Magnetic Navigation Overview

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AIR FORCE INSTITUTE OF TECHNOLOGY

ANT CENTER

DSIAC
Defense Systems Information Analysis Center

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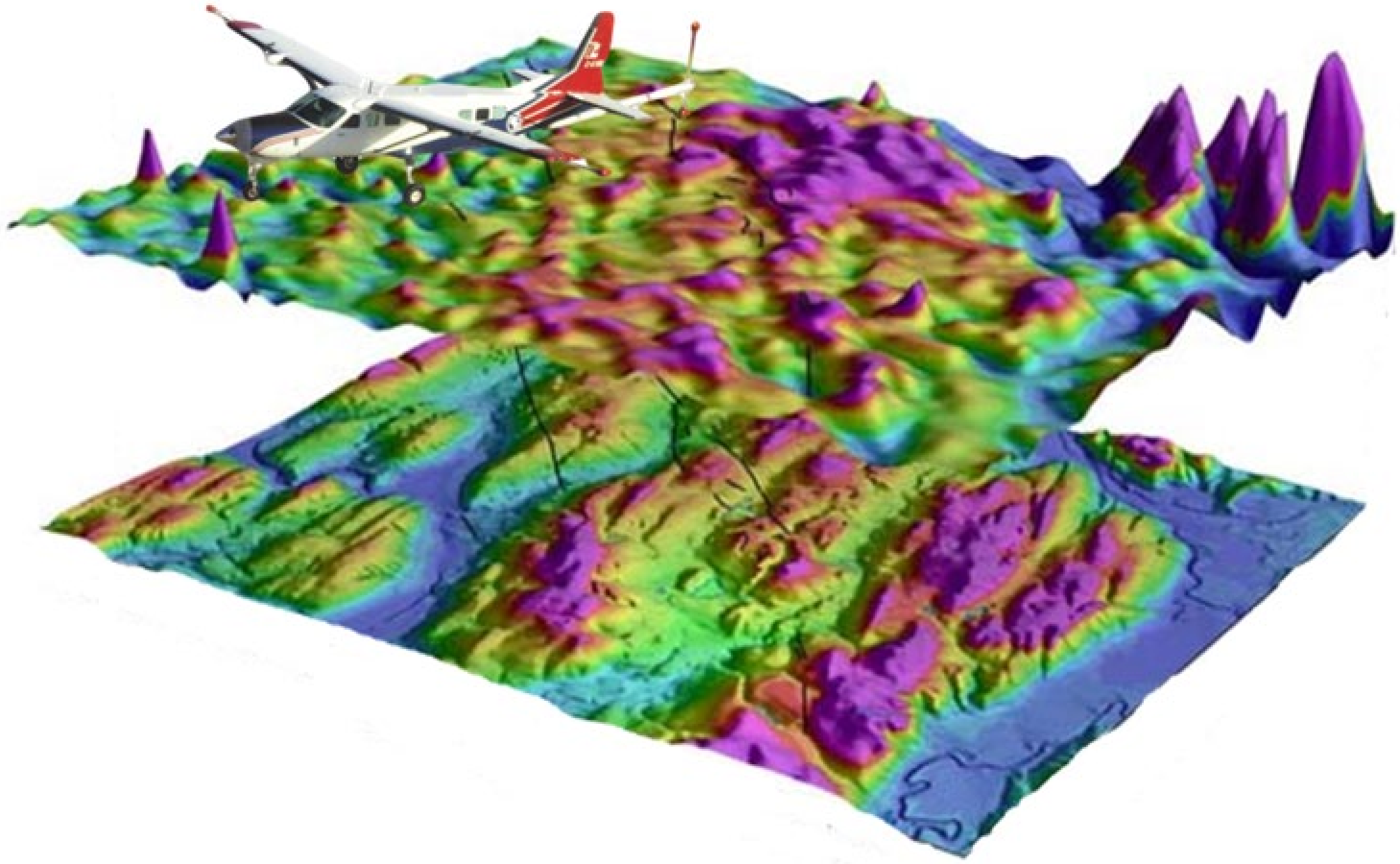
What is Magnetic Navigation?

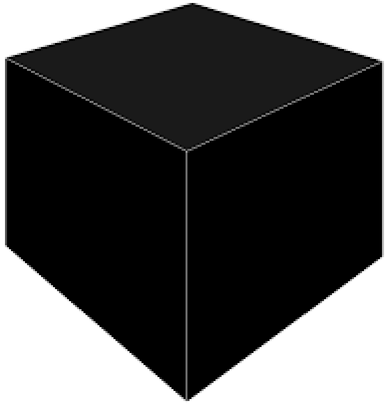


Benefits of Magnetic Navigation

Vision?

Terrain Following?

Passive



SOO?

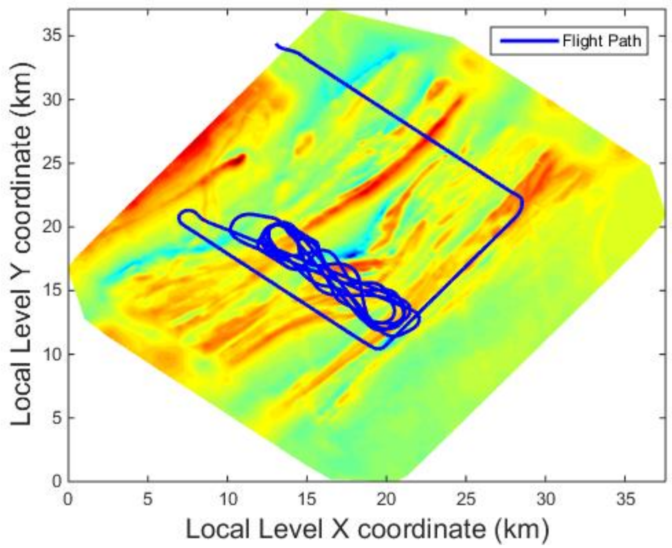
$r^3 >> r^2$

Star Tracker?

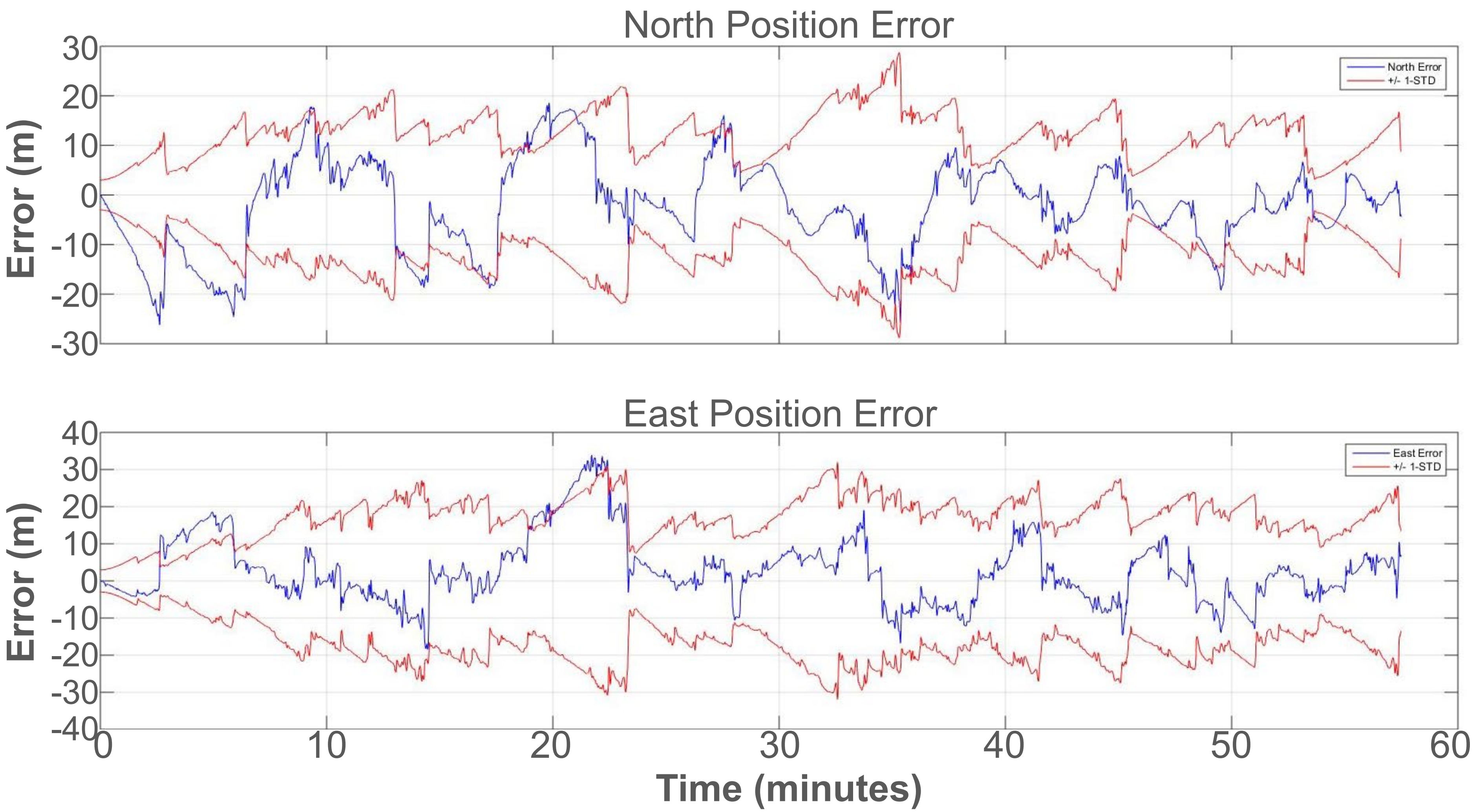
Current State of Magnetic Navigation

- **Scalar magnetic navigation is a flight-test proven navigation technique**
- **Two ideal-case flight tests have taken place**
  - High quality magnetic maps
  - Clean magnetic environment (calibrated)
  - Lower altitudes
  - Achieved accuracies of tens of meters over time-scales of hours
- **Two other flight tests have taken place with**
  - Inaccurate magnetic maps
  - Uncalibrated platform
  - Higher altitudes

Flight Test 1



Flight Test 1

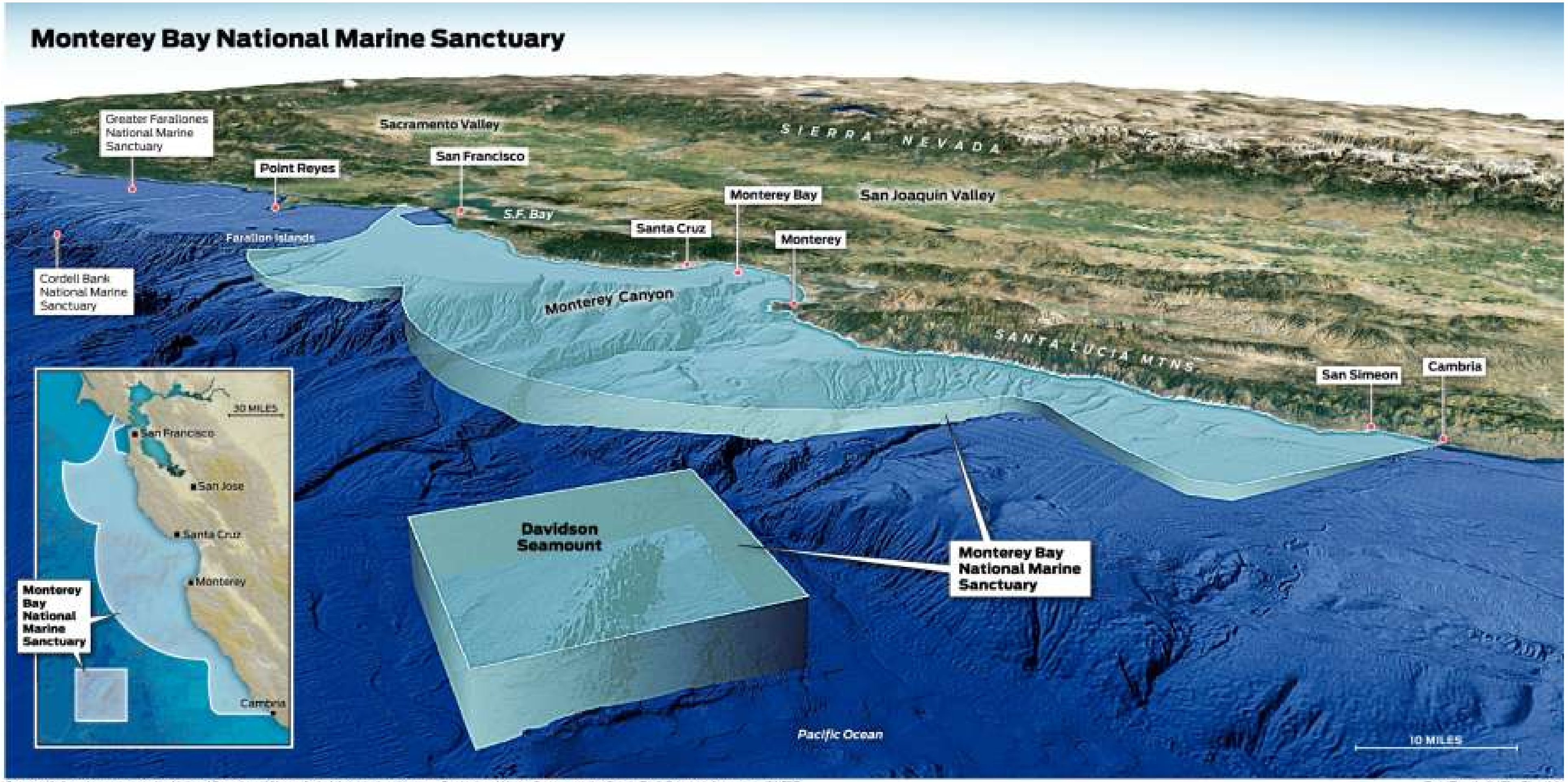


Flight Test 1

	North Channel	East Channel
Mean	-2.2 m	2.7 m
Standard Deviation	9.0 m	8.9 m
DRMS	13.1 m	
Unaided INS DRMS	230 m	

