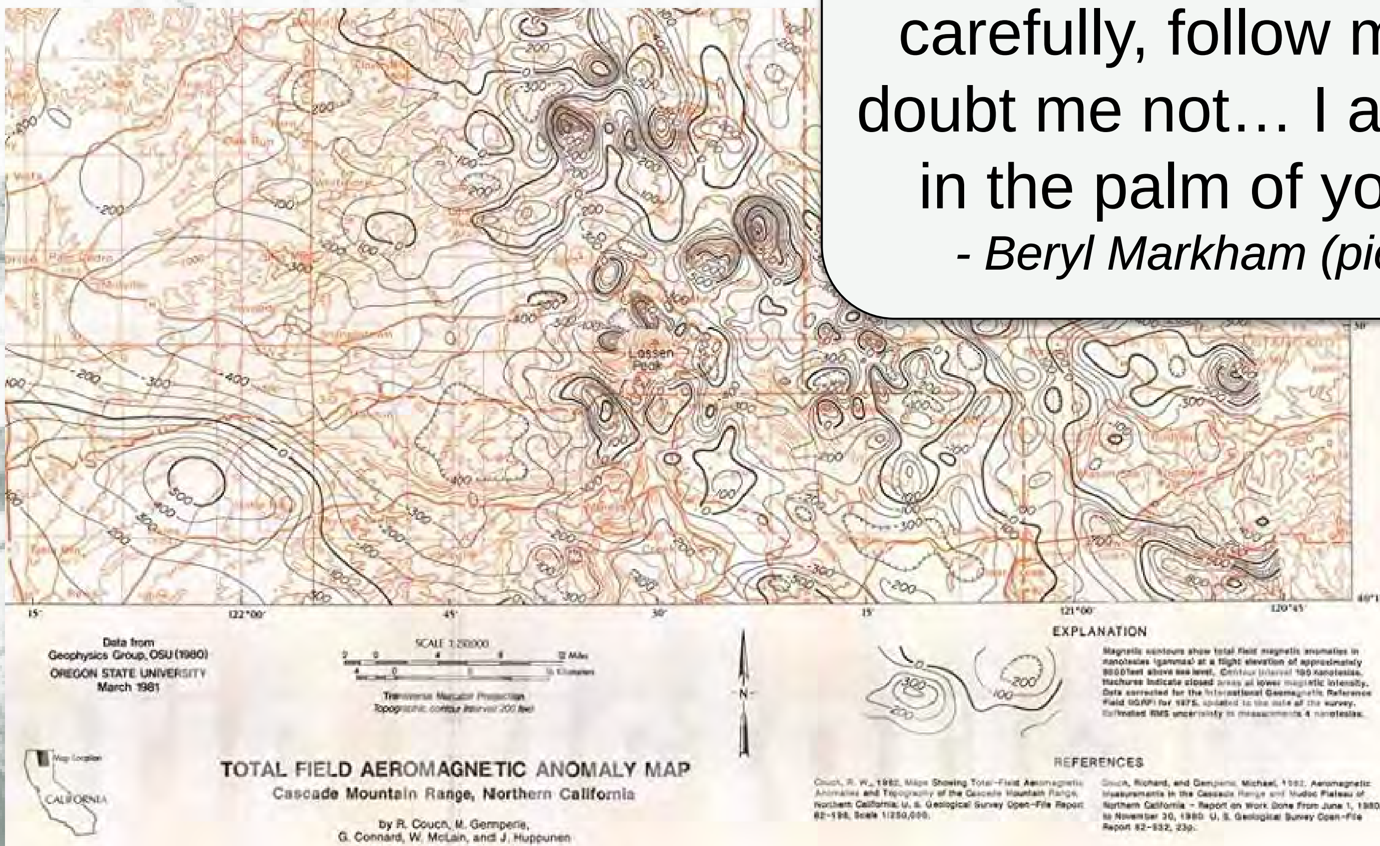
Magnetic Maps

IEEE/ION PLANS 2023
MagNav Workshop



"A map says to you. Read me carefully, follow me closely, doubt me not… I am the earth in the palm of your hand."

- Beryl Markham (pioneering aviator)

Rick Saltus richard.saltus@colorado.edu
CIRES/NOAA Geomagnetics Team
https://geomag.colorado.edu/

Cooperative Institute for Research in Environmental Sciences
UNIVERSITY OF COLORADO **BOULDER** and **NOAA**

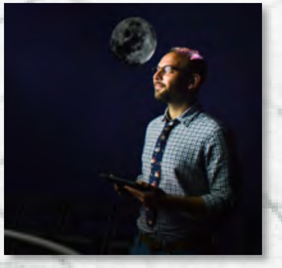
Introduction

CIRES/NOAA Geomagnetics Team

Patrick Alken
Research Scientist

Arnaud Chulliat
Research Scientist
Team Lead

Annette Balmes
Associate Scientist



Brian Meyer
NOAA Federal

Nir Boneh
Associate Scientist

Manoj Nair
Research Scientist

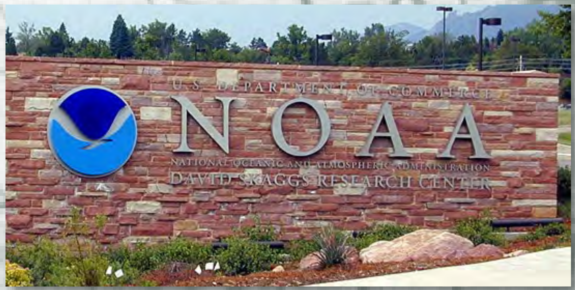
Sam Califf
Research Scientist

Rick Saltus
Research Scientist

CIRES

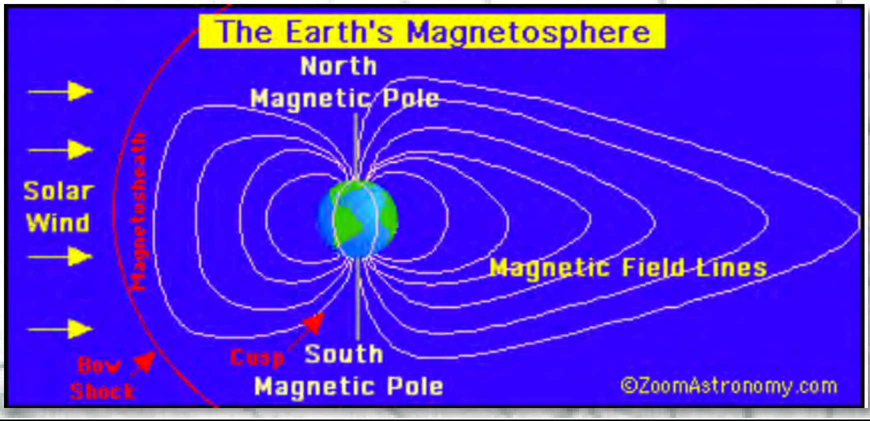
University of Colorado Boulder

NOAA

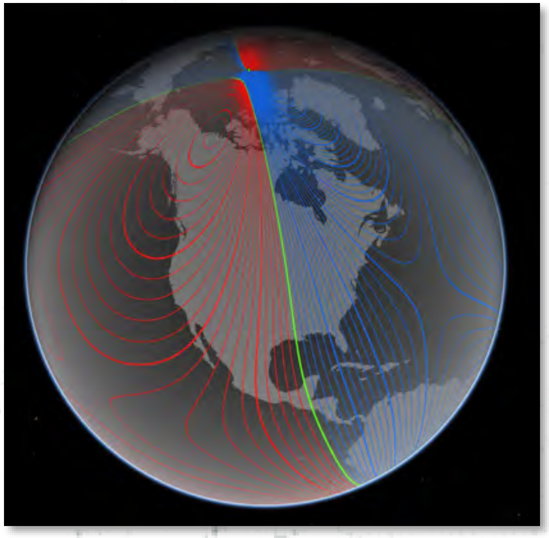


Outline

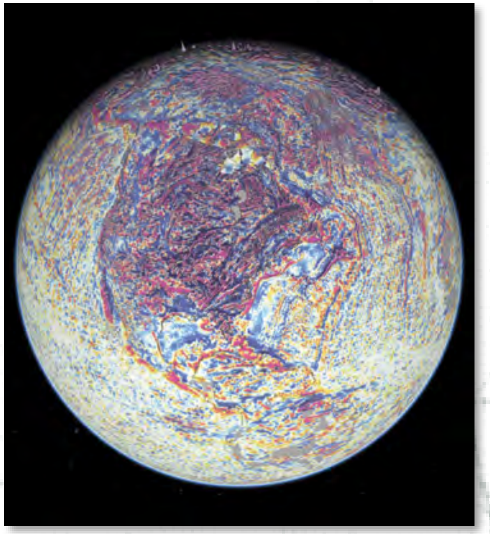
1. Earth's magnetic field [8 slides + quiz]
2. Existing maps and models [7/quiz]
3. Map and model creation [15/quiz/exercise]
4. Map coverage and gaps [5]
5. Uncertainty [24/quiz]
6. Maps for navigation [8/quiz/exercise]



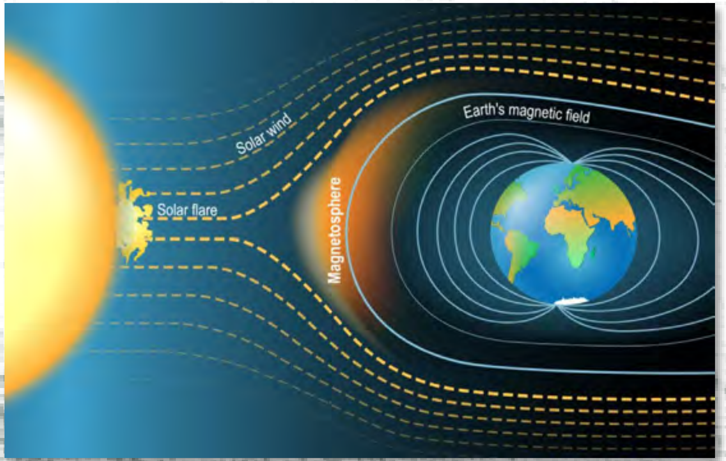
Earth's magnetic field



Core field (declination shown)



Lithospheric (crustal) field (amplitude)

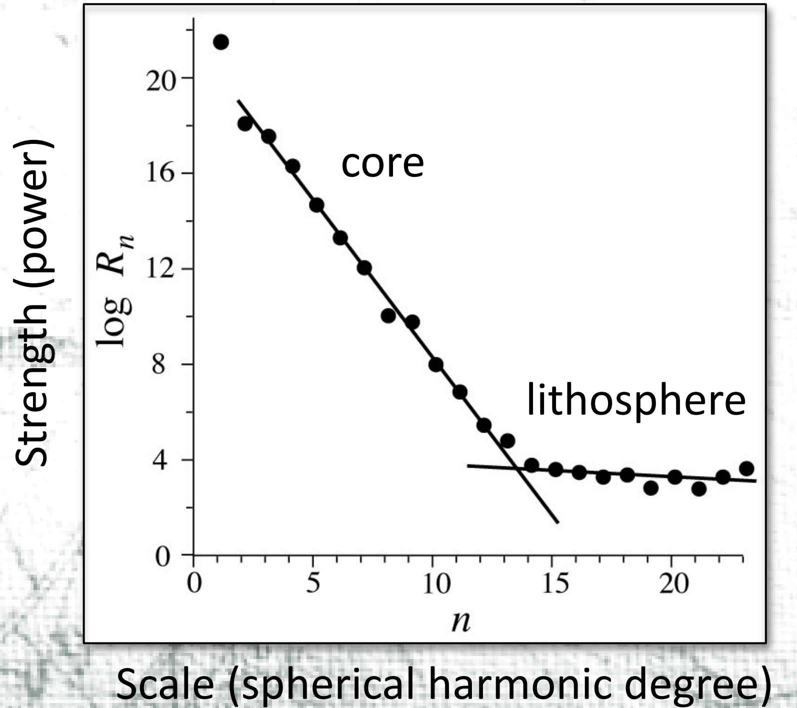


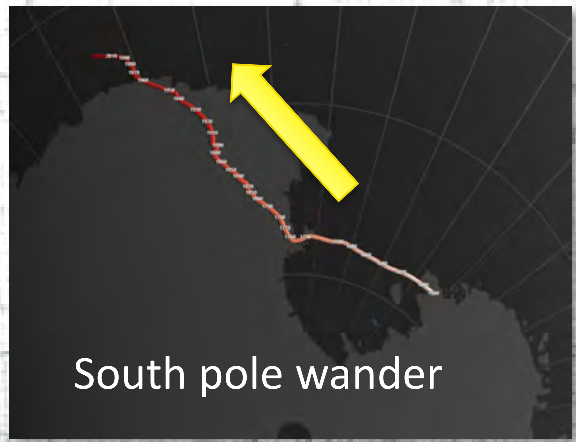
External field cartoon

	Amplitude (nT OM)	Time scale	Nav status
Internal			
Core	50,000	years	models
Lithosphere	100's	eons	maps
Cultural	100's	days/years	unmapped noise
External			
High Lat	>100's	hours	poorly modeled noise
Mid Lat	10's	daily	partially modeled noise
Low Lat	10's	daily	partially modeled noise

Earth's magnetic field

$$B_{obs}(r,t) = B_{core}(r,t) + B_{litho}(r,\sim t) + B_{ext}(r,t) + B_{other}(r,t)$$



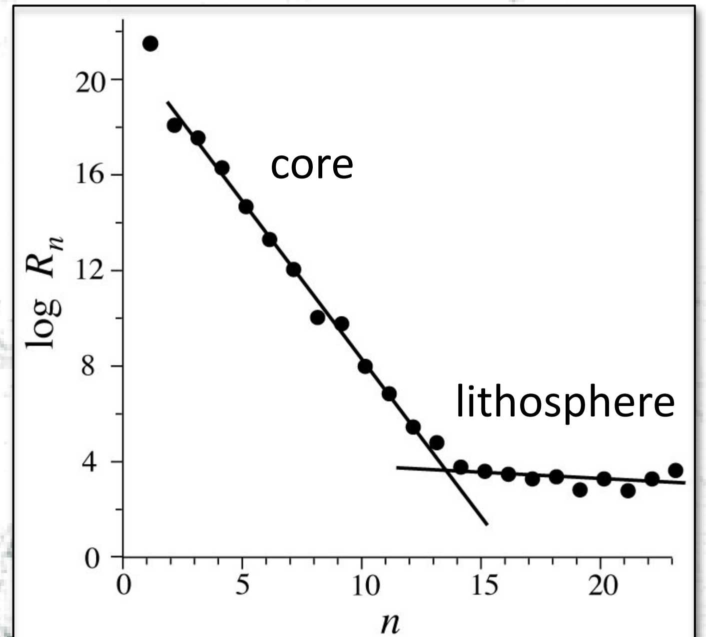


Earth's magnetic field

$$B_{obs}(r,t) = B_{core}(r,t) + B_{litho}(r,\sim t) + B_{ext}(r,t) + B_{other}(r,t)$$

$B_{core}(r,t)$	$B_{litho}(r,\sim t)$	$B_{ext}(r,t)$	$B_{other}(r,t)$
model	map	monitor	fix or estimate

Strength (power)

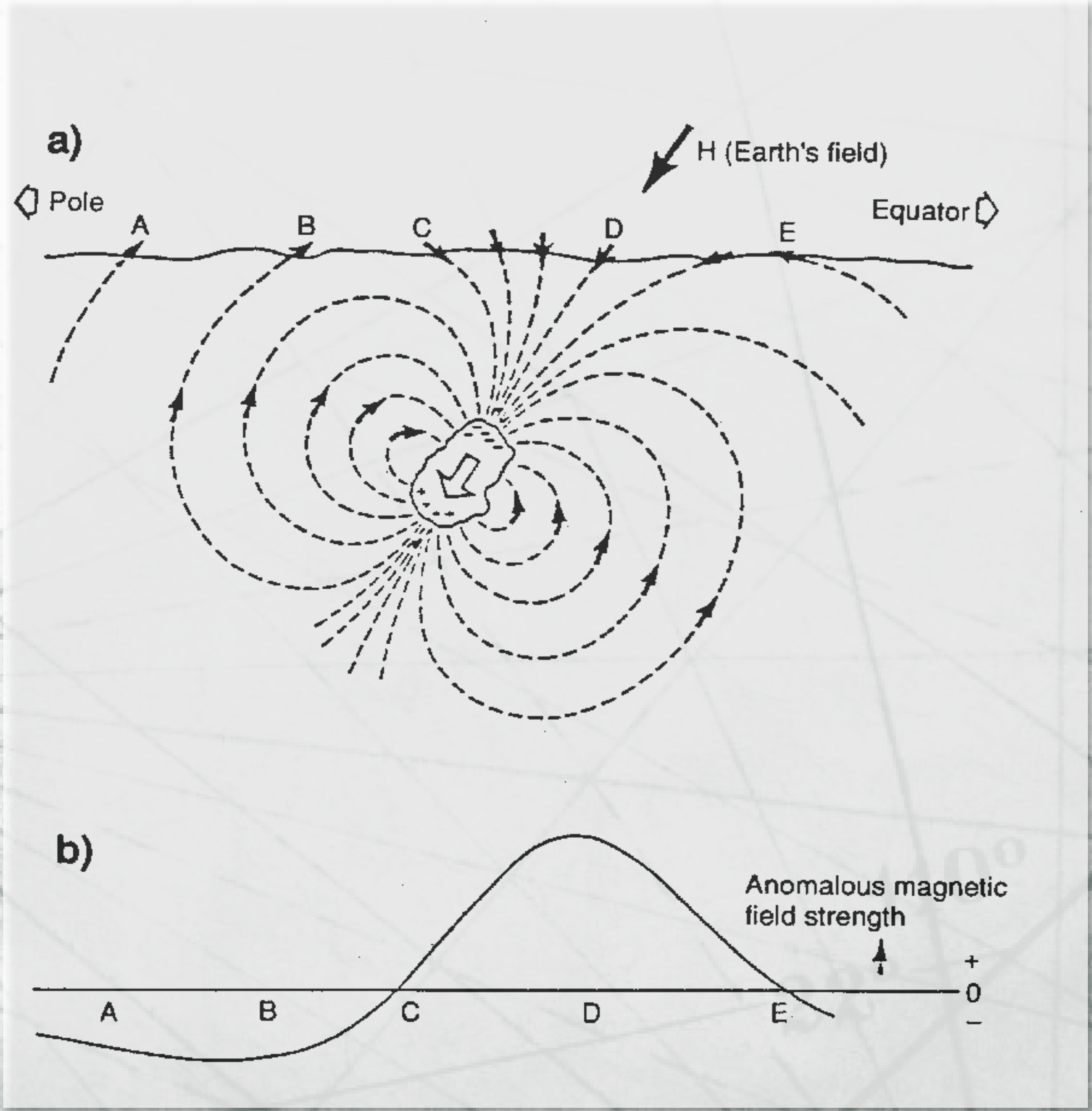


Scale (spherical harmonic degree)

Induced Magnetic Anomaly

Visualization

John Milsom,
Field Geophysics
GSL Handbook



Sphere of radius r_s:

Mag

$$\frac{Mr_s^3}{3z^3}\frac{2-(x/z)^2}{[1+(x/z)^2]^{5/2}}$$

Gravity

$$\frac{4\pi G\rho r_s^3}{3z^2}\frac{1}{[1+x^2/z^2]^{3/2}}$$

Horizontal cylinder of radius r_c:

Mag

$$\frac{Mr_c^2}{2z^2}\frac{2-(x/z)^2}{[1+(x/z)^2]^2}$$

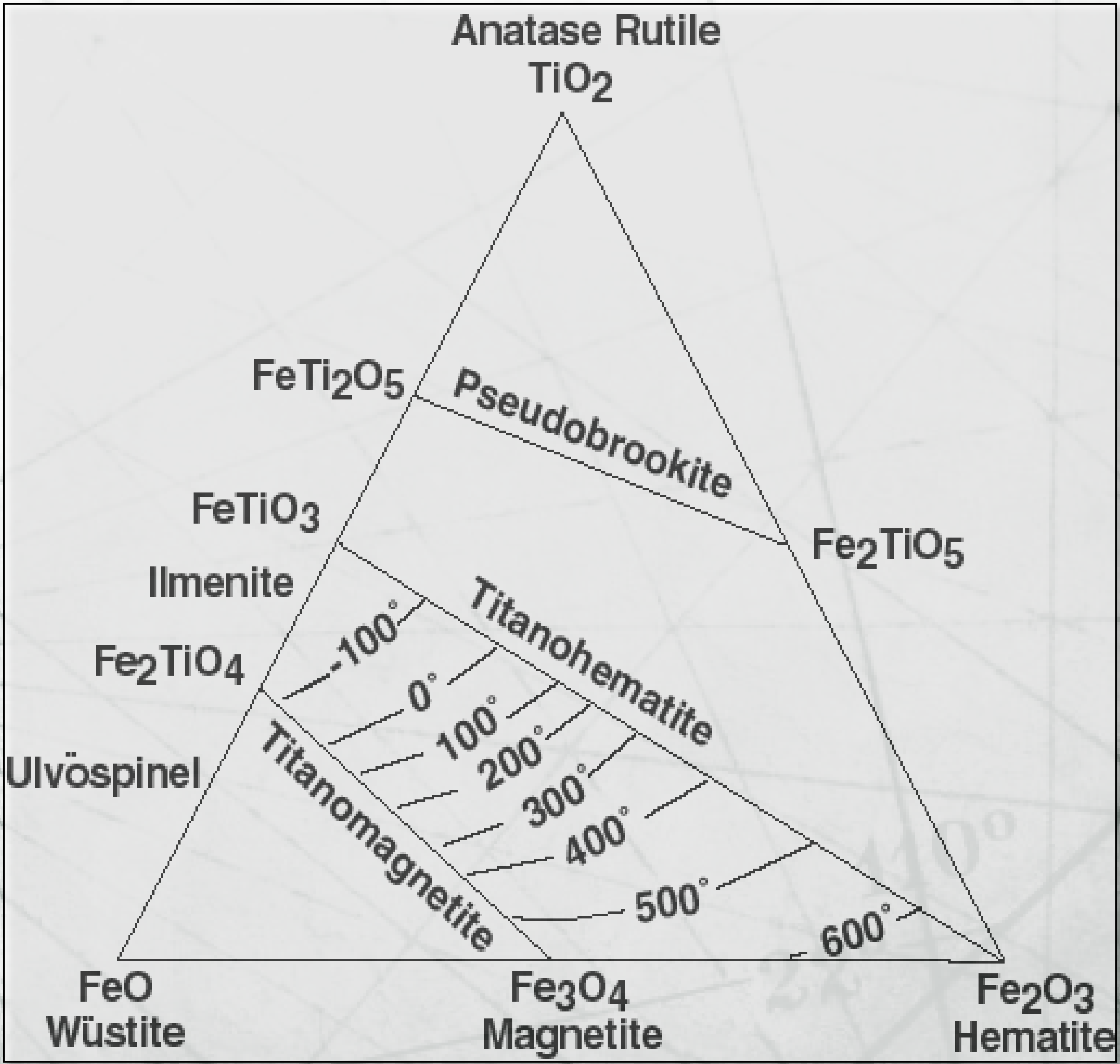
Gravity

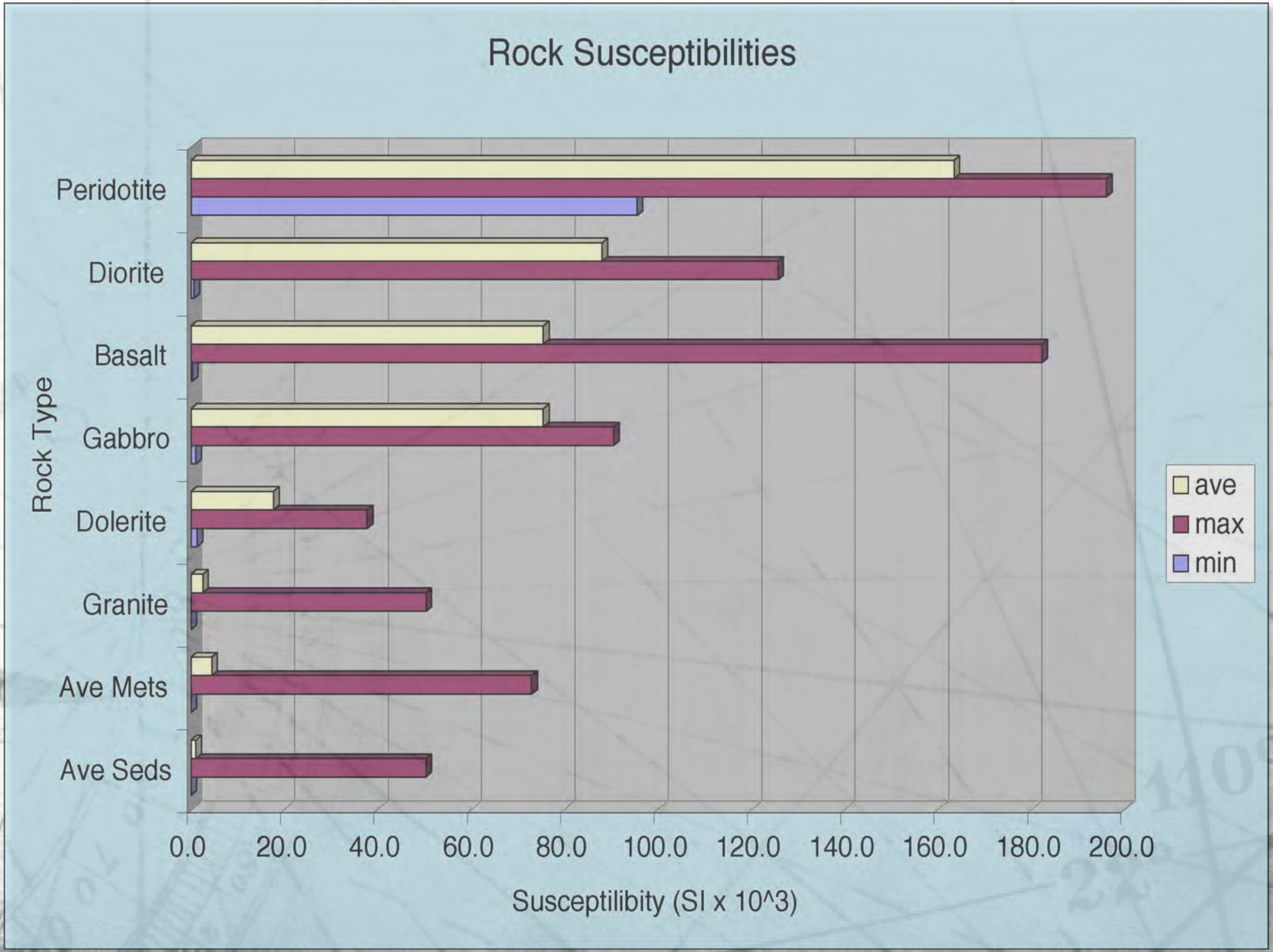
$$\frac{4\pi G\rho r_c^2}{2z}\frac{1}{1+(x/z)^2}$$

Some 2D analytic formulae for scalar anomaly (mag) and gravity

Magnetic Minerals

(mostly magnetite)




Rock Susceptibilities
Peridotite
Diorite
Basalt
Gabbro
Dolerite
Granite
Ave Mets
Ave Seds
Rock Type
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Susceptilibity (SI x 10^3)
ave
max
min

Fourier filters for magnetic data:

Upward continuation (by Δz):

$$F[h_U(x,y)] = F[h(x,y)]e^{-\Delta z|k|}$$

Downward continuation:

$$F[h_U(x,y)] = F[h(x,y)]e^{+\Delta z|k|}$$

Reduction to the pole (RTP):

$$F[h_P(x,y)] = F[h(x,y)]\frac{-2\pi}{\theta(k_x,k_y)}$$

Pseudogravity transformation:

$$F[h_{PSG}(x,y)] = F[h(x,y)]\frac{-2\pi}{\theta(k_x,k_y)}\frac{A}{|k|}$$

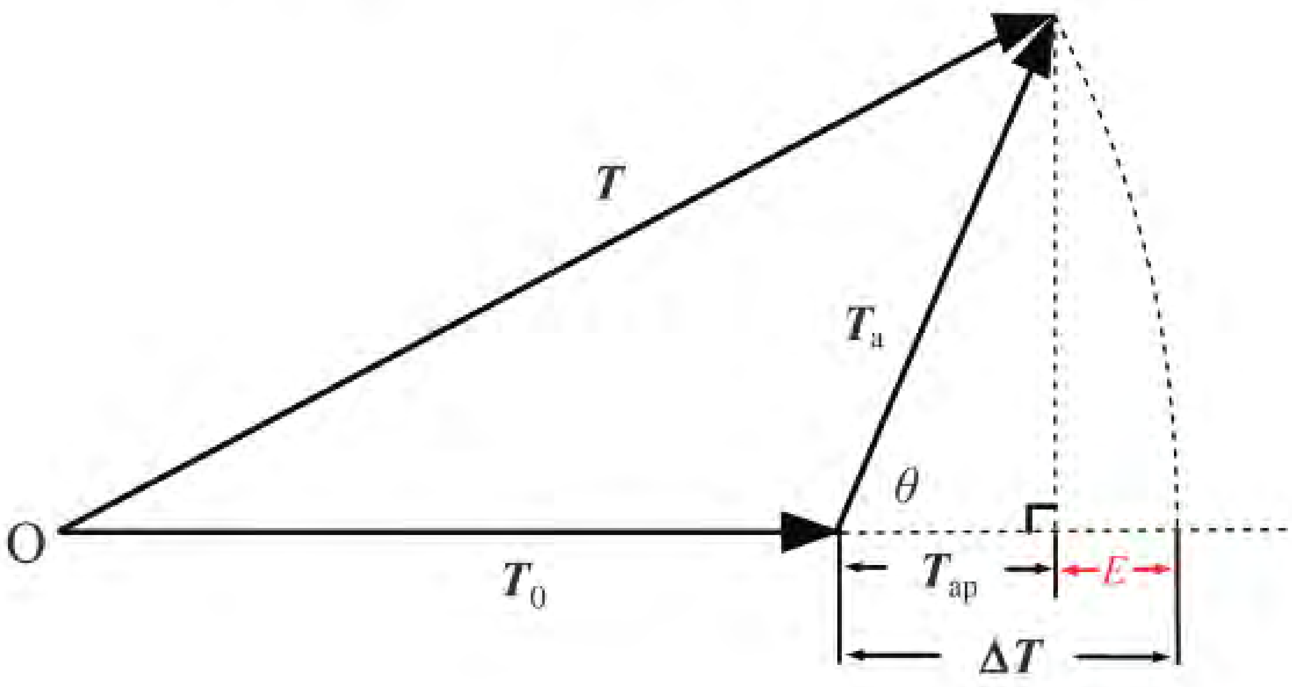
k = wavenumber,

$\theta(k_x,k_y)$ = a complicated function that depends only on the direction and magnitude of the Earth's magnetic field.

