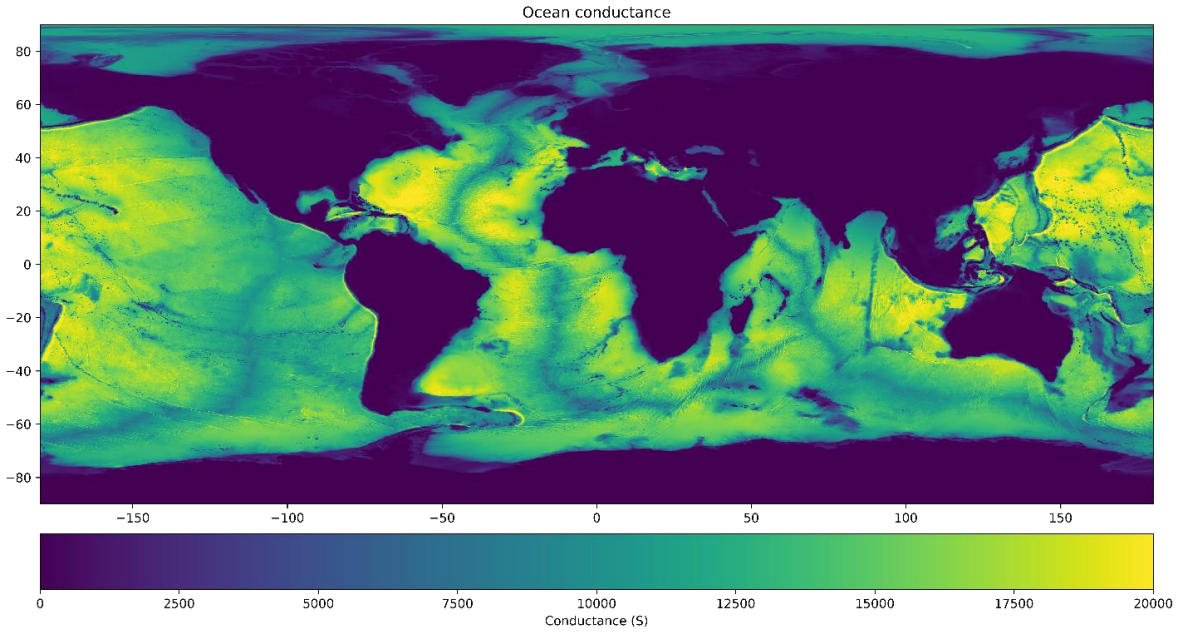
Table 1
Open Data Sets of Electrical Conductivity of the Ocean and Marine Sediments

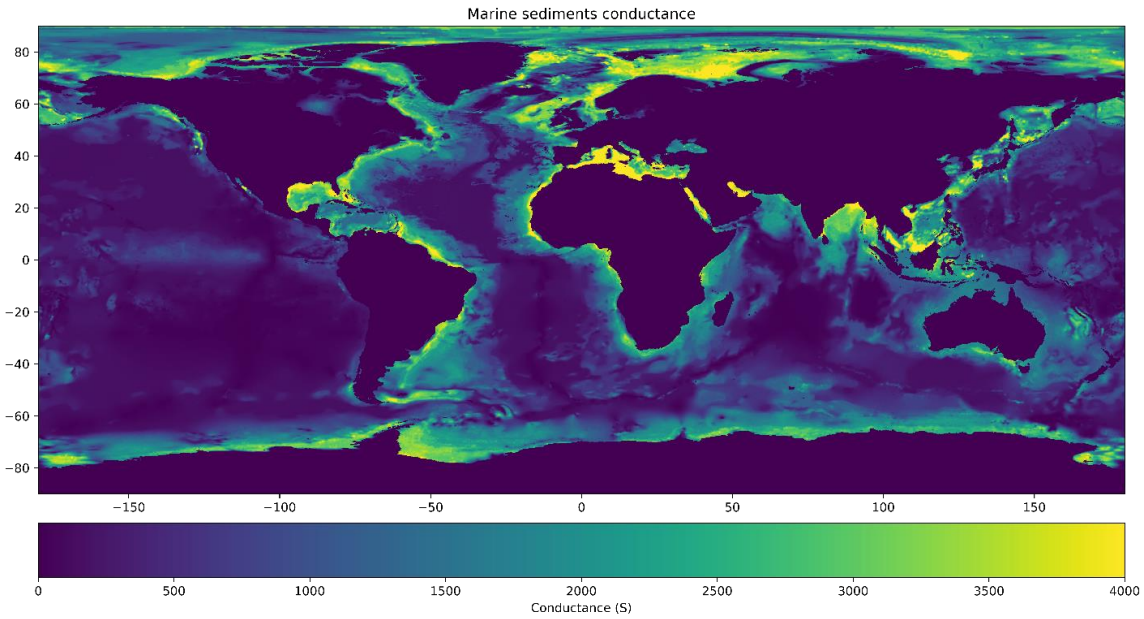
Source	Lateral resolution	Ocean conductivity	Sediment lateral resolution	Sediment conductivity
This study	0.1°–0.25°	3-D[a]	5″[b]	3-D
Reagan et al. (2019)	0.25°	3-D[c]	N/A	N/A
Tyler et al. (2017)	1°	3-D[d]	N/A	N/A
Grayver et al. (2016)	1°	2-D[e]	N/A	N/A
Alekseev et al. (2015)	0.25°	Uniform σ = 3.0 S/m	1°[f]	0.5 S/m (water depth ≤ 500 m)
				0.7 S/m (water depth > 500 m)
Everett et al. (2003)	1°	Uniform σ = 3.2 S/m	1°[f]	0.8 S/m ≤ 7,000 m.b.s.l.
				0.02 S/m > 7,000 m.b.s.l.[g]

Note. "N/A" stands for not available.

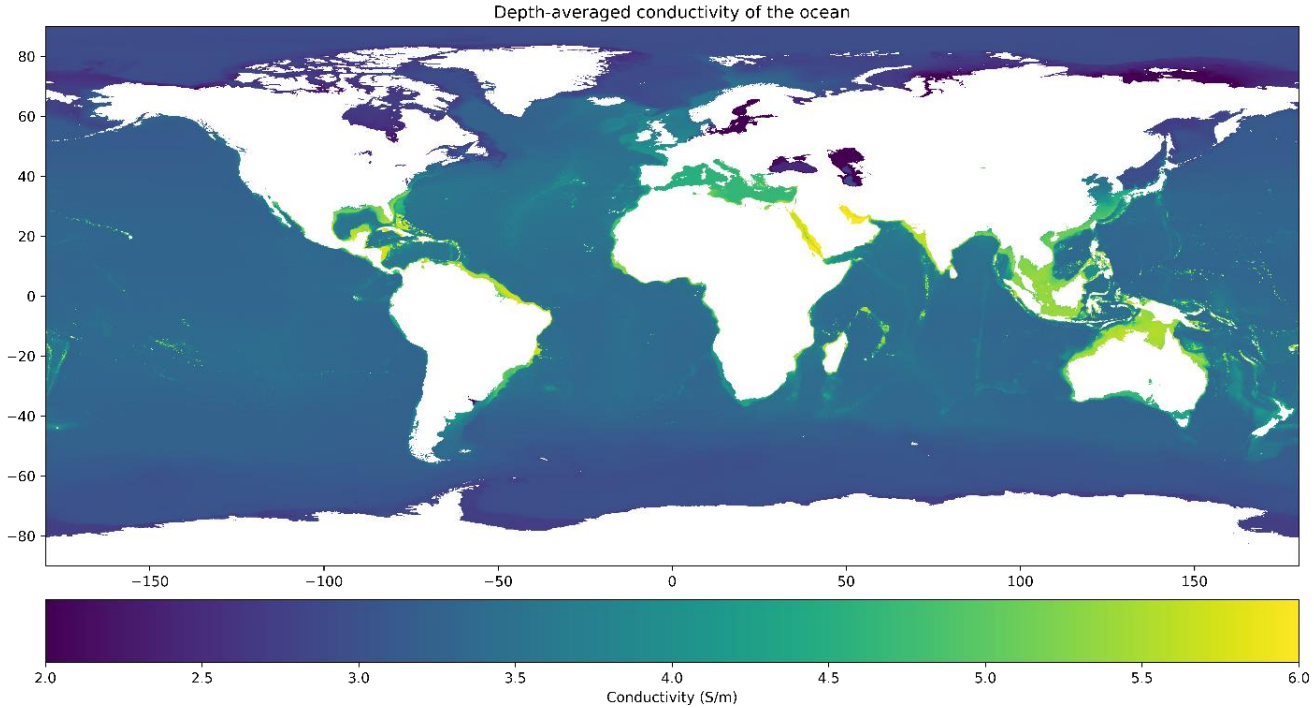
[a]See Table 2 for more information on data sources. [b]GlodSed 5-arc-minute grid by Straume et al. (2019). [c]World Ocean Database 2018 (Boyer et al., 2013). [d]World Ocean Database 2013 (Boyer et al., 2013). [e]Depth-averaged conductivity based on World Ocean Atlas 2013 (Locarnini et al., 2013; Zweng et al., 2013). [f]Laske (1997). [g]"m.b.s.l." stands for meters below sea level.