Low Altitude ☑
Good Map ☑
Clean Platform ☑

Flight Test 2

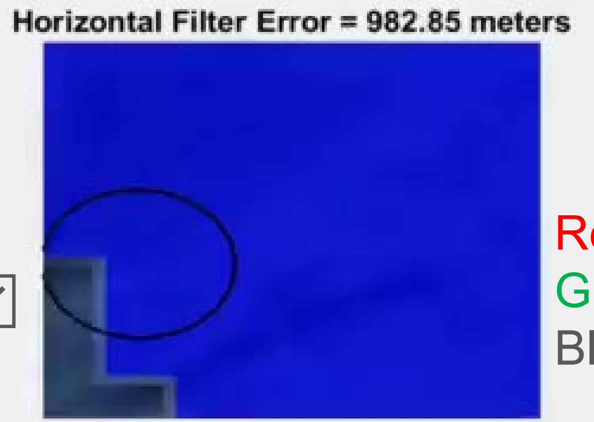


Sources: Underwater map created by National Oceanic and Atmospheric Administration/Monterey Bay National Marine Sanctuary using Google Earth Pro; maps4news.com/©HERE

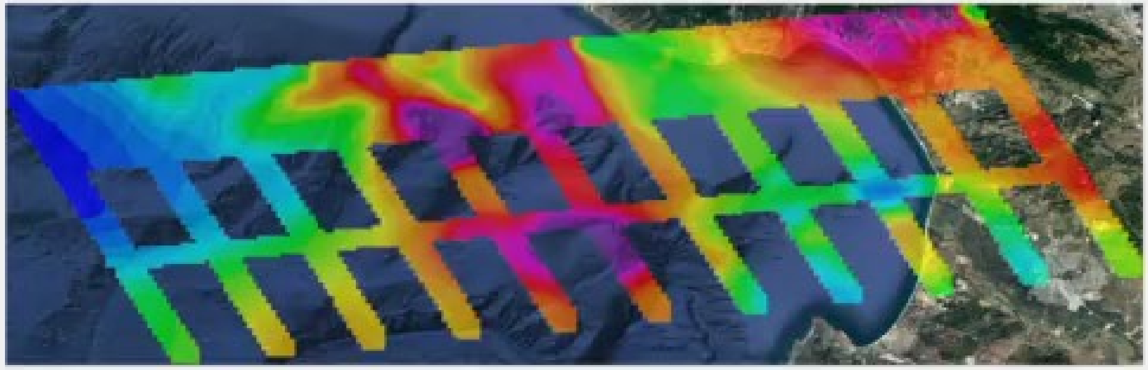
Todd Trumbull / The Chronicle

Flight Test 2

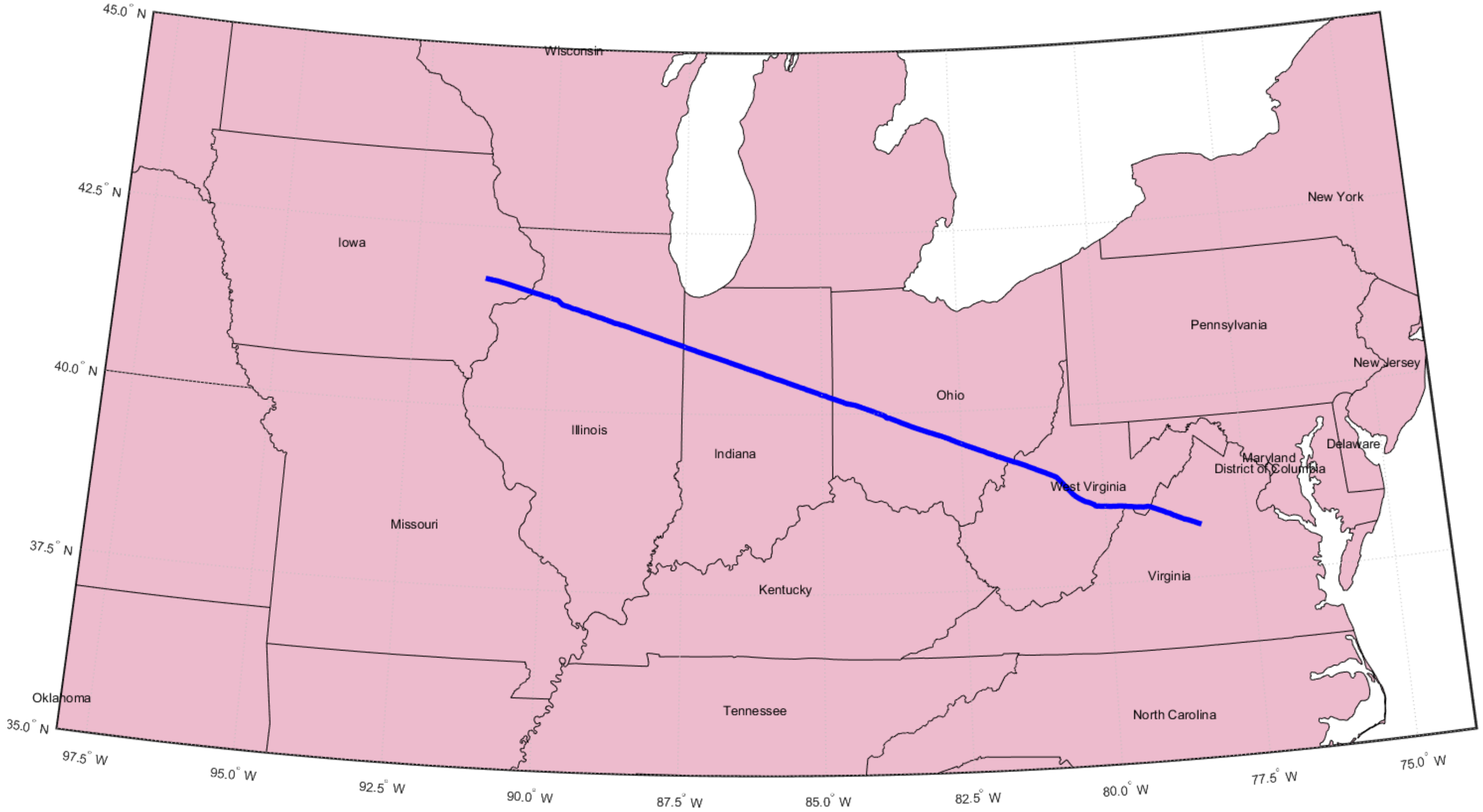
Low Altitude ☑
Good Map ☑
Clean Platform ☑



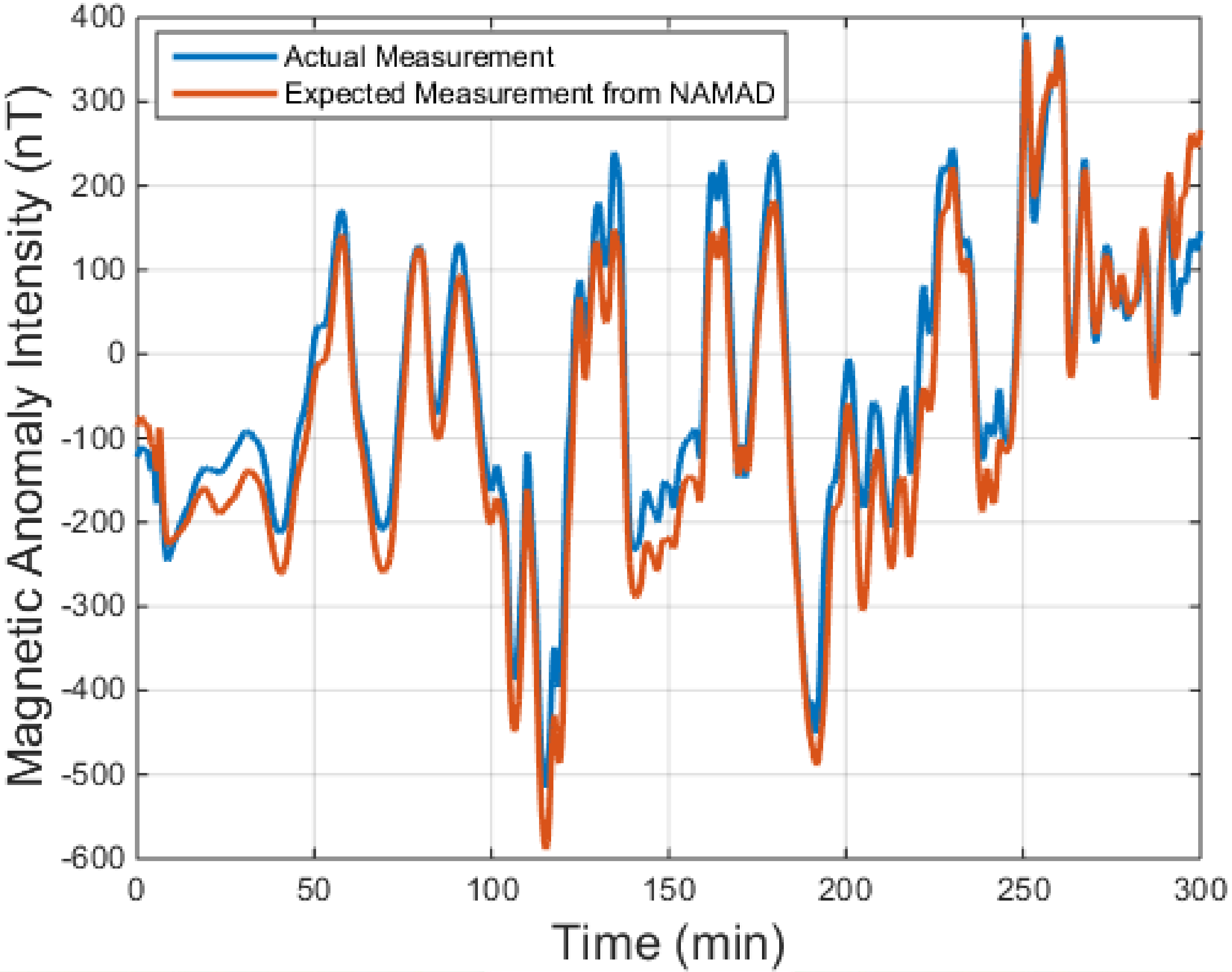
Red = Truth
Green = INS
Black = Mag-Nav Filter



Flight Test 3



Flight Test 3

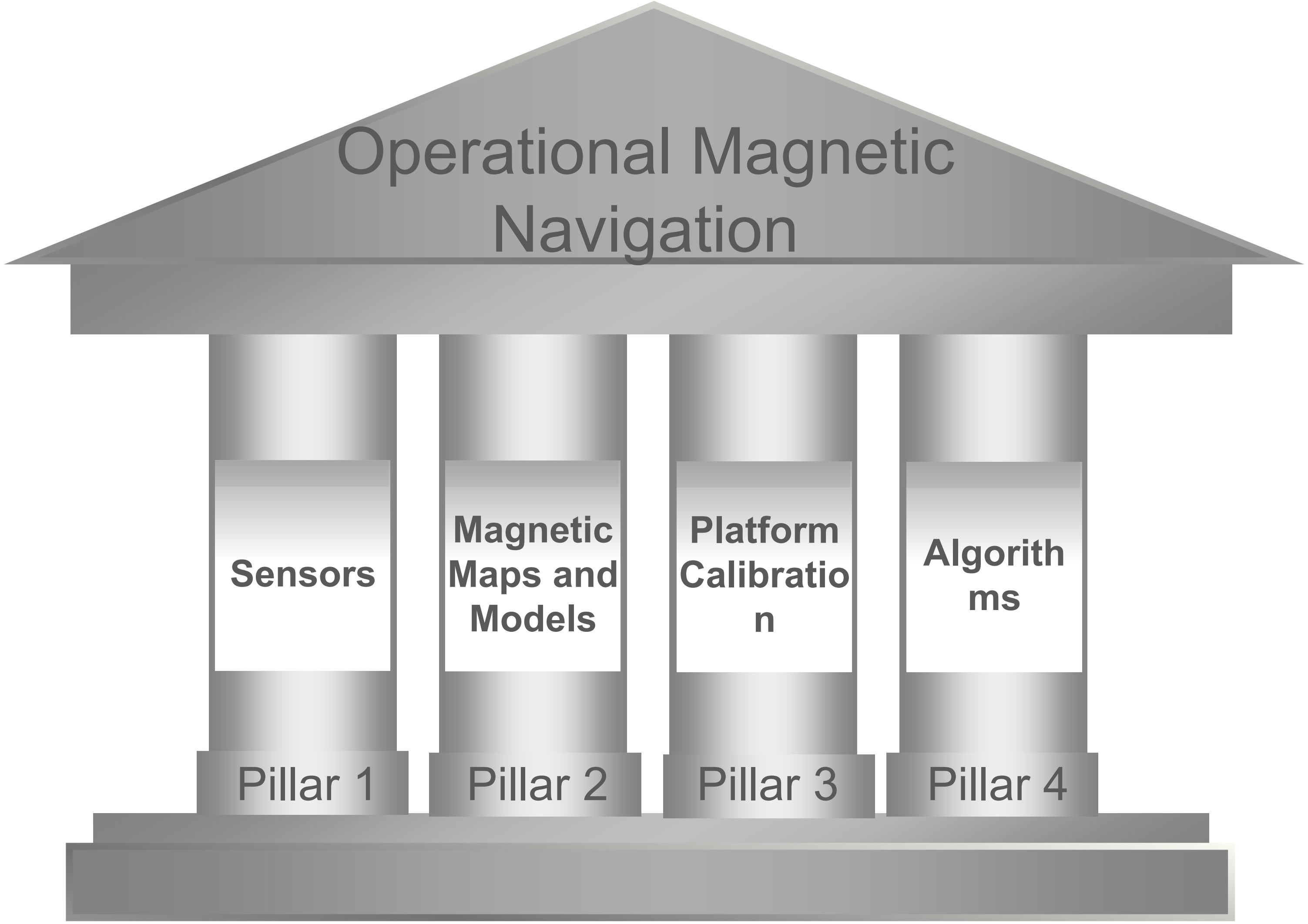


Low Altitude ☒
Good Map ☒
Clean Platform ☑

Flight Test Take-Aways

- **Altitude will always be a variable**
  - Higher altitude decreases accuracy
  - Filter covariance “understands” this
  - Solution will converge better as altitude decreases
- **While current world map products *can* be used for navigation, their errors do affect navigation accuracy**
- **Platform calibration will be critical to real-world applications**

The Four Pillars of Magnetic Navigation



MAGNAV SEMINAR

Earth Magnetic Fields Tutorial

“But I thought the magnetic field changes over time…”