A = a constant based on the expected ratio of pseudo-density to magnetization

Technical Point: A Standard Approximation in Potential Field Theory

Yuan et al. (2015) find through experiments that the maximum difference E is 0.1 nT when the magnetic anomaly is 100 nT, and it increases to 10 nT when the magnetic anomaly is 1000 nT.



T_0 = core field
T_a = anomaly
T = totalfield

T_{ap} = projection
E = approx. error
$\Delta T = T_{ap} + E$

θ = difference in field vector between main field and anomaly

Zhen and Yang, 2019

Quiz – Question 1

What is the difference between a map and a model?

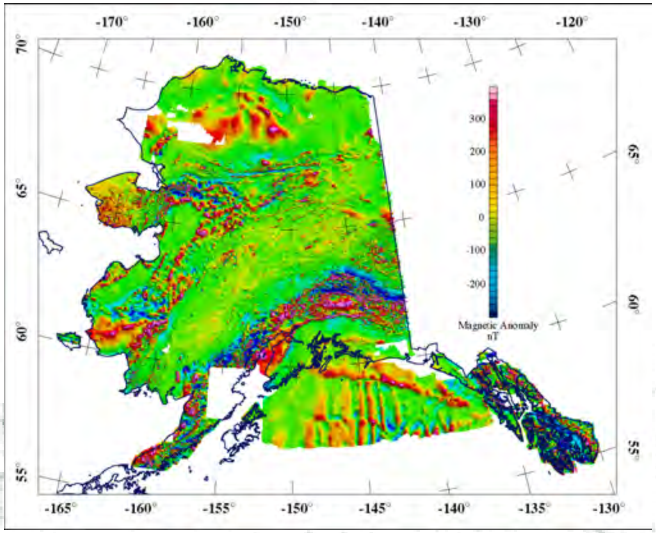
Quiz – Question 1

What is the difference between a map and a model?

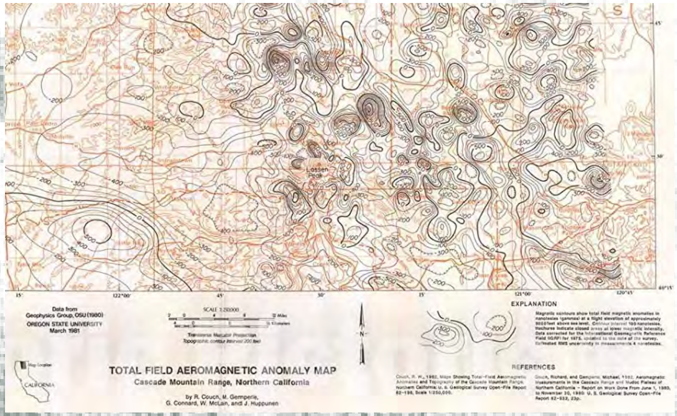
ChatGPT says:

```
A map is a representation of a space, while
a model is a representation of a system.
Maps are often used for navigation or
visualization, while models are used for
understanding or prediction.
```

Existing Maps and Models



Maps - static



Models - dynamic

$$V(r,\theta,\phi,t) = a\sum_{n=1}^{N}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}\left[g_n^m(t)\cos(m\phi) + h_n^m(t)\sin(m\phi)\right]P_n^m(\cos\theta)$$

"… a map is a representation of a space, while a model is a representation of a system. Maps are often used for navigation or visualization, while models are used for understanding or prediction." – *ChatGPT (30 Mar 2023)*

Map and model overview

Magnetic model resolution in spherical harmonics and distance (at the equator)						
Global model or grid	Scale range of models: light gray = sat data dark gray = survey data		Spherical Harmonic degree and order	Distance kilometers	Distance degrees	Distance minutes
		CORE	2	16012.1	180.00	10800.0
			8	4709.4	45.00	2700.0
WMM			12	3202.4	30.00	1800.0
IGRF			13	2965.2	27.69	1661.5
			15	2582.6	24.00	1440.0
			20	1952.7	18.00	1080.0
CHAOS			50	792.7	7.20	432.0
			100	398.3	3.60	216.0
MF7		LITHOSPHERE	133	299.9	2.71	162.4
LCS-1			166	240.4	2.17	130.1
			300	133.2	1.20	72.0
			500	80.0	0.72	43.2
			750	53.3	0.48	28.8
HDGM, EMM			790	50.6	0.46	27.3
			1000	40.0	0.36	21.6
BGGM			1440	27.8	0.25	15.0
			2000	20.0	0.18	10.8
			3000	13.3	0.12	7.2
			4000	10.0	0.09	5.4
			5000	8.0	0.07	4.3
			7000	5.7	0.05	3.1
WDMAM, EMAG2*			10000	4.0	0.04	2.2

*not spherical harmonic models

WMM - World Magnetic Model
[https://www.ncei.noaa.gov/products/world-magnetic-model]

IGRF - International Geomagnetic Reference Field
[https://www.ncei.noaa.gov/products/international-geomagnetic-reference-field]

CHAOS - CHAMP, Orsted, and SAC-C model of the Earth's magnetic field
[https://www.space.dtu.dk/english/research/scientific_data_and_models/magnetic_field_models]

MF7 - Magnetic Field Model 7
[https://geomag.colorado.edu/magnetic-field-model-mf7.html]

LCS-1 - Lithosphere from Champ and Swarm
[http://www.spacecenter.dk/files/magnetic-models/LCS-1/]

HDGM - High Definition Geomagnetic Model
[https://www.ncei.noaa.gov/products/high-definition-geomagnetic-model]

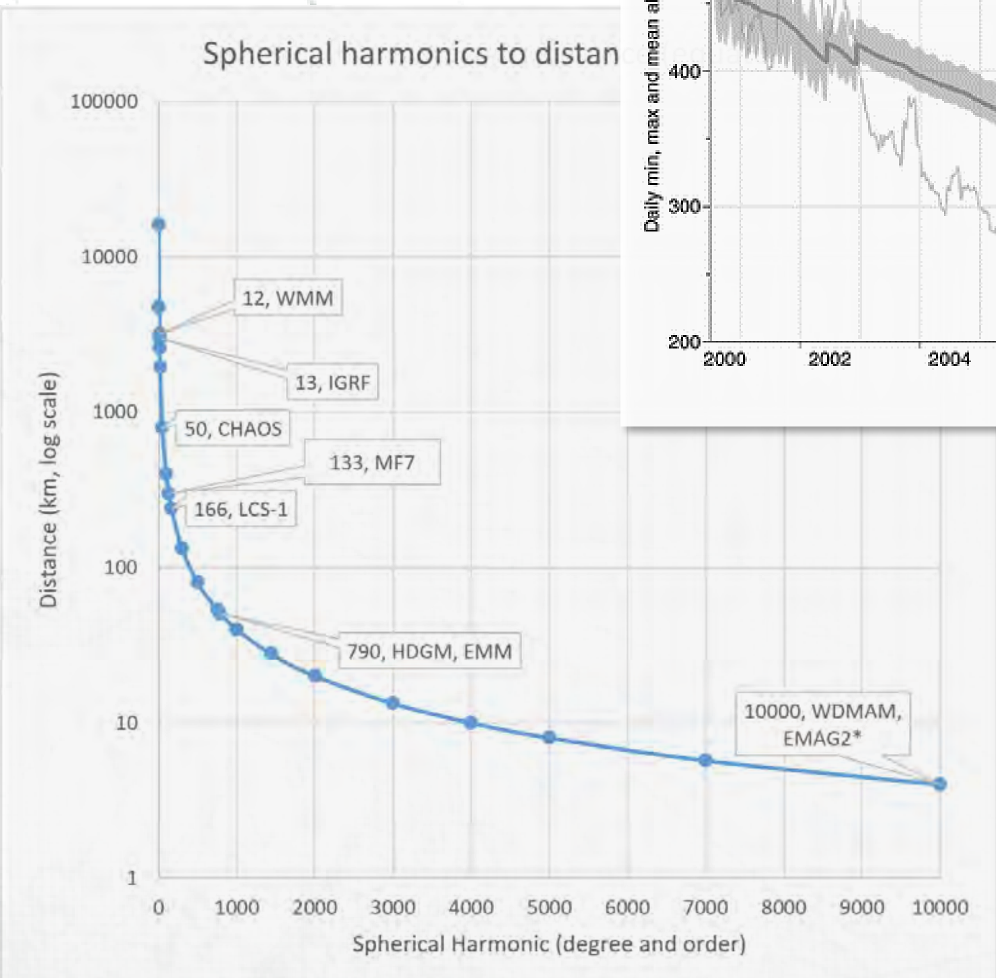
EMM - Enhanced Magnetic Model
[https://www.ncei.noaa.gov/products/enhanced-magnetic-model]

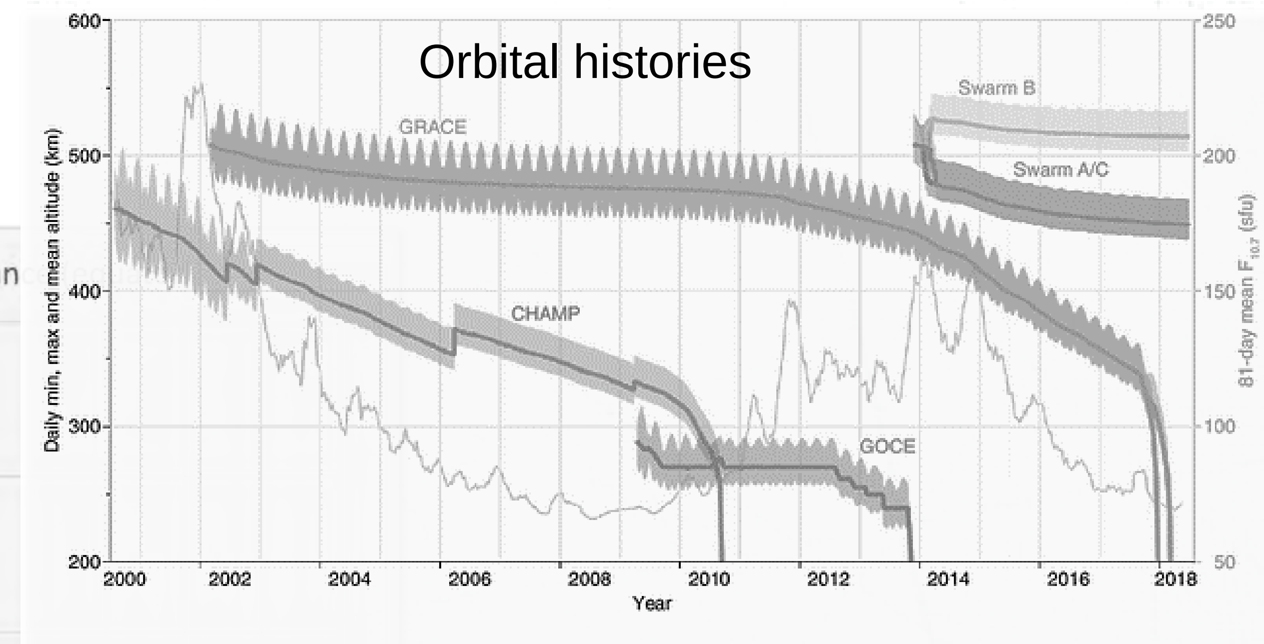
BGGM - BGS Global Geomagnetic Model
[http://www.geomag.bgs.ac.uk/data_service/directionaldrilling/bggm.html]

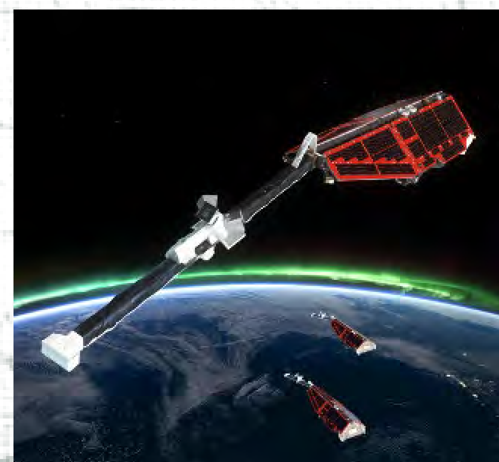
WDMAM - World Magnetic Anomaly Model
[http://wdmam.org/]

EMAG2 - Earth Magnetic Anomaly Grid* Not a spherical harmonic model
[https://geomag.colorado.edu/emag2-earth-magnetic-anomaly-grid-2-arc-minute-resolution.html]

Satellite-based models-data







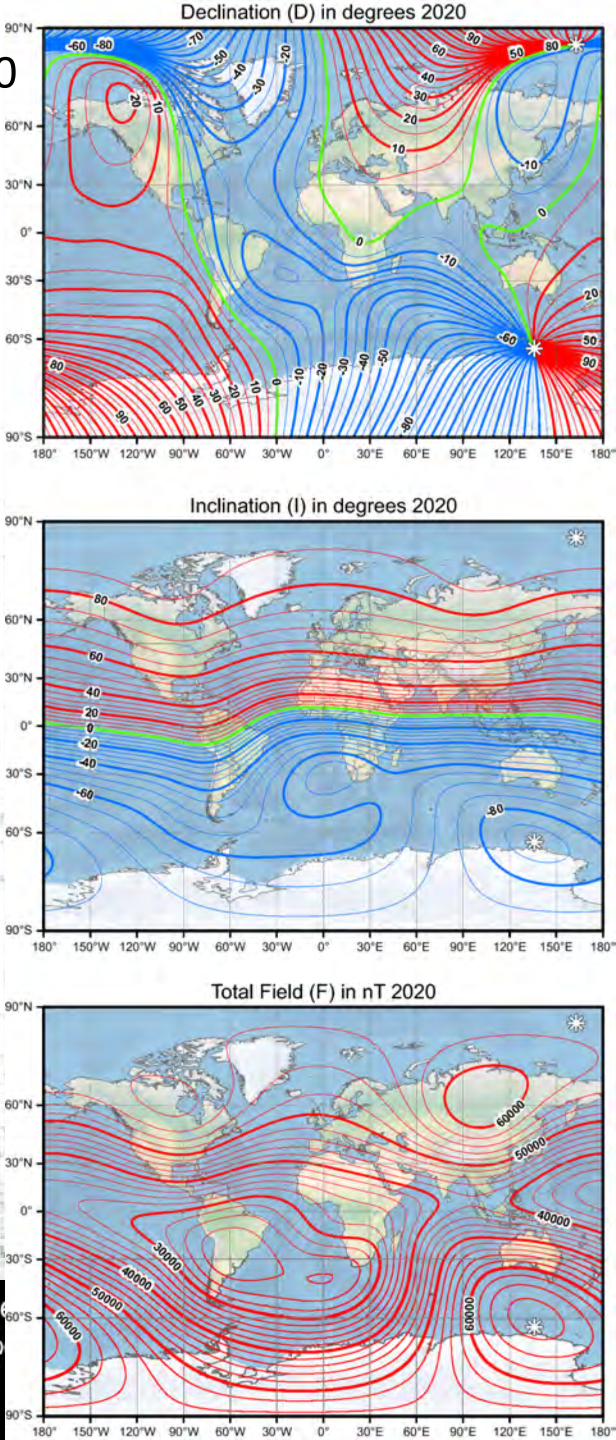
SWARM satellites

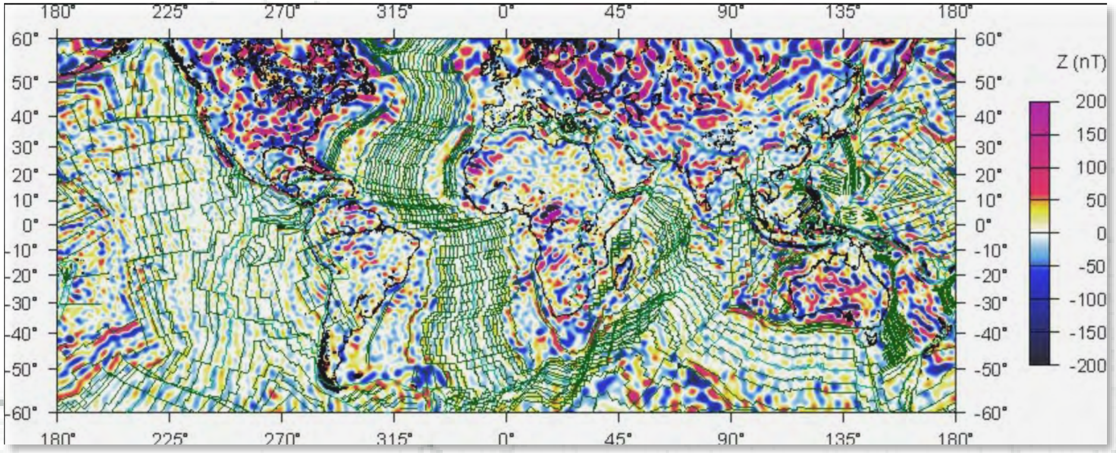
Magnetic observatories used for WMM

Figure 5: Locations of observatories whose data contributed to BGS parent model.

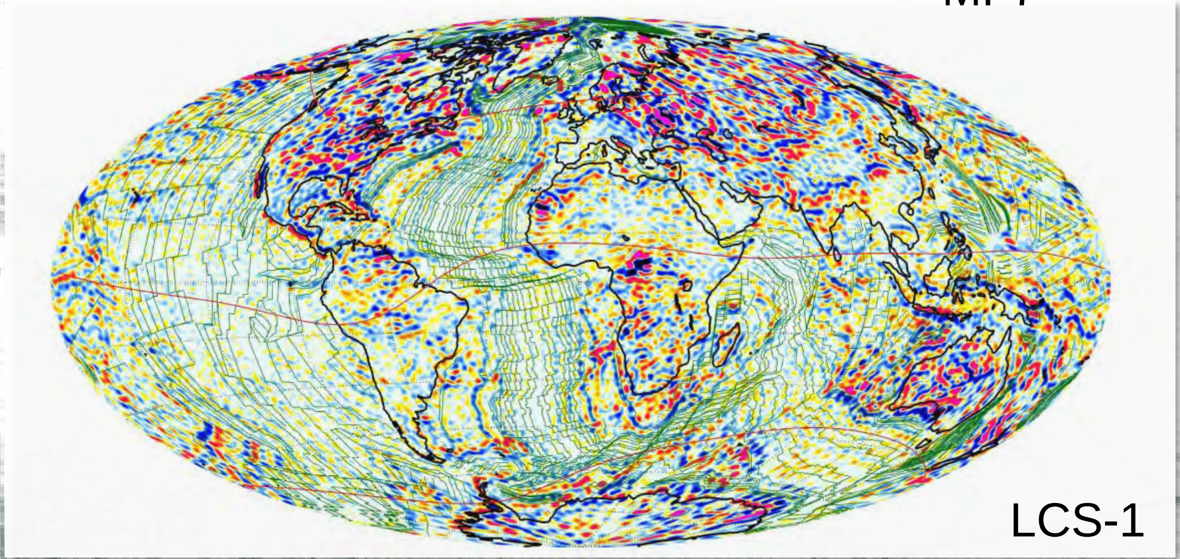
Satellite-based models

IGRF 2020





MF7



LCS-1

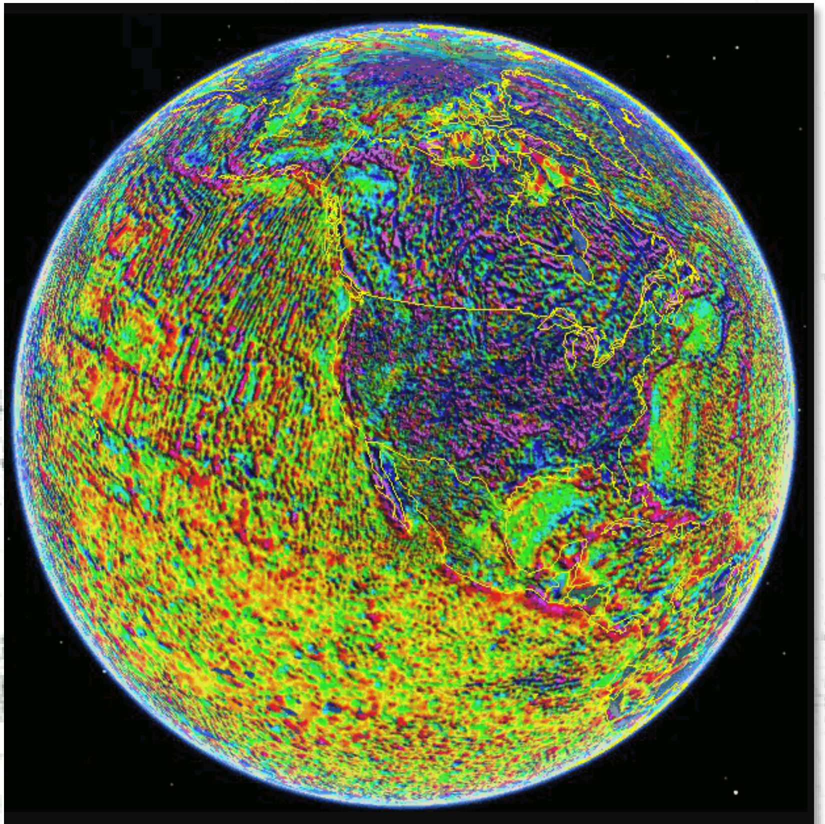
Quiz – Question 2

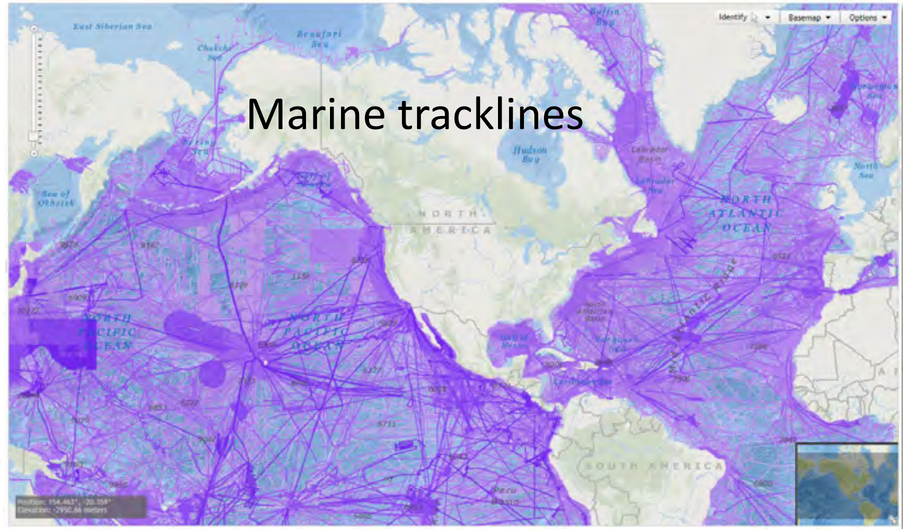
Where is the Earth's magnetic field the strongest?

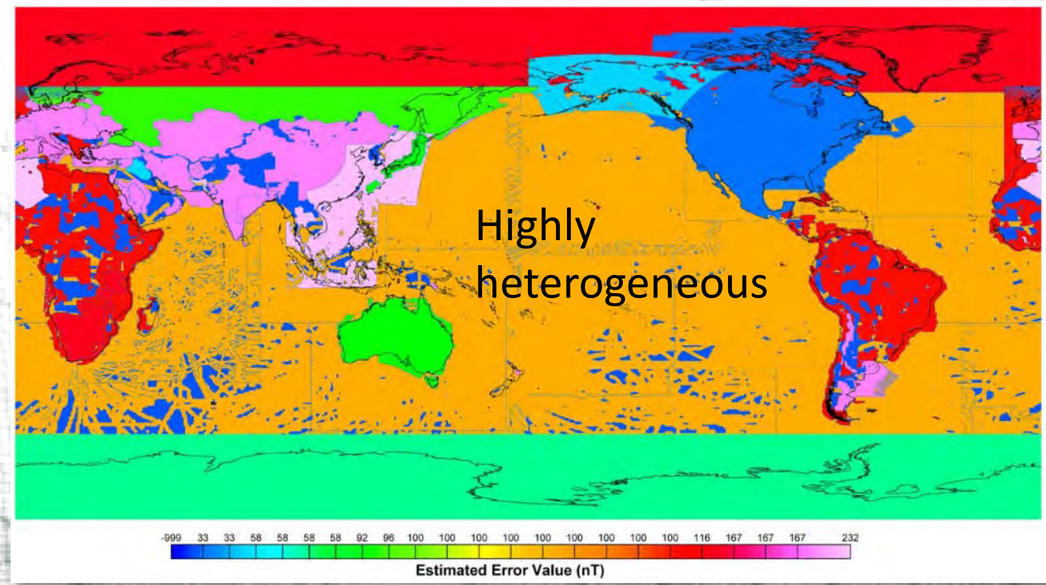
Quiz – Question 2

- The strength of the Earth's magnetic field varies depending on the location and altitude. At the Earth's surface, the strength of the magnetic field is strongest near the magnetic poles and weakest near the equator.
- The exact location of the strongest magnetic field depends on whether we are talking about the north magnetic pole or the south magnetic pole. The north magnetic pole is currently located in the Arctic Ocean, near the Canadian island of Ellesmere, while the south magnetic pole is located in Antarctica.
- However, it's important to note that the strength of the Earth's magnetic field is constantly changing and is influenced by a variety of factors, such as the movement of the Earth's molten iron core, solar winds, and other external magnetic fields.

Survey-based maps/grids

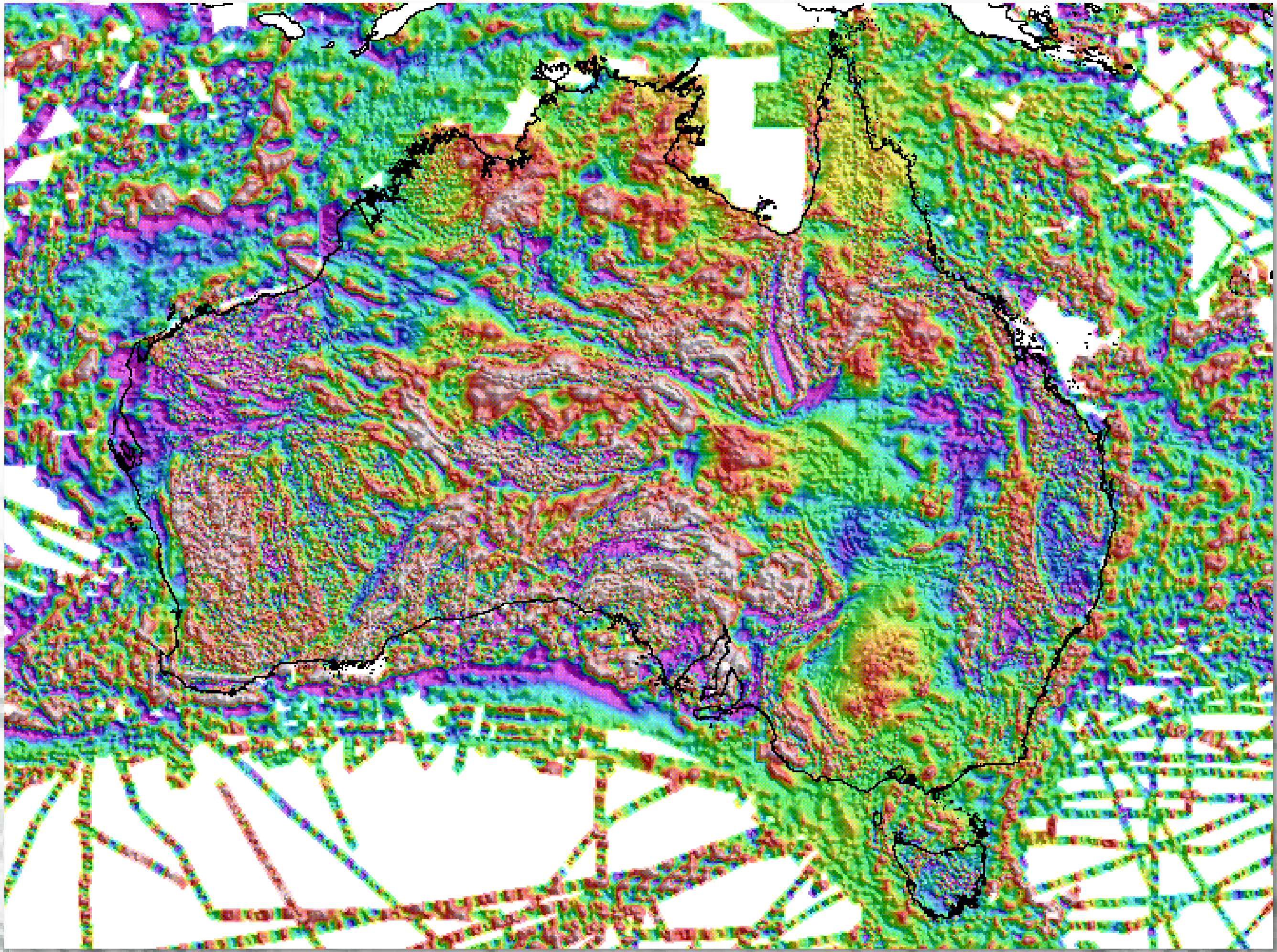






EMAG2v3
Global, 4 km, NCEI/CIRES
Meyer et al., 2017

Survey-based maps/grids



Australia – the gold standard

Map and Model Creation

"You can't use an old map to explore a new world."