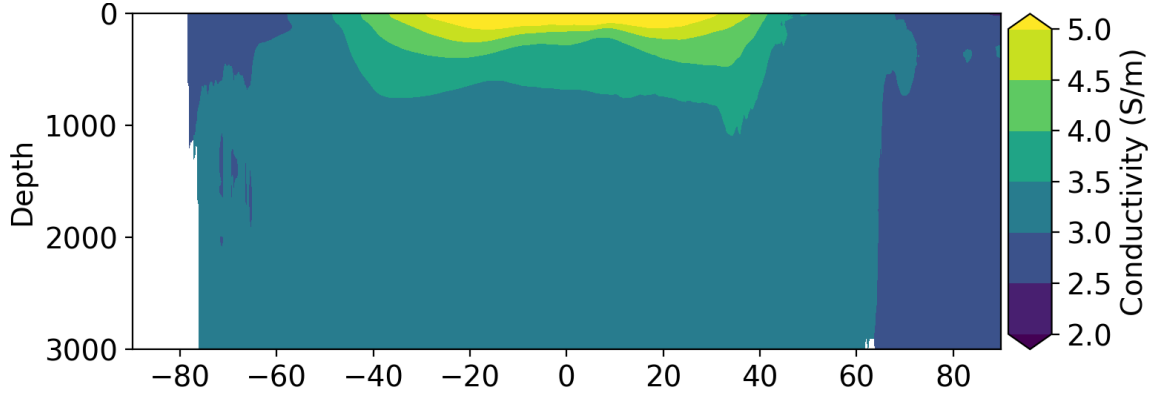
Conductivity models of the ocean and sediments





Conductivity models of the ocean and sediments





Handling complex (unknown) sources

Magnetic field representation and GDS responses

Above the ground and in the source-free region,

$$\nabla \times \vec{B} = 0.$$

Therefore, $\vec{B}$ is a potential field and can be written as

$$\vec{B} = -\nabla V. \tag{15}$$

By virtue of Gauss' law of magnetism, $\nabla \cdot \vec{B} = 0$. Thus, a scalar potential V satisfies the Laplace's equation,

$$\nabla^2 V = 0. \tag{16}$$

Magnetic field representation and GDS responses

allow us to write the magnetic field above the Earth as

$$\vec{B}(\vec{r},\omega) = \vec{B}(\vec{r},\omega)^{\text{ext}} + \vec{B}(\vec{r},\omega;\ \sigma)^{\text{int}}$$

or in the component form

$$\begin{aligned}
B_r &= -\sum_{n,m} n\varepsilon_n^m(\omega)\left(\frac{r}{a}\right)^{n-1} S_n^m(\theta,\phi) \\
&\quad + \sum_{k,l}(k+1)\iota_k^l(\omega;\ \sigma)\left(\frac{a}{r}\right)^{k+2} S_k^l(\theta,\phi), \\
\vec{B}_\tau &= -\sum_{n,m} \varepsilon_n^m(\omega)\left(\frac{r}{a}\right)^{n-1} \nabla_\perp S_n^m(\theta,\phi) \\
&\quad - \sum_{k,l} \iota_k^l(\omega;\ \sigma)\left(\frac{a}{r}\right)^{k+2} \nabla_\perp S_k^l(\theta,\phi),
\end{aligned}$$

Where:

$$\sum_{n,m} = \sum_{n=1}^{\infty}\sum_{m=-n}^{n}$$

$$S_n^m(\theta,\phi) = P_n^{|m|}(\cos\theta)\exp(\mathrm{i}m\phi)$$

Magnetic field representation and GDS responses

Magnetic field within a conductive body (slightly below the surface, assuming 1-D radial conductivity):

$$B_r(\vec{r}_a, \omega; \sigma) = \sum_{n,m} (2n+1) n \epsilon_n^m(\omega) \frac{Z_n}{i\omega\mu_0 a - nZ_n} S_n^m(\theta, \phi), \qquad (1)$$

$$\vec{B}_\tau(\vec{r}_a, \omega; \sigma) = -\sum_{n,m} \frac{2n+1}{n+1} \epsilon_n^m(\omega) \frac{i\omega\mu_0 a}{i\omega\mu_0 a - nZ_n} \nabla_\perp S_n^m(\theta, \phi). \qquad (2)$$

Here, $Z_n \equiv Z_n(r, \omega; \sigma)$ is the spectral impedance of a spherical conductor (e.g. Srivastava 1966).

Assuming that the external inducing field is described by a ***single*** spherical harmonic S_n^m and noting that $Z_n = -i\omega\mu_0 C_n$, the local C_n response becomes:

$$C_n = \frac{a}{n(n+1)} \frac{\partial_\theta S_n^m}{S_n^m} \frac{B_r}{B_\theta}.$$

If the geometry of the inducing field is described by the first zonal harmonic $S_1^0 = P_1^0$, we get

$$C_1 = -\frac{a}{2} \tan\theta \frac{B_r}{B_\theta},$$

← Z/H method (Banks 1969), GDS response

What is the problem with Z/H method?

If the geometry of the inducing field is described by the ***single*** first zonal harmonic $S_1^0 = P_1^0$, we get

$$C_1 = -\frac{a}{2}\tan\theta\frac{B_r}{B_\theta},$$

← Z/H method (Banks 1969), GDS response

- Source is always more complex than P10, even at mid geomagnetic latitudes.
- Assuming P10 still ok for global average 1-D models → source effects are averaged.
- Not ok for global/regional 3-D studies because:
  - Inverse problem is highly non-unique due to sparse data
  - Source effects are much stronger than 3-D response from deep mantle anomalies
  - Source effects propagate to the conductivity model in an uncontrolled way
  - Impossible to discriminate between source effects and 3-D conductivity

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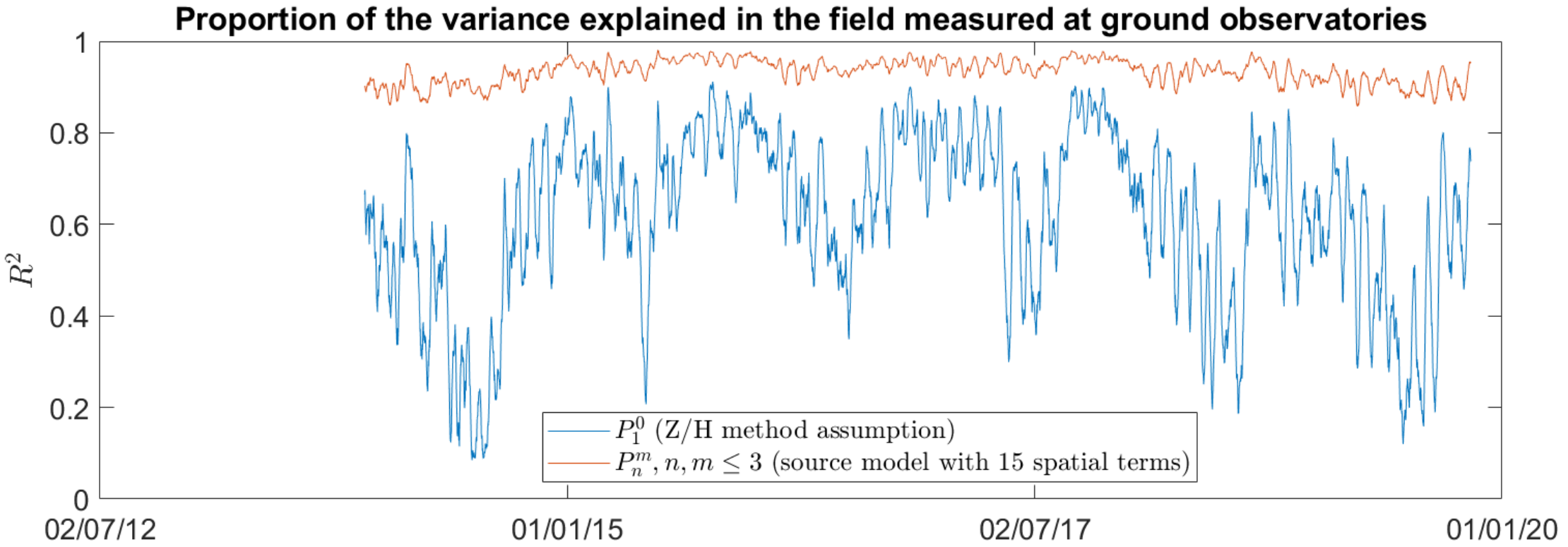

*Only mid geomagnetic latitude observatories (5°-56°) are used.

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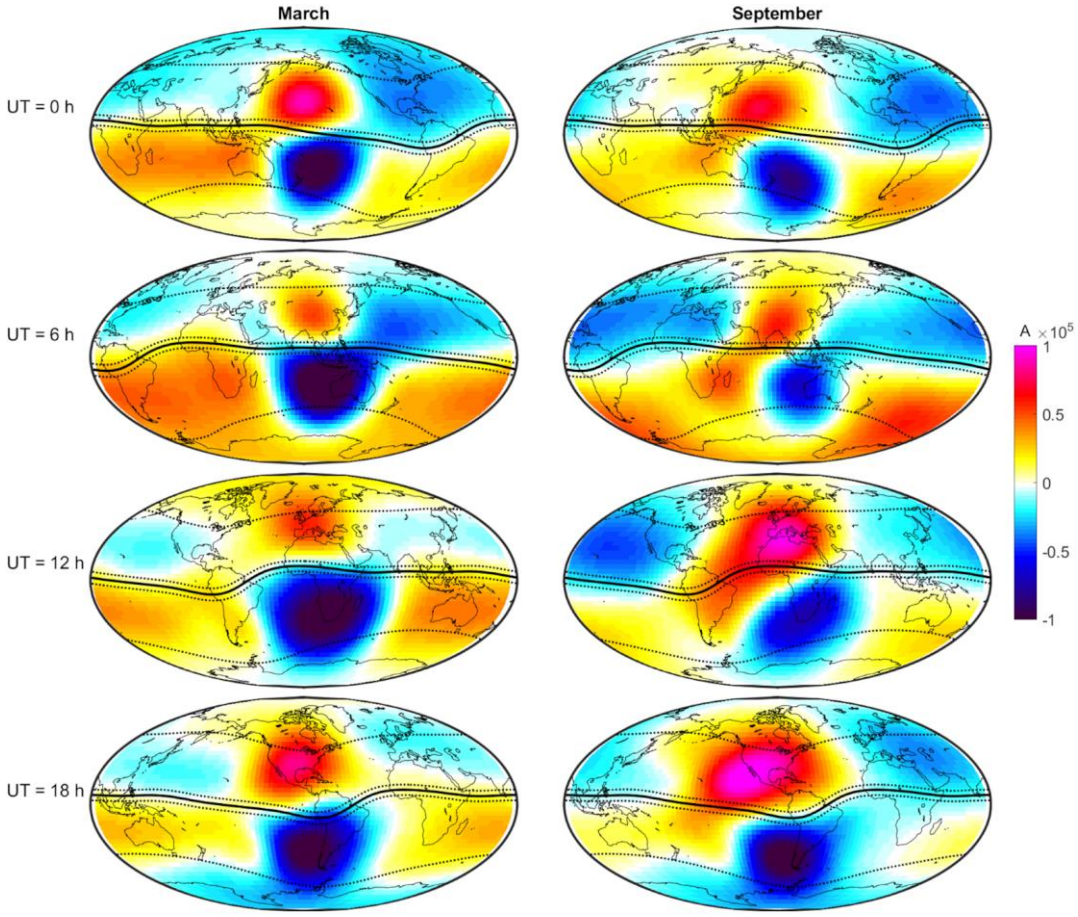
- **Solution?** Acknowledge the source is complicated and invest into methods that can handle complex and more realistic sources.