Magnetic navigation faced with deep skepticism due to several misunderstandings

Session Goal: Give everyone a common understanding of the proposed navigation signal – the Earth’s magnetic anomaly field

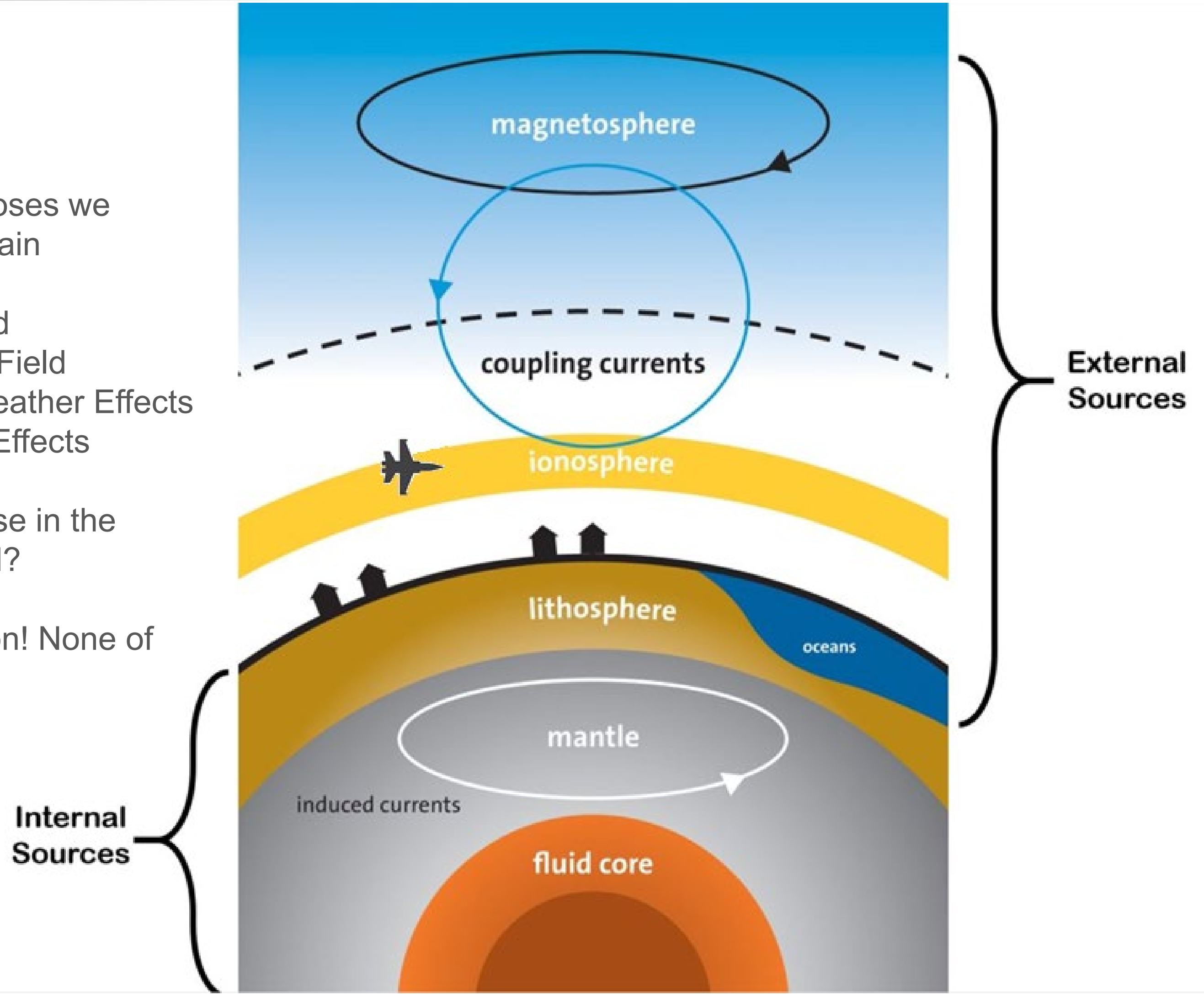
Earth Magnetic Field Components

For our purposes we consider 4 main contributions

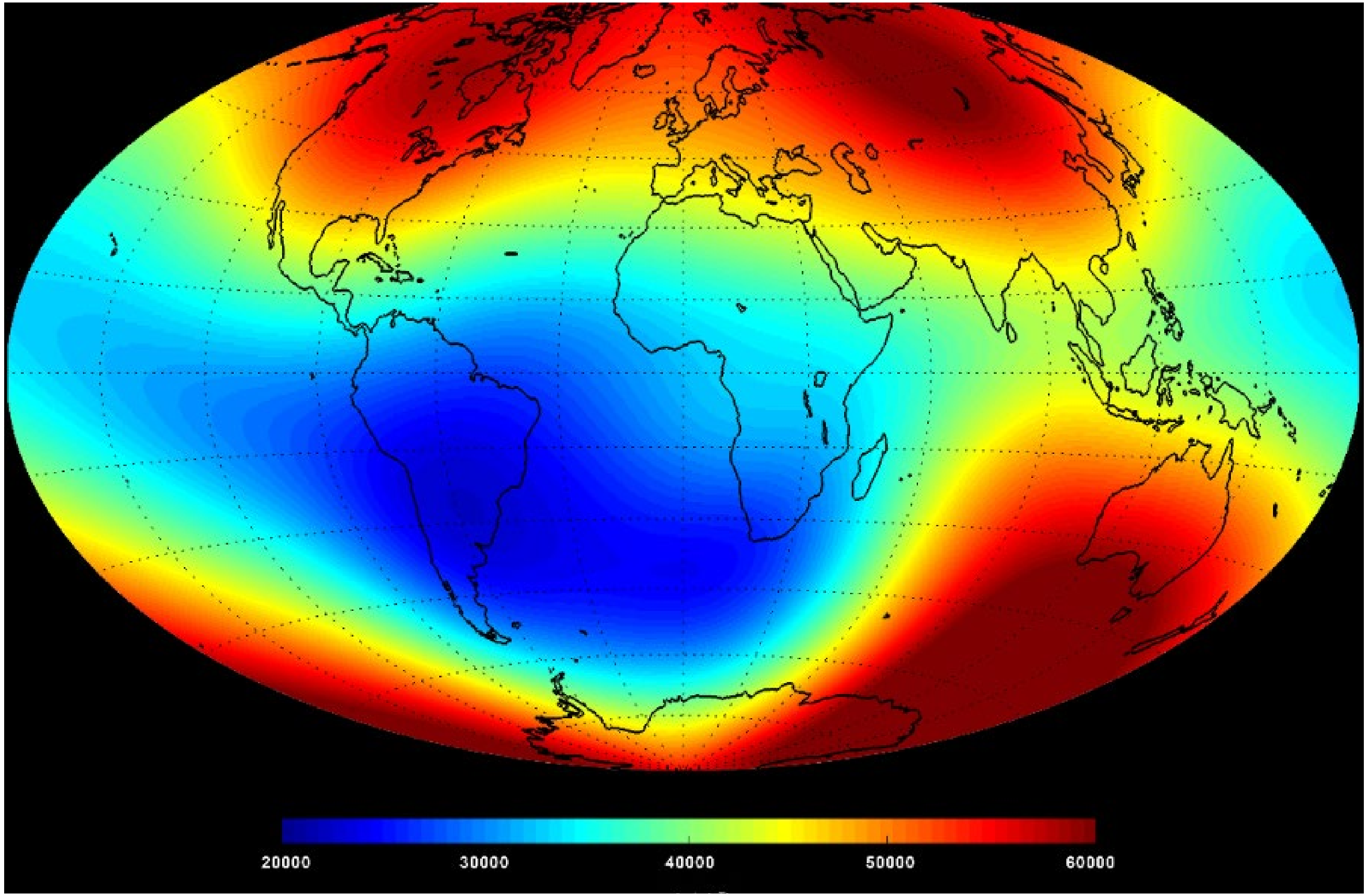
1. Core Field
2. Anomaly Field
3. Space Weather Effects
4. Platform Effects

Which of these in the anomaly field?

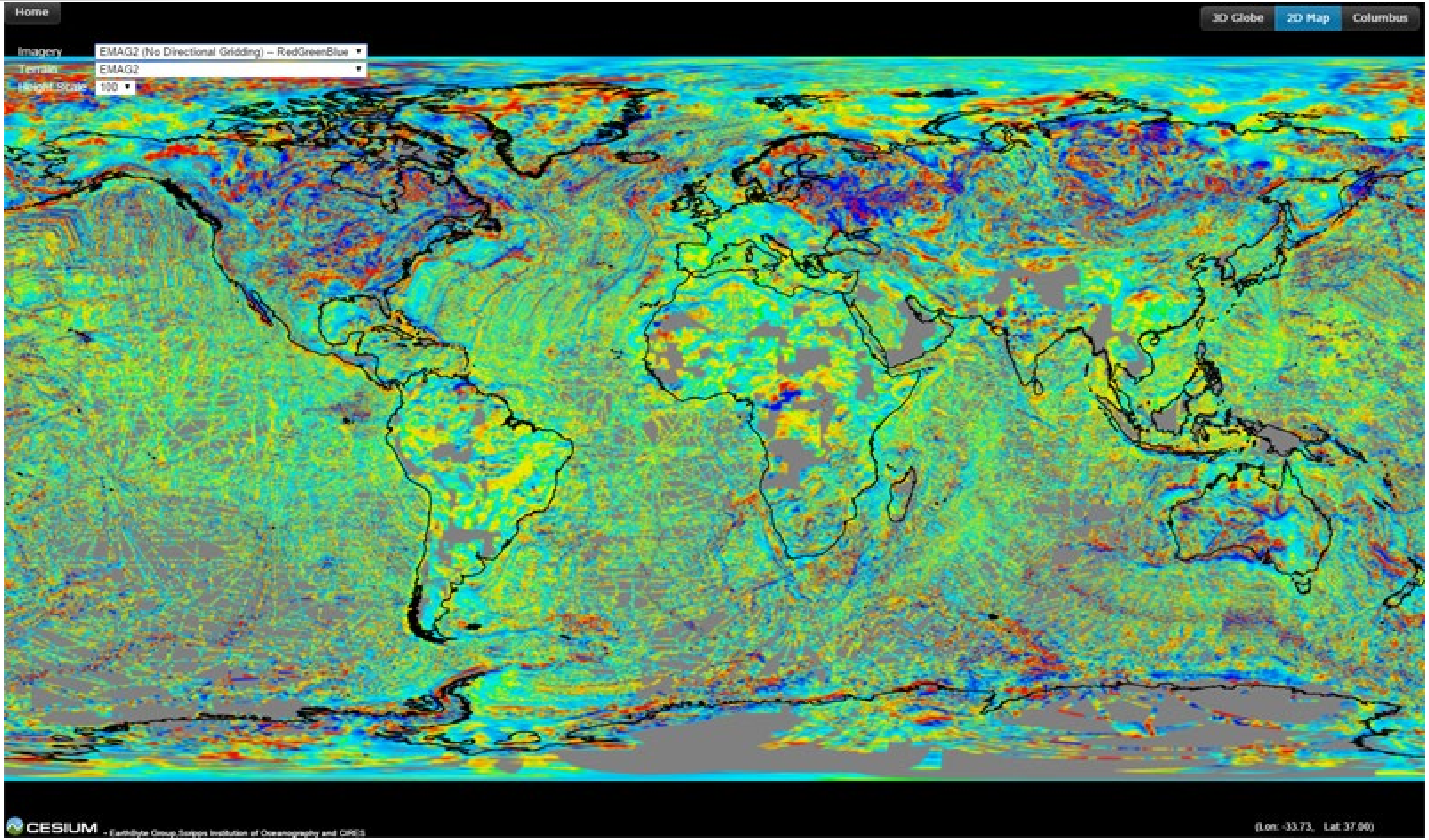
Trick Question! None of them!



The Earth’s Core Field

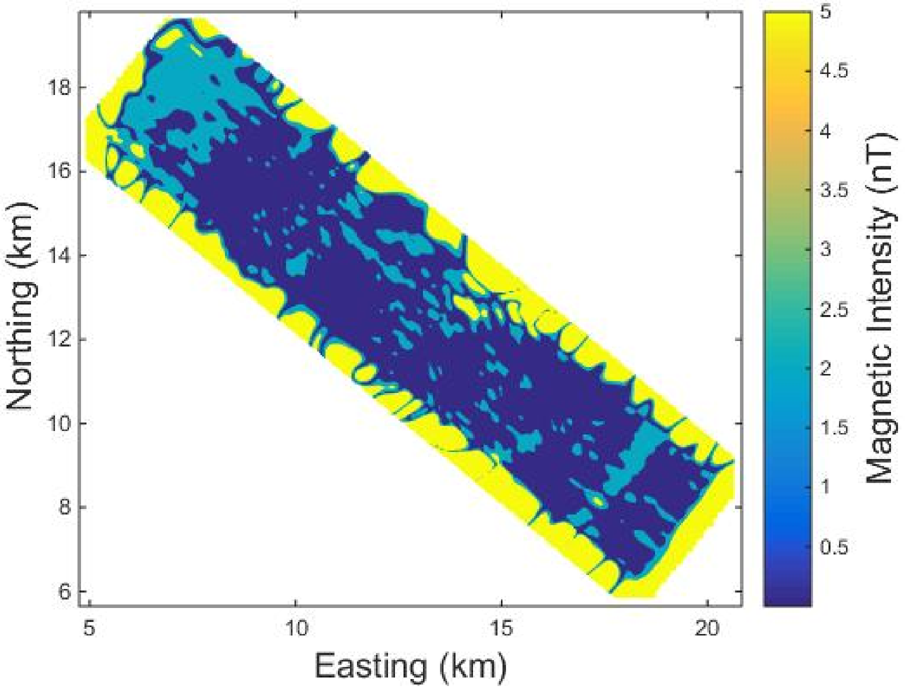


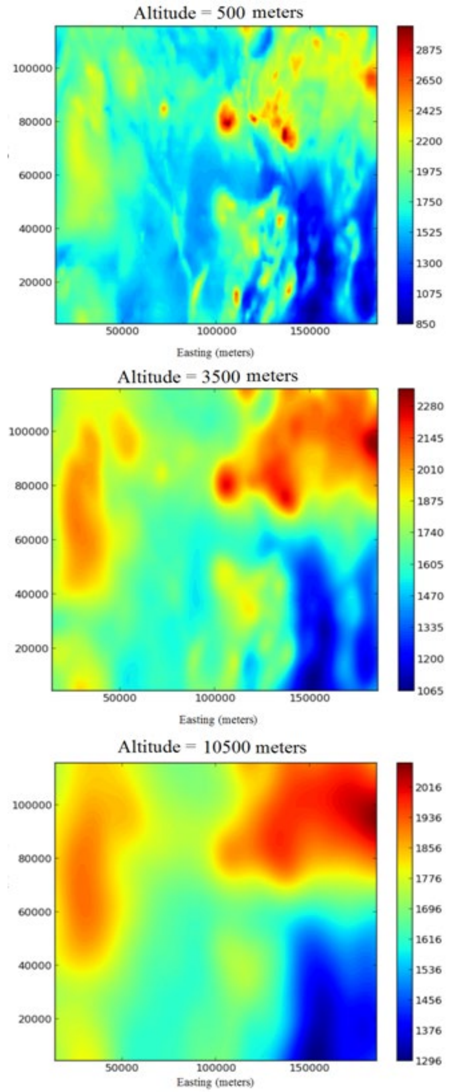
The Earth's Crustal Magnetic Field (EMAG2 Model Shown)