- Albert Einstein

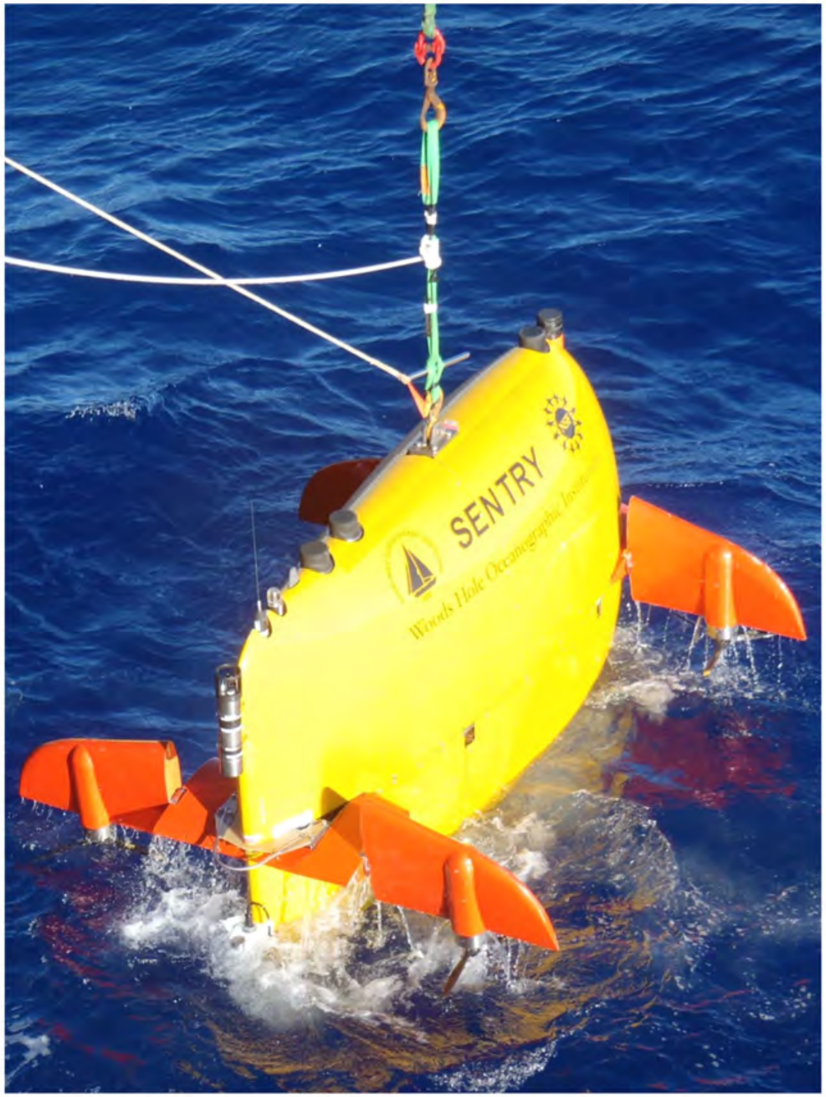
Data Collection

Helicopters

Fixed-wing aircraft

Sea surface

AUV (Autonomous Underwater Vehicle)



Photos provided by Fabio Caratori Tontini (GNS Science, New Zealand).

2011 New Zealand—American Submarine Minerals Sentry Cruise

Eos

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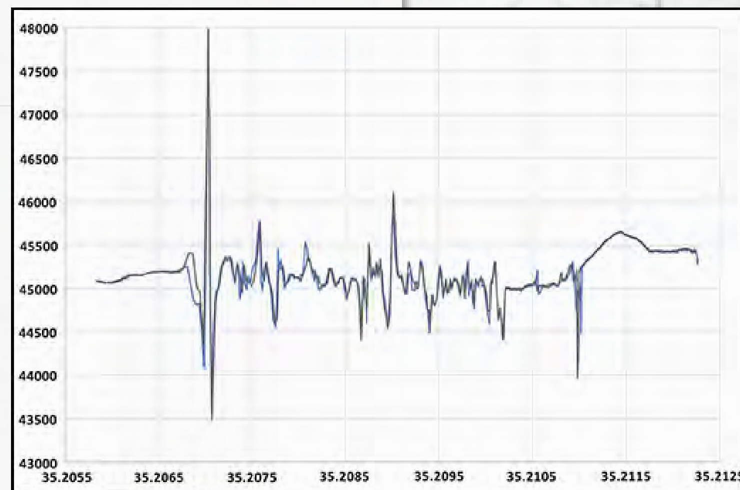
A Bike Built for Magnetic Mapping

Mounting a magnetic sensor on a bicycle offers an efficient, low-cost method of collecting ground magnetic field data over rough terrain where conventional vehicles dare not venture.

By U. Schattner 25 April 2017

Uri Schattner (the author) tests the bike-mag system, a mountain bike equipped with a magnetic sensor and GPS capabilities, across the shoulder of the Dead Sea fault valley in northeastern Israel. Such a bike offers a simple, efficient, cost-effective alternative to walking for making local magnetic measurements. Credit: Amit Segev (Geological Survey of Israel)



Map and model creation

Cooperative Institute for Research in Environmental Sciences
UNIVERSITY OF COLORADO **BOULDER** and **NOAA**

Backpacks

Rick Blakely (USGS)

Geometrics cesium-vapor magnetometer system

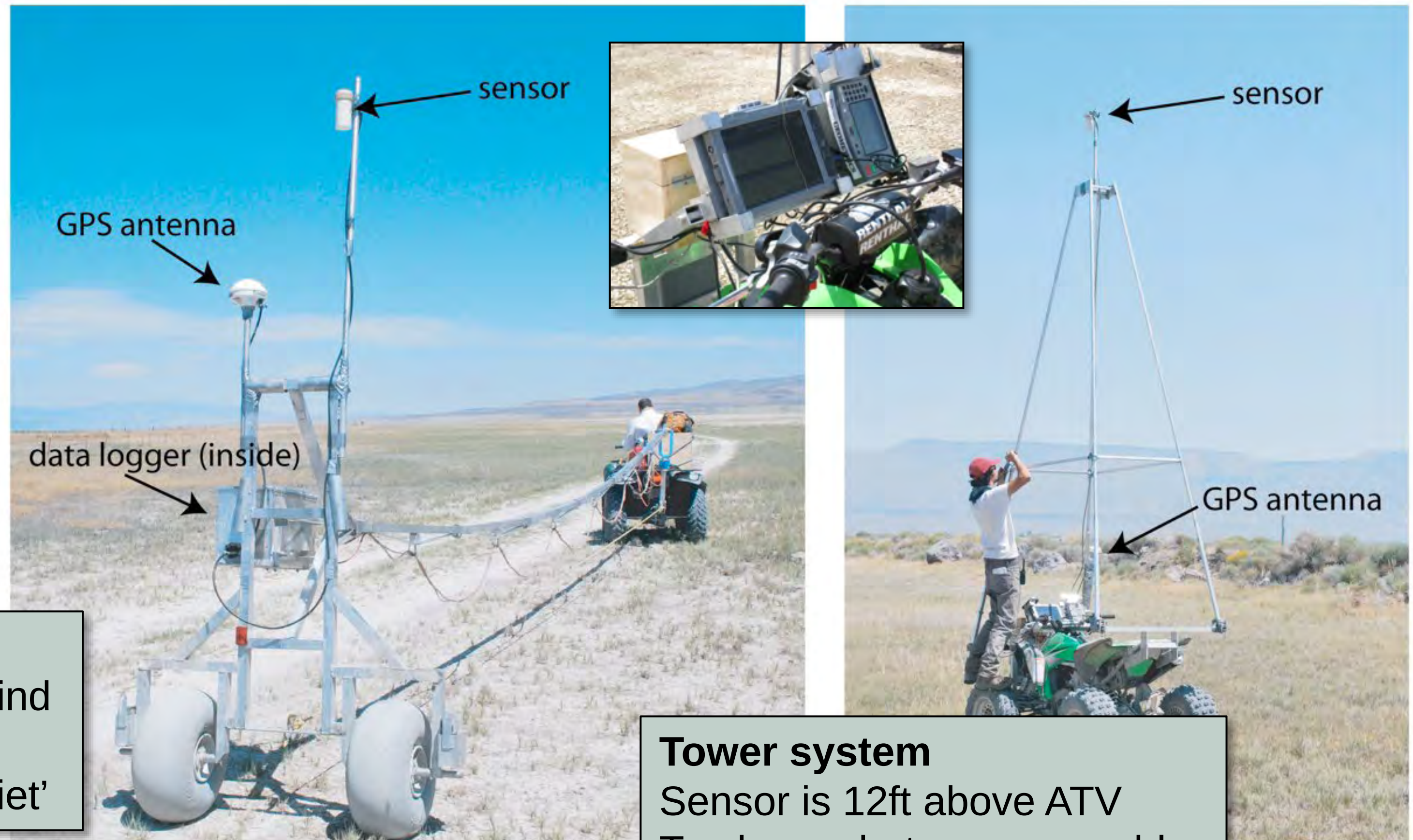
Mark Bultman (USGS)

Small boats

Rick Blakely (USGS)

ATV (all-terrain vehicle) systems

Jonathan Glen
(USGS)

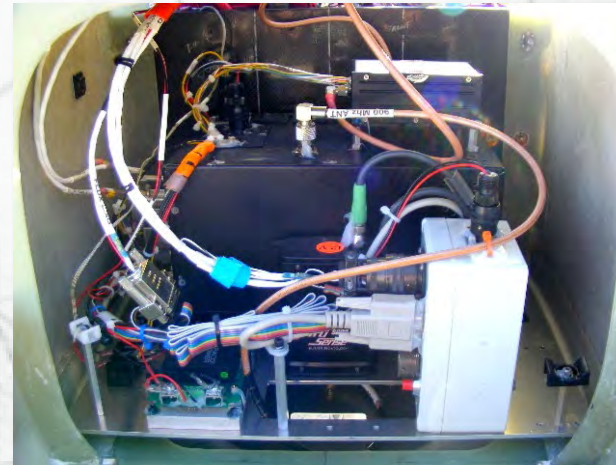


Towed system
Sensor is 30ft behind ATV
Less agile, but 'quiet'

Tower system
Sensor is 12ft above ATV
Top heavy but maneuverable

UAV (Unmanned Aerial Vehicle), under development

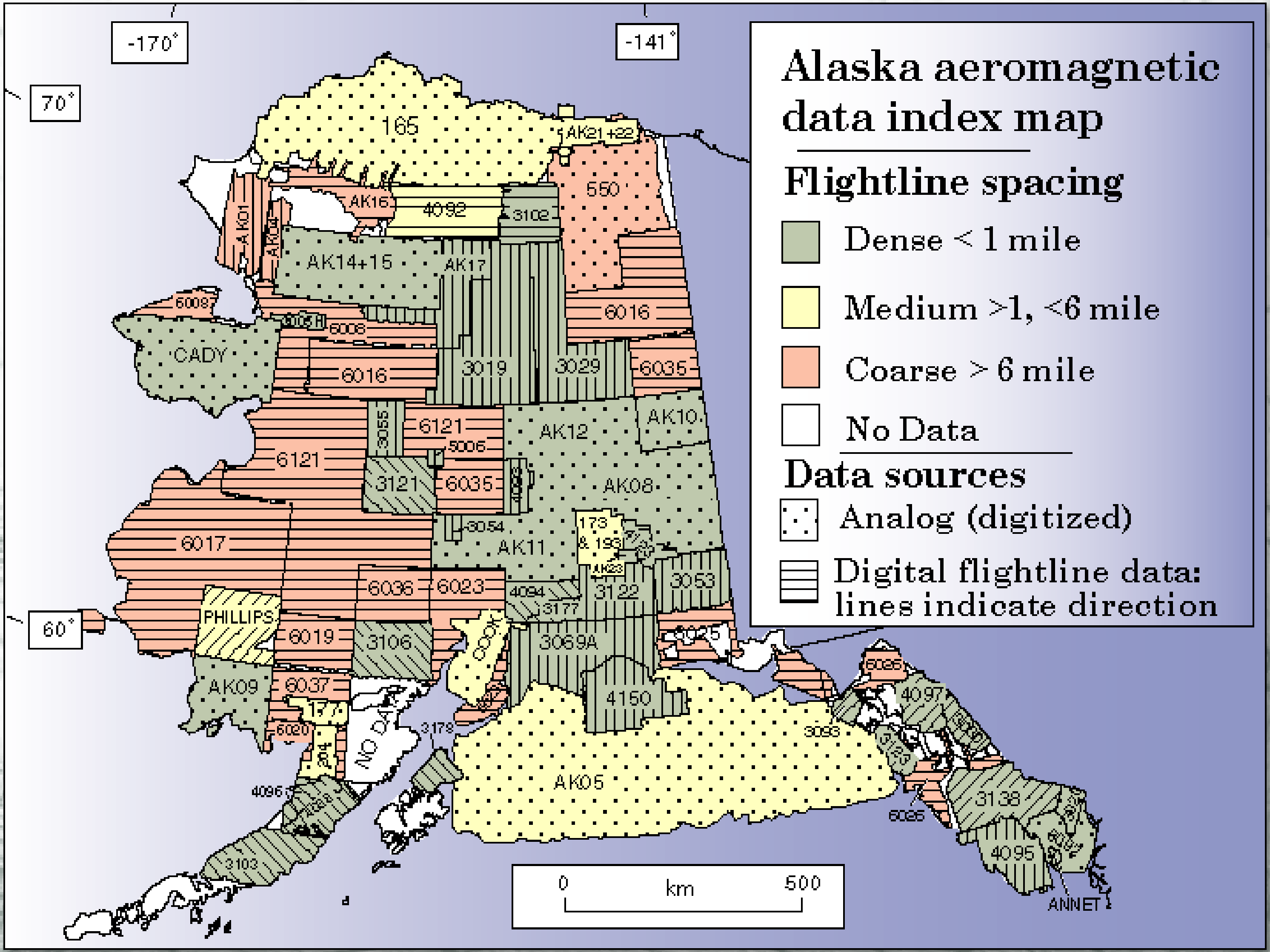
by Jonathan Glen, USGS

Vintage data - airborne


U.S. Navy aircraft used for
1945/1946 aeromagnetic survey
of the National Petroleum Reserve,
Alaska
PBY-5A

Regional magnetic anomaly grids are patchwork quilts



Regional magnetic anomaly grids are made for use in geologic interpretation

Vol. 9, No. 3 March 1999
GSA TODAY
A Publication of the Geological Society of America

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• Medalists and Awardees, p. 15
• Cordilleran Section Centennial Meeting, p. 36

A New Magnetic View of Alaska

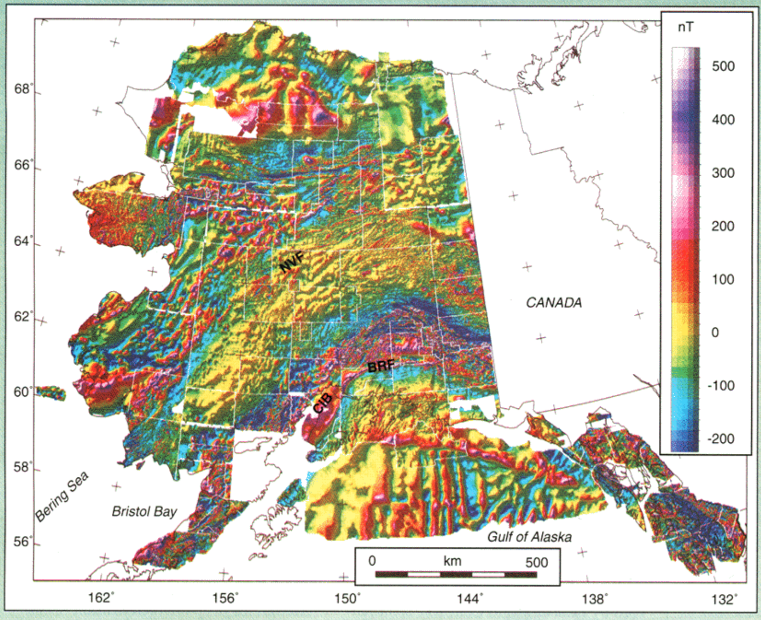


Figure 1. Composite aeromagnetic map of Alaska that depicts total field magnetic data values (International Geomagnetic Reference Field has been removed) from a compilation of 85 separate surveys and two grids. Thin data gaps mark the boundaries between data sets. CIB—Cook Inlet Basin, NVF—Nowitna volcanic field, BRF—Border Ranges fault. Data set can be downloaded from the Web at: ftp://greenwood.cr.usgs.gov/ pubs/ open-file-reports/ofr-97-0520/ data. A 1:2,500,000 plot file of this data set is available at: ftp://greenwood.cr.usgs.gov/ pubs/open-file-reports/ ofr-97-0520/plots.

Richard W. Saltus*, U.S. Geological Survey, Mail Stop 964, Denver, CO 80225-0046*
Travis L. Hudson*, Applied Geology, P.O. Box 1428, Sequim, WA 98382-1428*
Gerald G. Connard*, Northwest Geophysical Associates, P.O. Box 1063, Corvallis, OR 97339-1063*

ABSTRACT

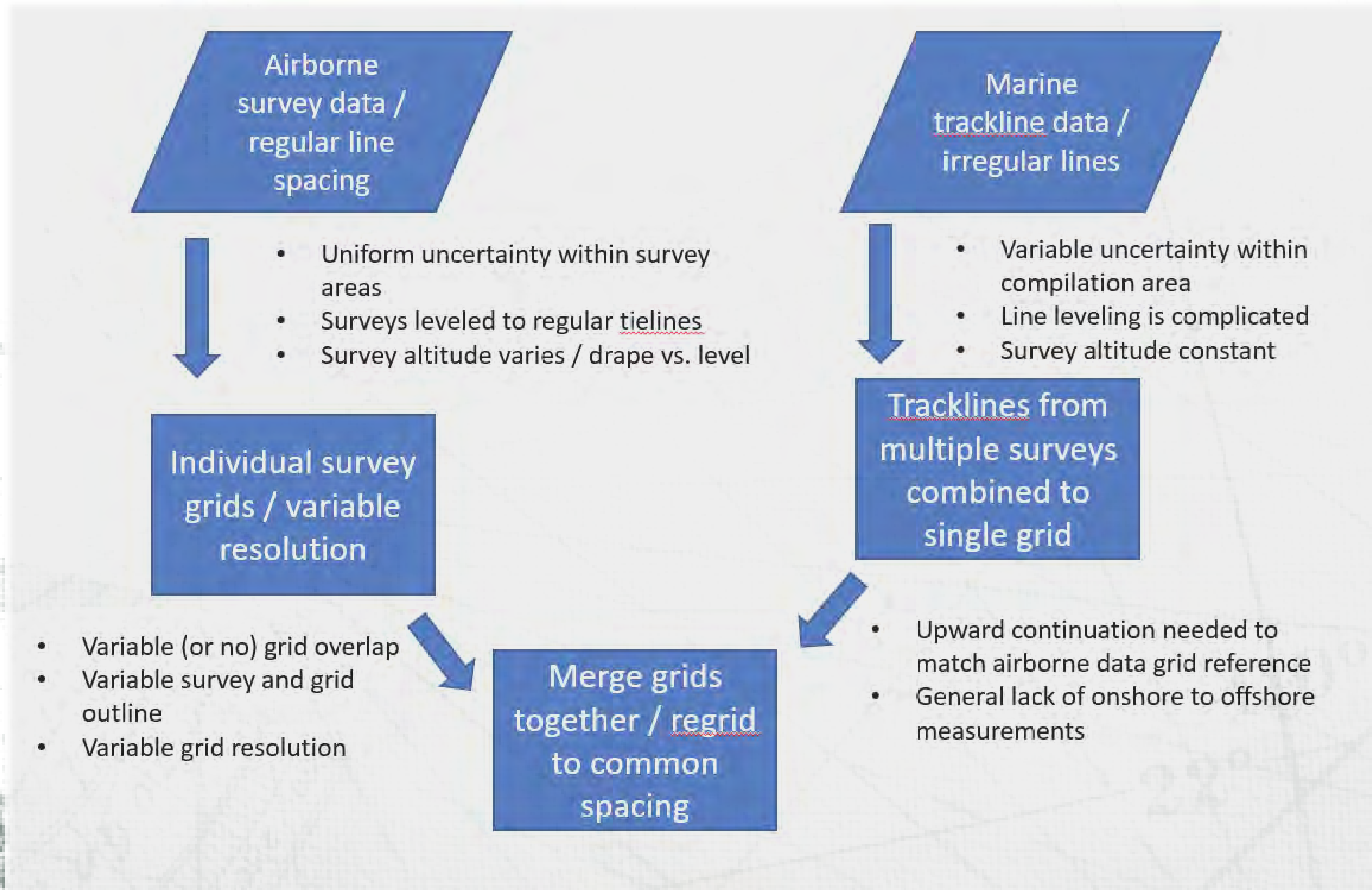
A new, publicly available aeromagnetic data compilation spanning Alaska enables analysis of the regional crustal character of this tectonically diverse and poorly understood part of the North American Cordillera. The merged data were upward-continued by 10 km (mathematically smoothed without assumptions about sources) to enhance crustal-scale magnetic features and facilitate tectonic analysis. This analysis reveals a basic threefold magnetic character: (1) a southern region with arcuate magnetic domains closely tied to tectonostratigraphic elements, (2) a magnetically neutral interior region punctuated locally by intermediate and deep magnetic highs representing a complex history, and (3) a magnetically subdued northern region that includes a large deep magnetic high. Our tectonic view of the data supports interpretations that Paleozoic extension and continental rift basins played a significant role in the tectonic development of northern and interior Alaska. Accretion of oceanic and continental margin terranes could be restricted to the southern region. The new magnetic view of Alaska can be compared and contrasted with other Pacific margin regions where convergent margin and accretionary tectonic processes are important.

INTRODUCTION

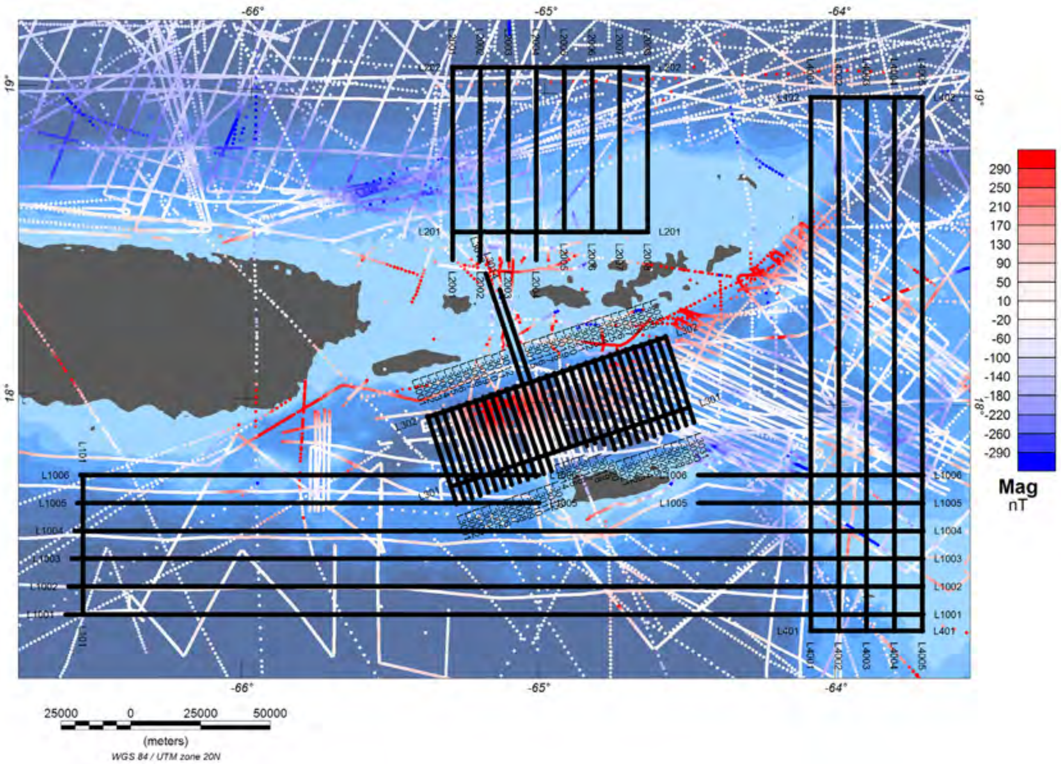
Alaska, an important part of the North American Cordillera, is a type example for the nature and significance of accretionary tectonics along a convergent continental margin (e.g., Coney and Jones, 1985; Plafker and Berg, 1994). The prevailing tectonic interpretation is that this vast part of North America has had a long history of accretion of diverse tectonostratigraphic terranes. These terranes are thought to represent a wide variety of oceanic, arc, and continental margin assemblages. They form an amalgamated, commonly 30-km-thick crust throughout

Magnetic View *continued on p. 2*

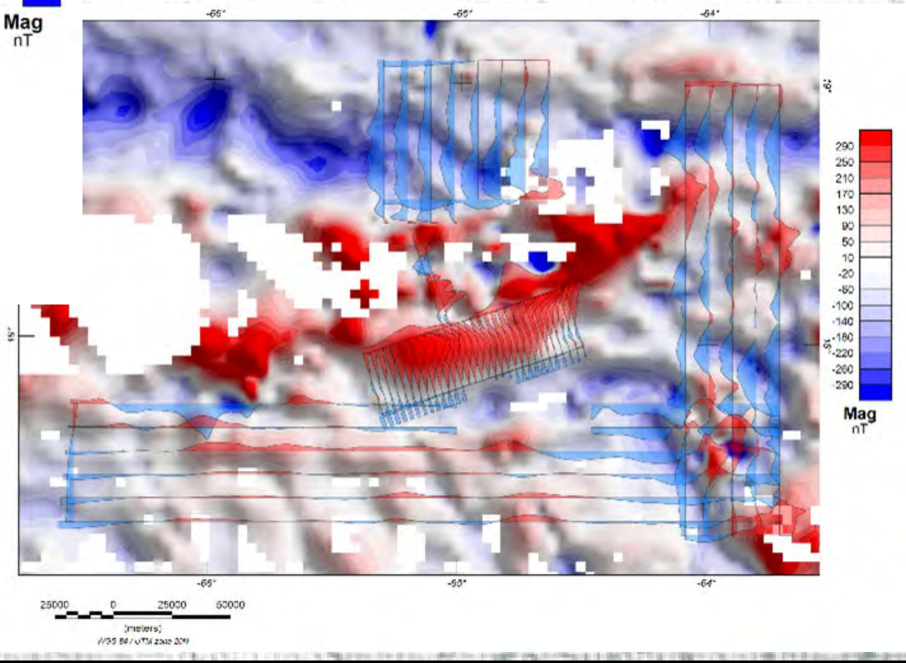
Survey-based maps/grids



Survey-based maps/grids



Caribbean Alt Nav Reference Experiment - CANREx



Map and model creation

Building Spherical Harmonic Models from Satellite Data

- Find "clean" satellite data (SWARM level 2)
- Data assimilation (quiet times, night-side, etc.)
- Inversion for coefficients (damping, etc.)
- Validation with independent data or against other models

Quiz – Question 3

Does a compass needle point to the north pole?

Quiz – Question 3

Does a compass needle point to the north pole?

Yes, a compass needle generally points towards the magnetic North Pole, which is located near the geographic North Pole but not exactly at the same location. This is because the Earth has a magnetic field that acts like a giant bar magnet, and the compass needle aligns itself with the magnetic field lines.