Handling complex sources

- Spatial parameterization:
  - General basis using spherical harmonics (Olsen 1999, Schmucker 1999, Püthe and Kuvshinov 2014, Guzavina et al. 2019)
  - Physics-based basis (Egbert et al. 2021; Zenhausern et al. 2021)
  - Current loops representation (Martinec et al. 2022)

Sq current system for a magnetically quiet day



Guzavina et al. 2019

Handling complex sources

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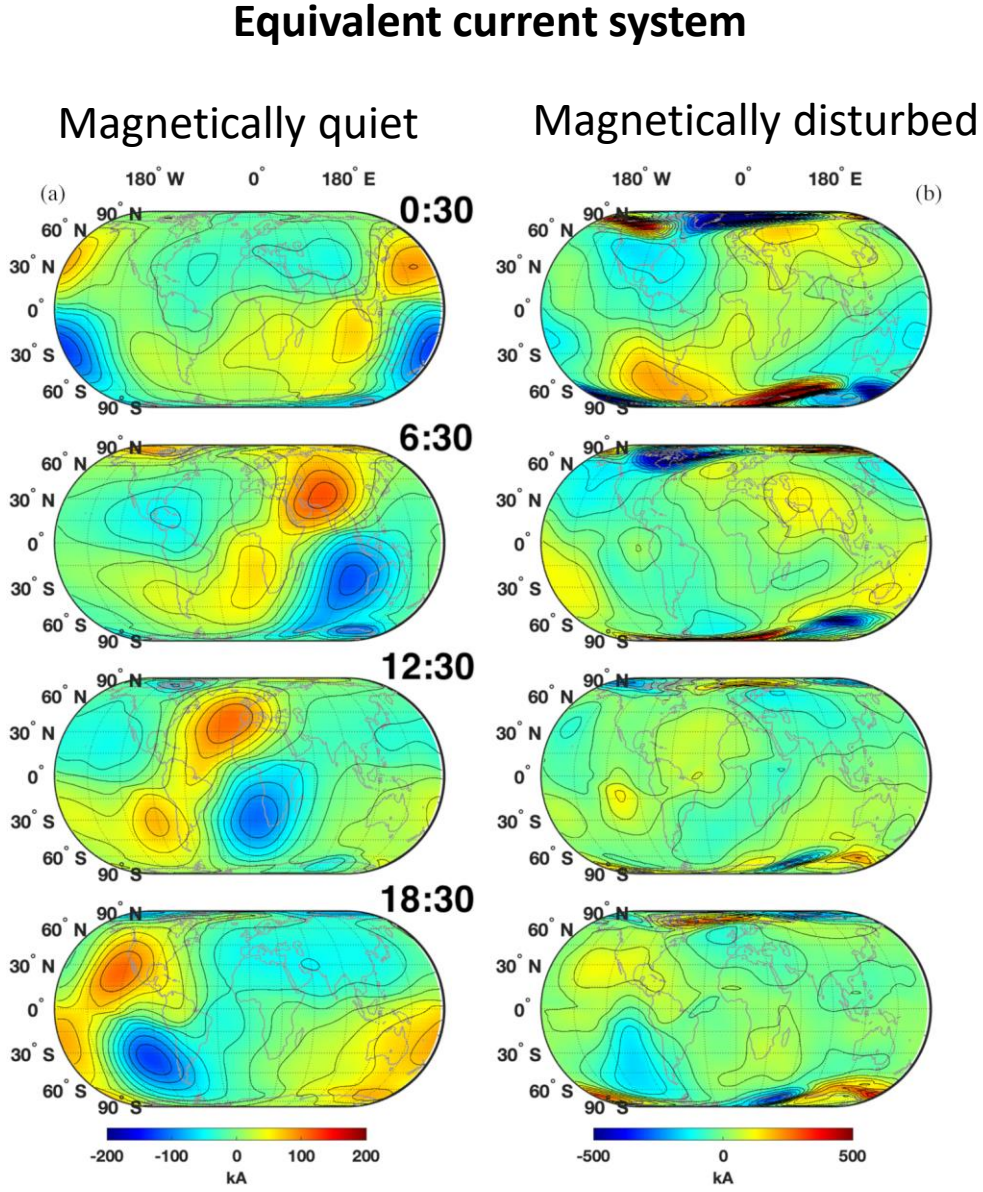


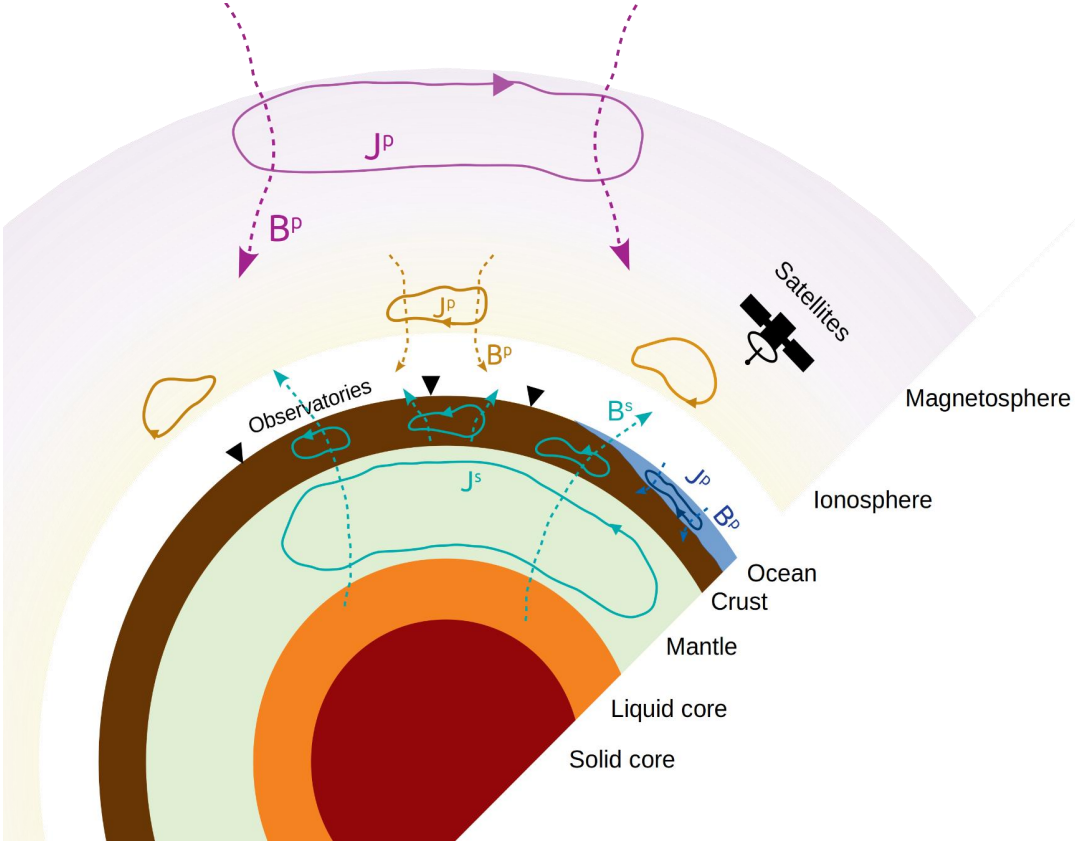
Egbert et al. 2021

Handling complex sources

Separable non-linear least squares (SNLS):

$$(1) \quad \min_{\sigma, j^p} \|d - F(\sigma) j^p\|_2^2 + R(\sigma, j^p)$$

How to solve a SNLS problem?



Solving SNLS problem: Alternating approach

Separable non-linear least squares (SNLS):

(1) $\min_{\sigma, j^p} \|d - F(\sigma) j^p\|_2^2 + R(\sigma, j^p)$

How to solve a SNLS problem?

1) Assume a fixed σ_0, then eq. (1) becomes a linear problem for j^p

2) Solve linear problem for source estimate $\tilde{j}^p$

3) Use source estimate $\tilde{j}^p$ to solve a non-linear problem for $\tilde{\sigma}$.

4) Go to step (1) and use new $\tilde{\sigma}$

Solving SNLS problem: Alternating approach

- Koch and Kuvshinov 2013: ionospheric Sq signals, regional 3-D inversion
- Püthe et al. 2015: generalization to arbitrary sources, 3-D

- Guzavina et al. 2019, Munch et al. 2020: inversion of ionospheric Sq + magnetospheric signals
- Zhang et al. 2022: Sq inversion, physics-based parameterization

- Grayver et al. 2021: formulation in time domain, incorporation of satellites

Solving SNLS problem: Variable Projection

$$\phi(t) = -\frac{d^2}{dt^2}\left(ce^{-\alpha t^2}\right) = 2c(\alpha - 2\alpha^2 t^2)e^{-\alpha t^2}$$