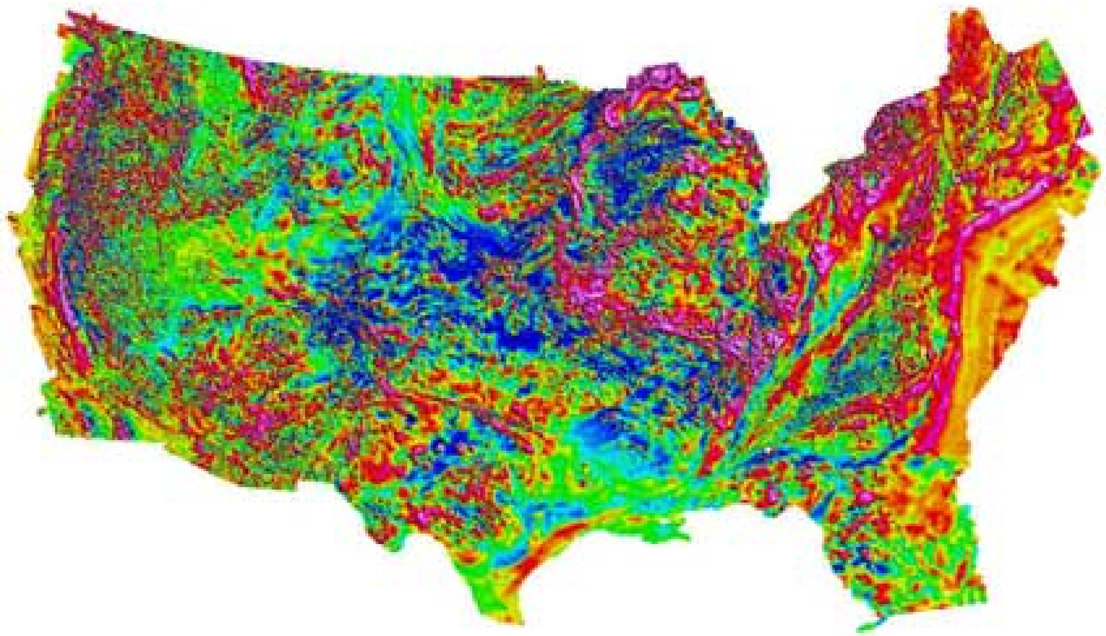
The Magnetic Anomaly Field as a Navigation Signal

- Stable over time
- Varies in three dimensions
- Increasing altitude essentially acts as a low-pass filter on the map data



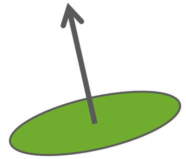


Available Signal By Altitude

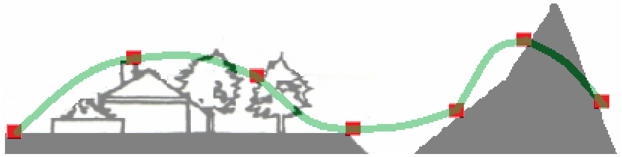


Field (AGL)	Mean (nT/km)	STD (nT/km)	Pred. Accuracy (m)
Anomaly 300m	34.0	76.0	29
Anomaly 1km	19.1	29.3	52
Anomaly 10km	3.9	3.4	256
IGRF 10km	5.8	1.0	172

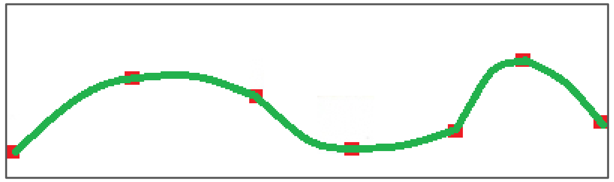
- IGRF field has very little variation within aircraft altitudes
- IGRF field looks like a plane on a regional level so navigation information only available in one direction



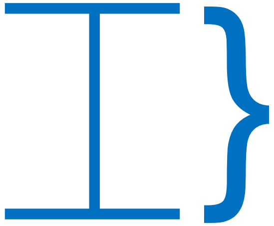
A Benefit of Potential Fields: Accurate Interpolation



Sampling Terrain Height



Sampling A Potential Field



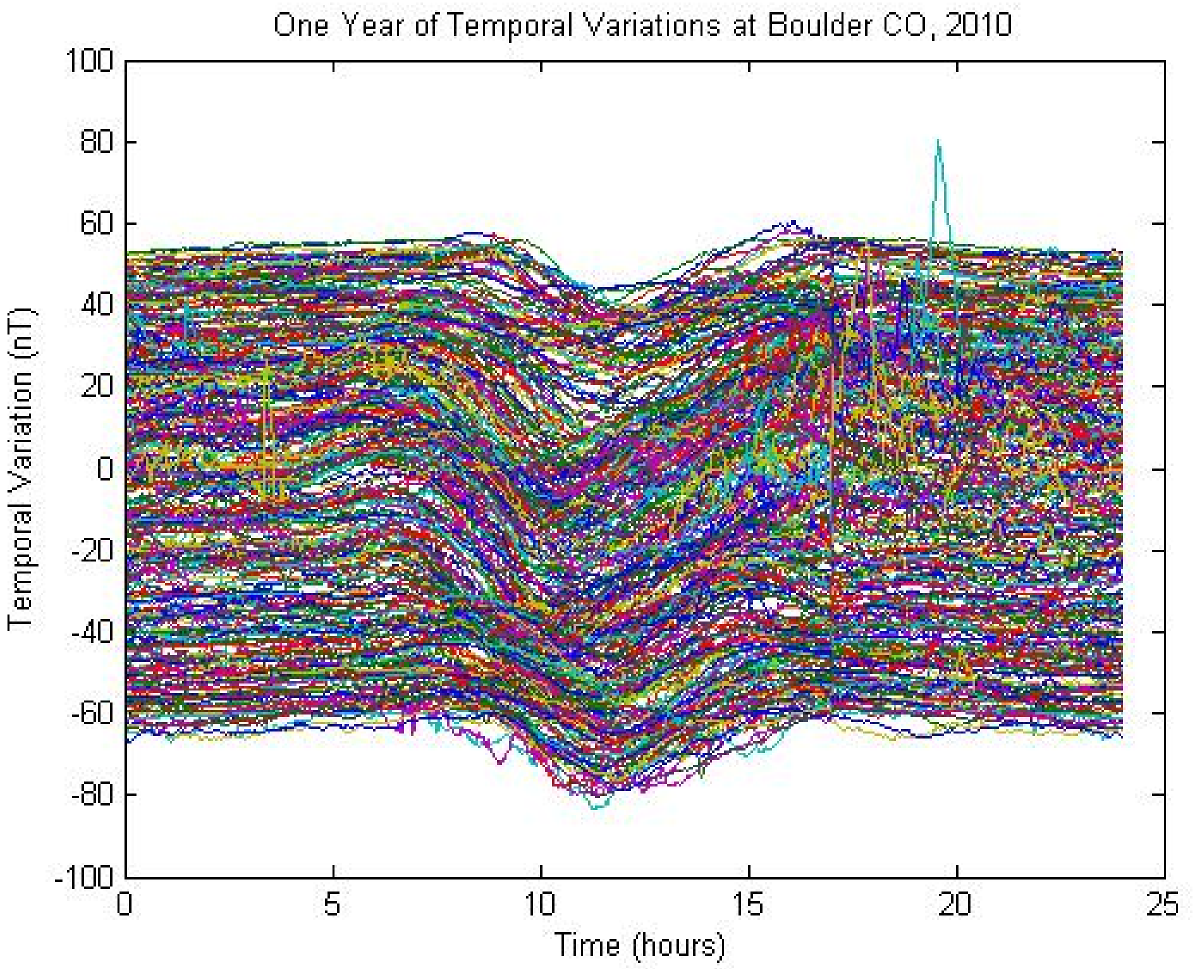
Measurement uncertainty must account for missed frequency content

Accurate interpolation allows smaller measurement uncertainty

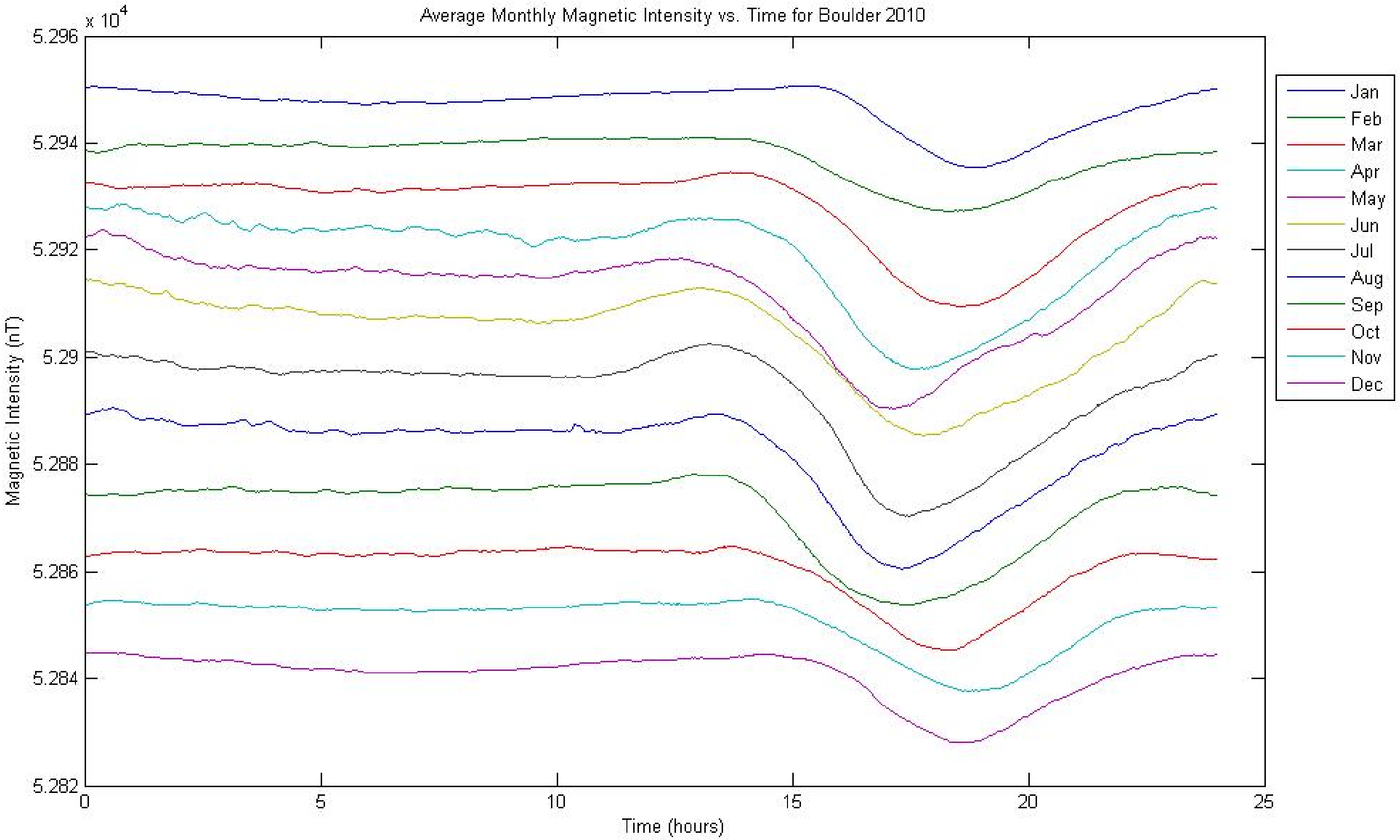
Space Weather Effects

- **All encompassing term for any time varying unpredictable field**
  - Ionosphere
  - Magnetosphere
  - Ocean currents
  - Induced currents in mantle
  - Coupling currents
- **The distinction is generally not important in magnav because none of them are easily removed from our measurements**
- **Generally small *in the frequency band of the measured anomaly field of a flying aircraft***
- **Much worse at Earth poles**