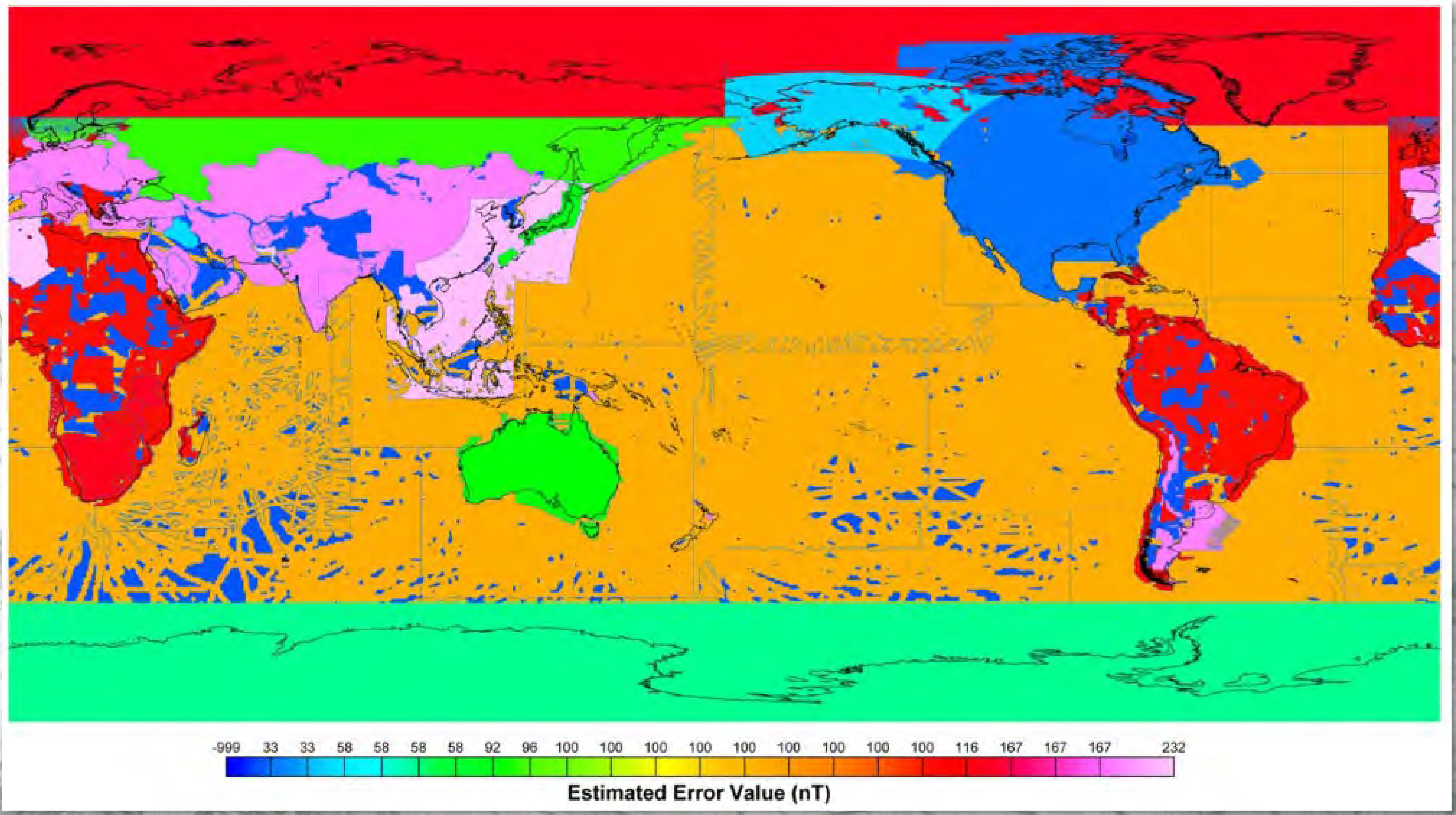
It is important to note, however, that the magnetic North Pole is not fixed and can shift over time due to changes in the Earth's magnetic field. Additionally, the needle may be affected by local magnetic anomalies or interference from nearby objects, which can cause it to deviate from pointing directly towards the magnetic North Pole.

Map Coverage and Gaps

"You can have data without information, but you cannot have information without data."

- Daniel Keys Moran

EMAG2v3 global data sources

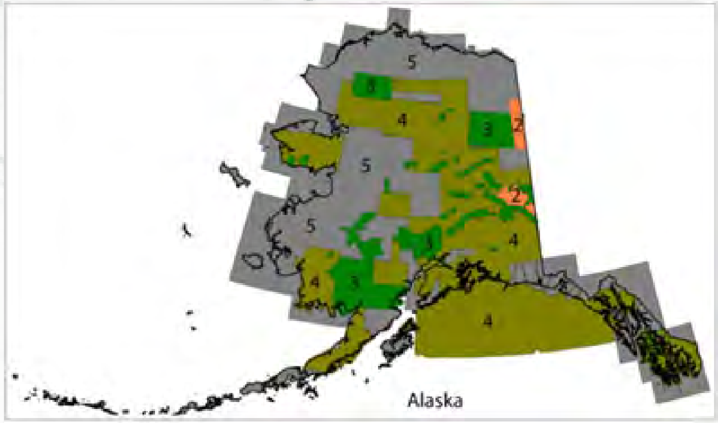


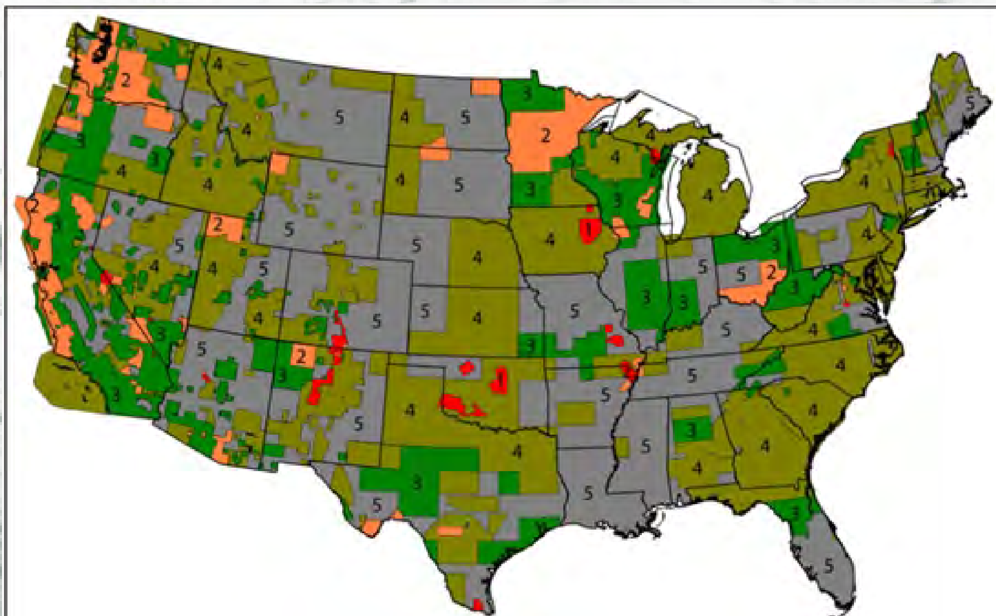
Map coverage and gaps

Finding the Gaps in America's Magnetic Maps

A 2017 executive order mandated a plan to evaluate U.S. access to critical mineral resources, but the airborne magnetic survey maps that support this effort are sadly out of date.

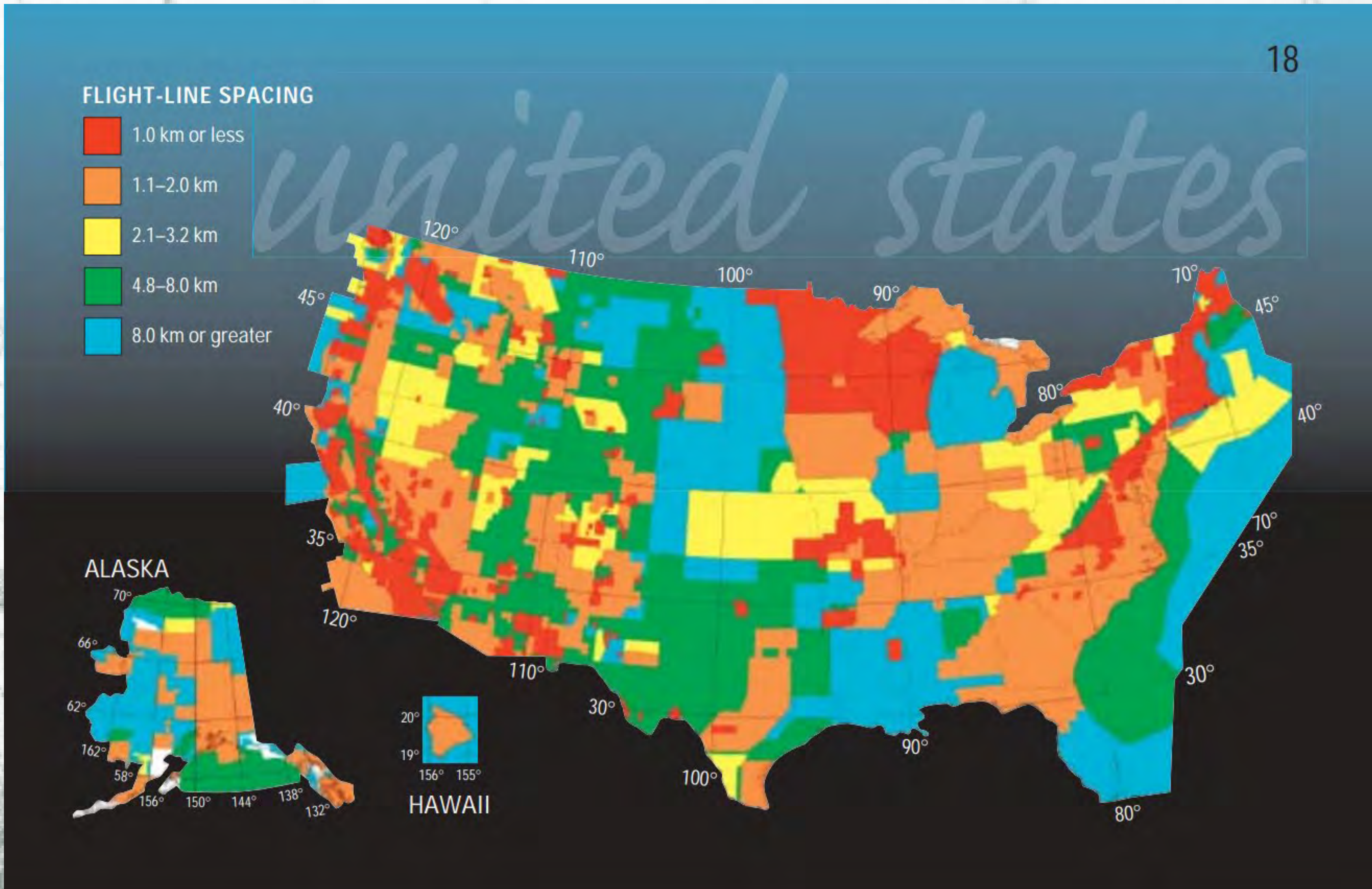
By **B. J. Drenth** and **V. J. S. Grauch**
16 April 2019





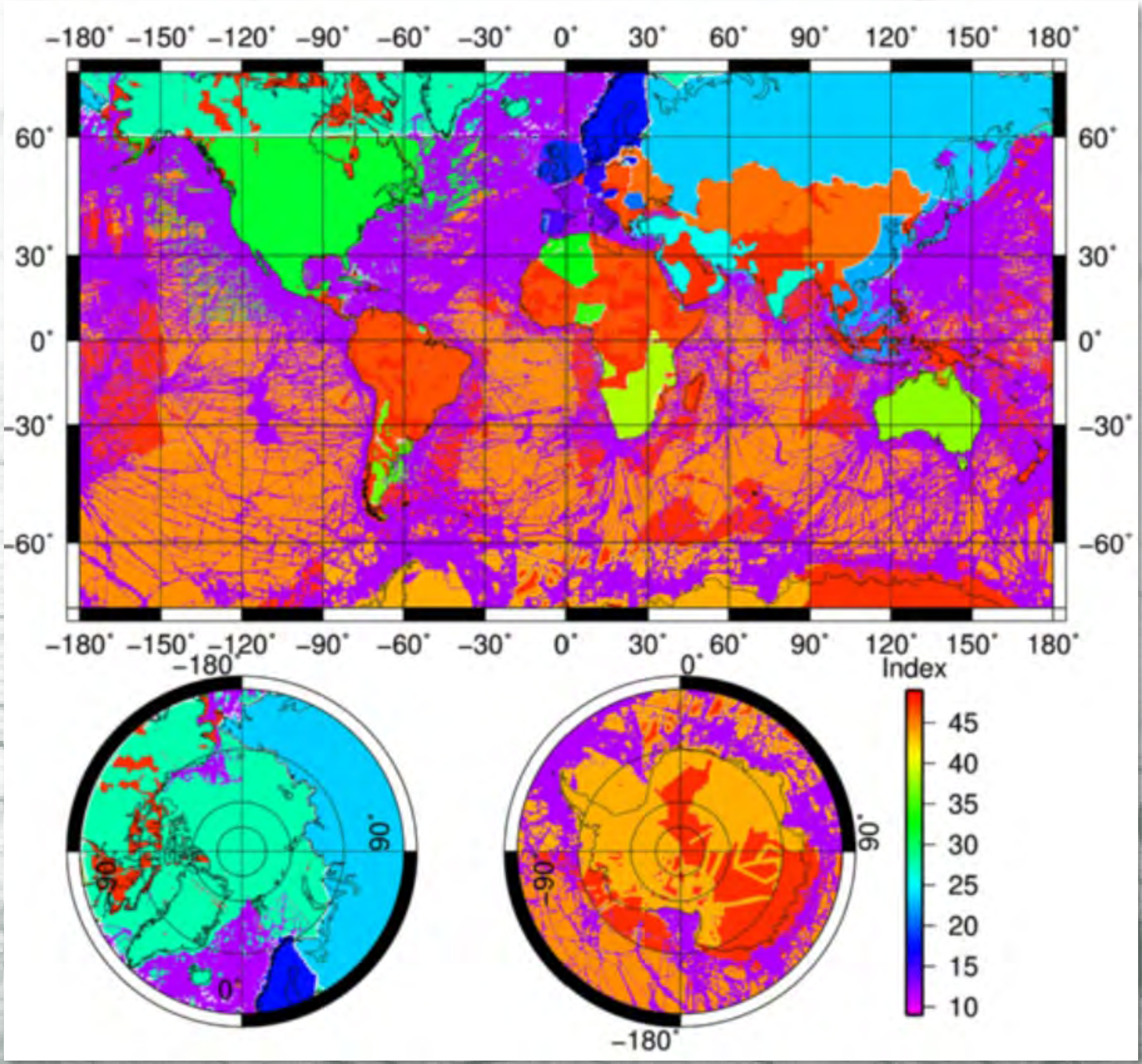
Map coverage and gaps

US Magnetic Survey Coverage



Map coverage and gaps

WDMAM coverage map



Map coverage and gaps

Half way mark – time check

Map/Model Uncertainty

"The only certainty is uncertainty."
- Pliny the Elder

Spherical Harmonic Core (Main) Field Models - Uncertainty

Any numerical model of the geomagnetic field can only be an approximation to the actual field, and we would like to have a reasonable estimate of the magnitude of the errors involved. Such an estimate is particularly necessary if the field model is used in further analysis…

- F.J. Lowes and N. Olsen (2004)

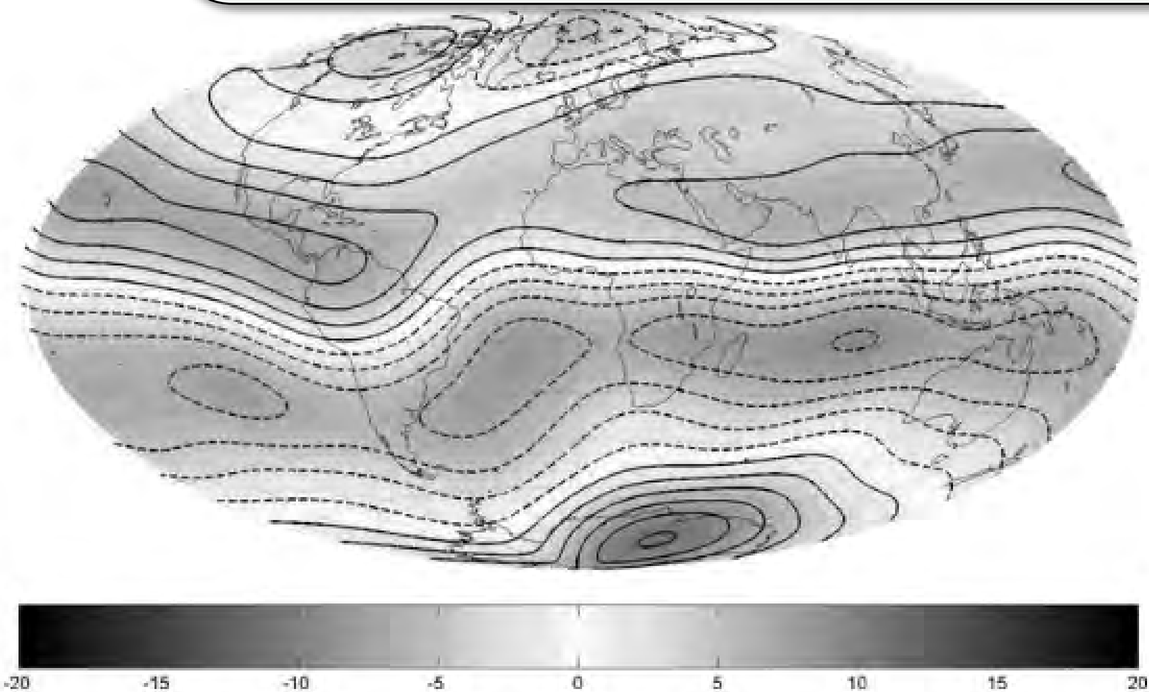
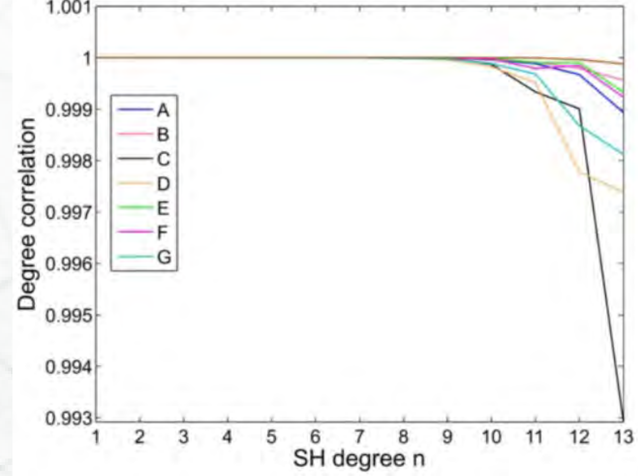


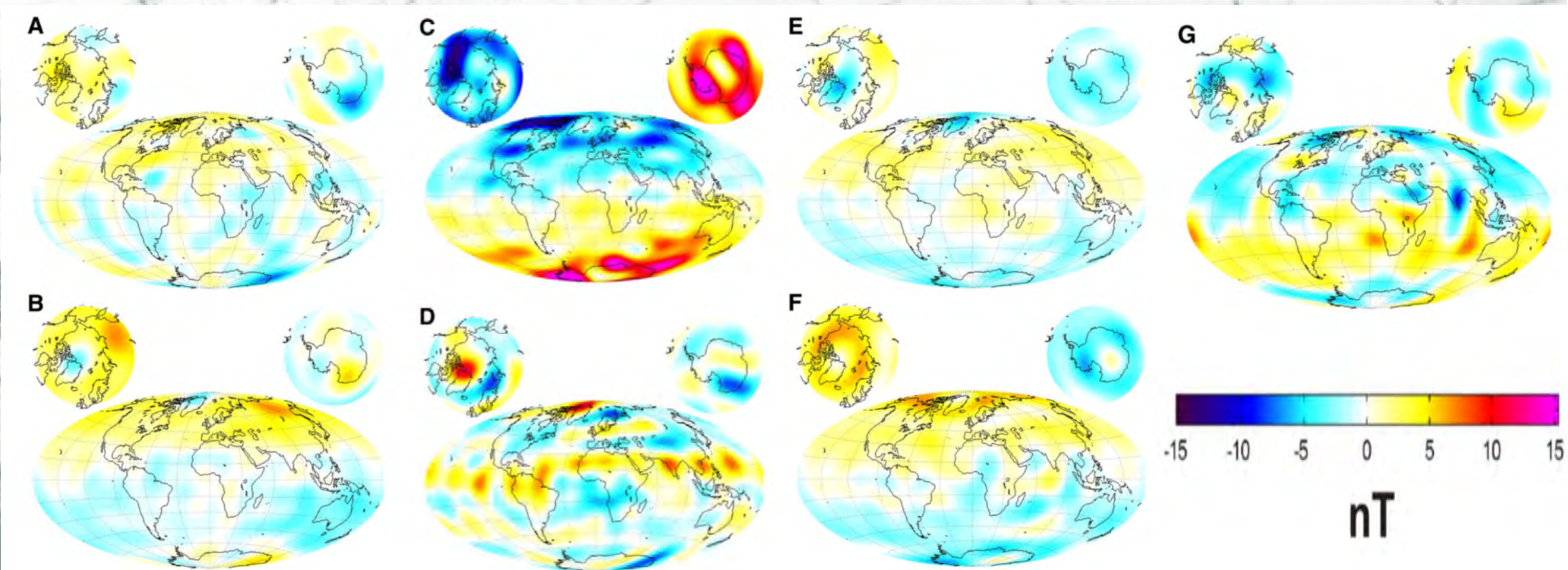
Figure 11. An estimate (truncated to $n = 8$) of the spurious field 'leaked' into the OSVM solution from the average ionosphere. The figure shows the radial component at ground level. Contour interval 2 nT; Hammer projection.

Map/model uncertainty

Variation in Candidate Models for IGRF-12

Nature of uncertainty in satellite spherical harmonic models of the core (main) field.





Thébault *et al. Earth, Planets and Space* (2015) 67:112

Map/model uncertainty

WMM uncertainty analysis

…it is not possible to precisely estimate the WMM2020 uncertainty in every location at the Earth's surface. What is achievable is a global estimate of the uncertainty, based upon a statistical analysis of the differences between the WMM2020 and its predecessors and independent geomagnetic measurements in as many locations as possible at the Earth's surface.

--Chulliat et al., 2020

Table 10: Formal commission errors at Earth's surface.

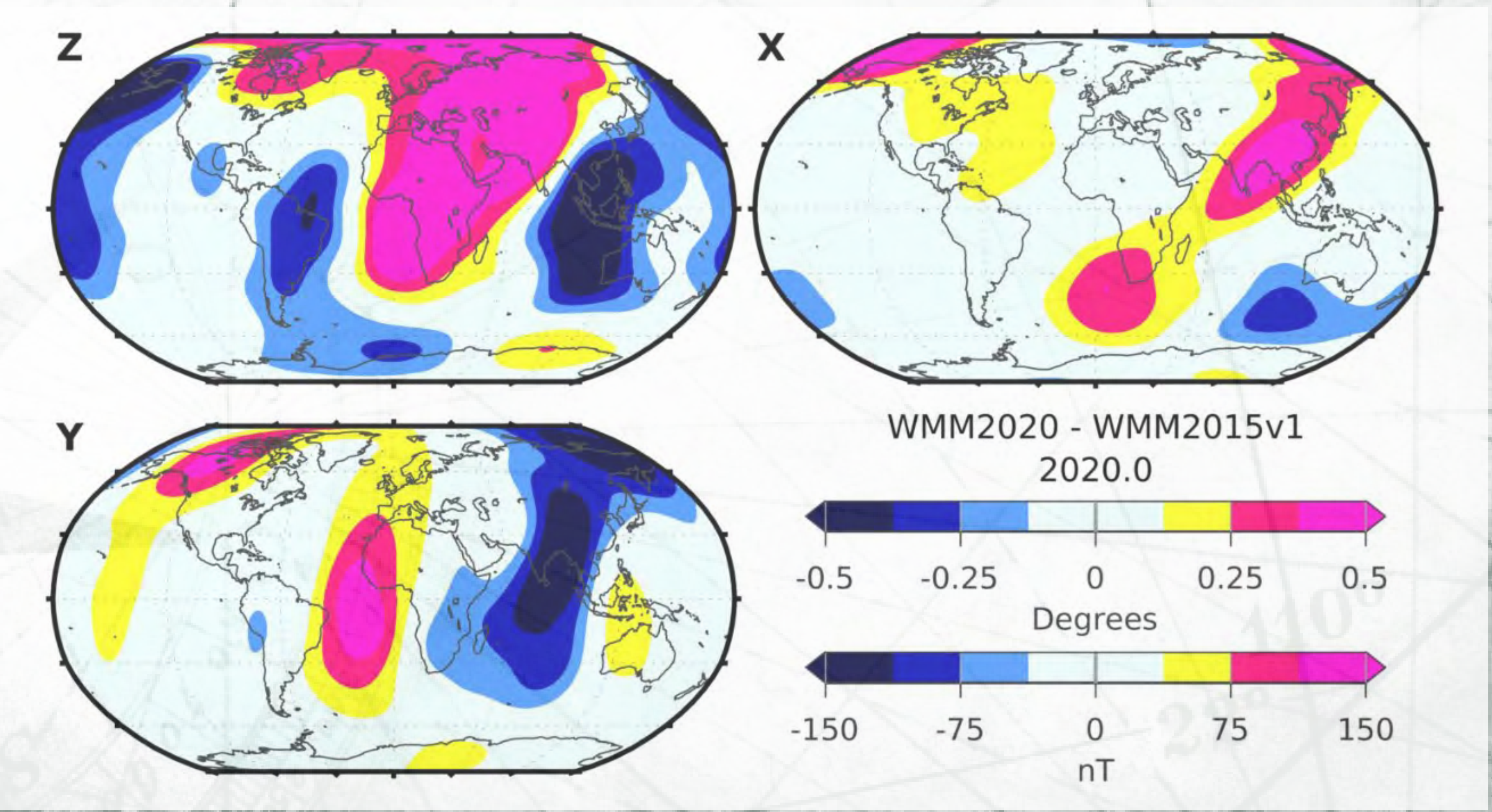
Row		X (nT)	Y (nT)	Z (nT)	H (nT)	F (nT)	I (°)	D (°)	GV (°)
1	Formal commission error at 2020.0	0.13	0.20	0.25	0.13	0.24	0.00	0.00	0.00
2	Formal commission error at 2025.0	0.49	0.76	0.92	0.49	0.88	0.02	0.00	0.02

WMM uncertainty analysis cont.

Table 15: Estimated global RMS errors in WMM2020. Higher values of GV (compared to D) reflect the larger uncertainties of the declination at high latitudes, the only regions where GV is defined. Higher values of GV_N compared to GV_S reflect the faster drift of the north dip pole compared to the south dip pole.