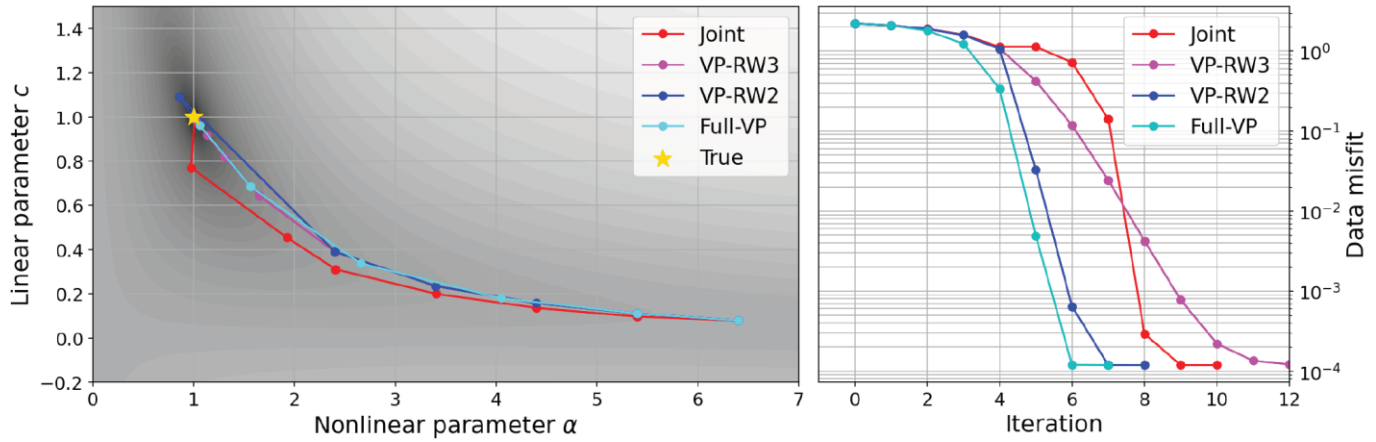
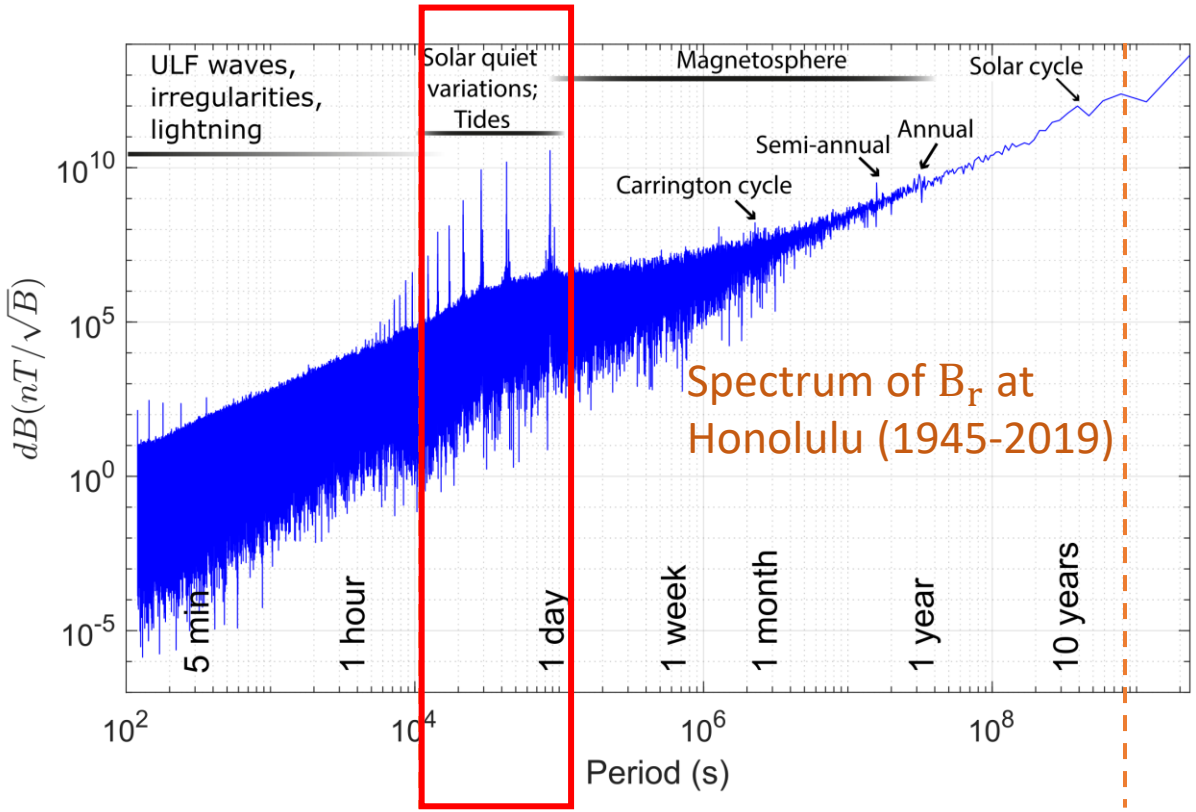


Figure B.1. Convergence of different inversion techniques on the wavelet fitting problem. Left: trajectories of inversion schemes in the parameter space for the wavelet fitting problem. The background color shows the data misfit in logarithmic scale. Right: data misfit as a function of iteration.

Variable Projection is the most efficient and consistent way to solve SNLS problems

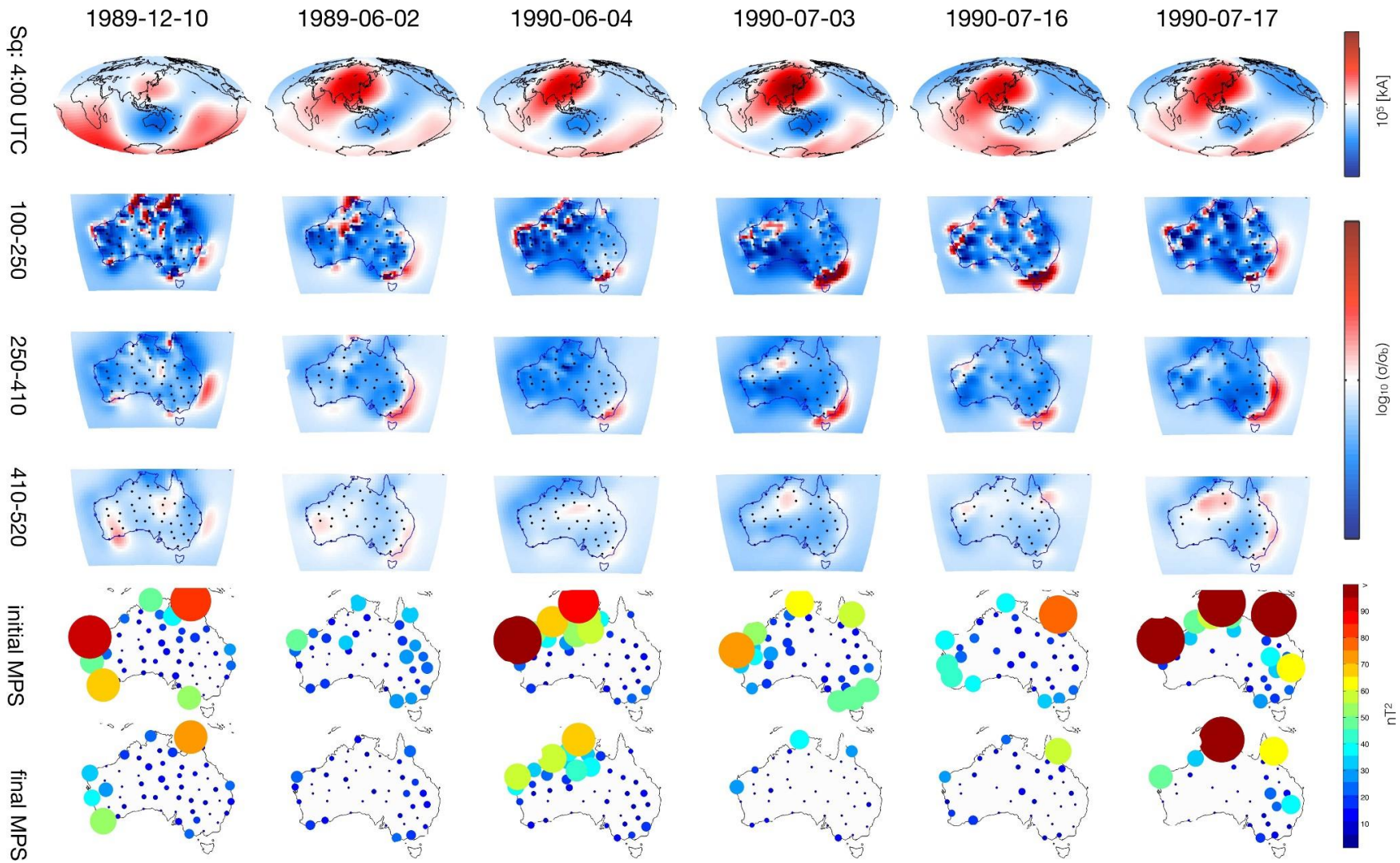
Min, J. and Grayver A., 2023, *"Simultaneous inversion for source field and mantle electrical conductivity using the Variable Projection approach"*, Earth, Planets and Space, ***accepted***

Ionospheric sources: case studies



Band:	"Plane wave"	"Daily"	"Magnetospheric"
Sounding depth (km):	< 350	200-500	> 400