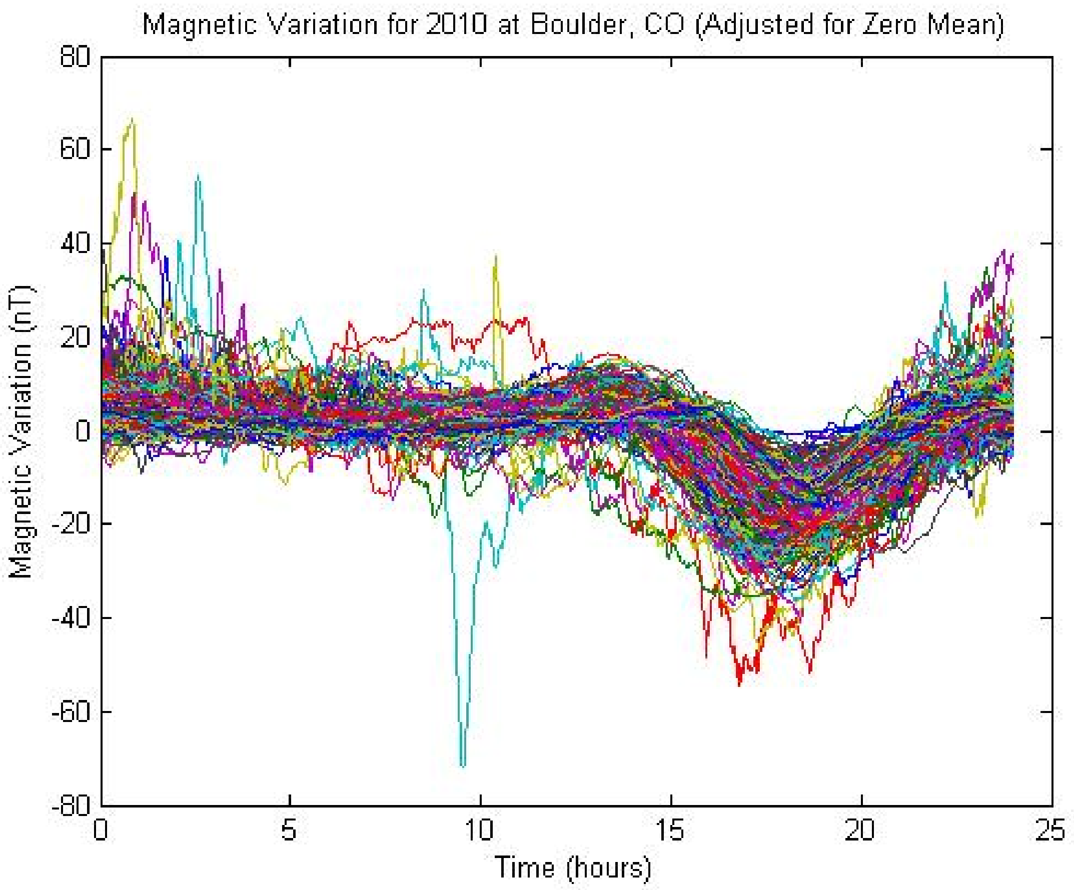
Temporal Variations



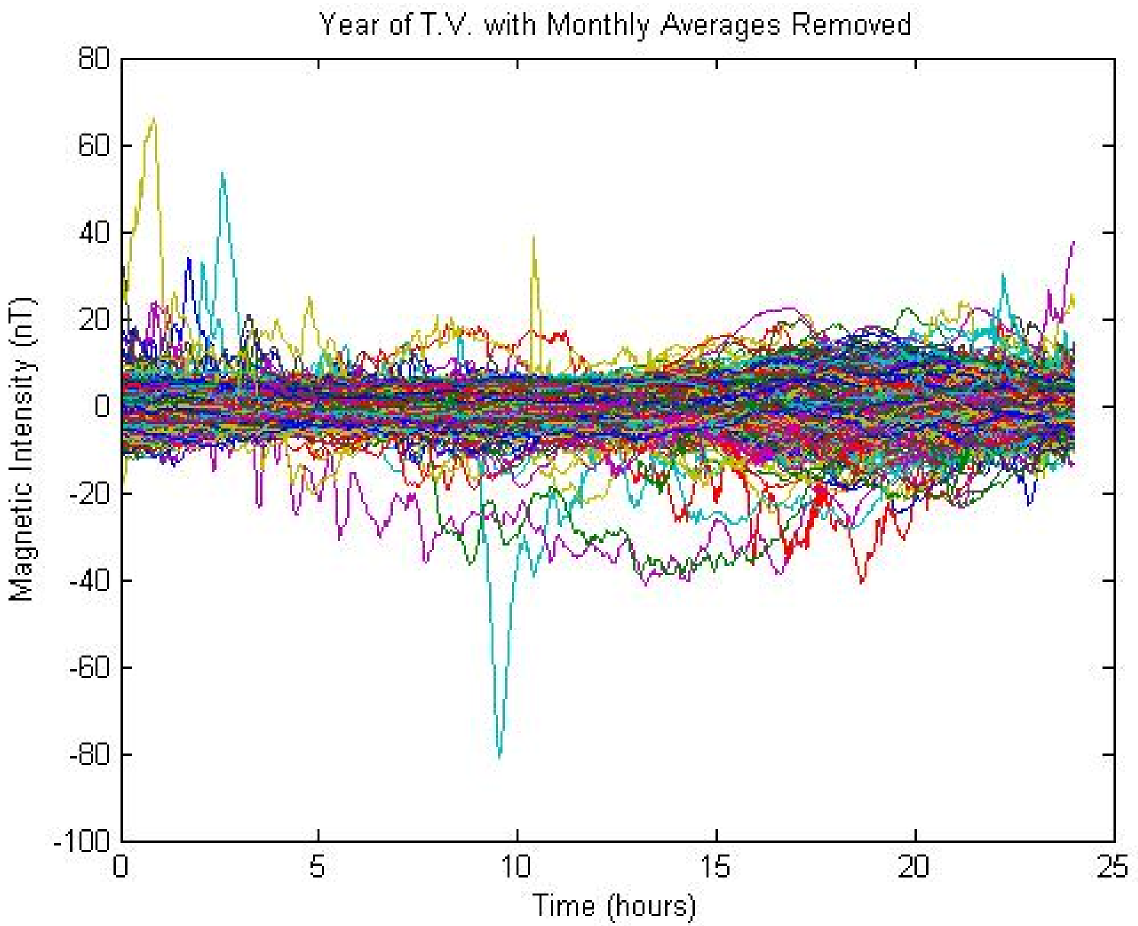
Secular Variations



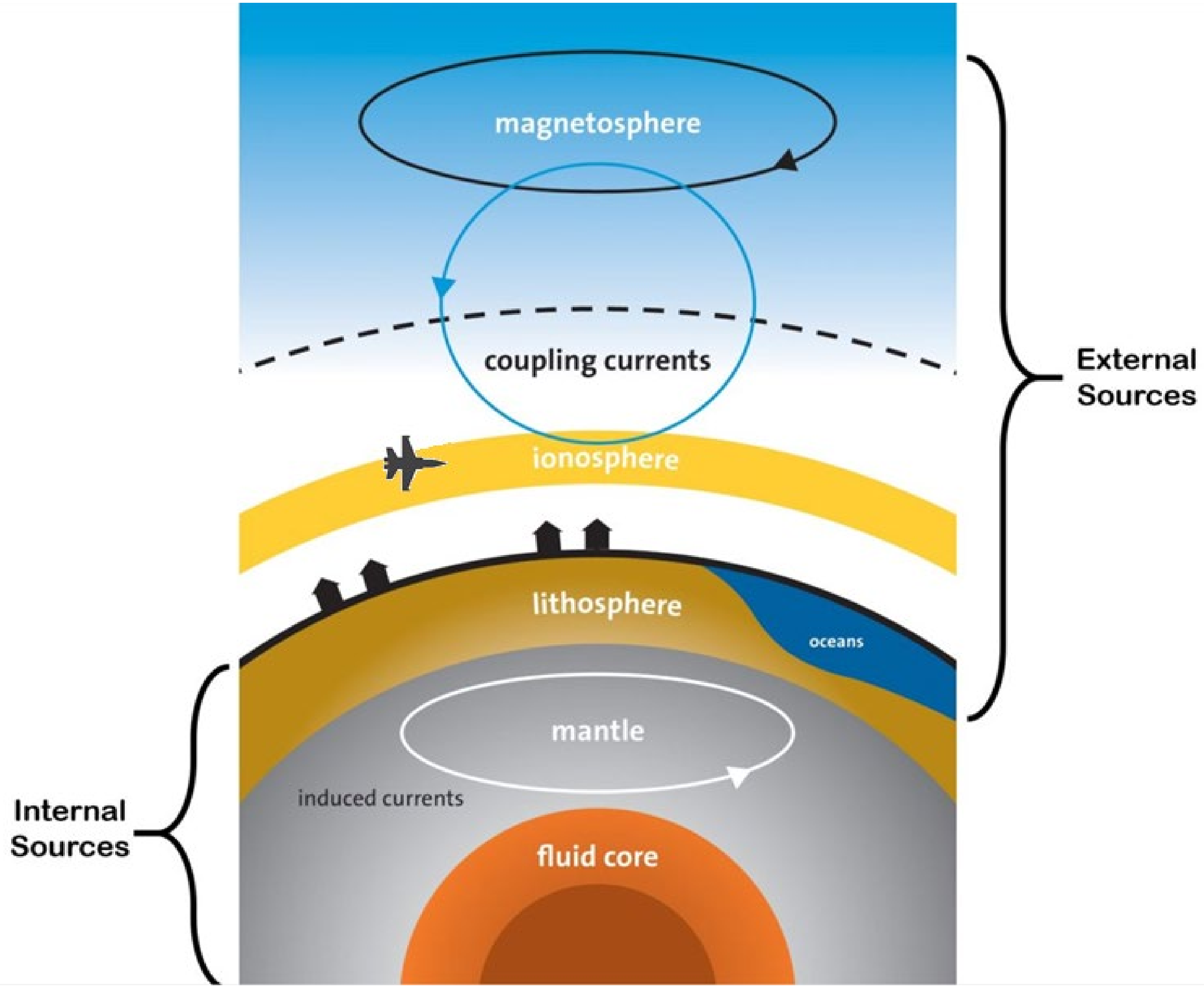
One Year Daily Variations with Secular Variation Removed



One Year Daily Variations with Secular and Daily (by month) Averages Removed



Summary of Earth Field Components



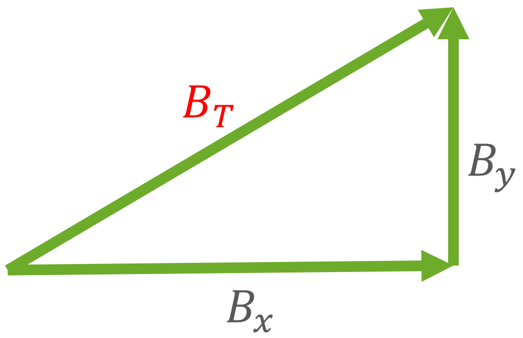
SENSOR DEVELOPMENT

Types of Magnetic Navigation

- Scalar Map Matching
- Directional Scalar Gradient Map Matching
- Total Scalar Gradient Map Matching
- Vector Map Matching
- Tensor Map Matching
- Tensor Eigenvalue Map Matching

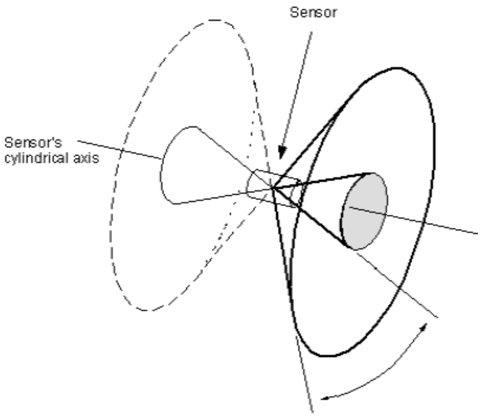
Scalar Measurements

- The magnetic field is a vector field with both length and direction
- Existing high sensitivity magnetometers are capable of *directly* measuring magnetic field intensity, or the length of the vector, B_t
- Measurement is invariant under rotation



Scalar Sensors

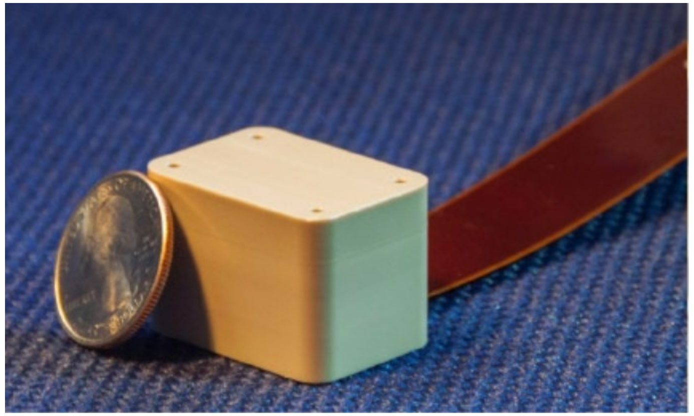
- **Low-SWAP scalar sensors needed for scalar mag-nav already exist**
- **Optically pumped atomic magnetometers exceed needed specifications for magnetic navigation**
  - Pico-tesla level sensitivities
  - Nano-tesla level absolute accuracies
- **Geometrics 823 sensor used for initial flight tests**
- **Existence of dead-zones in these types of sensors could be problematic for operational use but can be mitigated with multiple sensors**



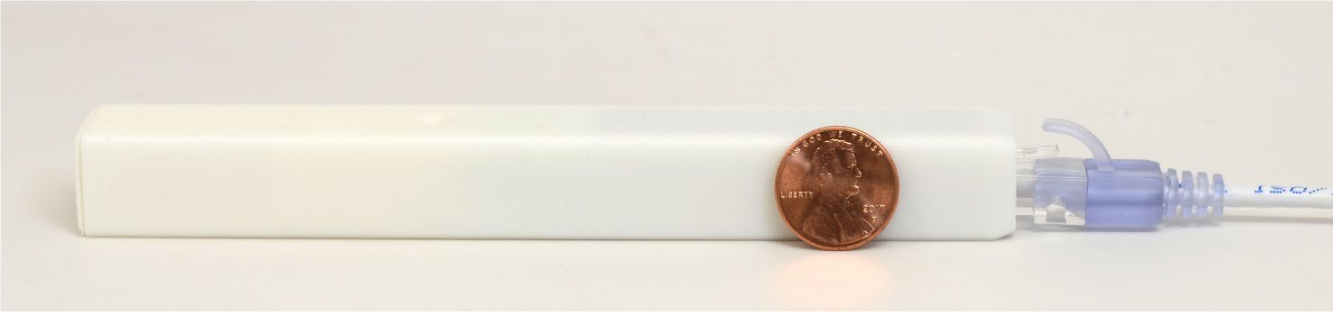
The sensors active zone extends fom between 15 and 75 from its cylindrical axis.