Row		X (nT)	Y (nT)	Z (nT)	H (nT)	F (nT)	I (°)	D (°)	GV (°)	GV_N (°)	GV_S (°)
1	Military specification MIL-W-89500B	N/A	N/A	N/A	200	280	1.00	1.00	N/A	1.00	1.00
2	Commission error at 2020.0	3	3	5	3	4	0.01	0.01	0.03	0.04	0.02
3	Commission error at 2025.0	46	53	84	47	64	0.11	0.20	0.38	0.49	0.21
4	Crustal field omission error	122	83	143	120	126	0.20	0.30	0.51	0.51	0.51
5	Disturbance field omission error	37	23	27	37	29	0.04	0.22	0.44	0.44	0.44
6	Combined error at 2020.0	127	86	146	126	129	0.20	0.37	0.67	0.67	0.67
7	Combined error at 2025.0	135	101	168	134	144	0.23	0.42	0.77	0.83	0.70

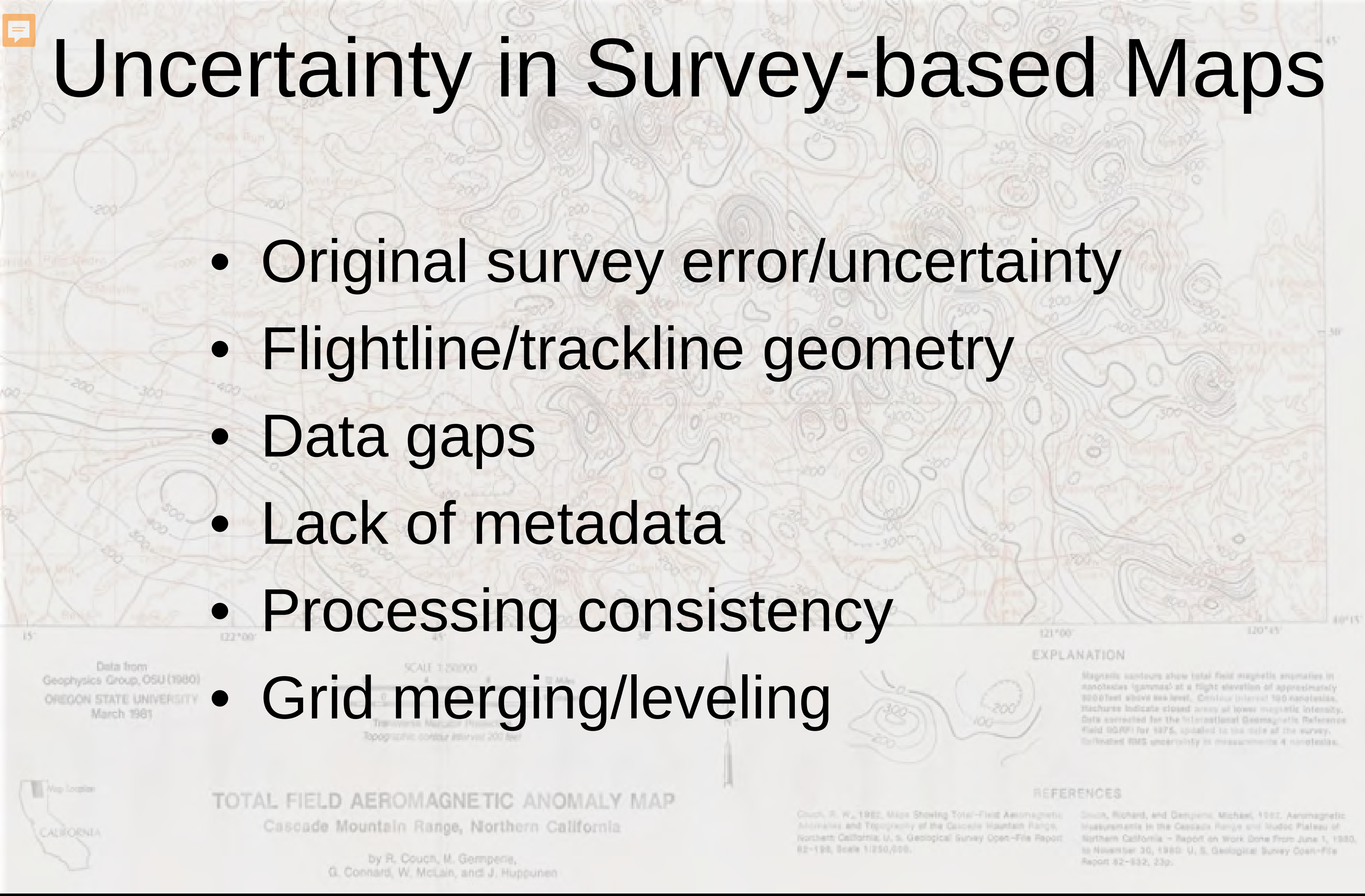
Five-year evolution of core (main) field



Map/model uncertainty

Uncertainty in Survey-based Maps

- Original survey error/uncertainty
- Flightline/trackline geometry
- Data gaps
- Lack of metadata
- Processing consistency
- Grid merging/leveling



EMAG2v3 Pre-compiled grid uncertainty estimates

SE = Survey level “errors”

GE = Gridding errors

RE = Regional errors

$$MEAN = SE_{mean} + GE_{mean} + RE_{mean}$$

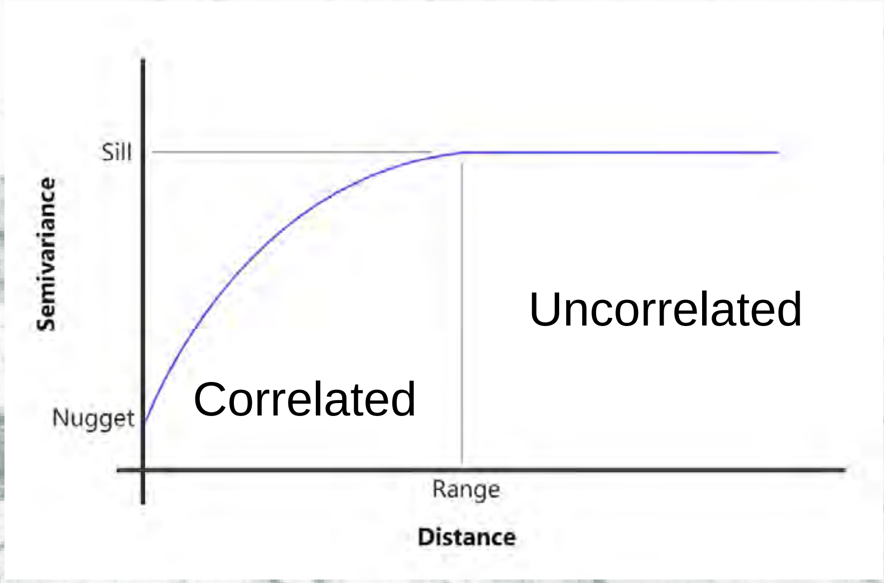
$$STDEV = \sqrt{(SE_{std}^2 + GE_{std}^2 + RE_{std}^2)}$$

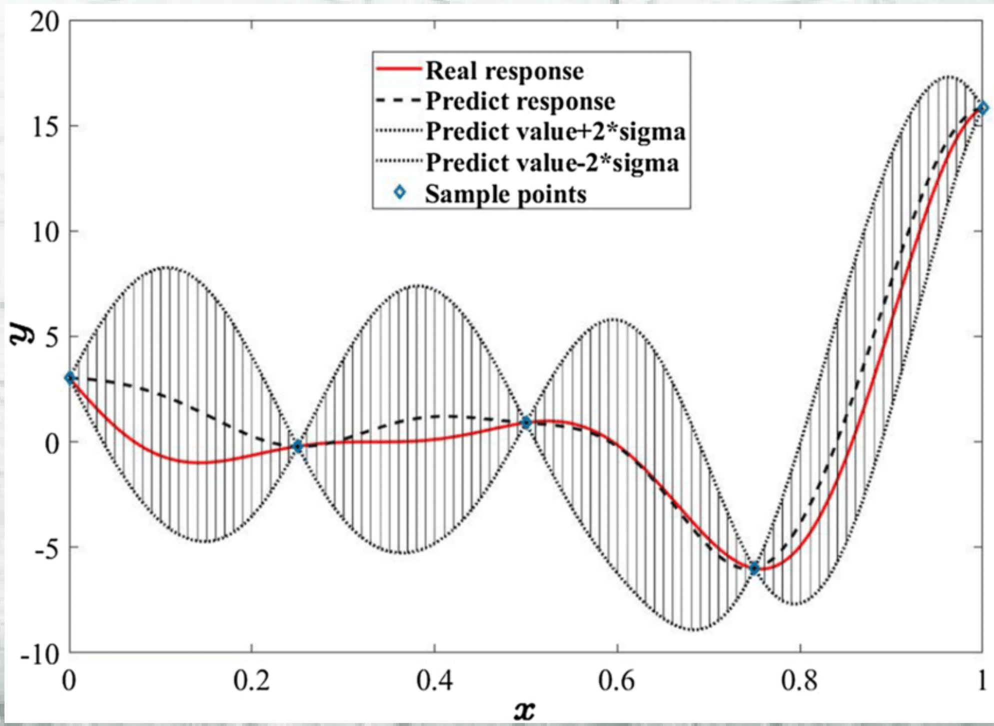
Pre-compiled grid uncertainty estimates

Table 2
List of Contributing Pre-Compiled Continental Grids With Source Contributor, Altitude, Altitude Type (Barometric = Constant Altitude; Topographic = Variable aka "draped" Altitude), Resolution, Total Error, Mean, and Standard Deviation

Region	Source contributor	Altitude (m)	Altitude type	Resolution	Total error (nT)	MEAN (nT) bias	STD (nT) precision
Europe	Wonik et al. (2001)	3,000	Barometric	5 km	59	35	47
Northern hemisphere	Verhoef et al. (1996)	300	Topographic	5 km	100	62	78
Middle east	Mostly Iran	300	Topographic	5 km	231	135	188
East Asia	Coordinating Committee for Coastal and Offshore Geoscience Program in East and Southeast Asia (CCOP) compilation 2002	300	Topographic	5 km	217	127	175
Former Soviet Union	National Centers for Environmental Information (NOAA NCEI) archives	300	Topographic	5 km	95	57	77
India	Rajaram et al. (2006)	0	Topographic	50 km	178	106	143
Global	GETECH global data compilation	300	Topographic	15 min	116	70	93
France	Institut de Physique du Globe de Paris	3000	Barometric	10 km	189	112	153
Spain	Socias et al. (1991)	3000	Barometric	5 km	217	127	175
South Africa	South African Development Community (SADC) compilation	300	Topographic	5 km	155	93	124
Tanzania	National Centers for Environmental Information (NOAA NCEI) archives	100	Topographic	5 km	164	97	132
Fennoscandia	Geological Survey of Finland (GTK); Korhonen et al. (2007)	5,000	Barometric	5 km	96	58	77
Italy	Eni Italy	2,500	Barometric	5 km	176	104	142
Canary Islands	Instituto Geografico Nacional (IGN); Socias and Mezcua (1991)	3,200	Barometric	5 km	214	126	173
Argentinia offshore	Max *et al.*, 1999	5,000	Barometric	5 km	214	126	173
Argentina onshore	Servicio Geologico Minero Argentino (SEGEMAR)	5,000	Barometric	5 km	214	126	173
Eurasia	National Centers for Environmental Information (NOAA NCEI) archives	300	Topographic	20 km	214	126	173

Kriging
(aka Gaussian process regression or Wiener-Kolmogorov prediction)





Three factor (Wang et al., 2014) grid cell uncertainty model

$$\sigma_T = \sqrt{E_m^2 + \sigma_s^2 + \sigma_u^2}.$$

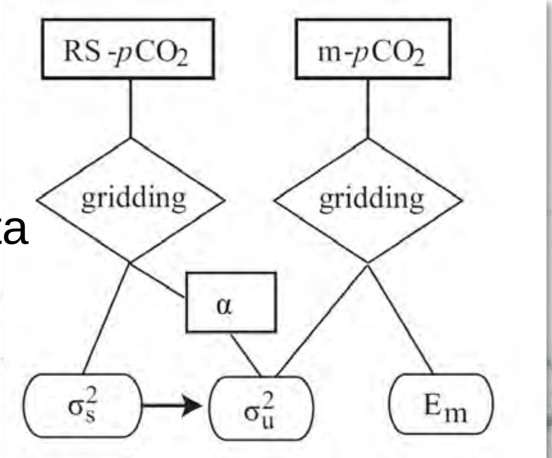
E_m = Calculated weighted uncertainty (standard lab methodology)

$$\sigma_s^2 = \frac{1}{N}\sum_{i=1}^{N}(P_i - \overline{P})^2$$

Use standard deviation of cell data (weighted in our application)

$$\sigma_u^2 = (\alpha \times \sigma_s^2)/(f \times K)$$

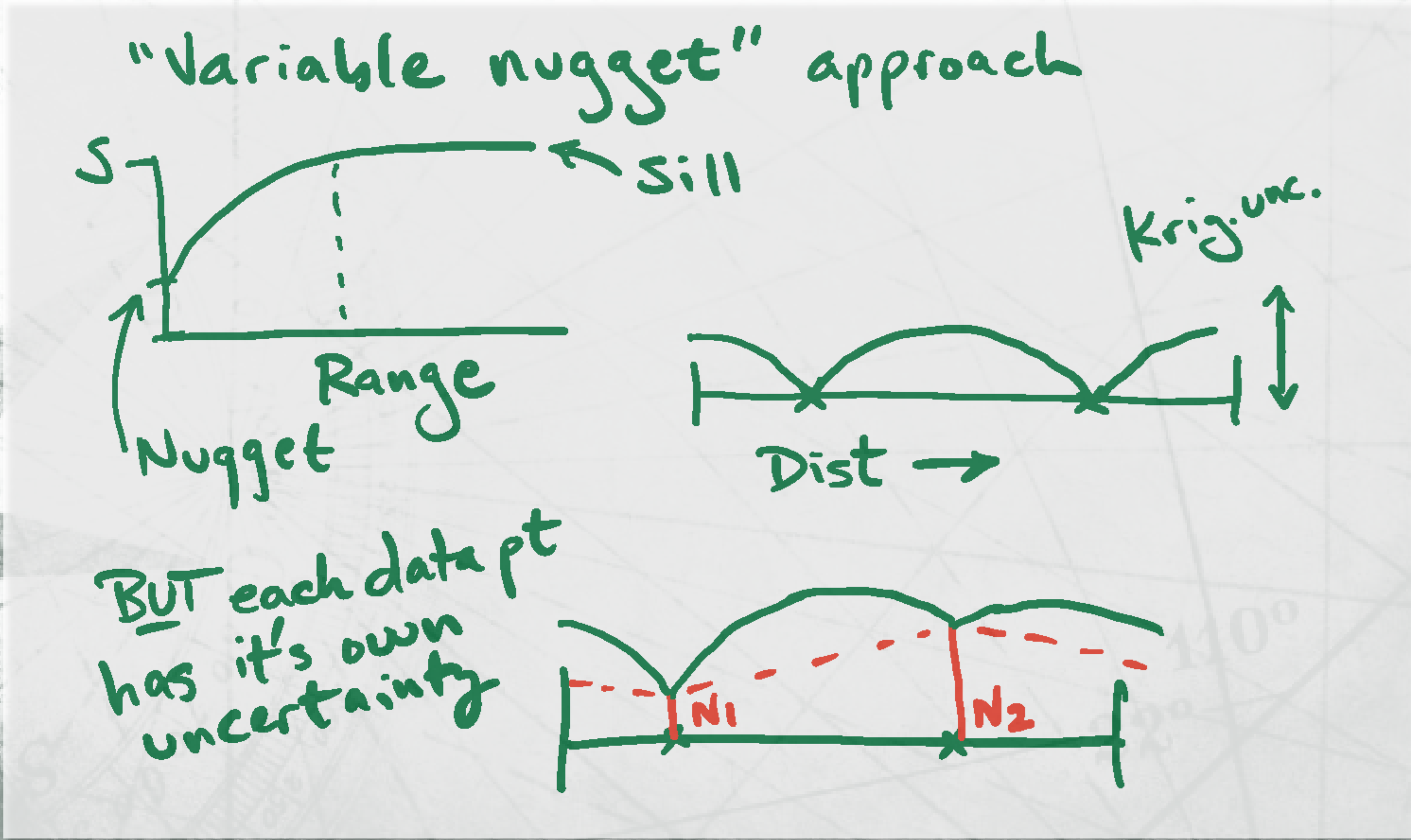
Find *f* as percentage of subcells with data
K is # data values in cell
Alpha (α) relates to consistency of standard deviation within a grid cell



Quantifying uncertainty sources in the gridded data of sea surface CO_2 partial pressure

Guizhi Wang[1,2], Minhan Dai[1,2], Samuel S. P. Shen[3], Yan Bai[4], and Yi Xu[1]

Adding cell and kriging uncertainties



Magnetic map uncertainty-crustal anomalies

- On-going research and development in support of alternate positioning/magnetic navigation
- Work at CIRES/NOAA supported by NGA and ONR
- Cooperating with AFIT, PSU, NRL, etc.
- Current active map areas – USVI and N Atlantic

Quiz – Question 4

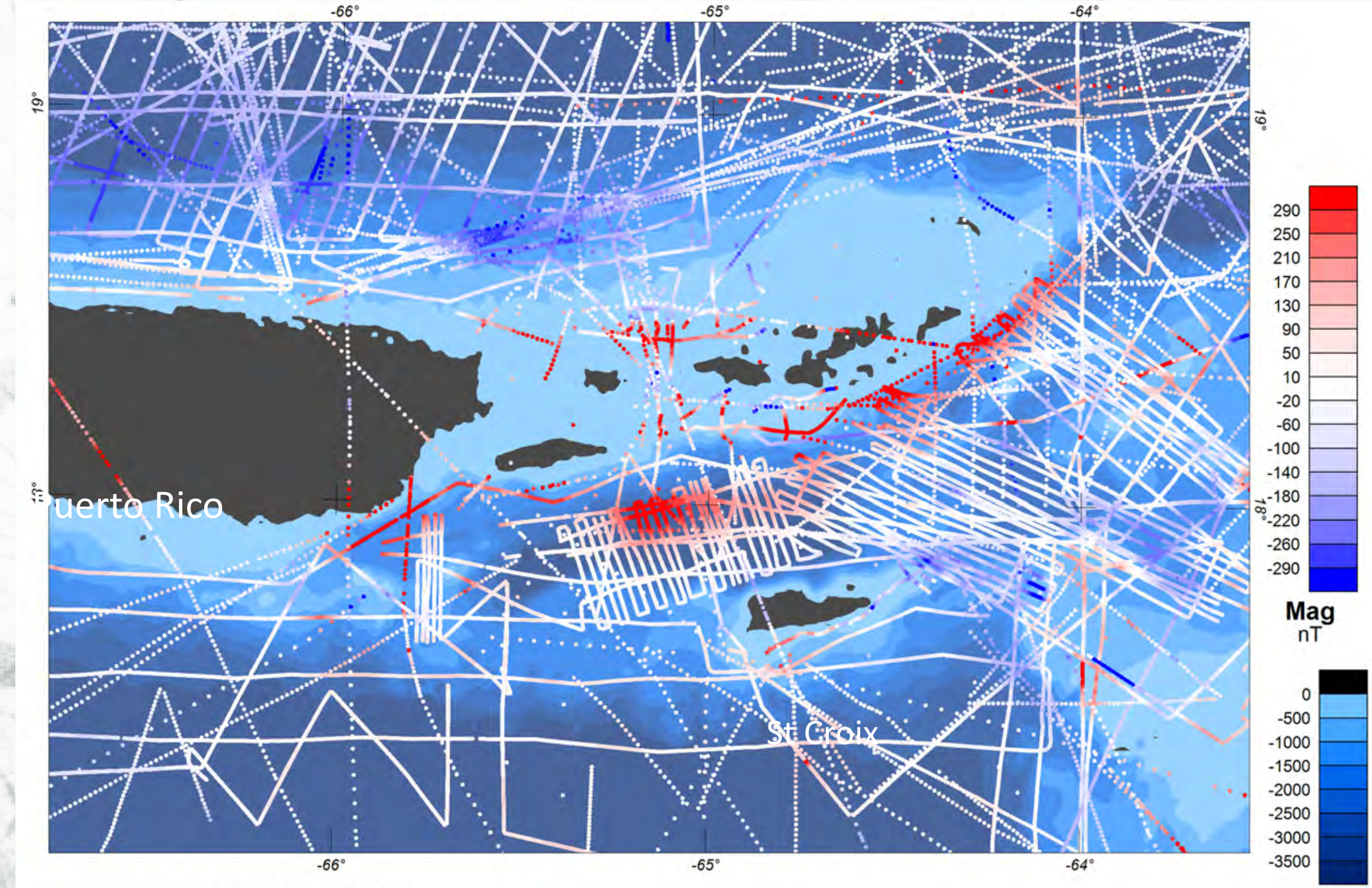
What is a magnetic anomaly?

Quiz – Question 4

A magnetic anomaly is a deviation from the expected or normal strength and direction of the Earth's magnetic field at a particular location. These anomalies can be caused by variations in the magnetic properties of the rocks and minerals beneath the Earth's surface, such as differences in their magnetization, composition, or temperature.

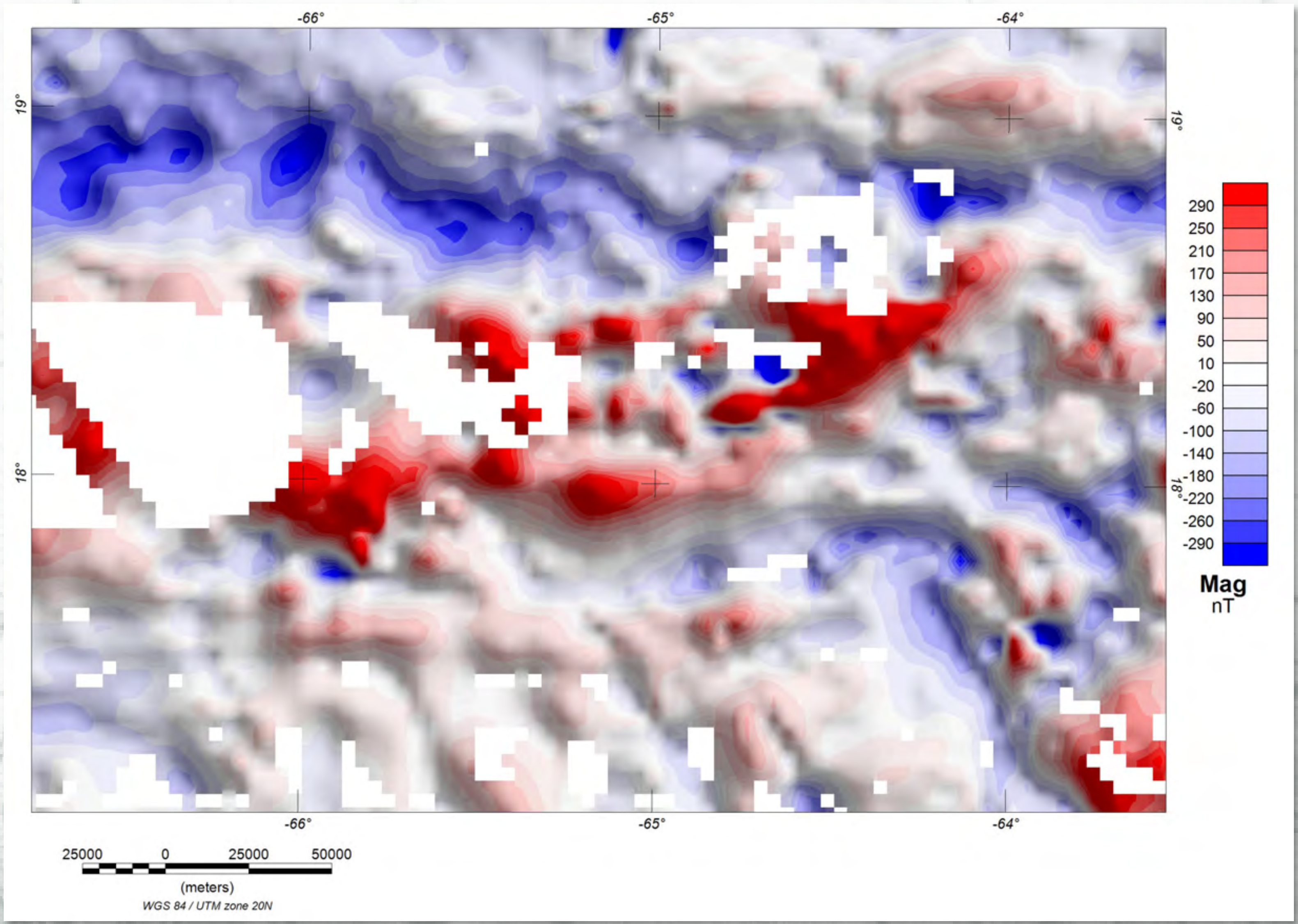
--- ChatGPT

CANREx experiment: data analysis and results



Regional bathymetry – Trackline magnetic data

CANREx data analysis and results – gridded mag anomaly



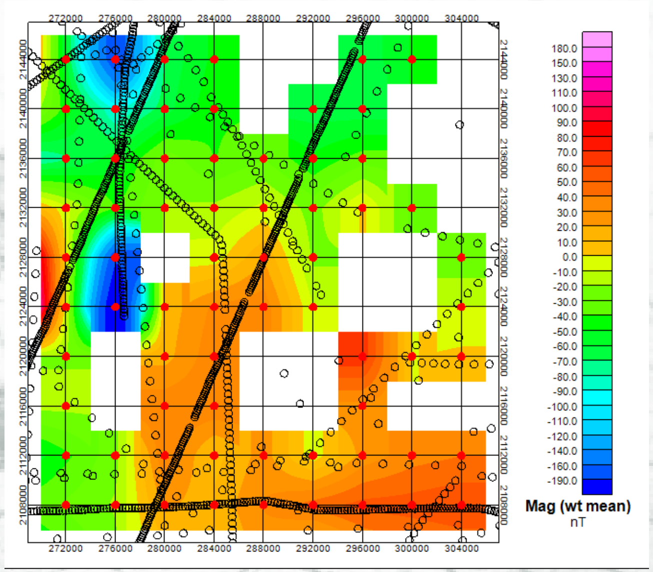
Map/model uncertainty

Uncertainty model (review)

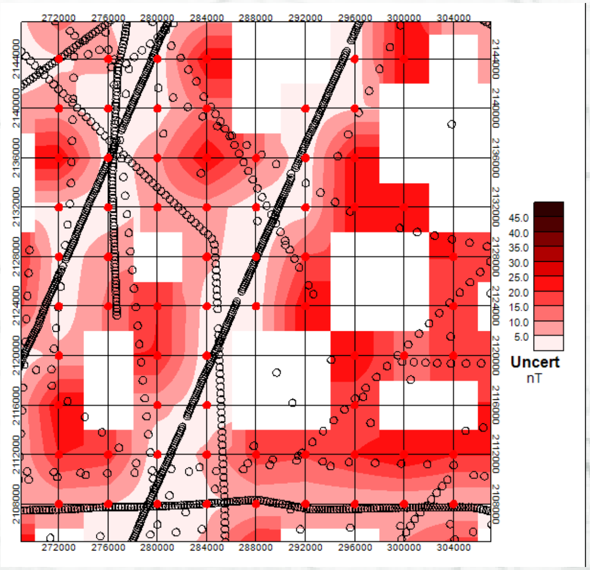
- Assign point-wise uncertainty values to original trackline data
- Define a data grid (4 km with 1333 m subgrid – EMAG2 resolution)
- For grid and subgrid cells with data calculate:
  - Weighted Average (μ_w)
  - Propagated uncertainty of the weighted average (E_m)
  - (Weighted) Standard deviation of data (σ_s)
  - Number of data points (n)
- Calculate the 3 components of Wang et al 2014 grid cell uncertainty:
  - E_m = propagated uncertainty of cell weighted average
  - σ_s = Standard deviation of data within the cell
  - σ_u = sqrt ($(1 + \sigma_s^2)$/((xsubcells/9) * numpts))
- Total cell uncertainty = sqrt ($E_m^2 + \sigma_s^2 + \sigma_u^2$) (Wang et al, 2014)
- Create an interpolated total cell uncertainty grid using linear grid filling
- Use the kriging methodology to calculate weighted average and uncertainty grids
  - Use a spherical variogram with Nugget = 0, Range = 60 km, Sill = 100 nT
- Calculate final uncertainty as sum of interpolated cell uncertainty and kriging uncertainty

Grid Stats Uncertainty Calculation

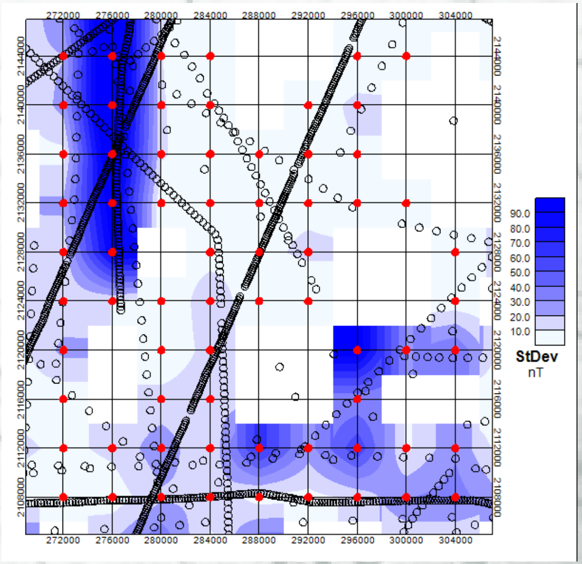
Propagation of uncertainty from survey point data to grid cell values