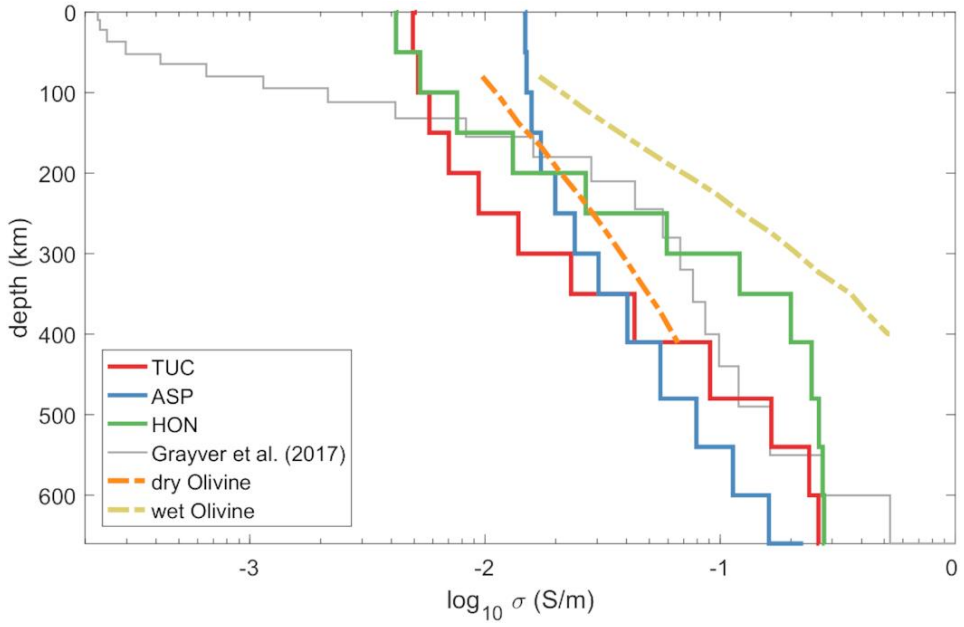
Inversion of daily variations



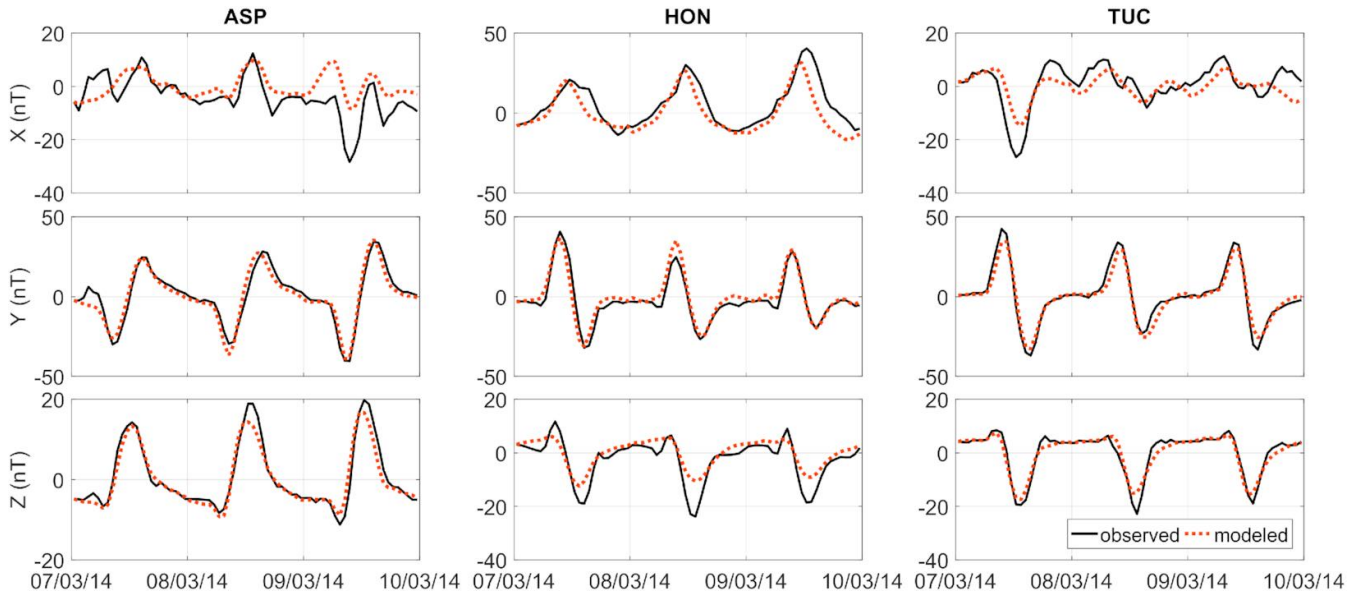
Koch and Kuvshinov 2015

Inversion of daily variations

Models at 3 locations

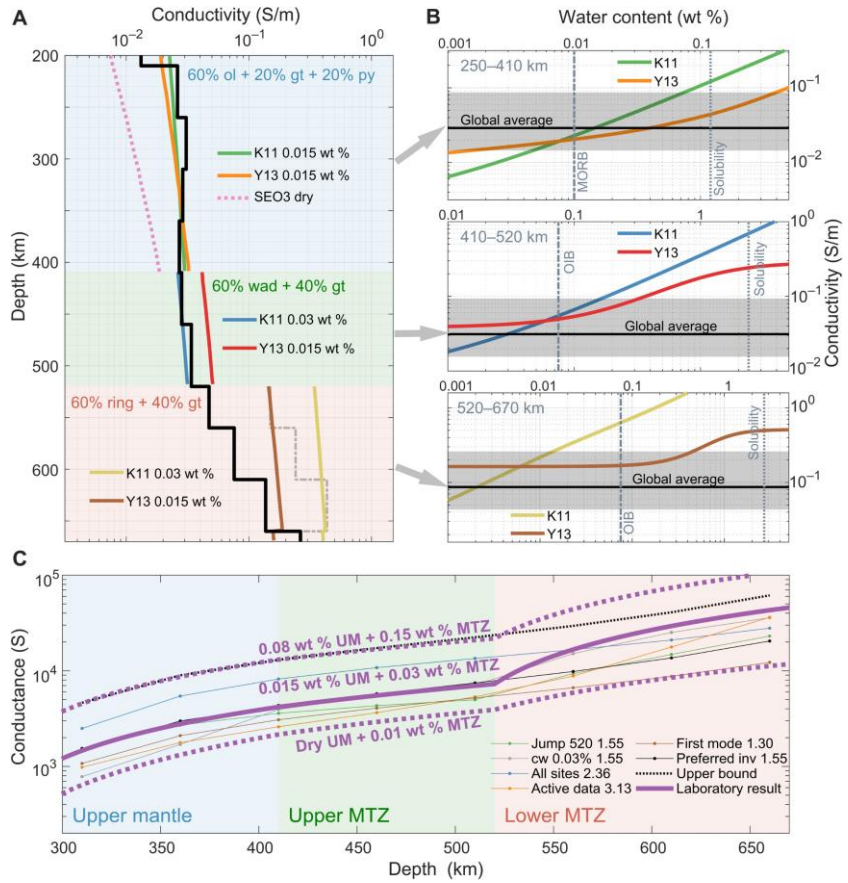


Data fit



Guzavina et al. 2019

Inversion of daily variations



Zhang et al. 2022, Egbert et al. 2021

Abstract, 25th EM Induction Workshop,Çeşmeı, Turkey, September 11-17, 2022

Deep geomagnetic sounding by Sq variations in Europe: A 3-D inversion based on the regional-to-local transfer functions

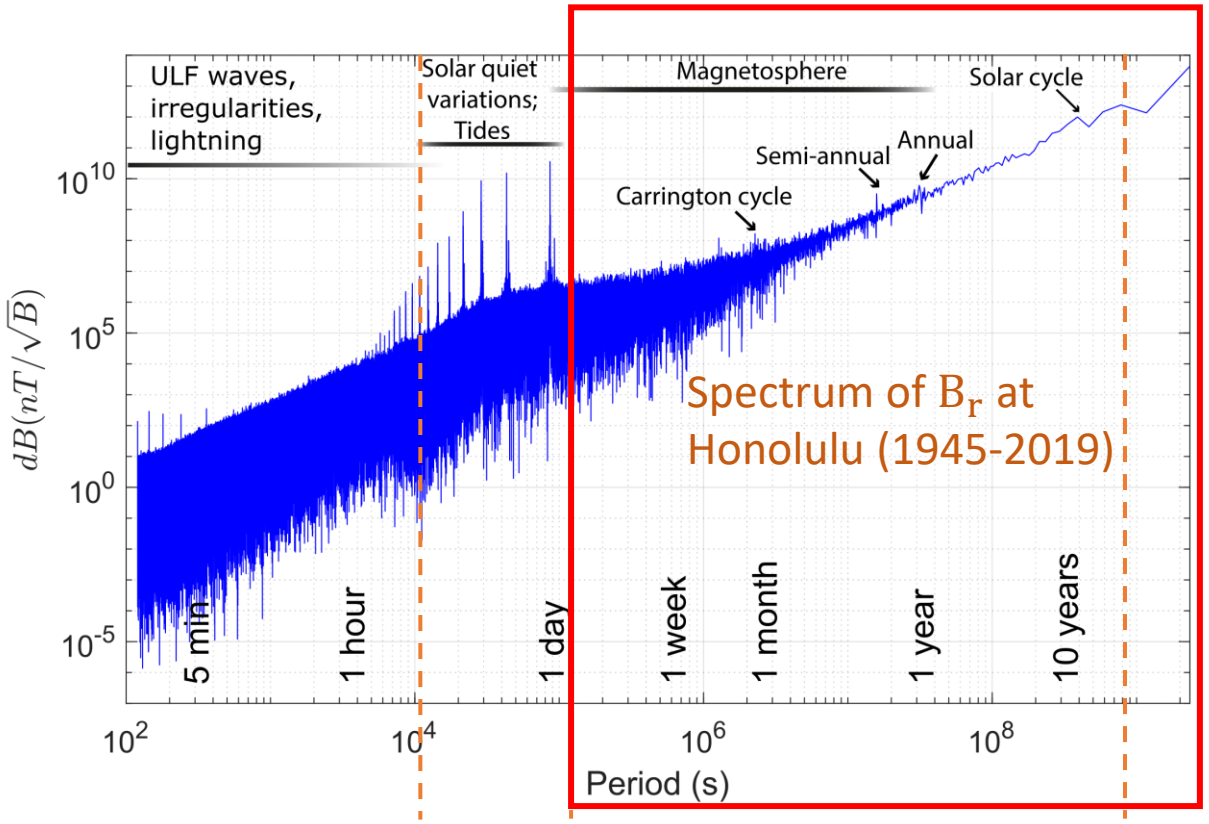
J. Velímský[1], L. Šachl[1] and O. Knopp[1]
[1]Dept. of Geophysics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic, jakub.velimsky@mff.cuni.cz

Abstract, 25th EM Induction Workshop, Çeşme, Turkey, September 11-17, 2022

Regionality of mantle conductivity inferred from geomagnetic daily variation analysis

Takao Koyama[1], Shigeru Fujita[2], Ikuko Fujii[3], Kiyoshi Baba[4] and Hisayoshi Shimizu[5]
[1]Earthquake Research Institute, The University of Tokyo, tkoyama@eri.u-tokyo.ac.jp
[2]The Institute of Statistical Mathematics, sfujita@ism.ac.jp
[3]Meteorological College, Japan Meteorological Agency, ifujii@mc-jma.go.jp
[4]Earthquake Research Institute, The University of Tokyo, kbaba@eri.u-tokyo.ac.jp
[5]Earthquake Research Institute, The University of Tokyo, shimizu@eri.u-tokyo.ac.jp

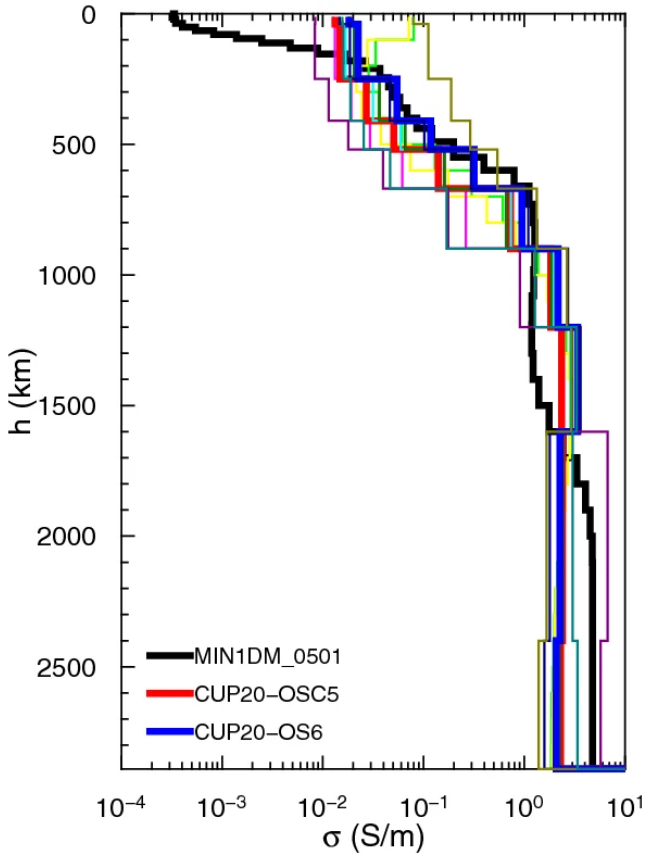
Magnetospheric sources



Band:	"Plane wave"	"Daily"	"Magnetospheric"
Sounding depth (km):	< 350	200-500	> 400