Emerging Low-SWAP Scalar Sensors

- **Geometrics MFAM sensor being used for summer flight tests**
  - Similar performance
  - 10x reduction in size
  - 15 cubic centimeters
  - 2 Watts



- **Additional low SWAP sensors are being developed by Twinleaf**

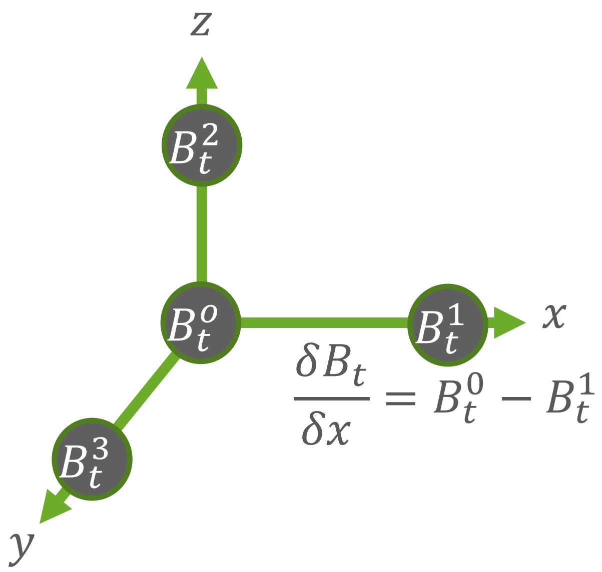


Directional and Total Scalar Gradient Measurements

- Finite differencing of scalar sensors can lead to a 3 element directional scalar gradient

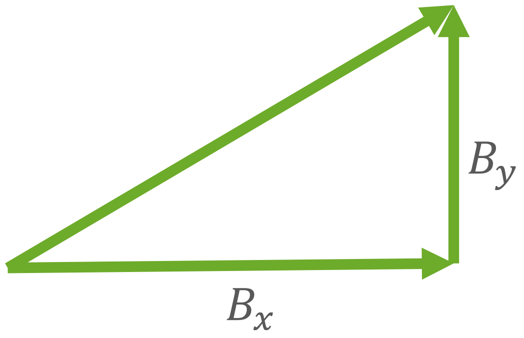
$$\frac{\delta B_t}{\delta x}, \frac{\delta B_t}{\delta y}, \frac{\delta B_t}{\delta z}$$

- A configuration of multiple scalar sensors can be used to measure the directional scalar gradient
- The directional gradient is measured in a *body frame*
- Total scalar gradient is simply the vector norm of the directional scalar gradient (invariant under rotation)
- Building a directional scalar gradient sensor is a goal of the DARPA AMBIIENT program
- May be critical for platform calibration



Vector Measurements

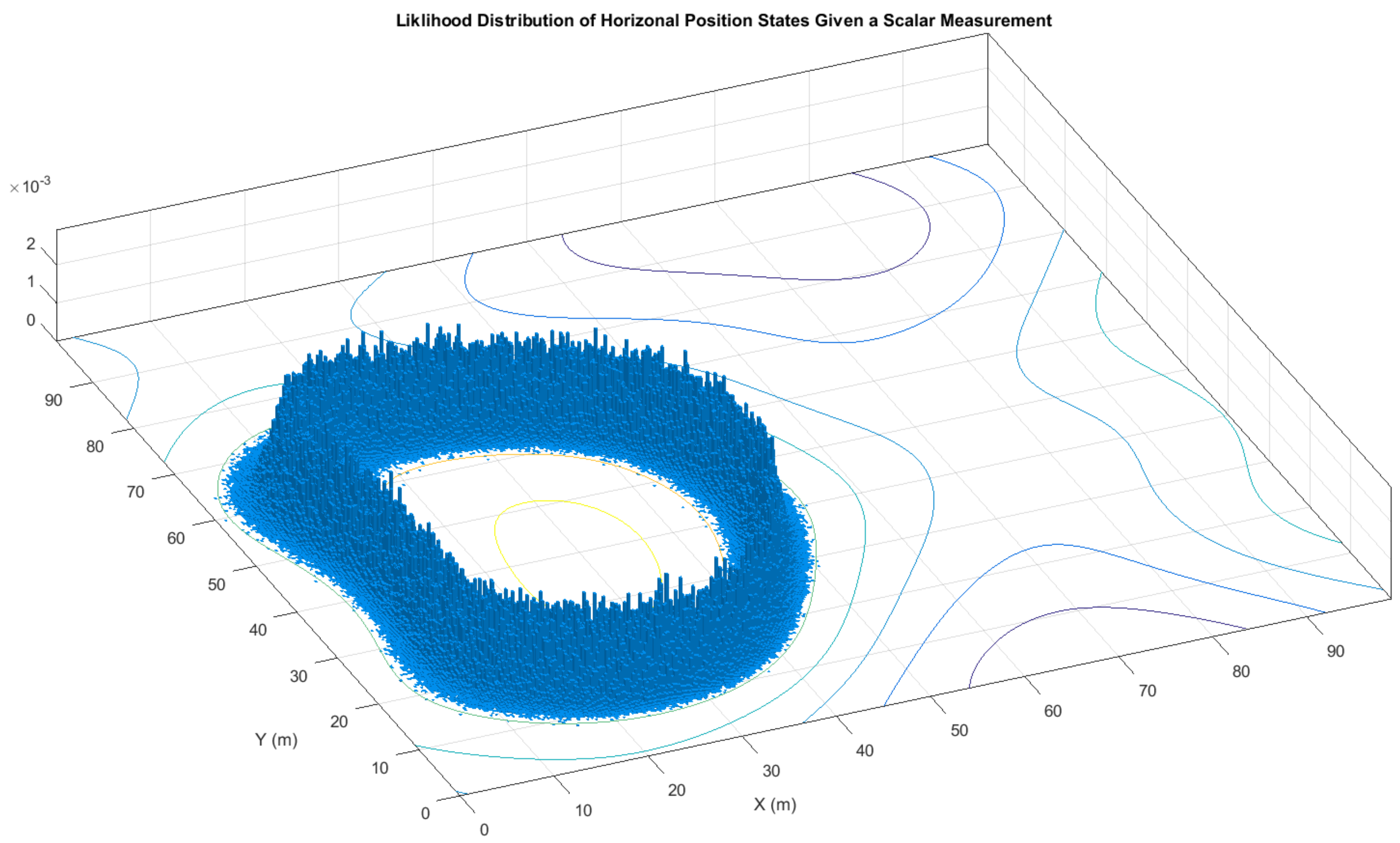
- Vector sensors measure the individual 3 orthogonal components of the magnetic field, and give information on both the direction and intensity of the magnetic field
- Vector measurements are made in a *body frame* but map-matching by necessity occurs in a *world frame*
- This causes vector magnetic navigation to require highly accurate attitude information



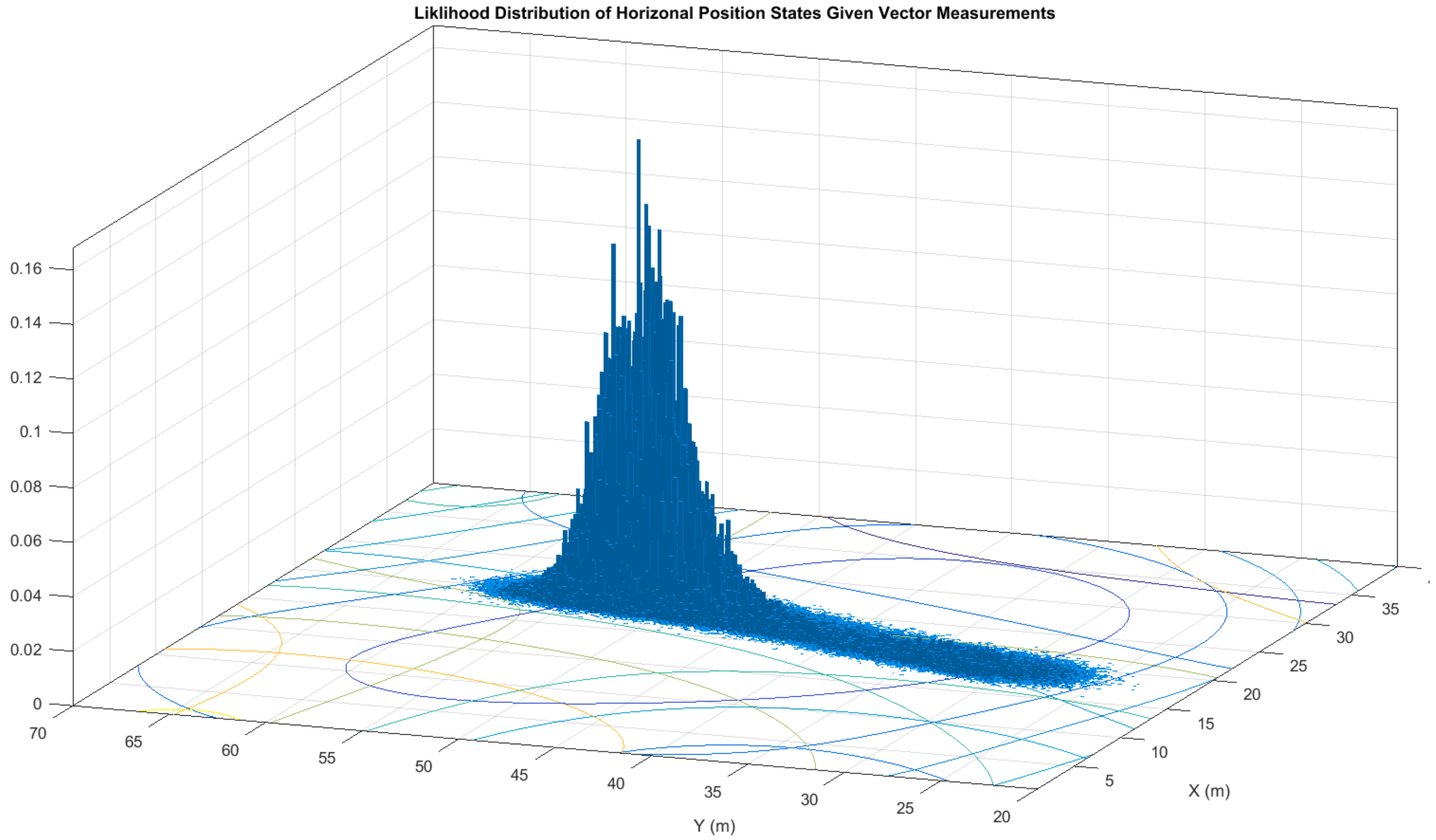
Existing Vector Sensors

- Commercially available vector sensors have lower sensitivities and accuracies than existing scalar sensors
- Low-SWAP fluxgate sensors have poor performance at low frequencies (<<1Hz), a critical requirement for accurate magnetic navigation
- Emerging vector magnetometer technology may enable the use of the full vector field to increase navigation performance
  - NV-Diamond
  - Nuclear Magnetic Resonance

Limitations of Scalar Measurements

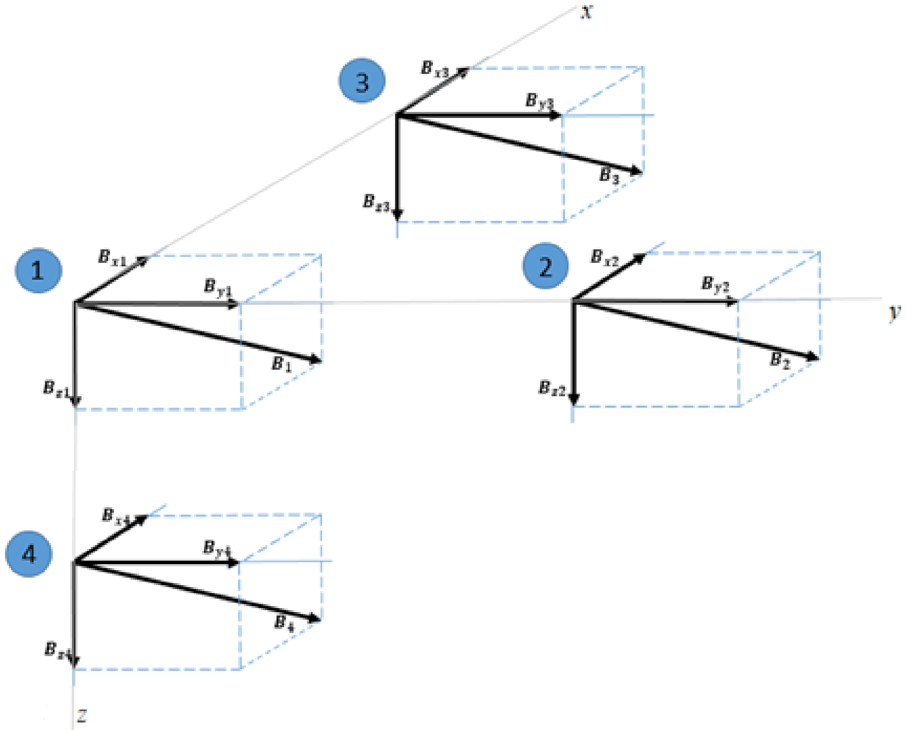


The Solution: Vector and Tensor Measurements



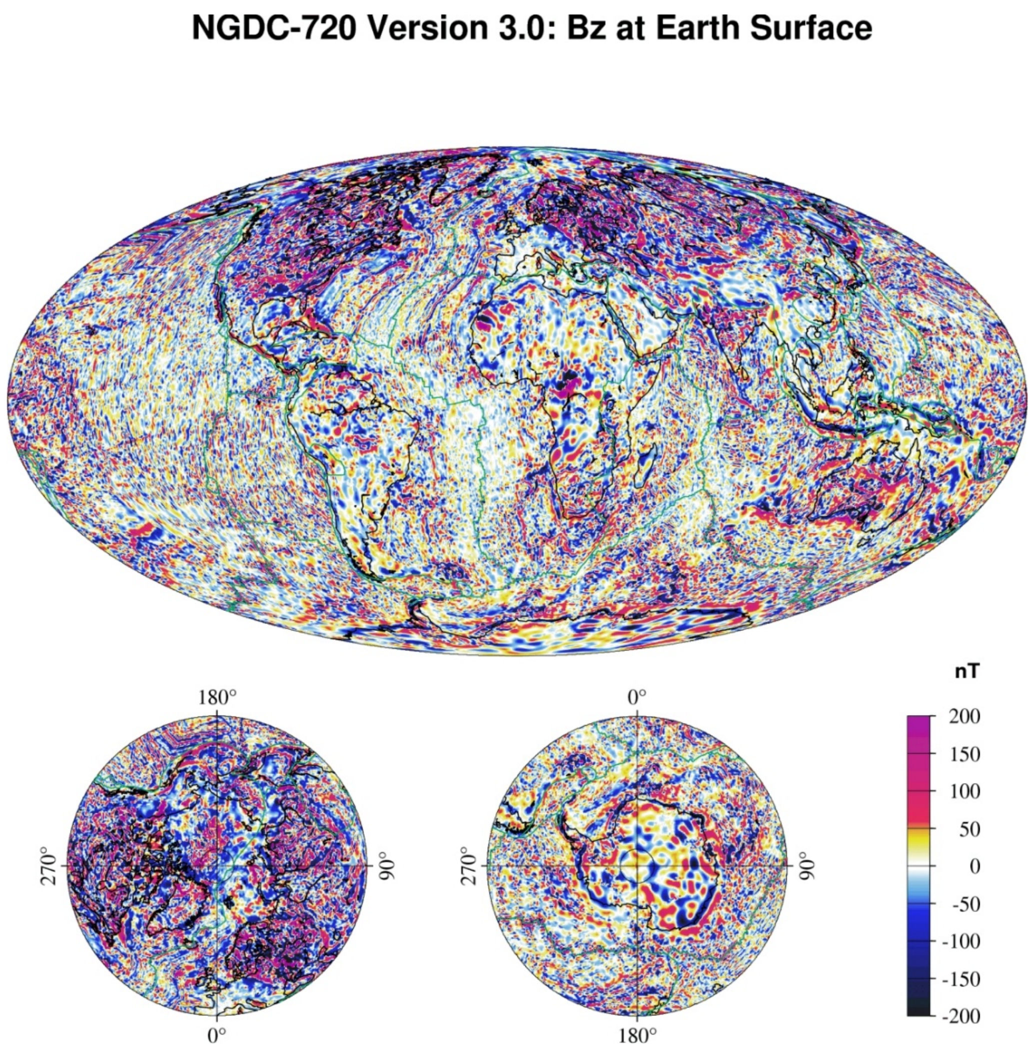
Tensor Measurements

- The magnetic tensor field is the spatial gradient of the magnetic vector field
- Measured in a *body frame*
- May be very useful for calibration



$$\nabla \mathrm{B} = \begin{bmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_x}{\partial y} & \frac{\partial B_x}{\partial z} \\ \frac{\partial B_y}{\partial x} & \frac{\partial B_y}{\partial y} & \frac{\partial B_y}{\partial z} \\ \frac{\partial B_z}{\partial x} & \frac{\partial B_z}{\partial y} & \frac{\partial B_z}{\partial z} \end{bmatrix}$$