Weighted Mean

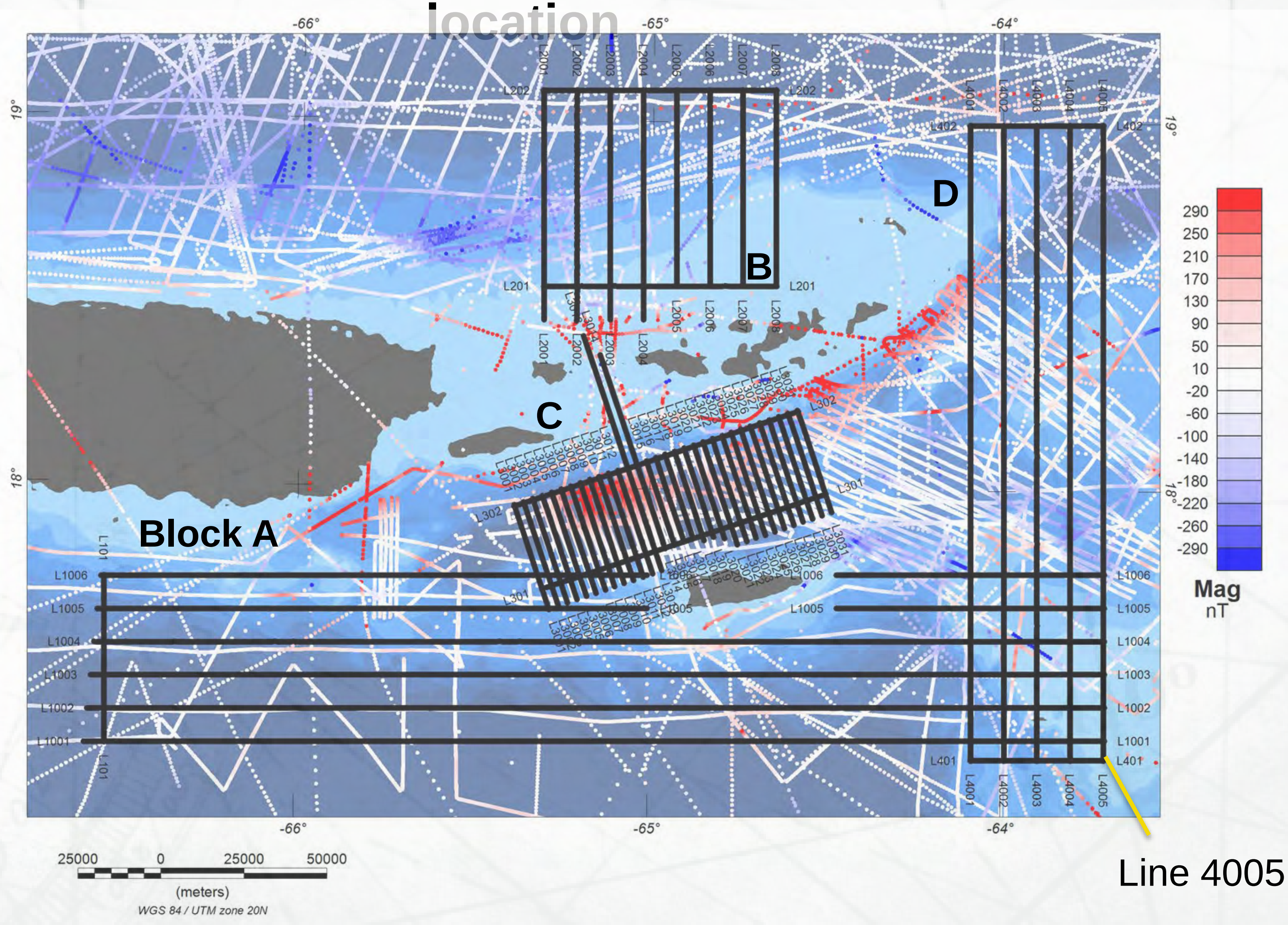


Uncertainty of the Weighted Mean



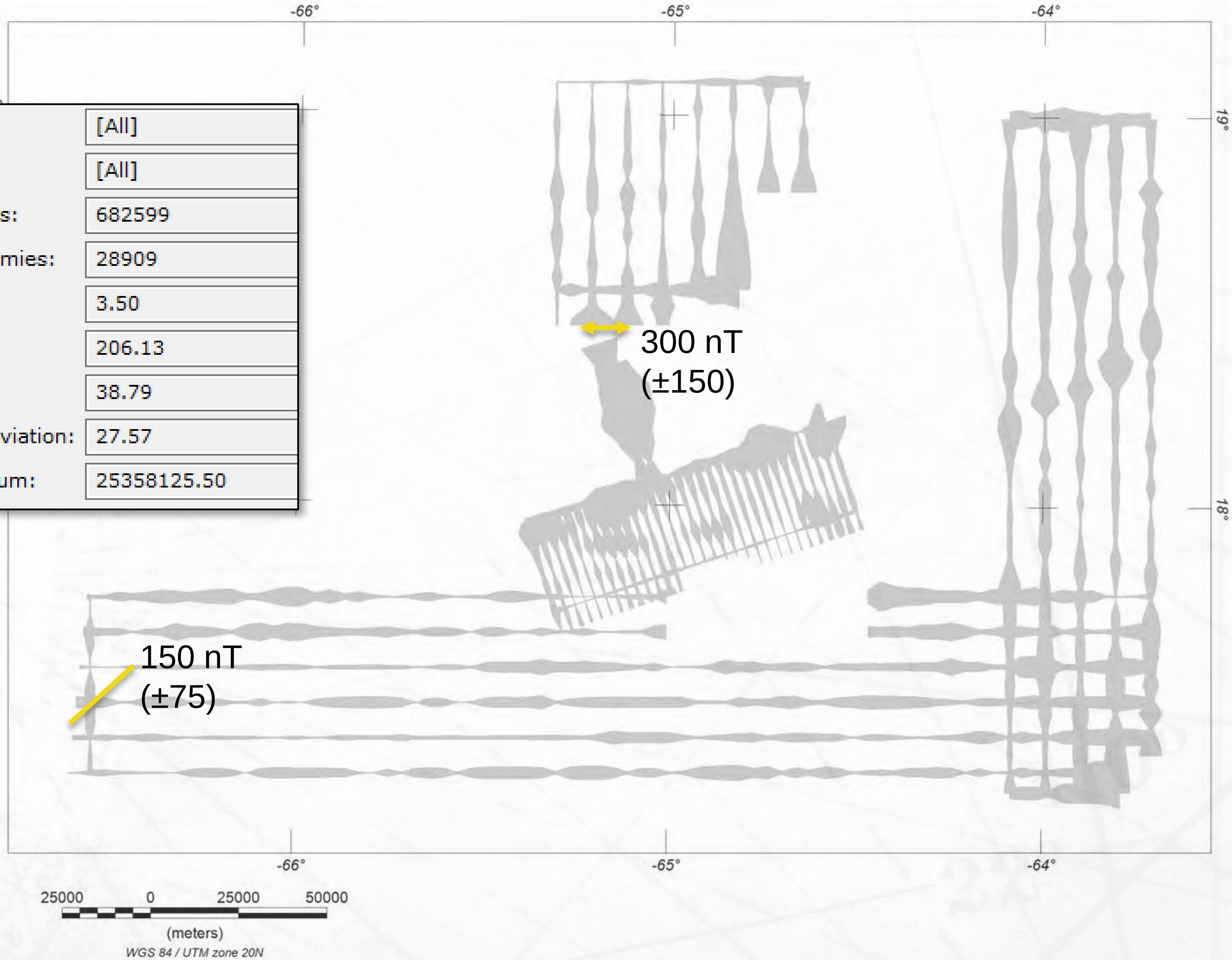
Standard Deviation of data within cell

CANREx data analysis and results – SGL test profile location



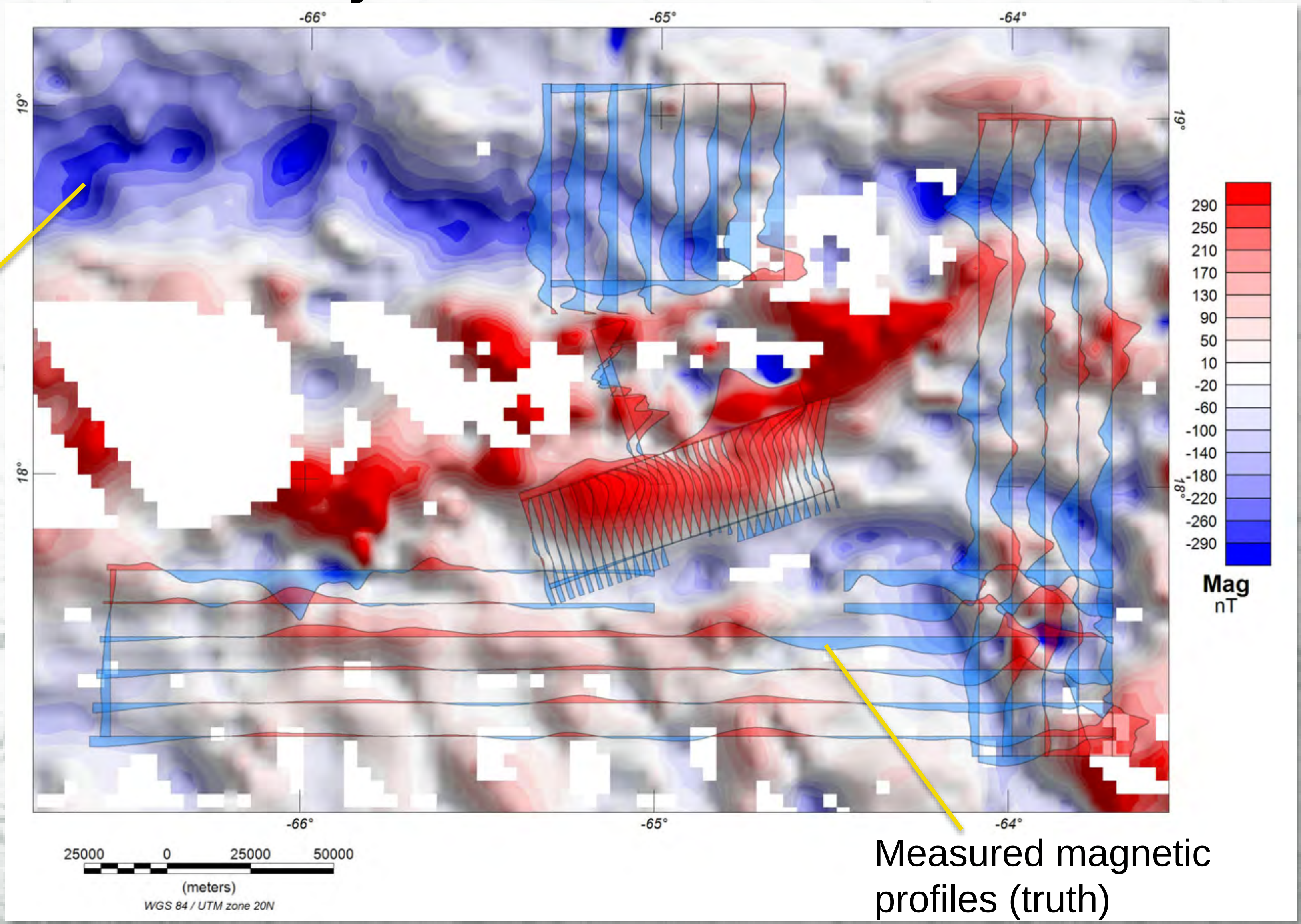
CANREx data analysis and results – uncertainty along SGL lines

Line(s):	[All]
Fid Range:	[All]
Num of items:	682599
Num of dummies:	28909
Minimum:	3.50
Maximum:	206.13
Mean:	38.79
Standard deviation:	27.57
Arithmetic sum:	25358125.50



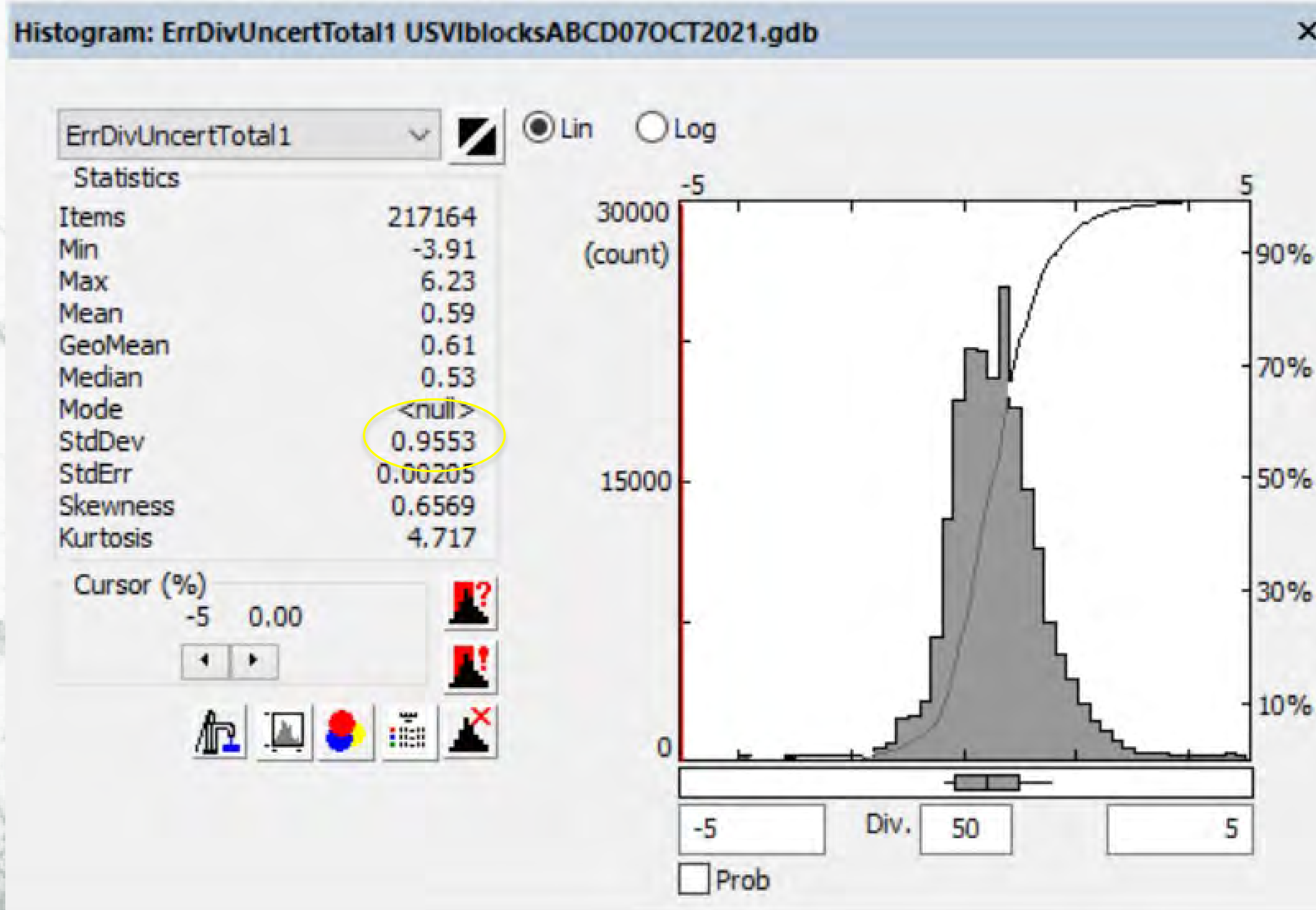
CANREx data analysis and results – SGL test data

Gridded trackline magnetic data (model)

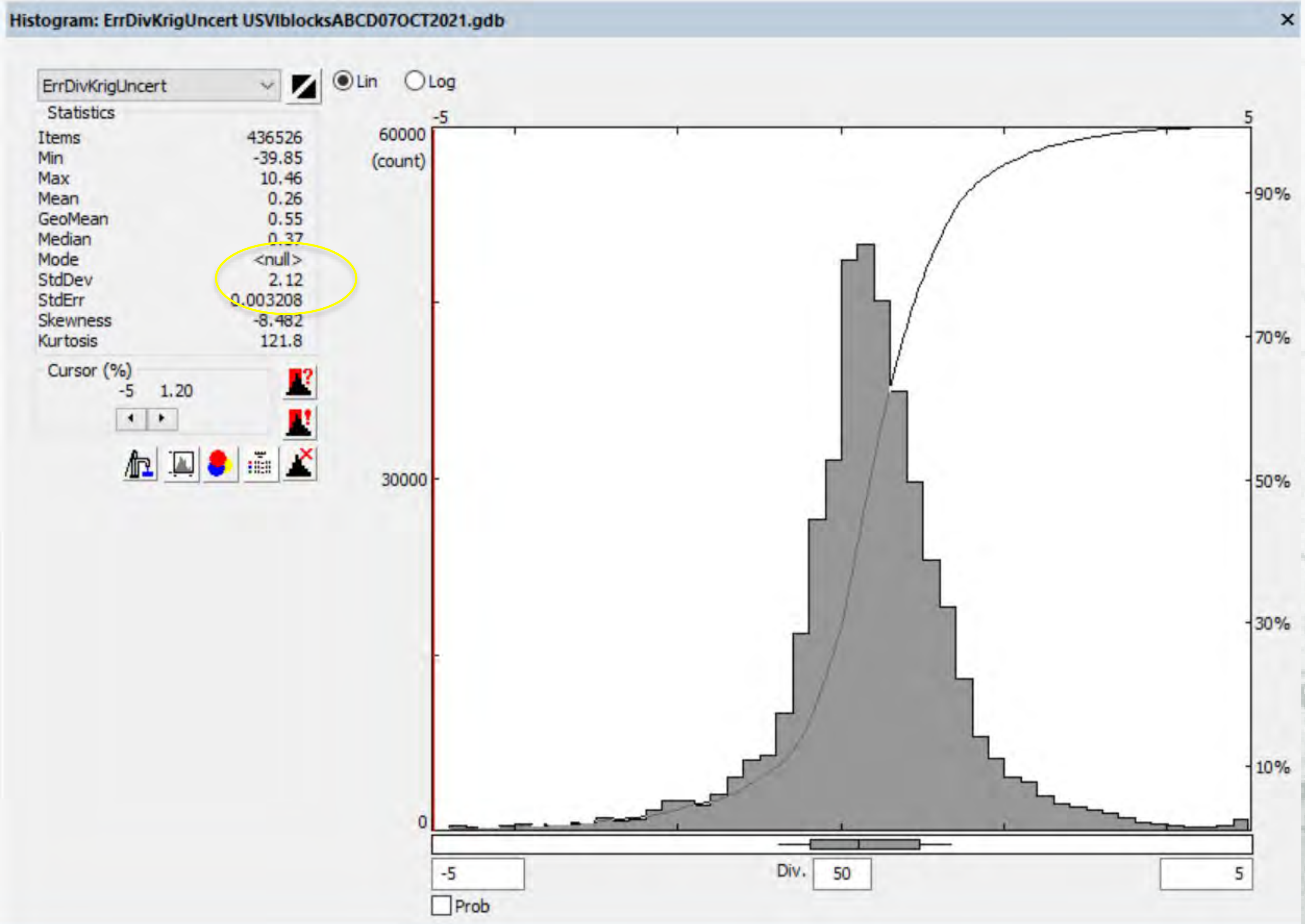


Measured magnetic profiles (truth)

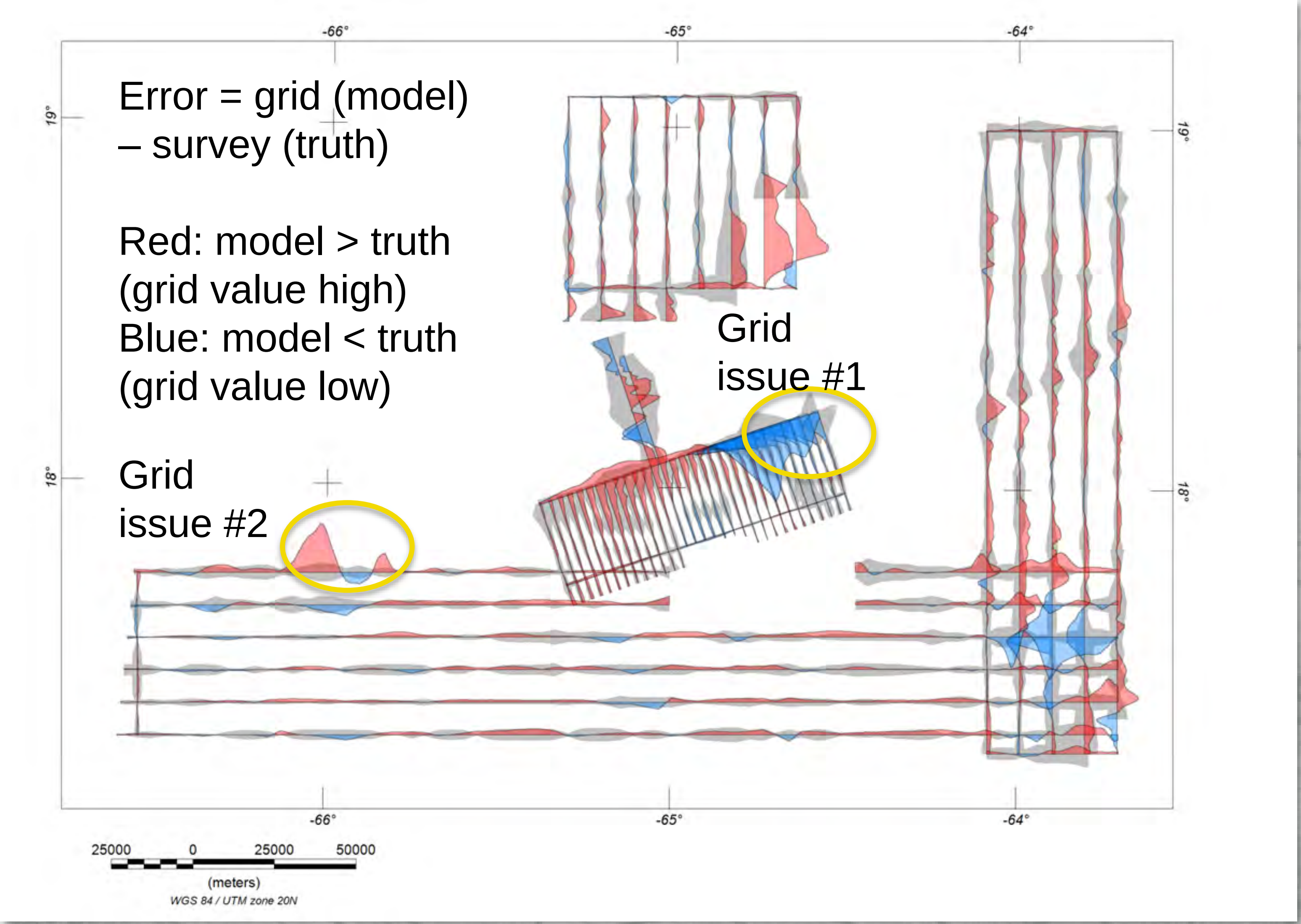
CANREx data analysis – lines traverse cells with data (Wang uncertainty)



CANREx data analysis – all interpolated cell uncertainties

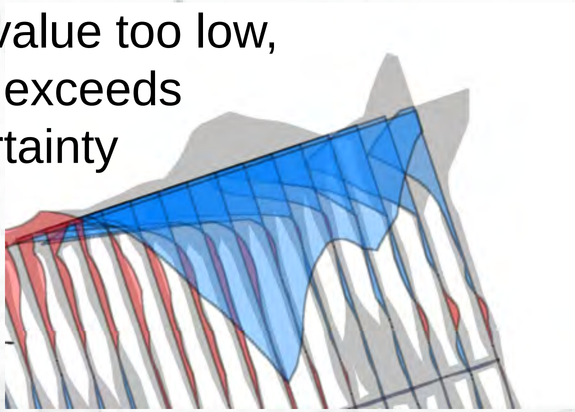


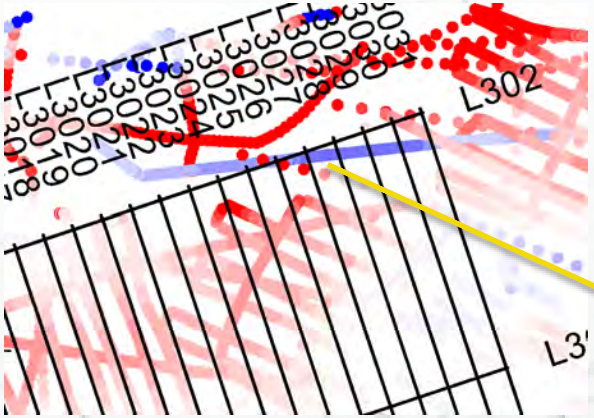
CANREx data analysis and results – error along SGL test profiles



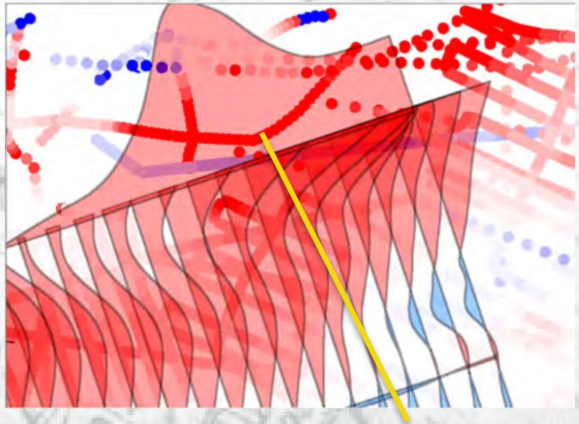
CANREx data analysis – isolated gridded data issue #1

Grid value too low,
Error exceeds
uncertainty

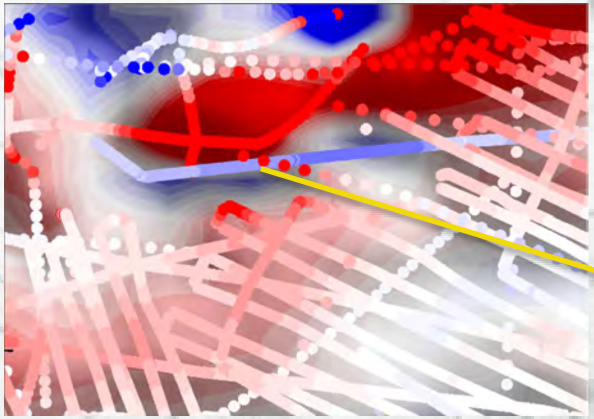




Bad
trackline
level



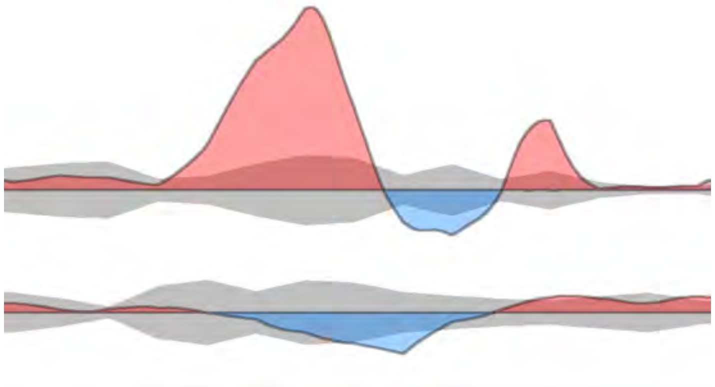
Survey measures
high value

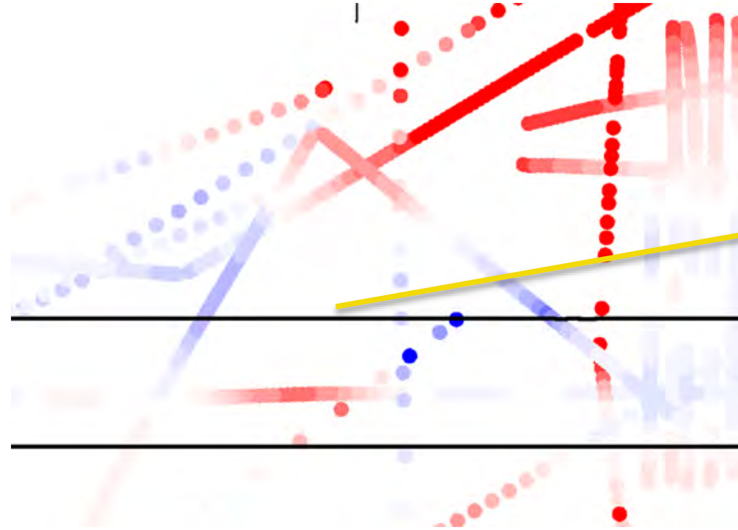


Grid has
low value
based on
bad
trackline

CANREx data analysis – isolated gridded data issue #2

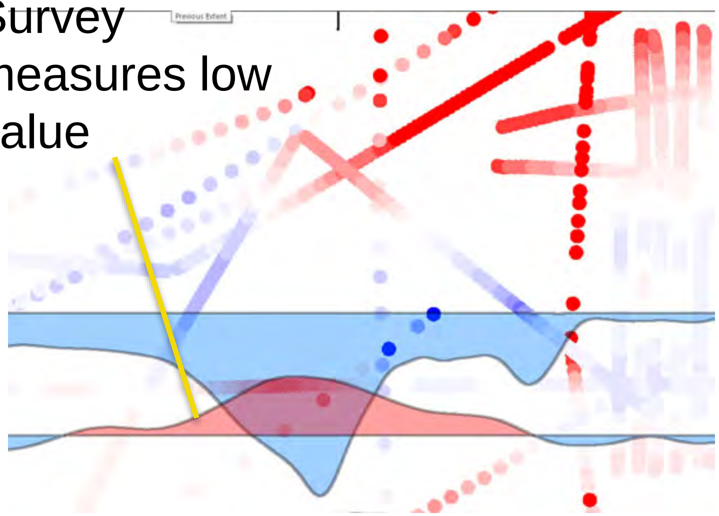
Grid value too high,
Error exceeds uncertainty

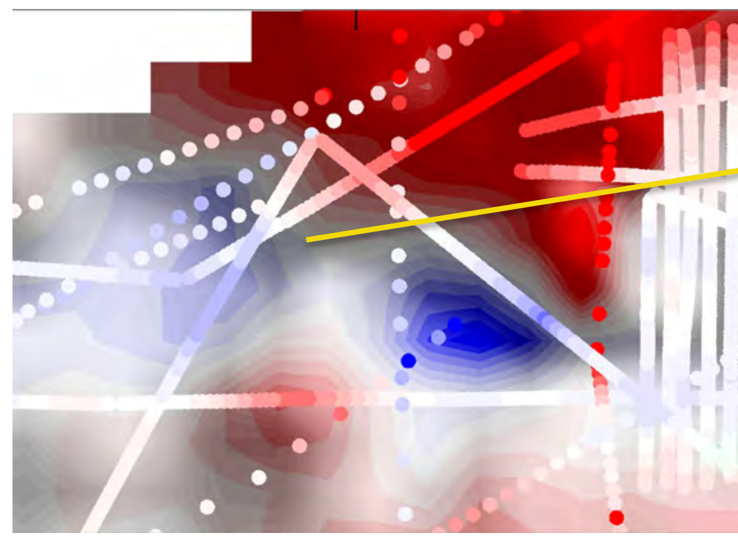




"Saddle" issue with gridding: Connect north-south highs or east-west lows?