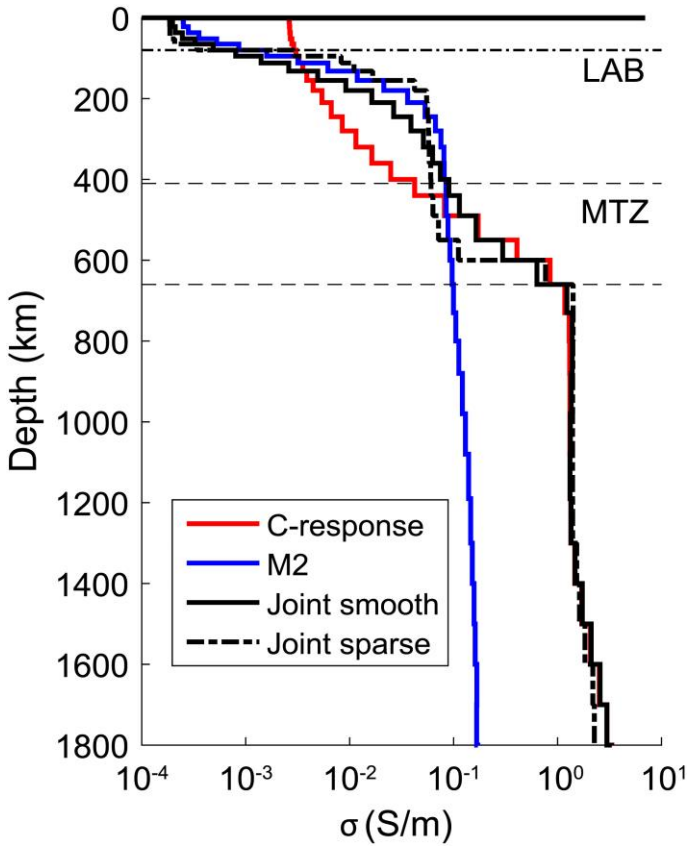
Global average conductivity profiles: examples

Obs+Swarm,
Ring current variations



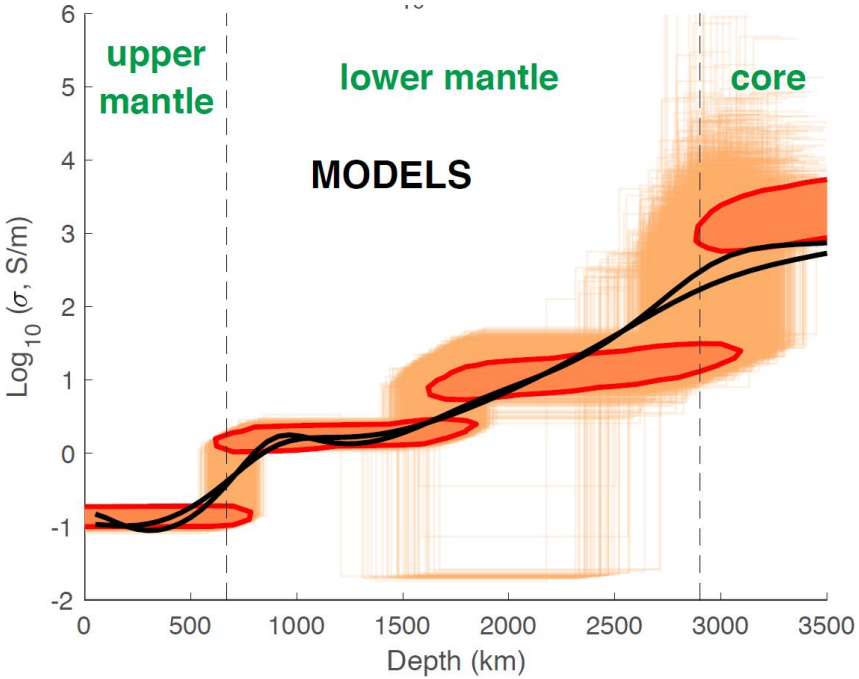
Velimsky et al. 2021

CHAMP+Swarm,
Ring current + Tides



Grayver et al. 2017

Observatories (> 100 years of data)
Ring current variations (T up to 11 years)

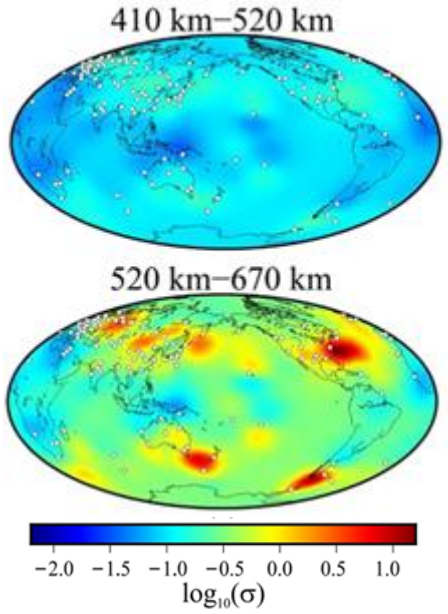


Constable et al., in prep

Present status of global 3-D models

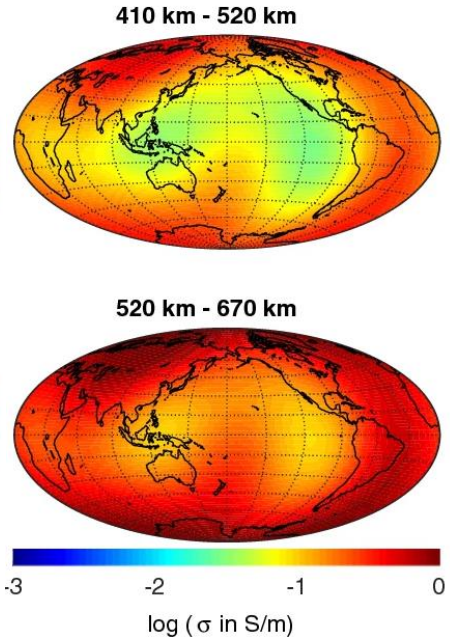
- Resolution is still very low
- Insufficient data coverage