Enhanced Magnetic Model 720

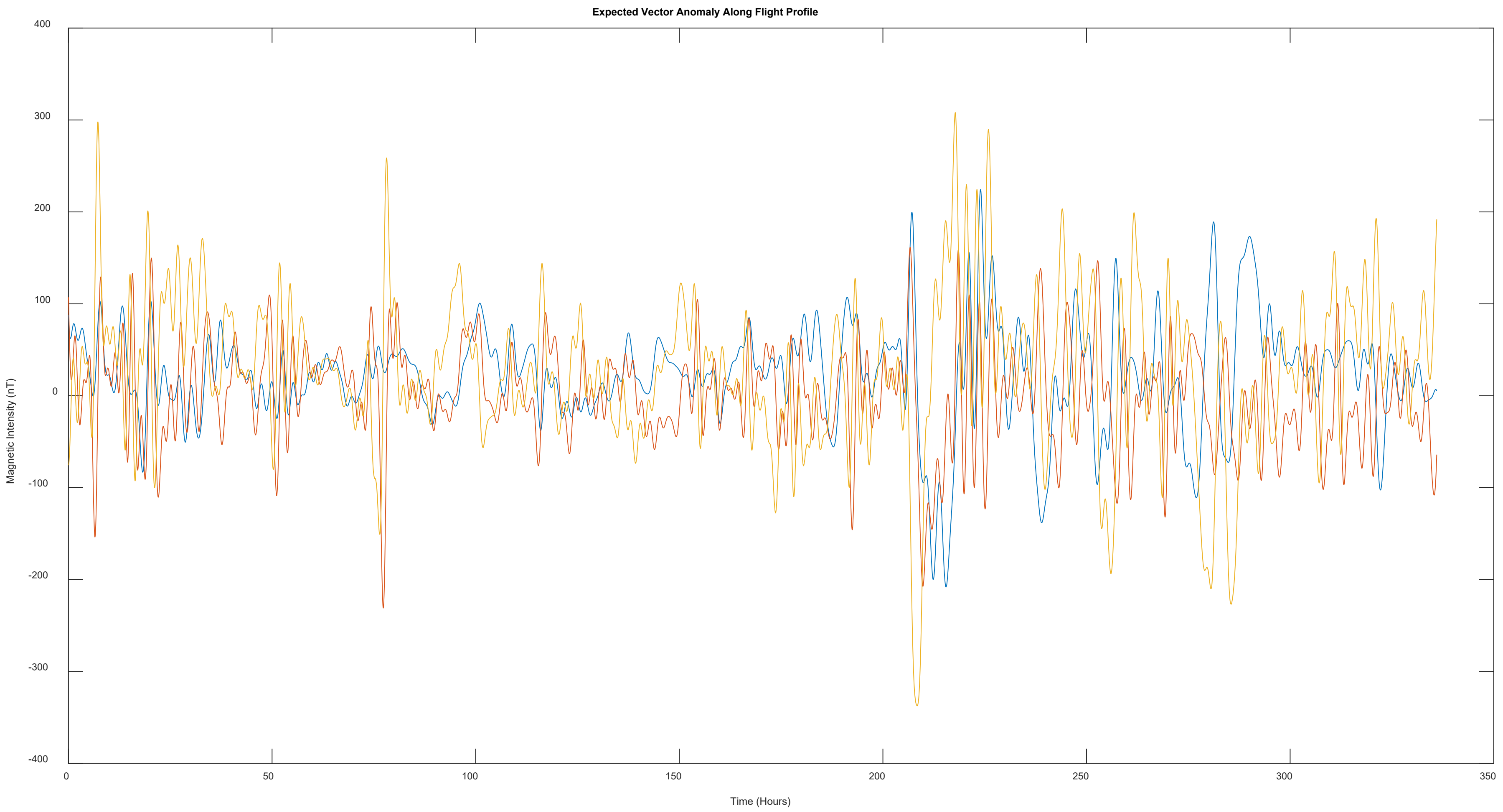


https://www.ngdc.noaa.gov/geomag/EMM/img/NGDC-720_V3_hanning_Bz_0km.jpg

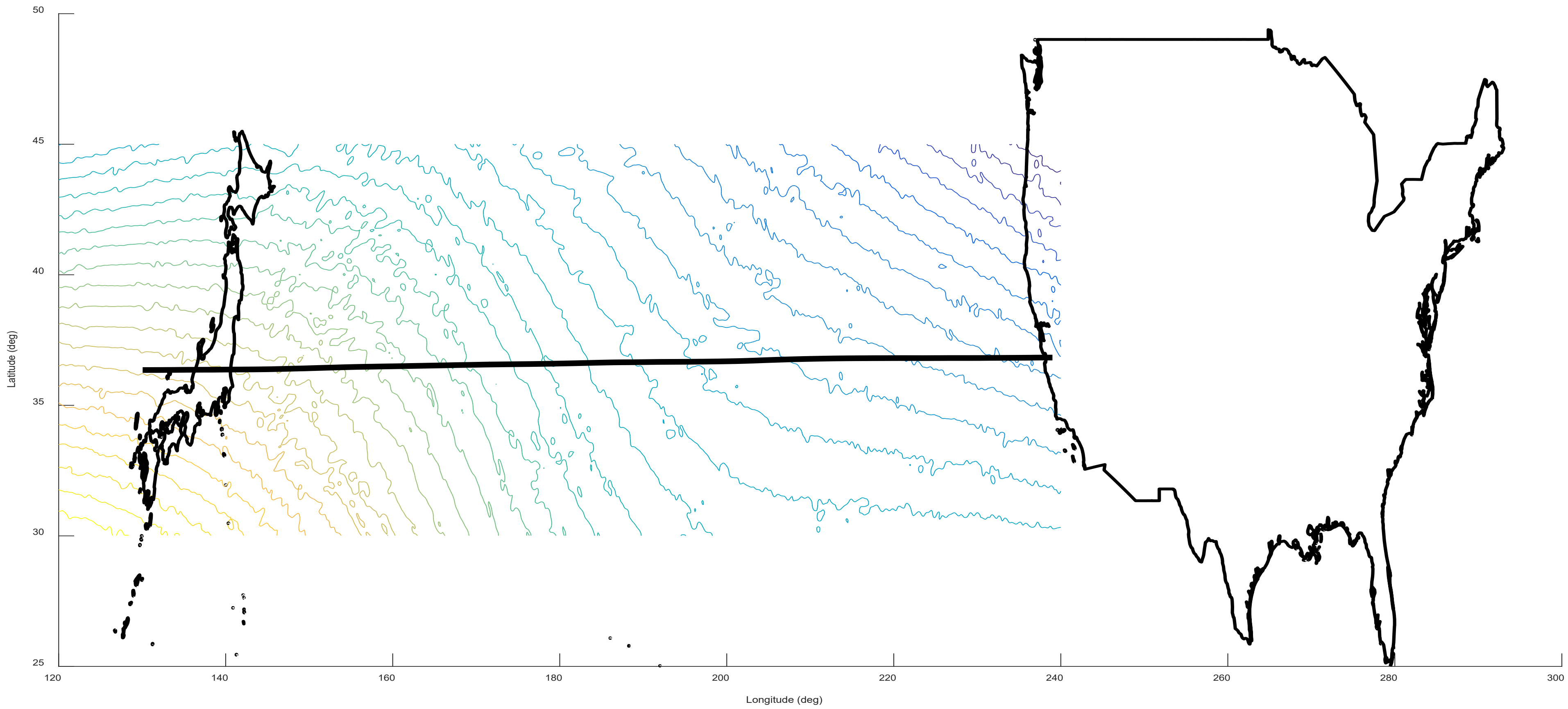
EMM720 Test Scenario: Crossing the Pacific in a Submarine

- **Navigation under-water is challenging**
- **Here we will demonstrate a 14-day underwater trip that leaves CA and arrives in Japan with 800 meters of uncertainty**
  - Completely passive system
  - Un-jammable