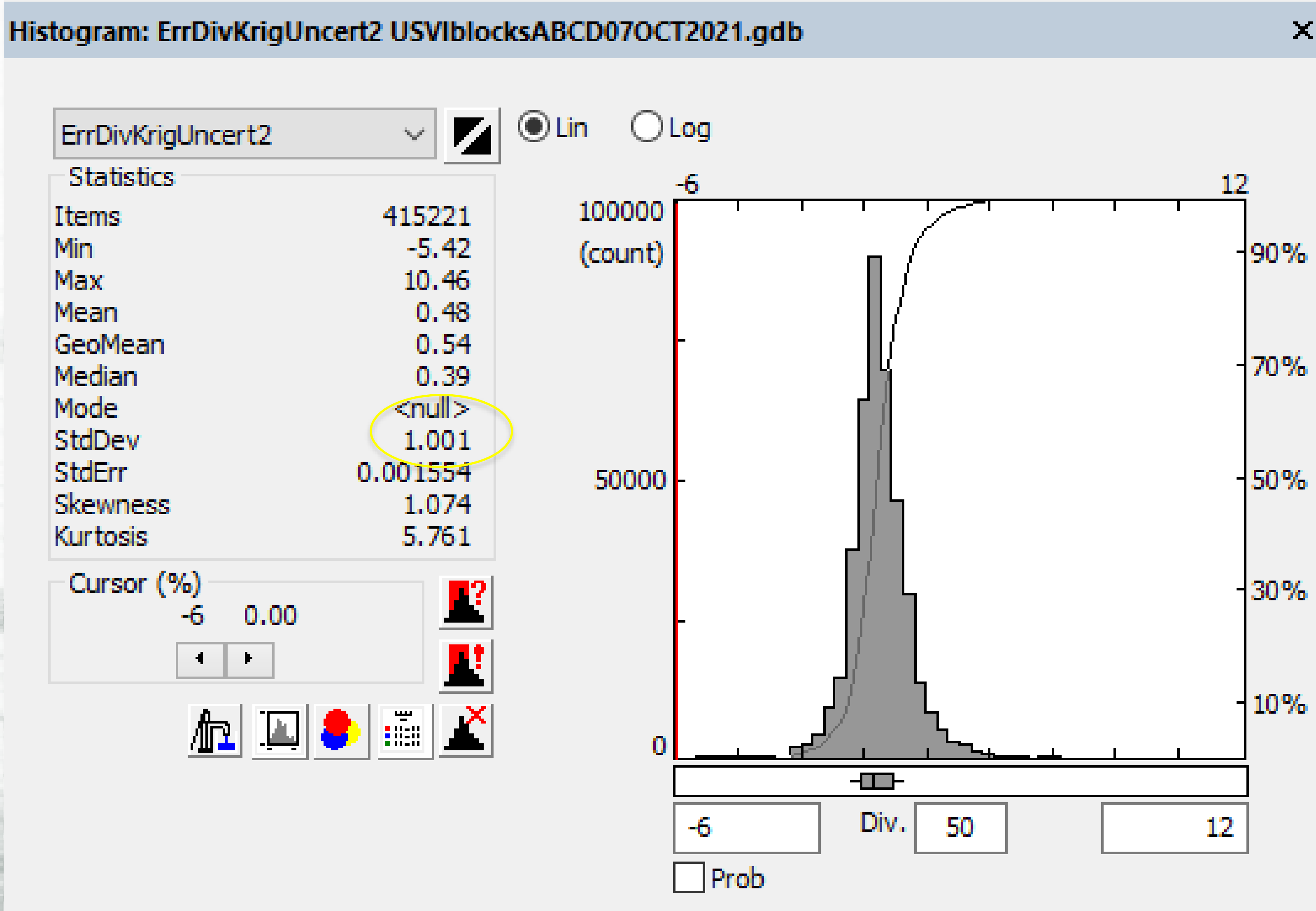
Survey measures low value

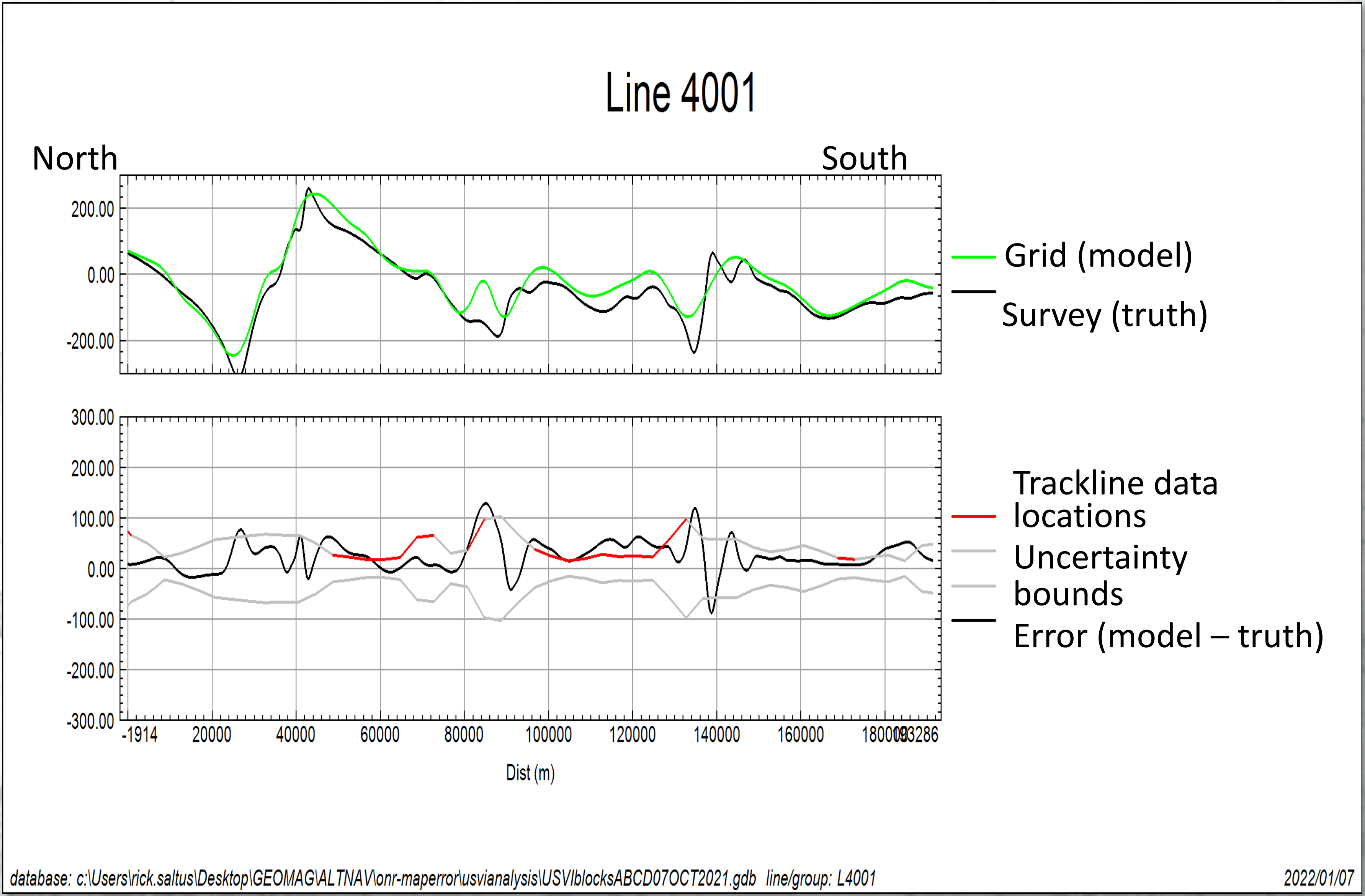




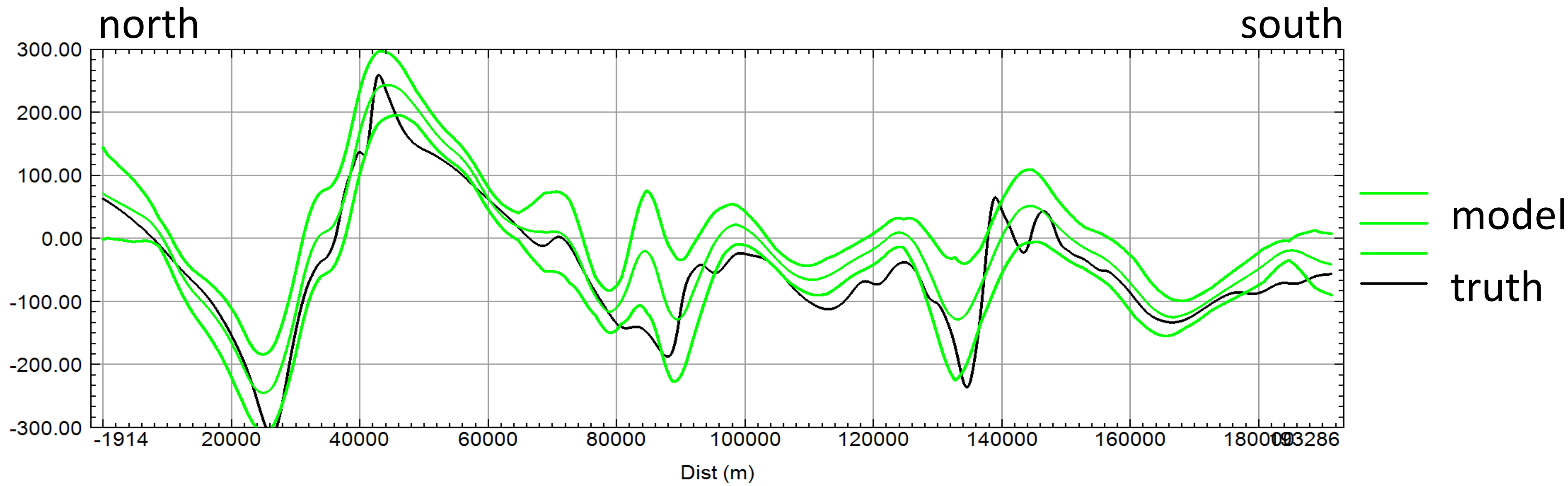
Grid has high saddle – trackline geometry a factor

CANREx data analysis – interpolated cells with outlier exclusion

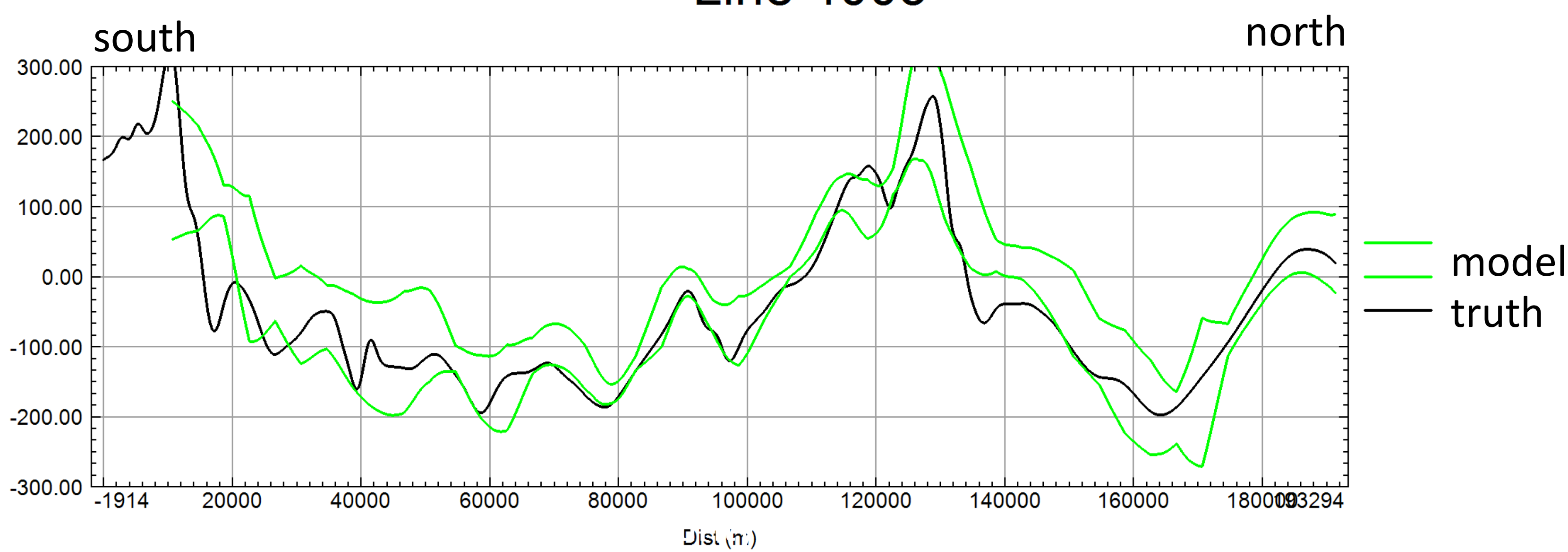



Line 4001
North
South
200.00
0.00
-200.00
Grid (model)
Survey (truth)
300.00
200.00
100.00
0.00
-100.00
-200.00
-300.00
-1914
20000
40000
60000
80000
100000
120000
140000
160000
180000
193286
Dist (m)
Trackline data locations
Uncertainty bounds
Error (model – truth)
database: c:\Users\rick.saltus\Desktop\GEOMAG\ALTNAV\onr-maperror\usvianalysis\USVIblocksABCD07OCT2021.gdb line/group: L4001
2022/01/07

Line 4001B

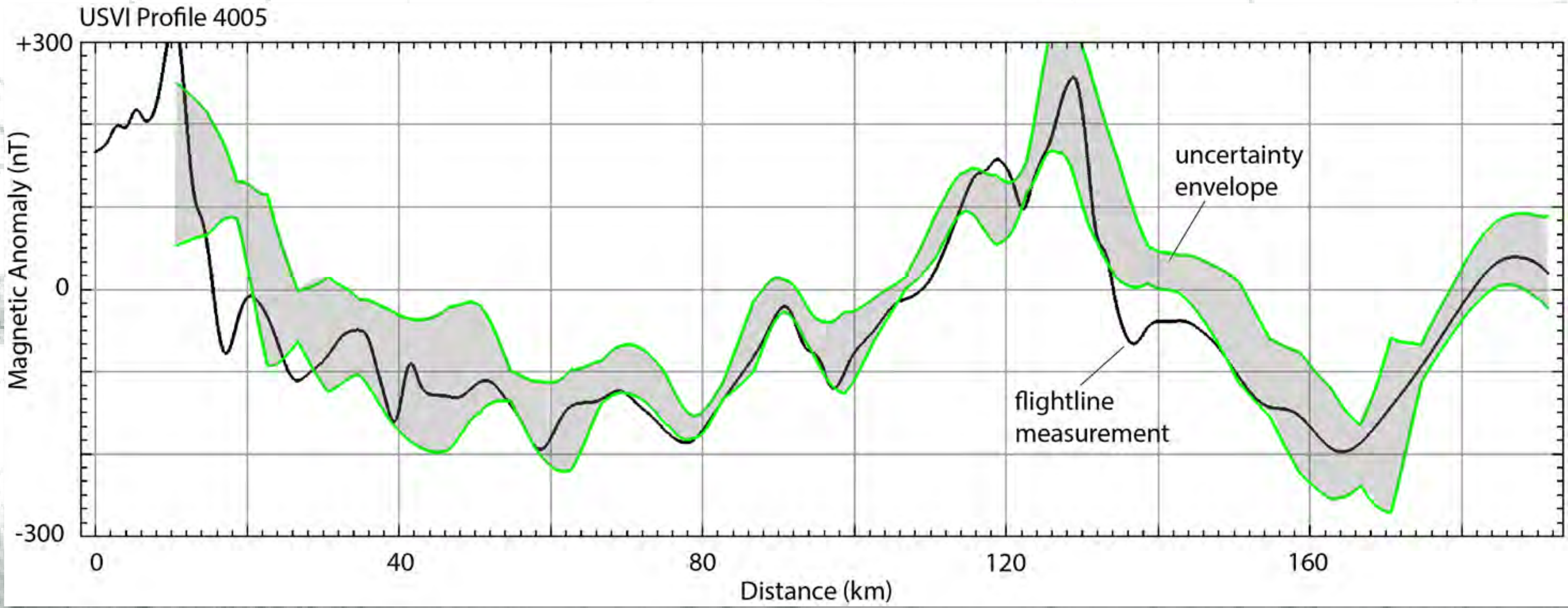


Line 4005

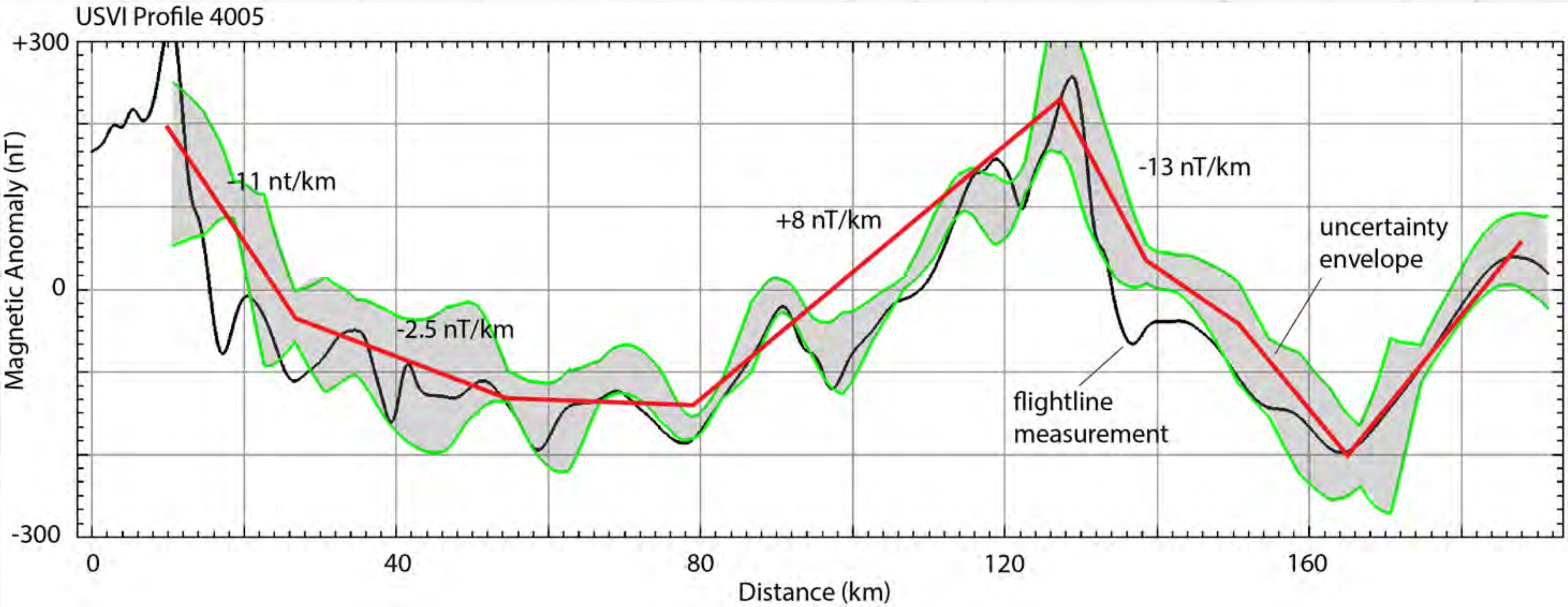


Use of magnetic uncertainty model in magnetic navigation (ideas and discussion)

- Flight data lies generally within uncertainty envelope
- True field varies smoothly within uncertainty envelope
- Overall signal greater than noise
- Best overall fit of flight data to uncertainty envelope cannot be shifted horizontally

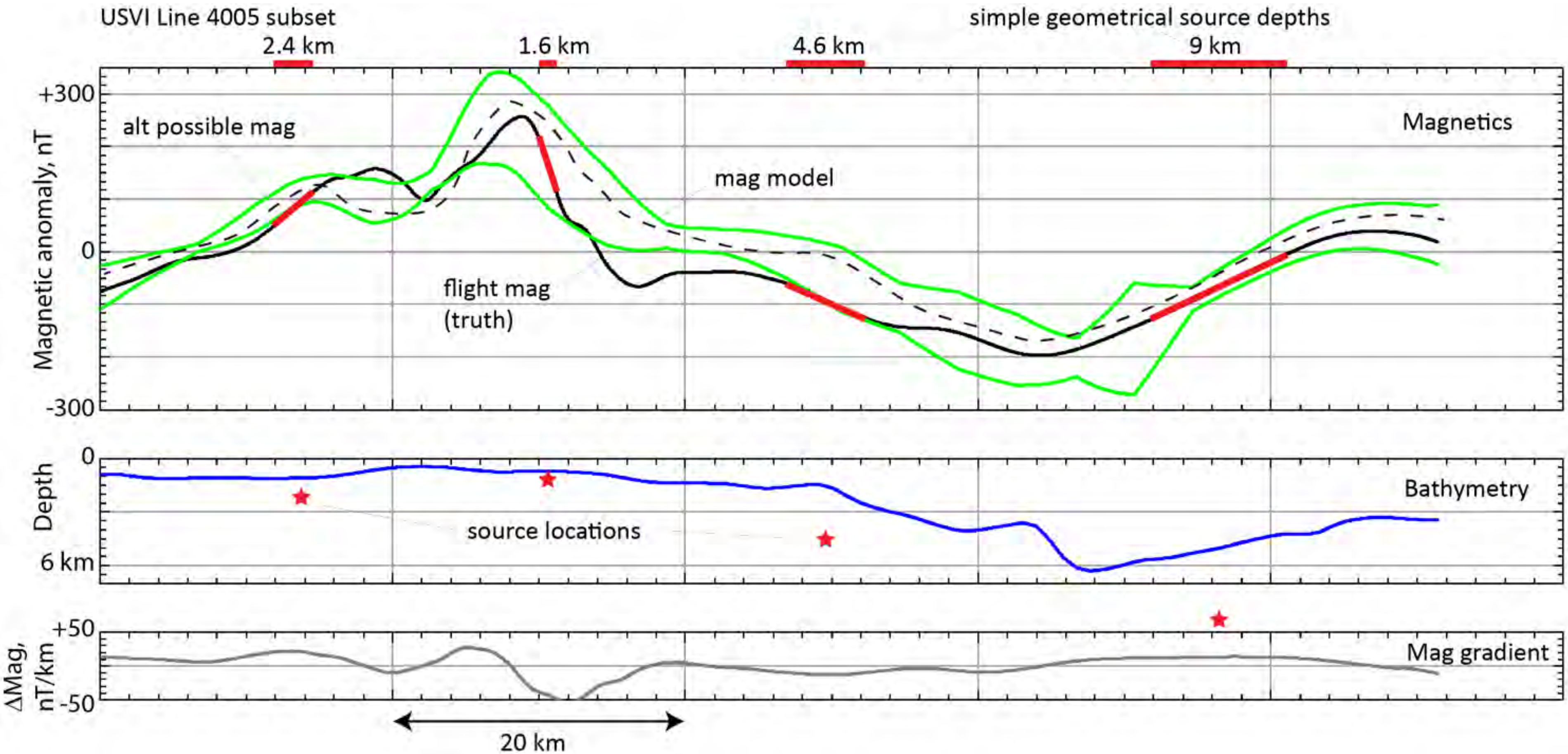


In addition to overall pattern matching, broad gradient zones are also traversed



Frequency content and anomaly amplitudes are constrained by potential field source strength and position

Character of "true" field within uncertainty envelope can be defined using a priori information and potential field theory



Maps/Models for Navigation

"No matter where you go,
there you are."
- Buckaroo Banzai

Quiz – Question 5

Why do people make magnetic maps?

Use in navigation

Quiz – Question 5

People make magnetic maps to better understand the Earth's magnetic field and its variations. These maps show the strength and direction of the Earth's magnetic field at different locations around the world.

One of the main uses of magnetic maps is for navigation. Since compass needles align with the Earth's magnetic field, magnetic maps can be used by pilots, sailors, and other navigators to determine their heading and navigate to their destination.

In addition, magnetic maps are also used in geology, particularly in the study of rocks and minerals. This is because some rocks contain magnetic minerals that can record the strength and direction of the Earth's magnetic field at the time the rock was formed. By analyzing the magnetic properties of rocks, geologists can reconstruct the history of the Earth's magnetic field and gain insights into the geological processes that occurred in the past.

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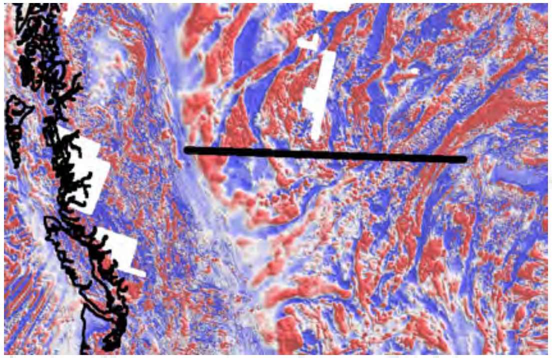
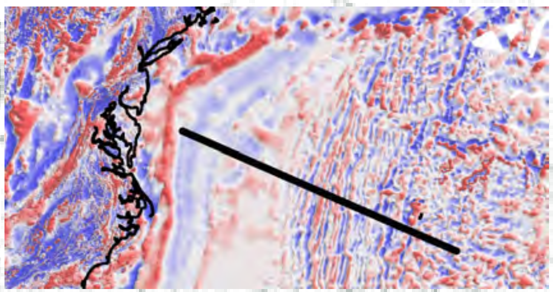
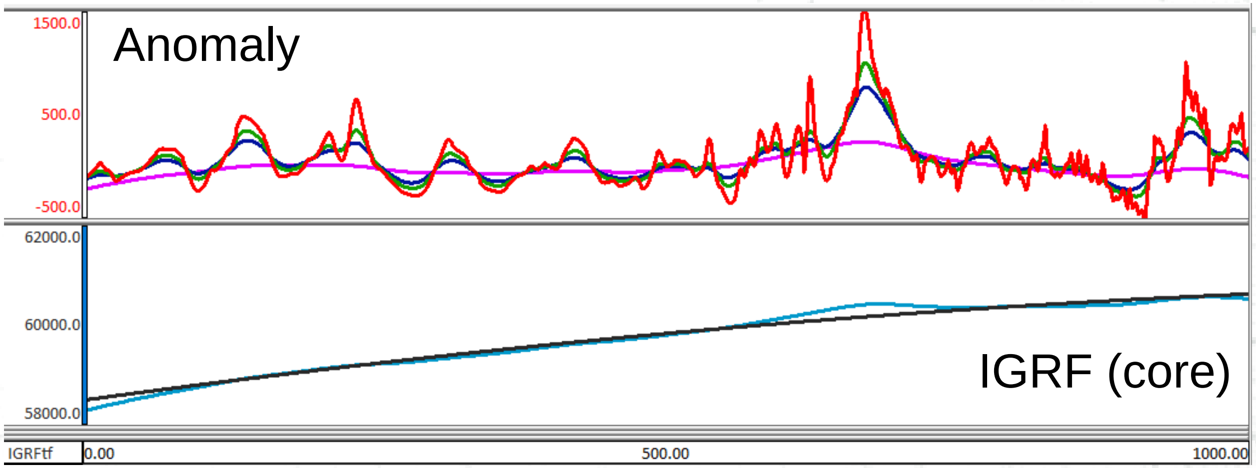
Use in navigation

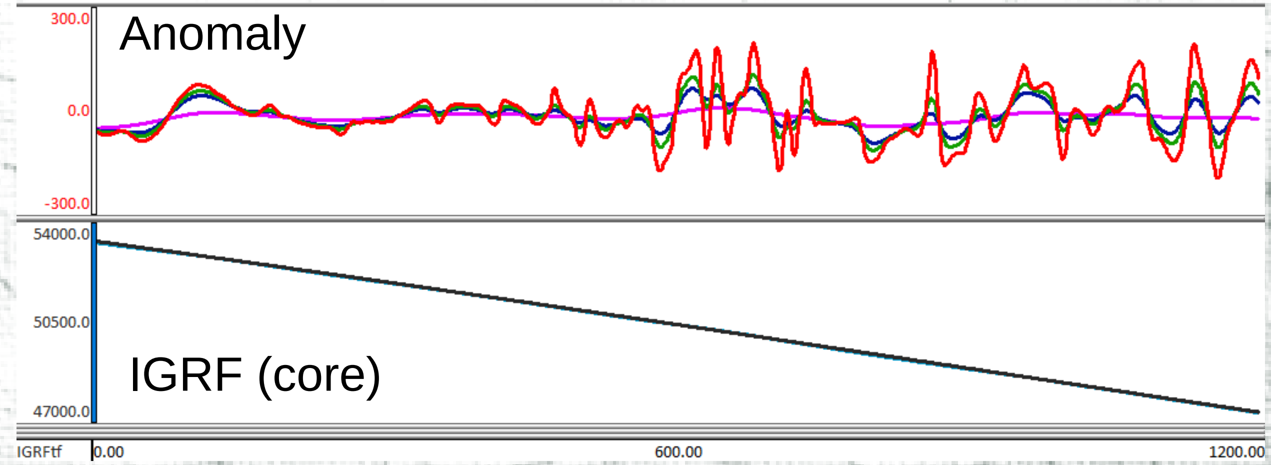
Alternative navigation usage – signal



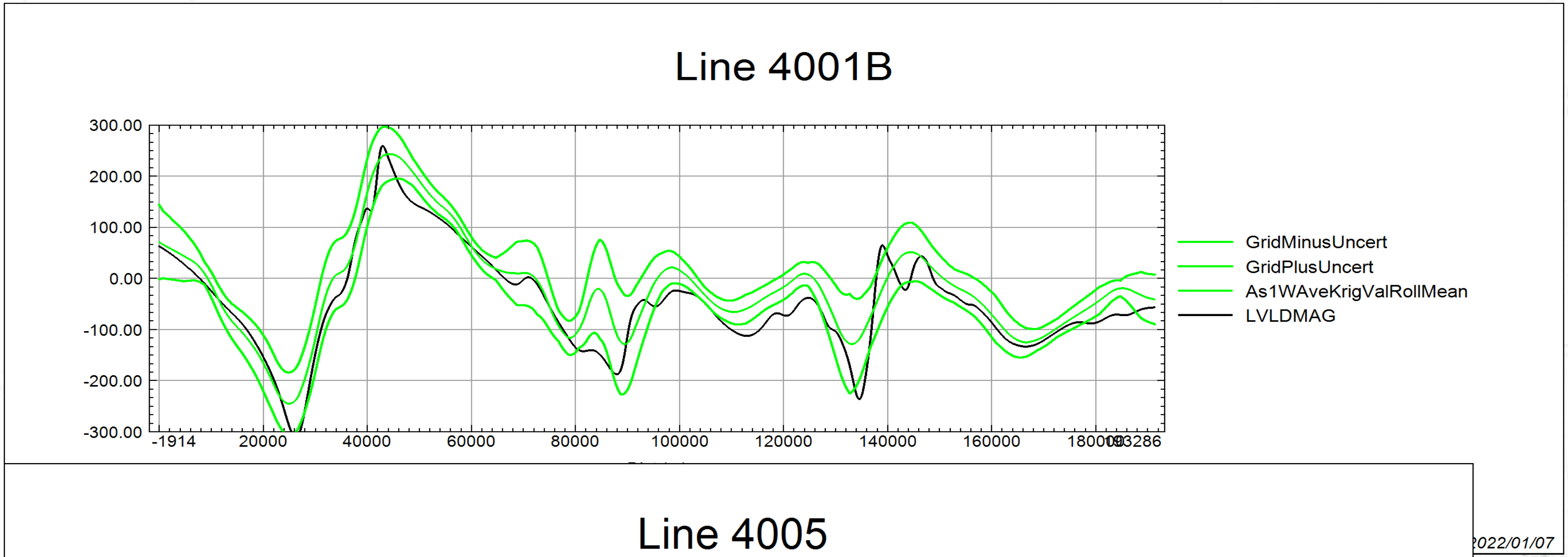
Red – 1 km
Green – 5 km
Blue – 10 km
Magneta – 50 km