Observatories
P10 source



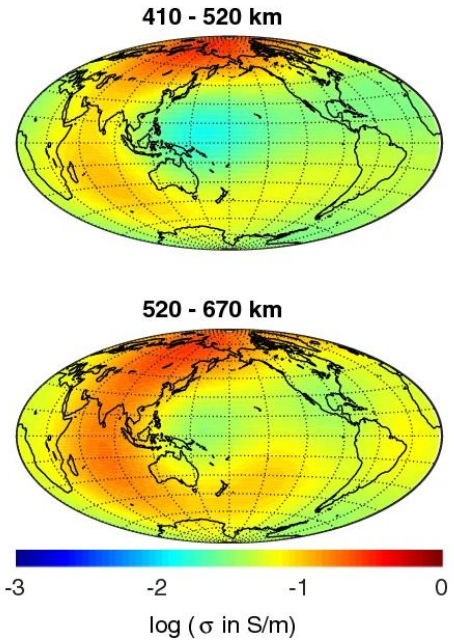
Li et al. 2021

Observatory+Swarm
More realistic source



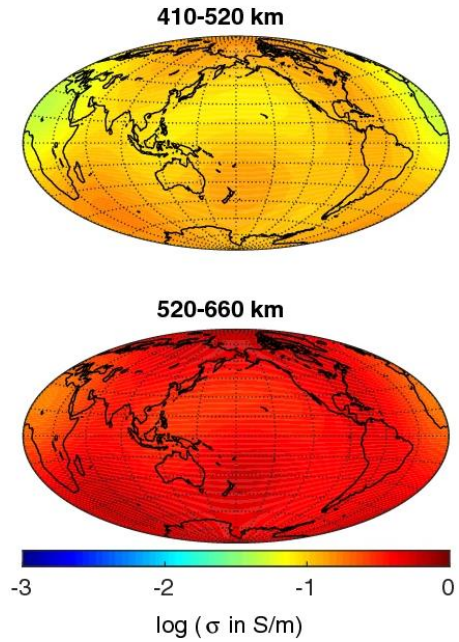
Velimsky et al. 2021

Observatories
P10 source + preprocessing



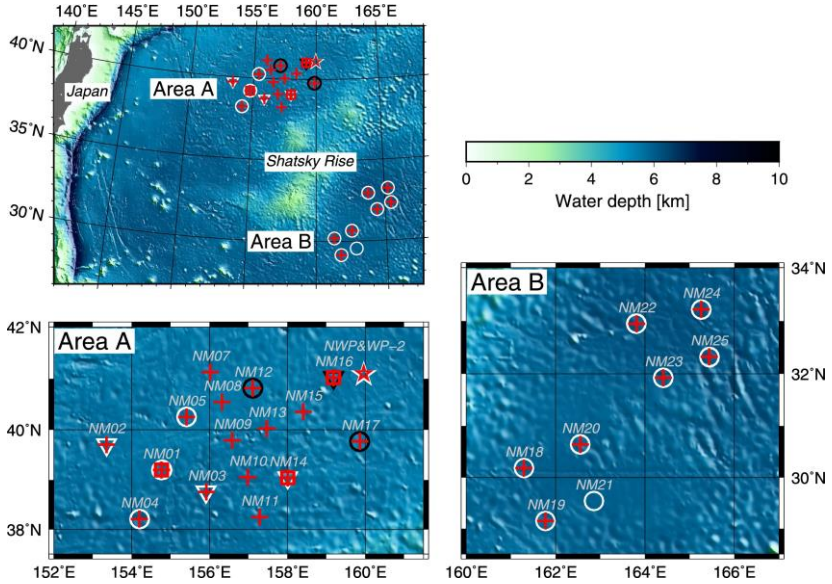
Kelbert et al. 2015

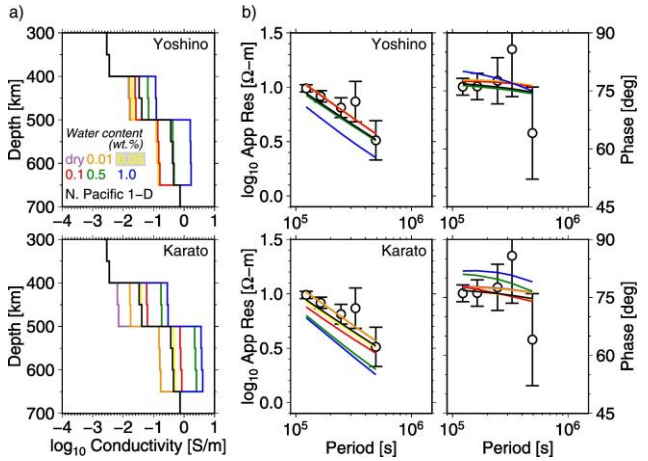
Observatory+Swarm
More realistic source



Kuvshinov et al. 2021

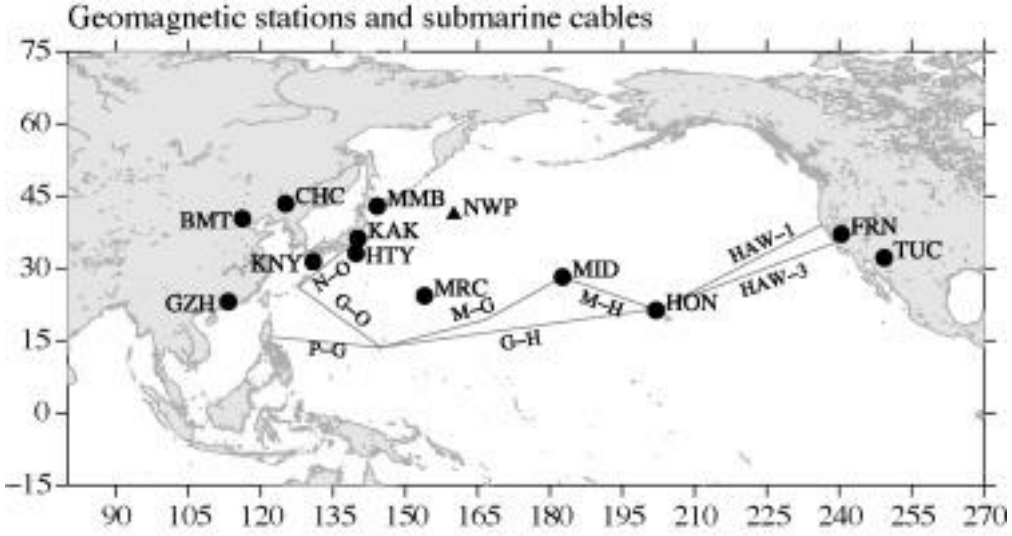
Semi-global studies

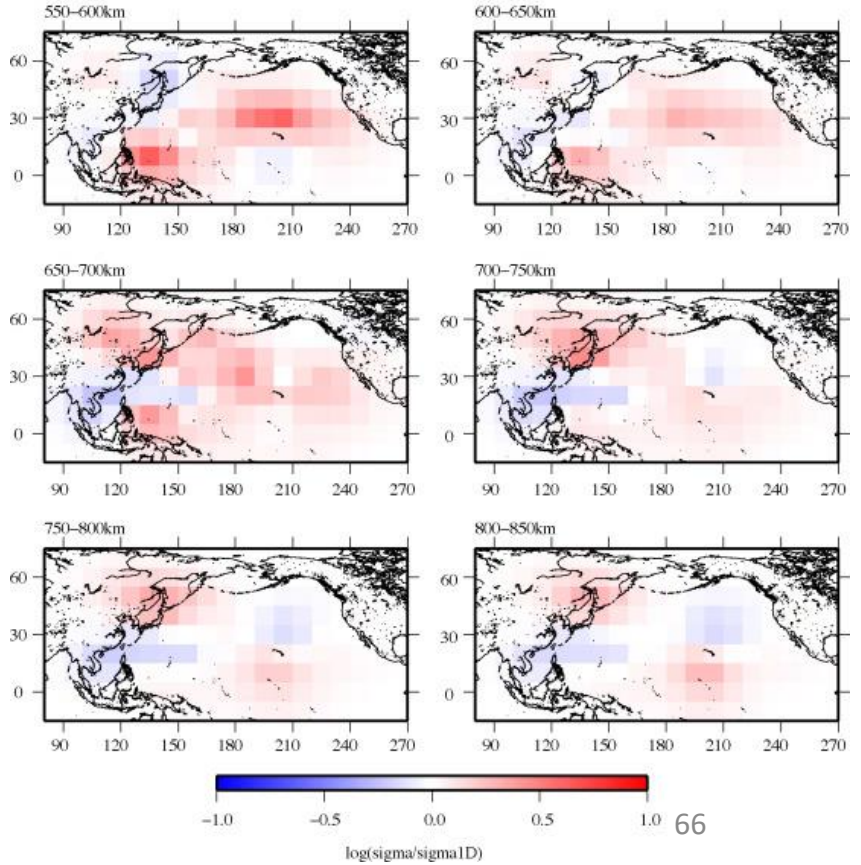




Matsuno et al. 2017

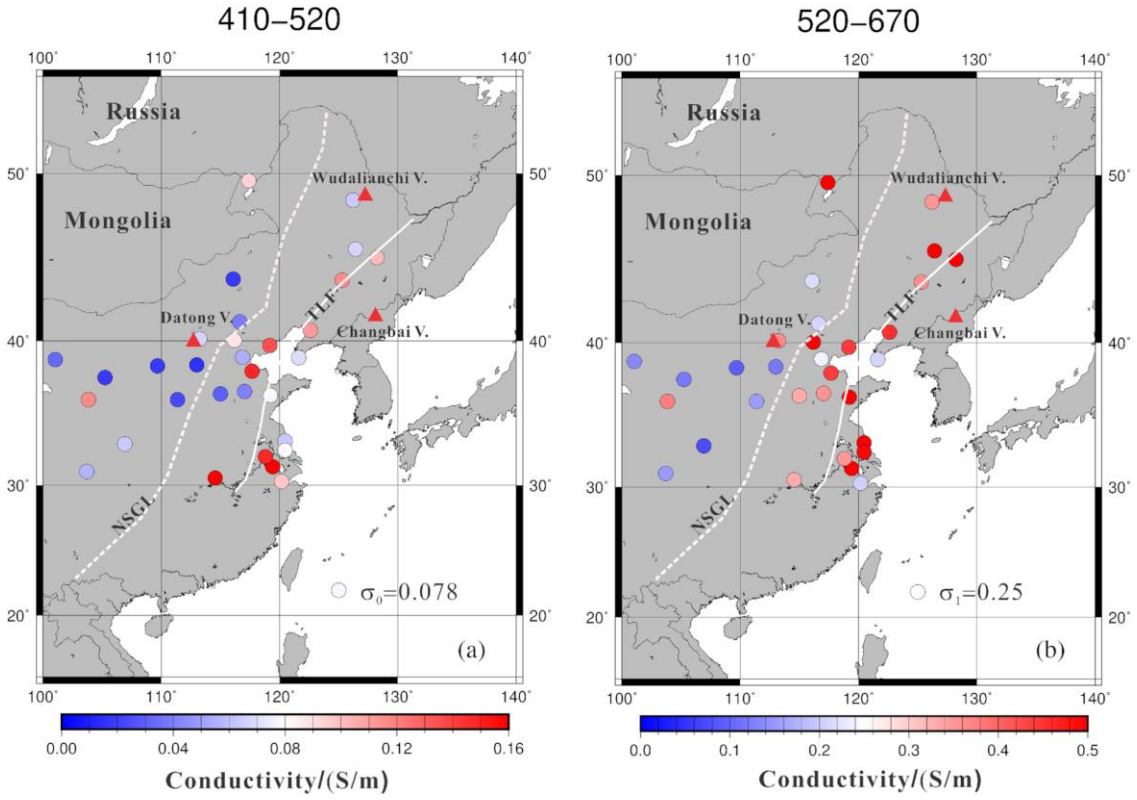
P10 source assumption





Shimizu et al. 2012

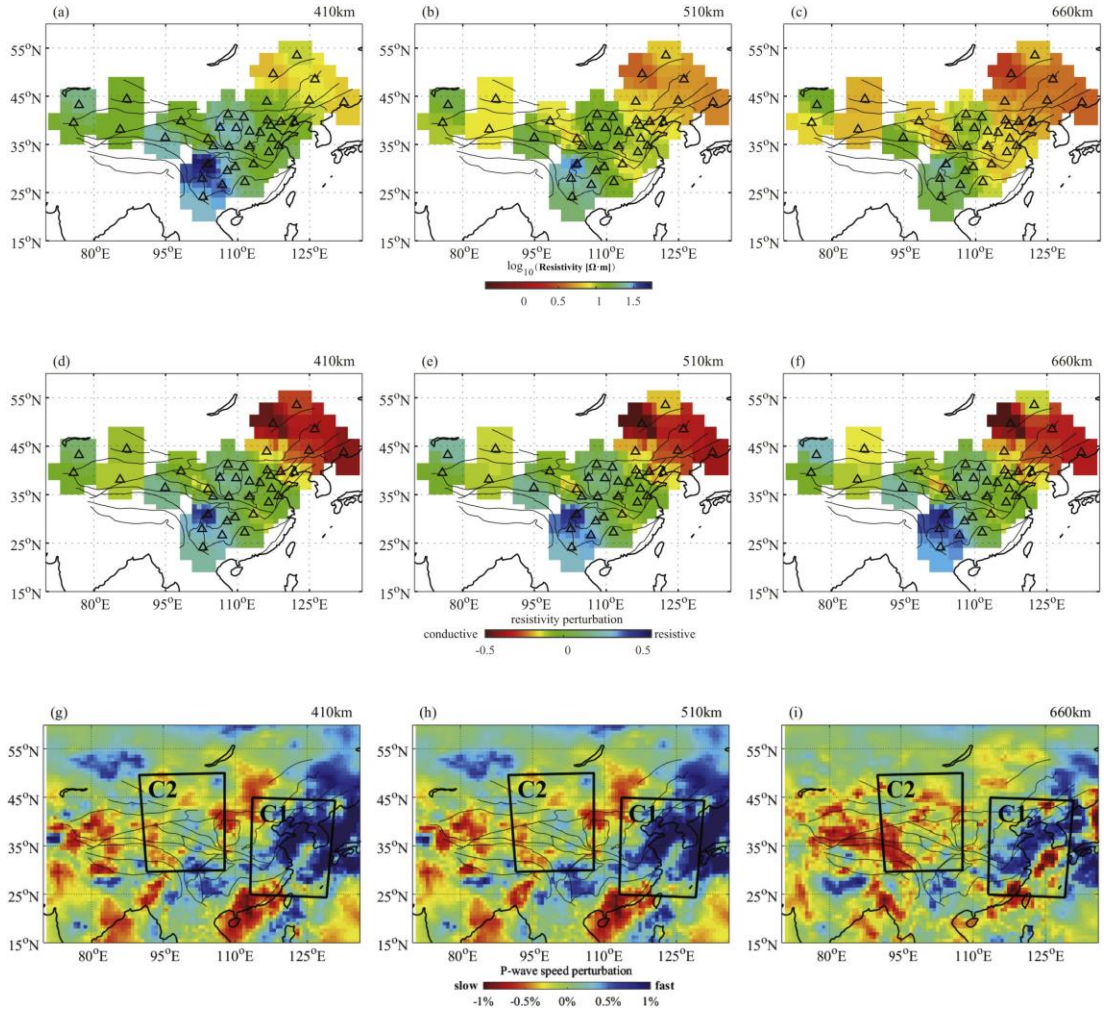
Semi-global studies



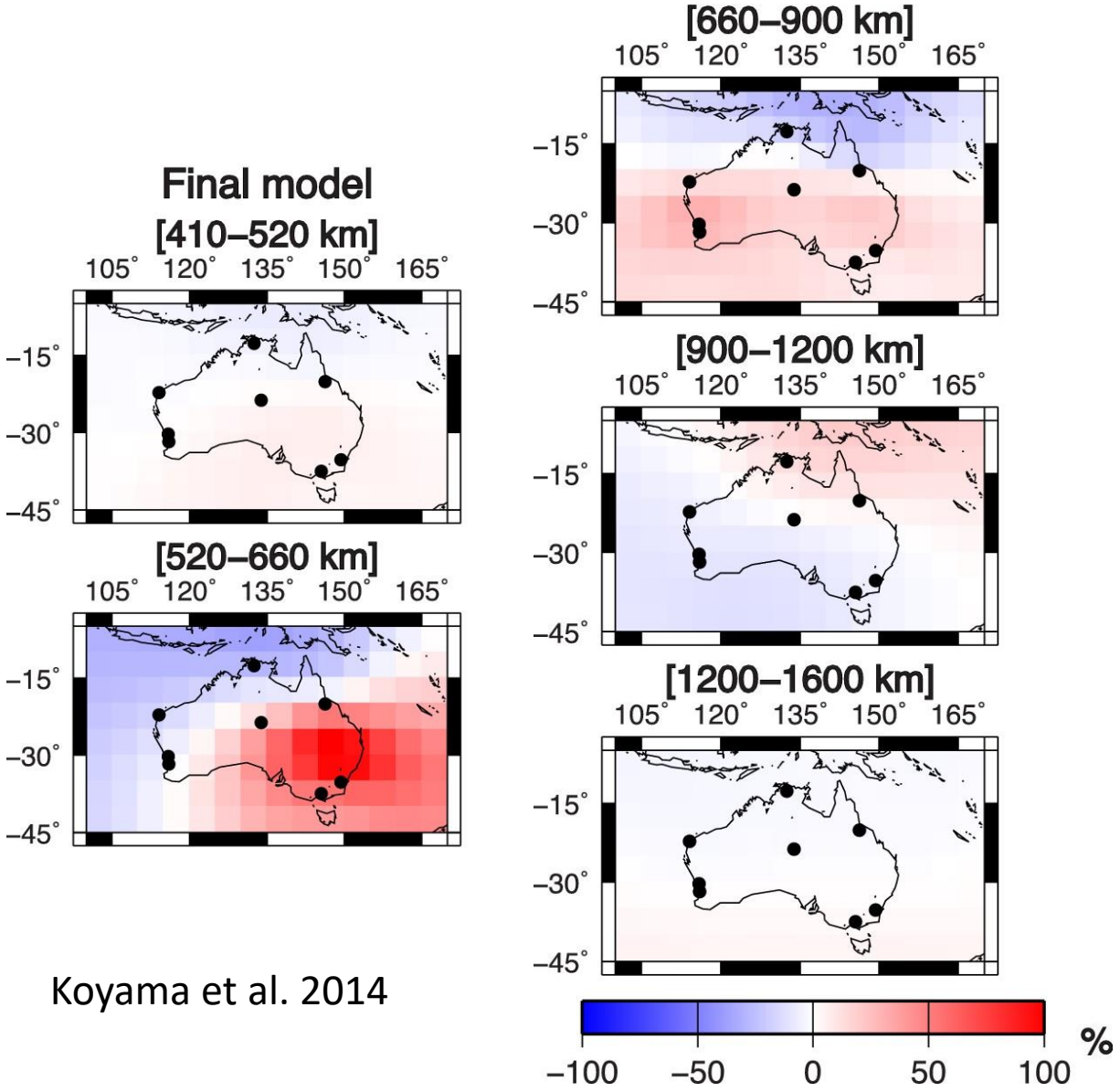
Zhang et al. 2020

P10 source assumption

Yuan et al. 2020



Semi-global studies

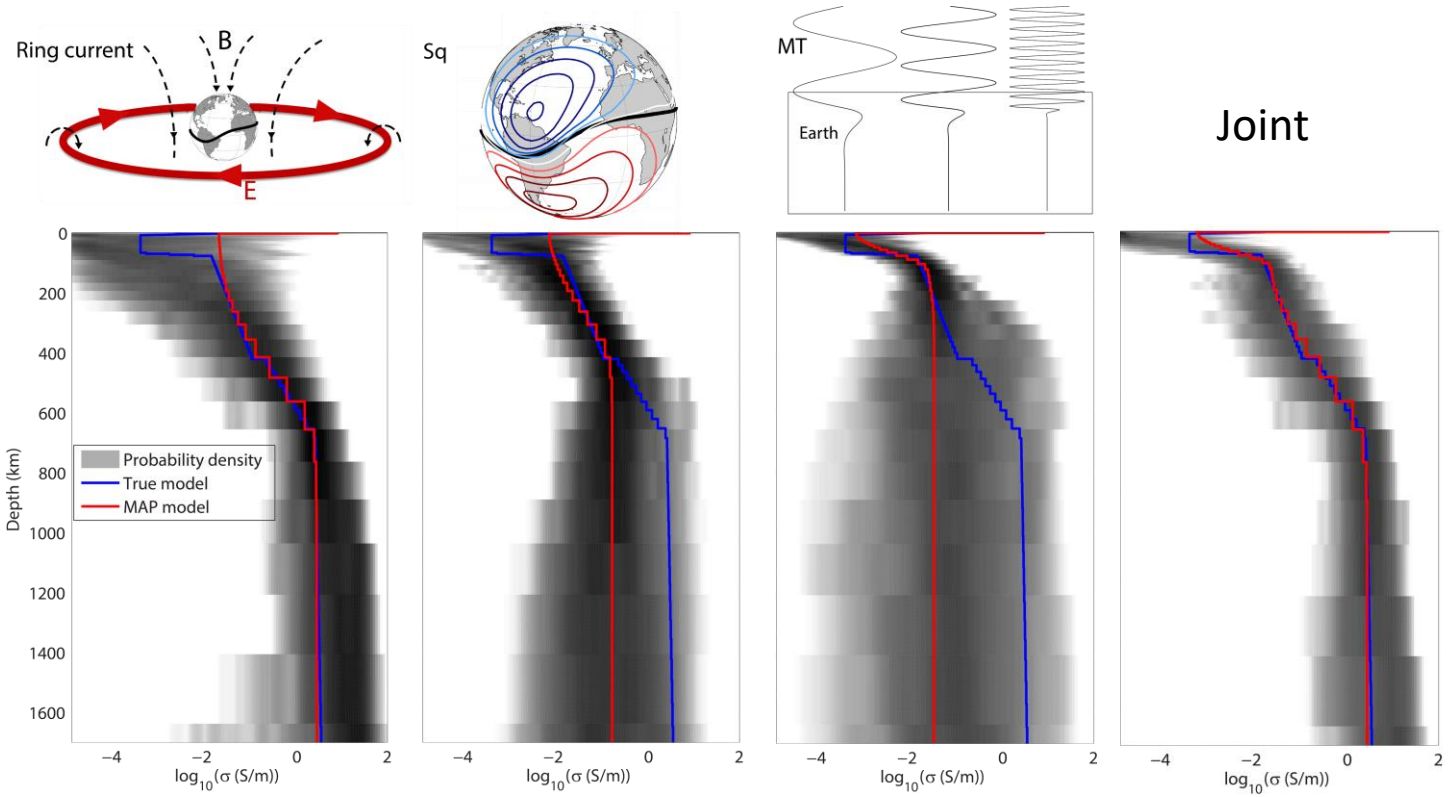


Koyama et al. 2014

P10 source assumption

Combining sources

$T > 1\ day$ $T = 4\ hours\ -\ 1\ day$ $T < 3\ hours$



Multi-source inversions:

- Matsuno et al. 2017: MT + RC
- Grayver et al. 2017: Tides + RC
- Zhang et al. 2019: Tides + MT
- Munch et al. 2020: Sq + RC
- Chen et al. 2022: MT + Sq + RC
- Rigaud et al. 2022 (poster): MT + Sq + RC

- All studies are 1-D (some with 3-D forward operator to model ocean/sediments)

Conclusions and outlook

Some highlights of the past decade

- Data:
  - Satellite constellations (Swarm + platform mags)
  - Regular large-scale ground arrays (US, AU, CN)
  - More often open data
- Modelling and inversion:
  - Modern parallel codes; multi-resolution grids; multi-source inversions
  - New 1D reference models, low-resolution global 3-D models.
- EM sources:
  - Oceanic tidal sources (we have data and tools)
  - New approaches for working with complex ionospheric/magnetospheric sources
  - Retirement of the Z/H method (*hard/impossible to discern source effects from conductivity variations in 3-D inversion*)

Some challenges for next decade(s)

- Data:
  - Integrating satellite and ground observations
  - Still lack of (open) data…
- Modelling and inversion:
  - 3-D inversion of multi-source data (MT + global TFs + tides + Sq)
  - Interpretation: what do our models mean and what do we learn from them?
- EM sources:
  - Need to better understand external sources (build bridges to Magnetosphere/Ionosphere physics communities)