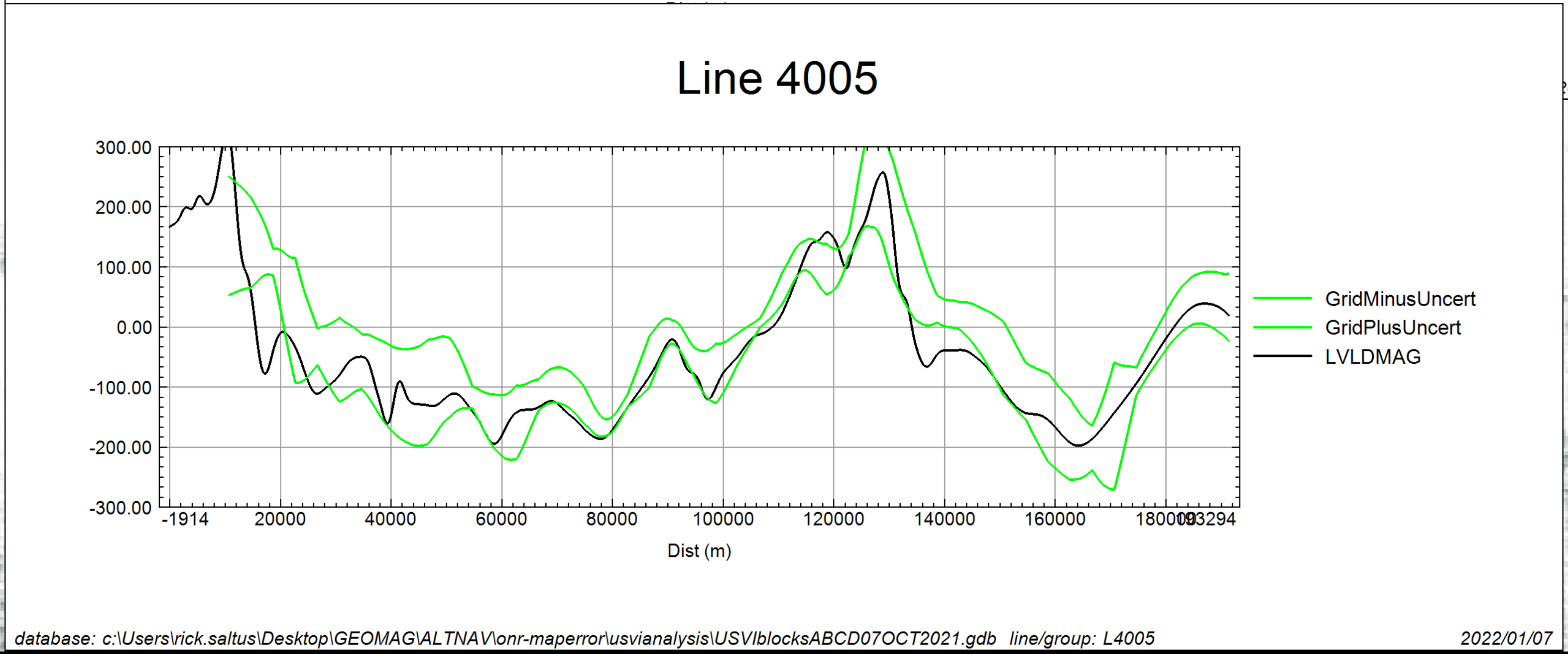






Alternative navigation usage - correlation





Assessment of navigation potential

- Complex problem
- Function of map data density/uncertainty, speed and direction of travel, altitude, platform calibration, nav algorithm
- Initial analysis considers magnetic feature amplitudes, density, uncertainty and direction

“NavPower”

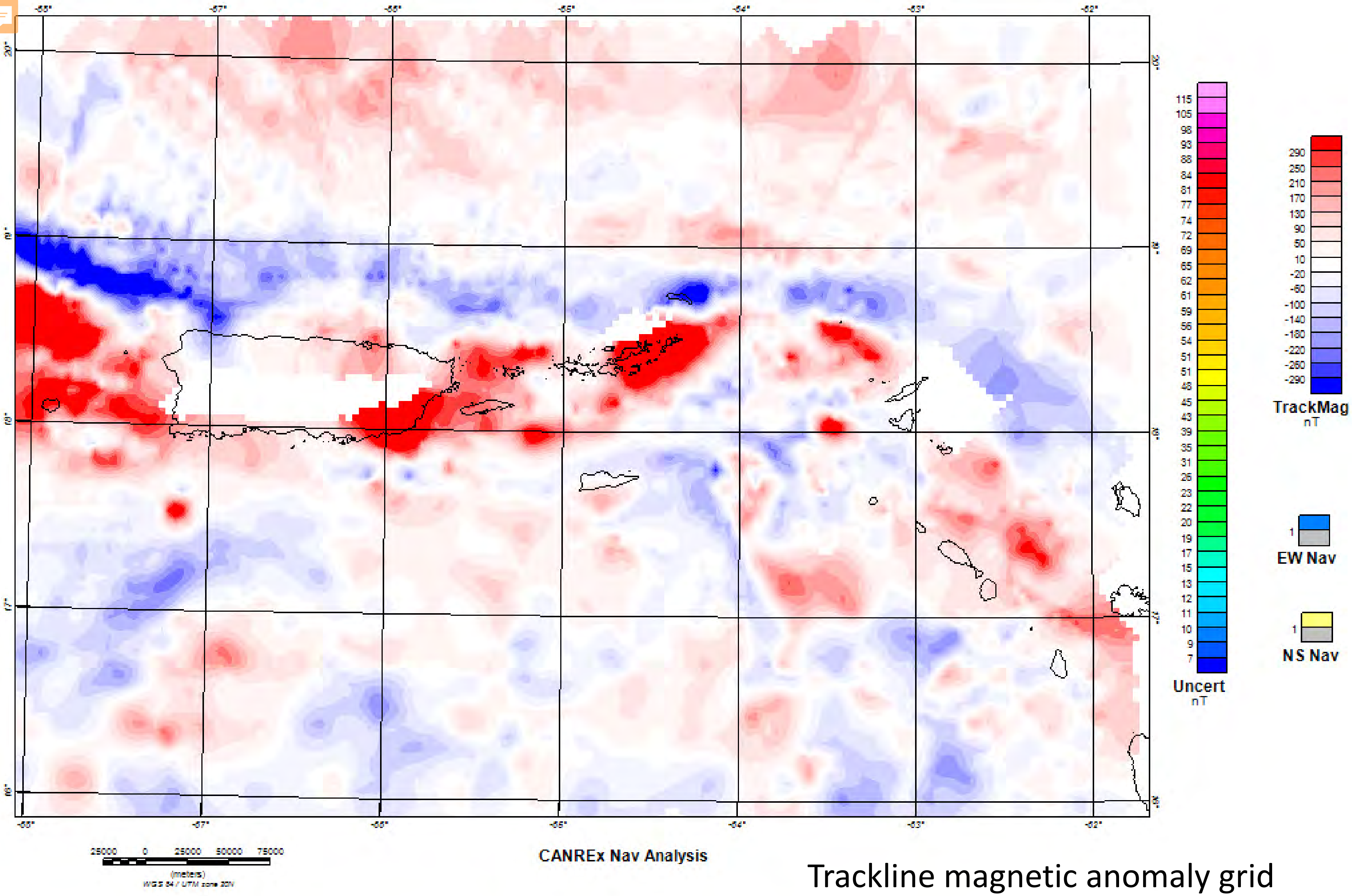
NP = TMag(stdev) / Uncertainty (mean) * #Anomaly peaks

TMag(stdev) = 5 cell directional standard deviation
Uncertainty(mean) = 5 cell directional mean

#Anomaly peaks = Number of zero crossings on directional mag gradient (will vary from 0 to 5 for the 5 cell calculation)

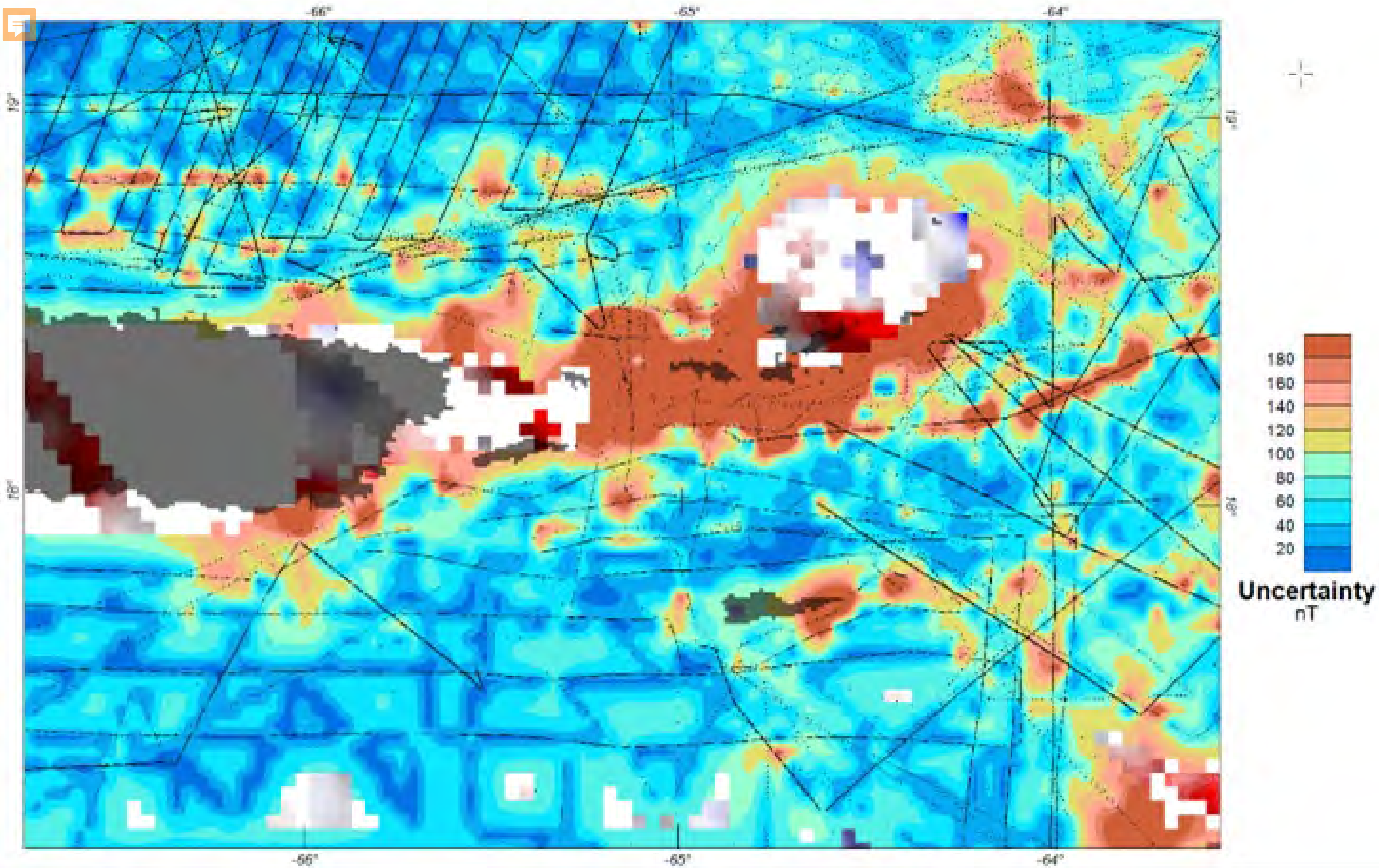
Logic: More power when magnetic variations exceed uncertainty and you have distinct anomaly features

Gives only a relative sense of navigation capability, accuracy dependent also on additional factors



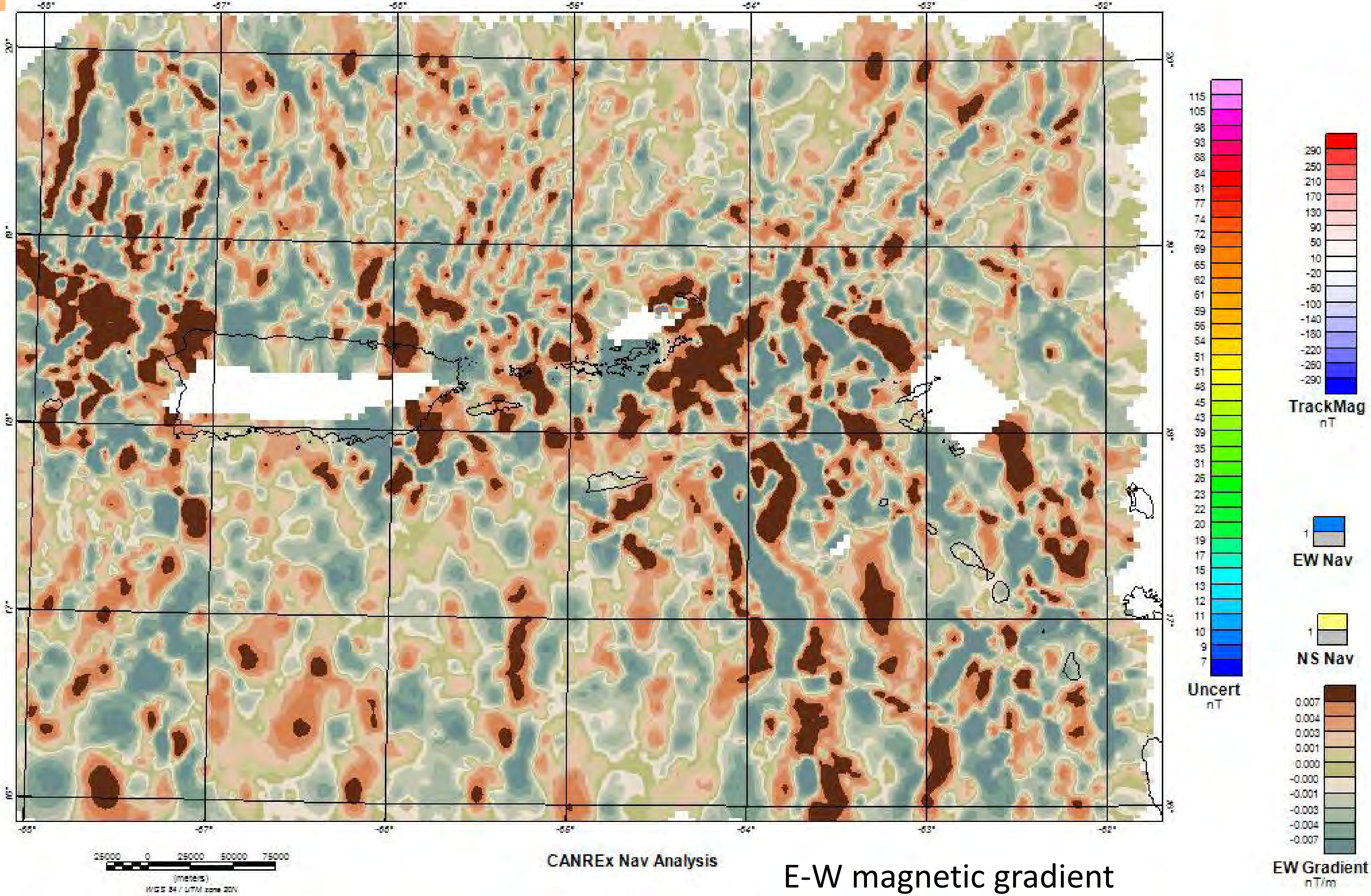
Trackline magnetic anomaly grid

Use in navigation



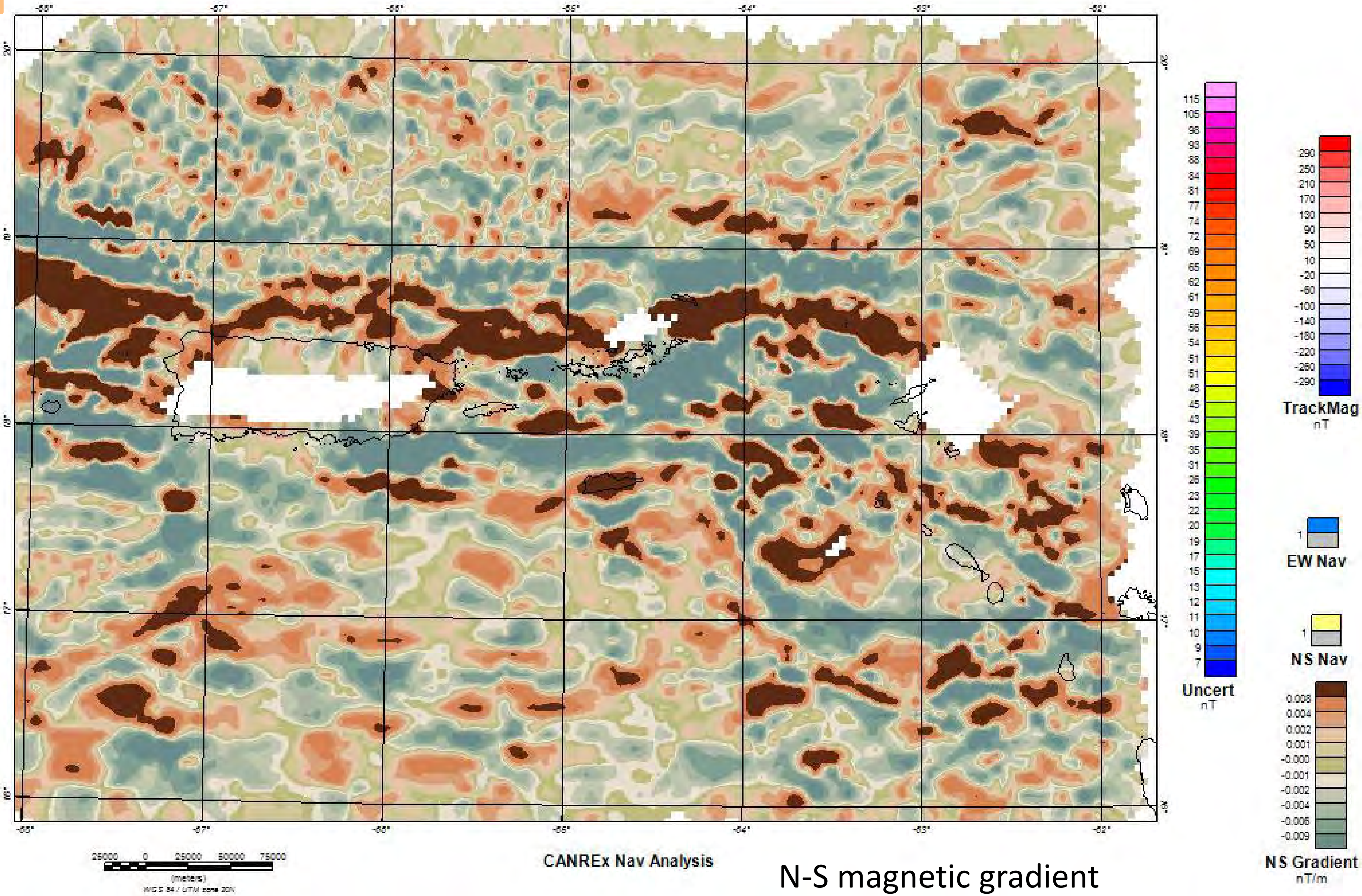
Total uncertainty of trackline mag grid

Use in navigation



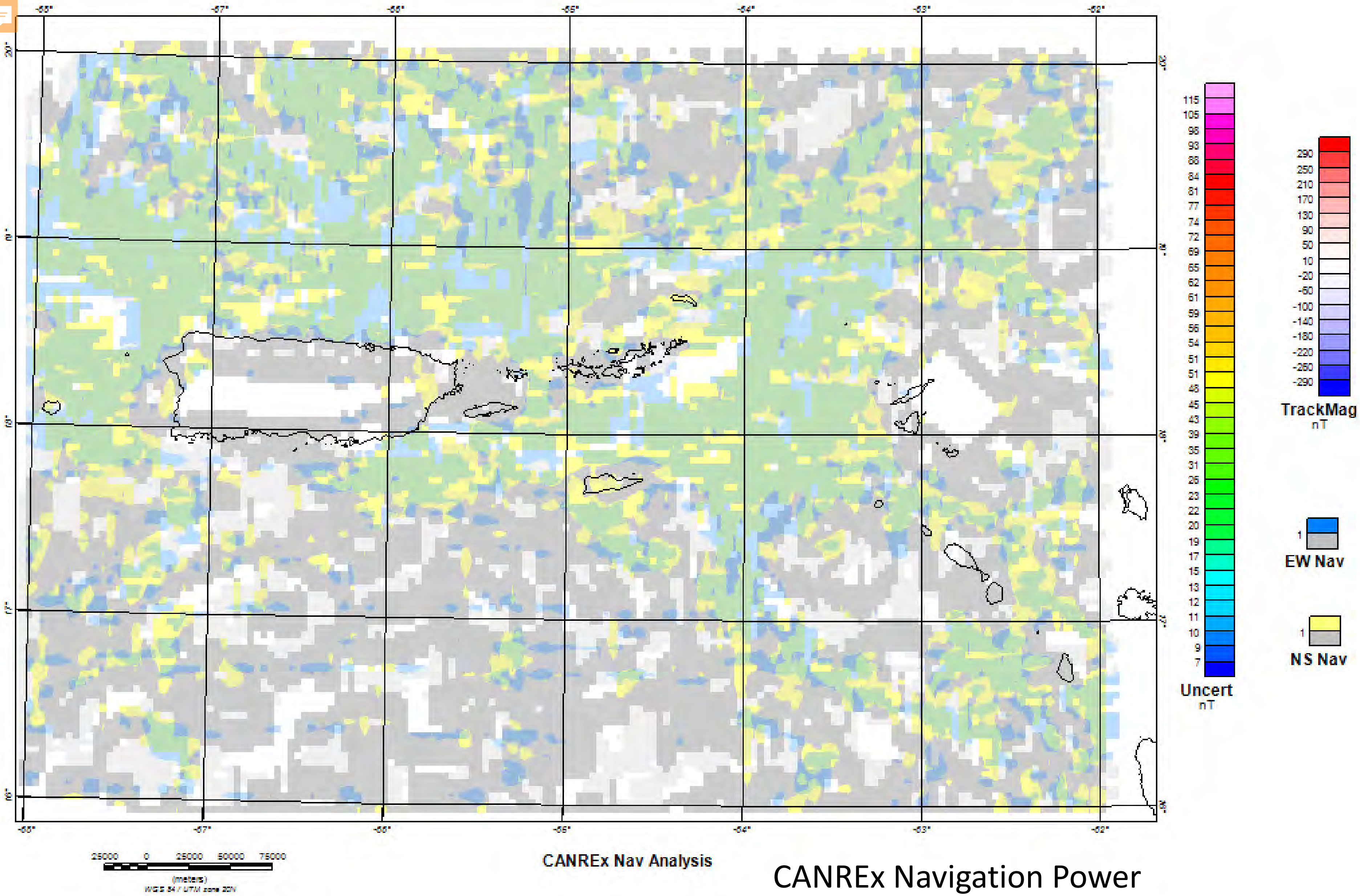
E-W magnetic gradient

Use in navigation



N-S magnetic gradient

Use in navigation



CANREx Navigation Power

Use in navigation

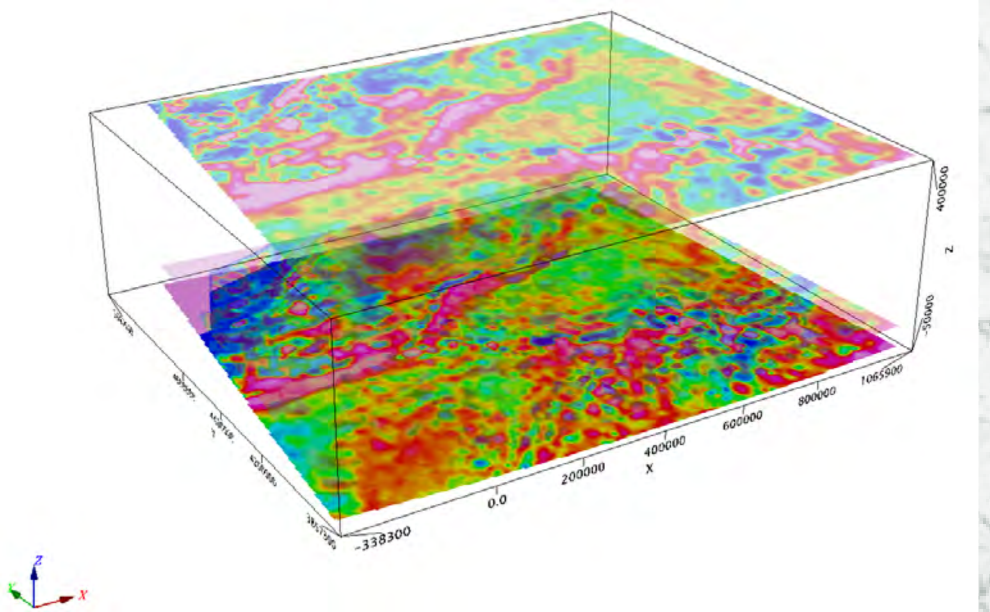
“(nested) Stack(s) of grids”

Grid resolution (e.g.)

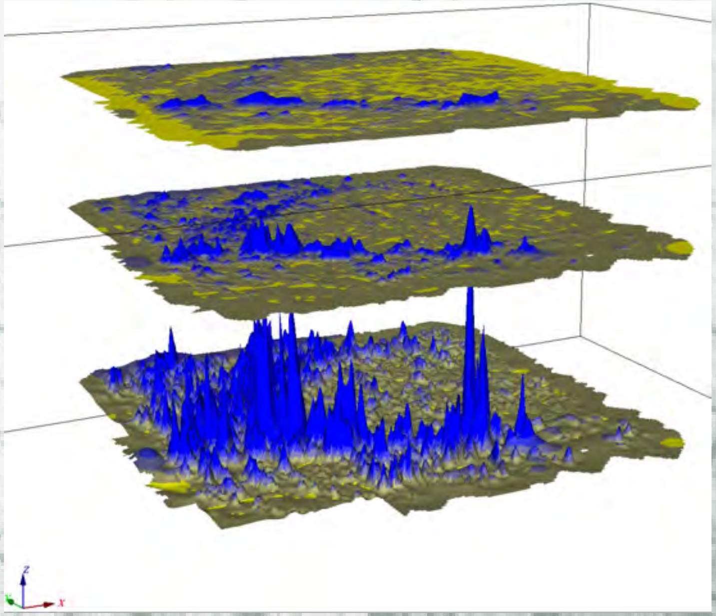
- 36 km
- 12 km
- 4 km
- 1.333 km

Altitude (e.g.)

- 10 km
- 4 km
- sealevel
- -500 m



Altitude stack: totalfield mag



Altitude stack: totalfield uncertainty

Conclusions/discussion

- Few magnetic field maps and models have been made specifically for MagNav.
- Evaluate the value of a given map or model for the navigation objective.
- Models have operational advantages, but may lack detail and localized knowledge of uncertainty.
- Maps are required for precise and low-level nav, but will typically require professional adaptation/upgrade for use in MagNav.
- More data are required to complete global coverage and for many specific operations, especially in marine regions.

LAND	Amplitudes (nT)					Gradients (nT/km)				Uncert	Gradient Signal (nT/min) at Velocity (km/hr)					
Altitude	Min	Max	Mean	AbsMean	Stdev	Min	Max	AbsMean'	Stdev	%	10 km/hr	25 km/hr	115 km/hr	170 km/hr	800 km/hr	4800 km/hr
1	-525	1517	28	192	200	-261	280	31	44	0.7	3.6	9	41.6	61.5	289.3	1736
5	-283	1010	23	144	149	-29	43	9	12	0.4	0.6	1.5	6.9	10.2	48	288
10	-215	774	18	121	124	-19	23	6	7	0.5	0.5	1.3	5.8	8.5	40	240
50	-262	245	-14	72	66	-4	2	1	2	0.6	0.1	0.3	1.2	1.7	8	48
IGRF 1 km	58519	60687	59802		635	1	3	2	1	1	0.3	0.8	3.8	5.7	26.7	160
OCEAN	Amplitudes (nT)					Gradients (nT/km)				Uncert	Gradient Signal (nT/min) at Velocity (km/hr)					
Altitude	Min	Max	Mean	AbsMean	Stdev	Min	Max	AbsMean'	Stdev	%	10	25	115	170	800	4800
1	-191	198	-11	58	73	-51	43	7	11	0.5	0.6	1.5	6.7	9.9	46.7	280
5	-112	106	-12	39	46	-14	13	3	4	0.4	0.2	0.5	2.3	3.4	16	96
10	-91	67	-12	30	35	-6	7	2	2	0.5	0.2	0.4	1.9	2.8	13.3	80
50	-48	10	-16	17	13	-0.5	0.6	0.2	0.3	0.6	0	0.1	0.2	0.3	1.6	9.6
IGRF 1 km	47403	53351	50426		1728	-5.1	-4.6	5	0.2	1	0.8	2.1	9.6	14.2	66.7	400

Aknowledgments

Discussions with Aaron Canciani, Aaron Nielsen, Dennis Brinkley, and others have informed and guided our research.

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Questions/comments?

"The one who knows all the answers has not been asked all the questions." – *Confucius*

Rick Saltus richard.saltus@colorado.edu
CIRES/NOAA Geomagnetics Team
https://geomag.colorado.edu/

Looking forward to further discussion