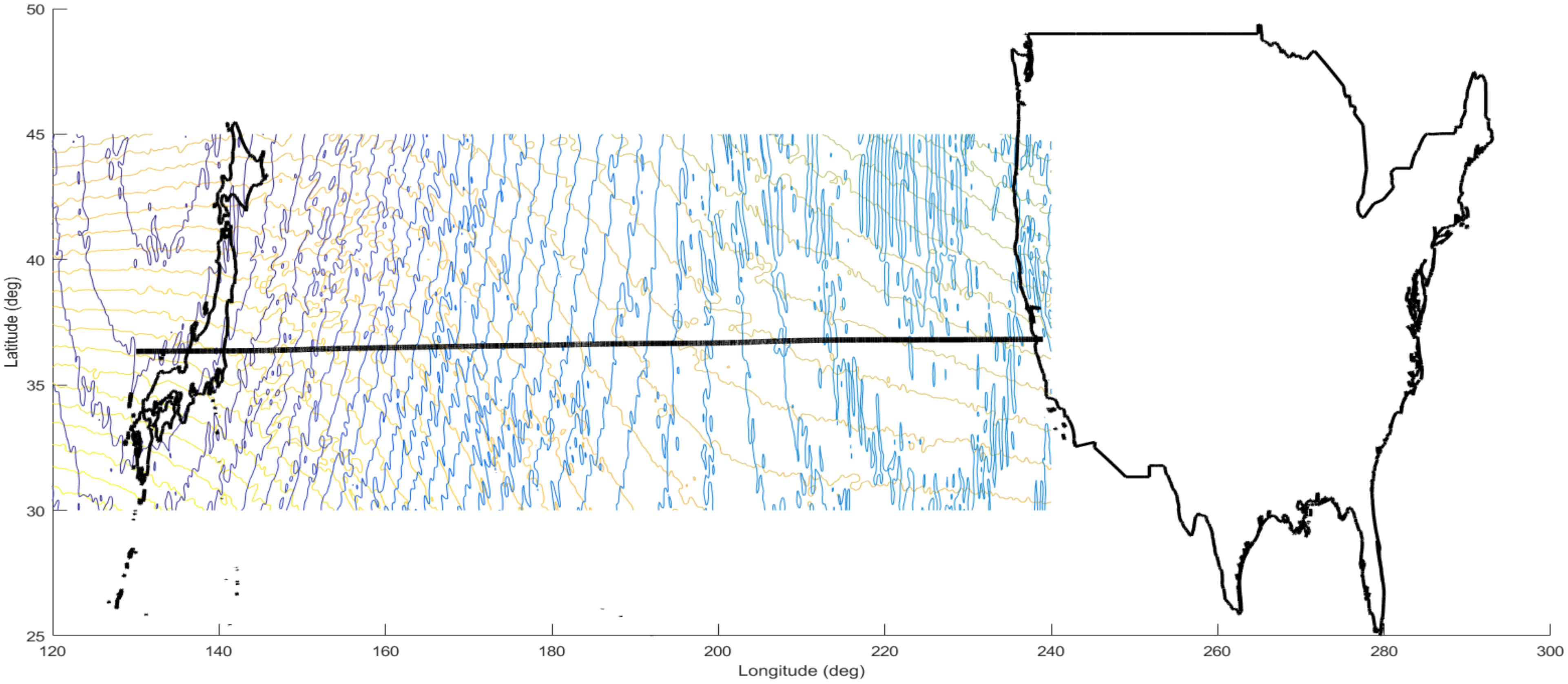
Submarine Measurements Along Trajectory



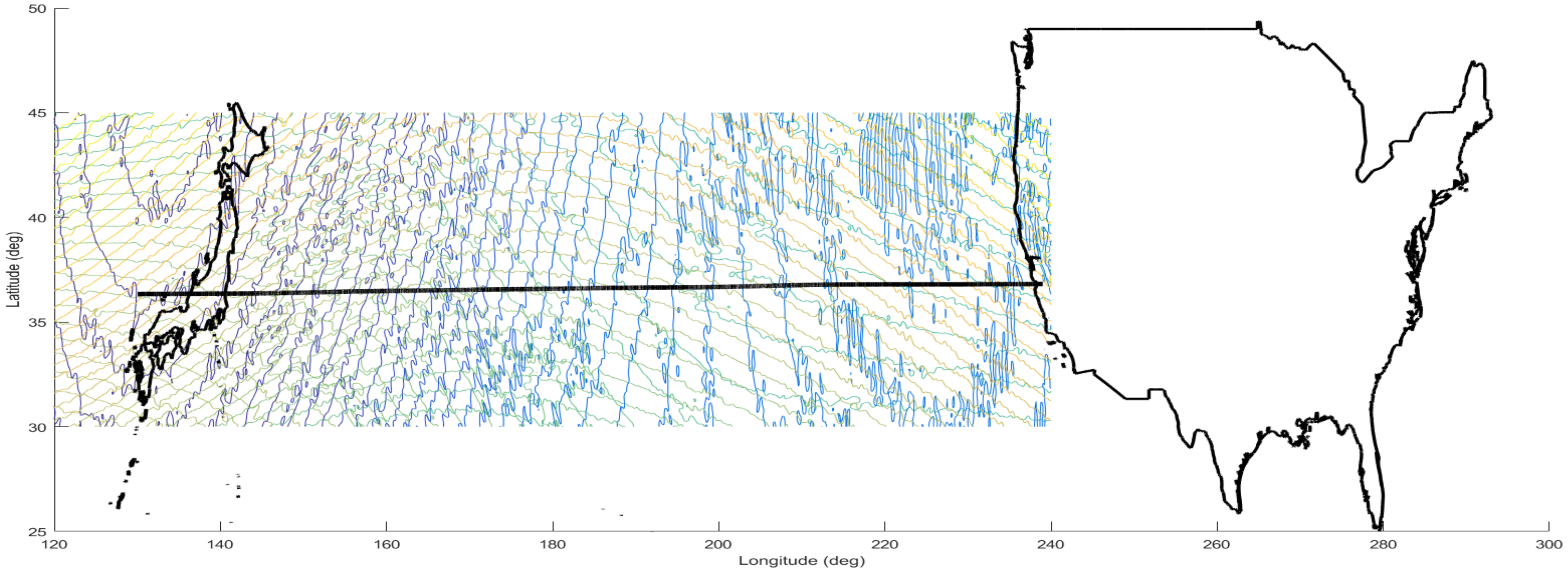
B_x Vector Component



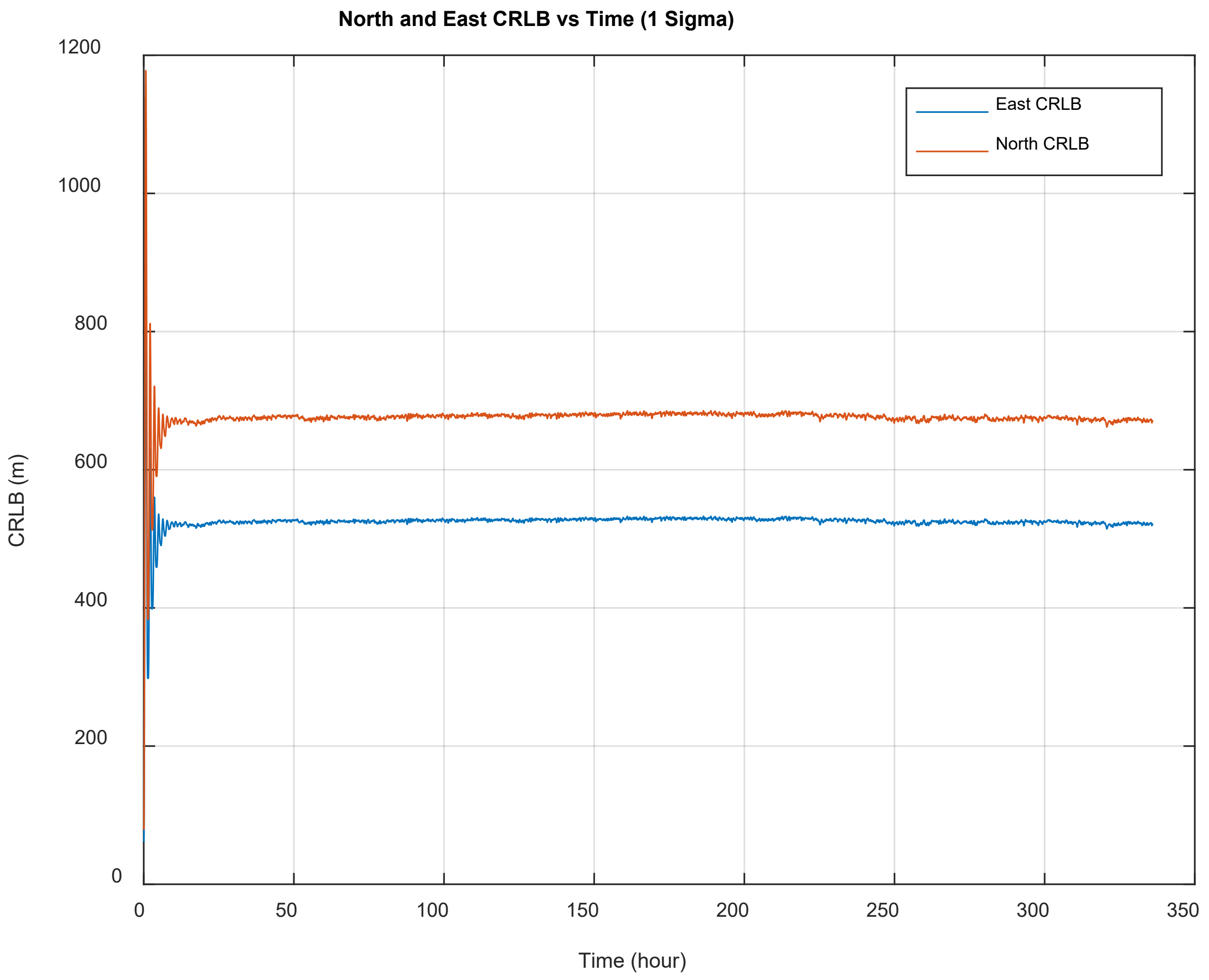
B_x and B_y Vector Component



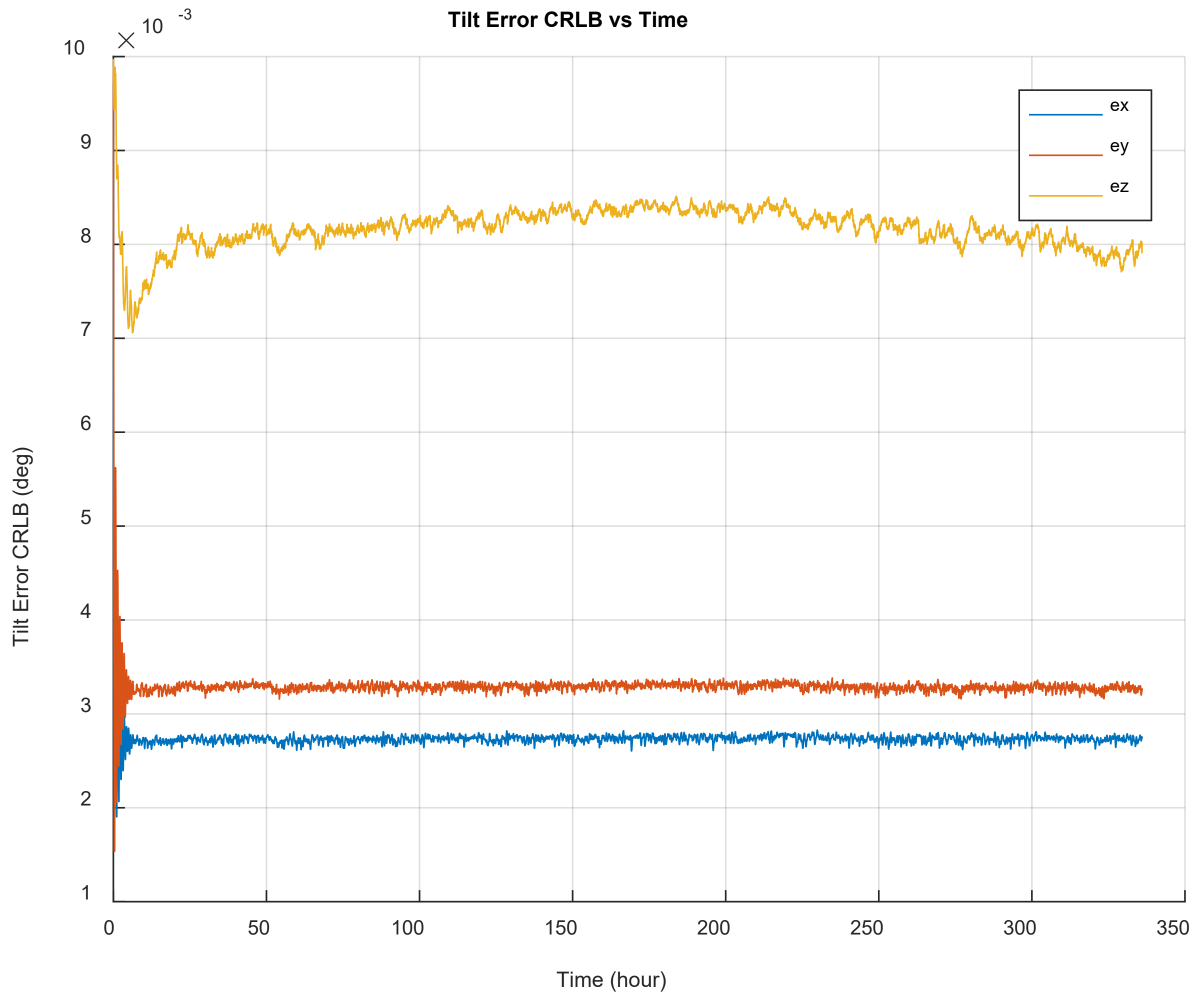
B_x, B_y and B_z Vector Component



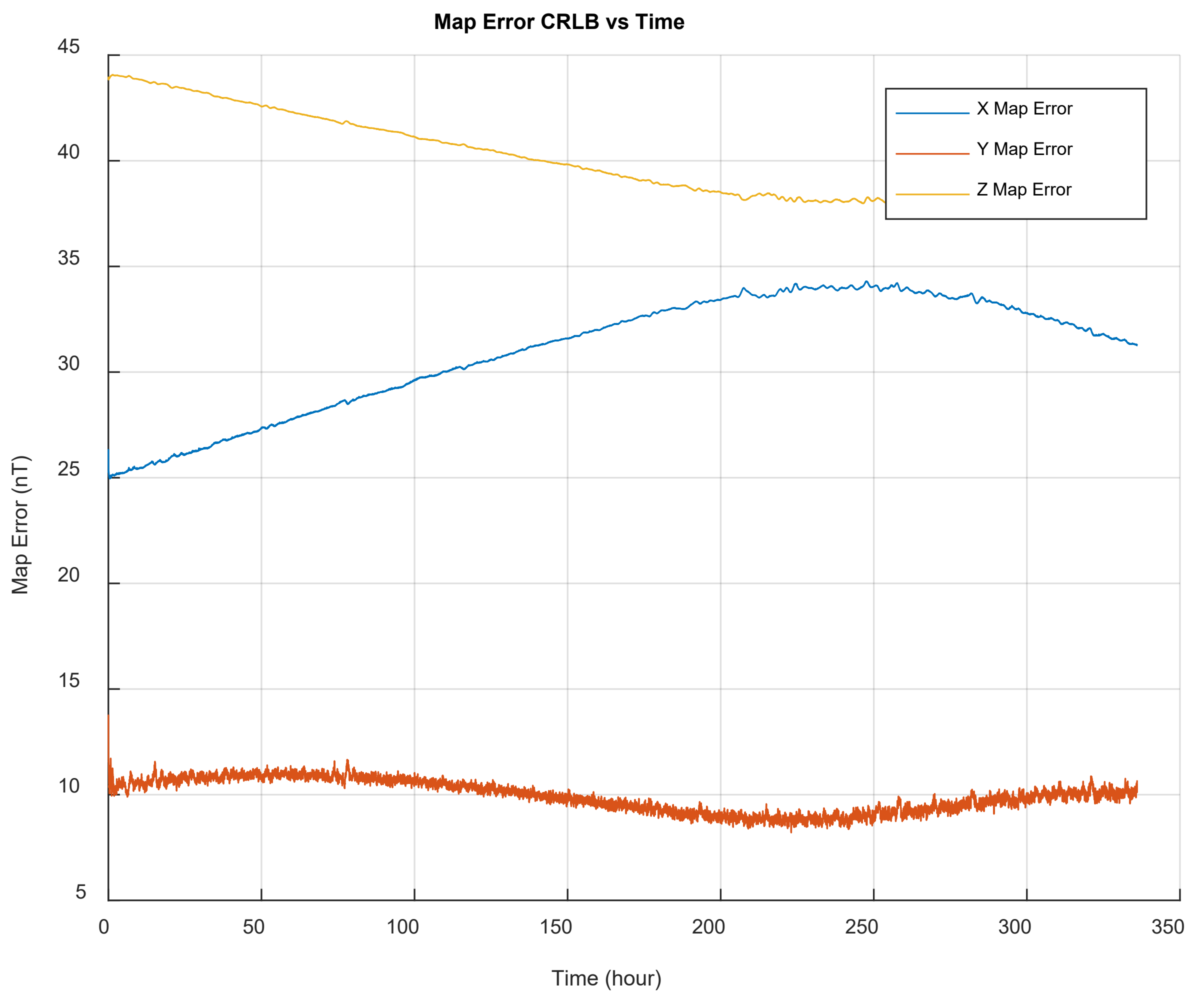
Position Performance



Attitude Performance



Map Uncertainty



What Makes a “Good” MagNav Sensor?

- Signal of interest manifests as very long time-domain frequencies – this requires high bias stability, or high sensitivity even at very low frequencies
- Vector and Scalar MagNav will never pT or even single-digit nano-Tesla absolute accuracies – aircraft errors, space weather, and map errors will always dominate
- Tensor sensor would need absolute accuracies high enough to measure pico-Tesla per meter fields in order to track the crustal field, which changes on the order of nano-Tesla per kilometer

Conclusions

- **Scalar MagNav is possible today with existing sensors**
- **Vector, gradient, and tensor sensors may improve navigation accuracy in two ways**
  - Directly yield more information for map-matching algorithms
  - Enable operational use through improved calibration techniques
- **Questions for discussion**
  - With a large selection of sensor modalities, where should we focus *first?*
  - What steps can be taken to confirm the usefulness of vector/gradient/tensor for calibration
    - High fidelity simulations?
    - Machine learning approaches?
    - What platforms should we test on?
  - Are certain modalities more applicable to different application spaces?

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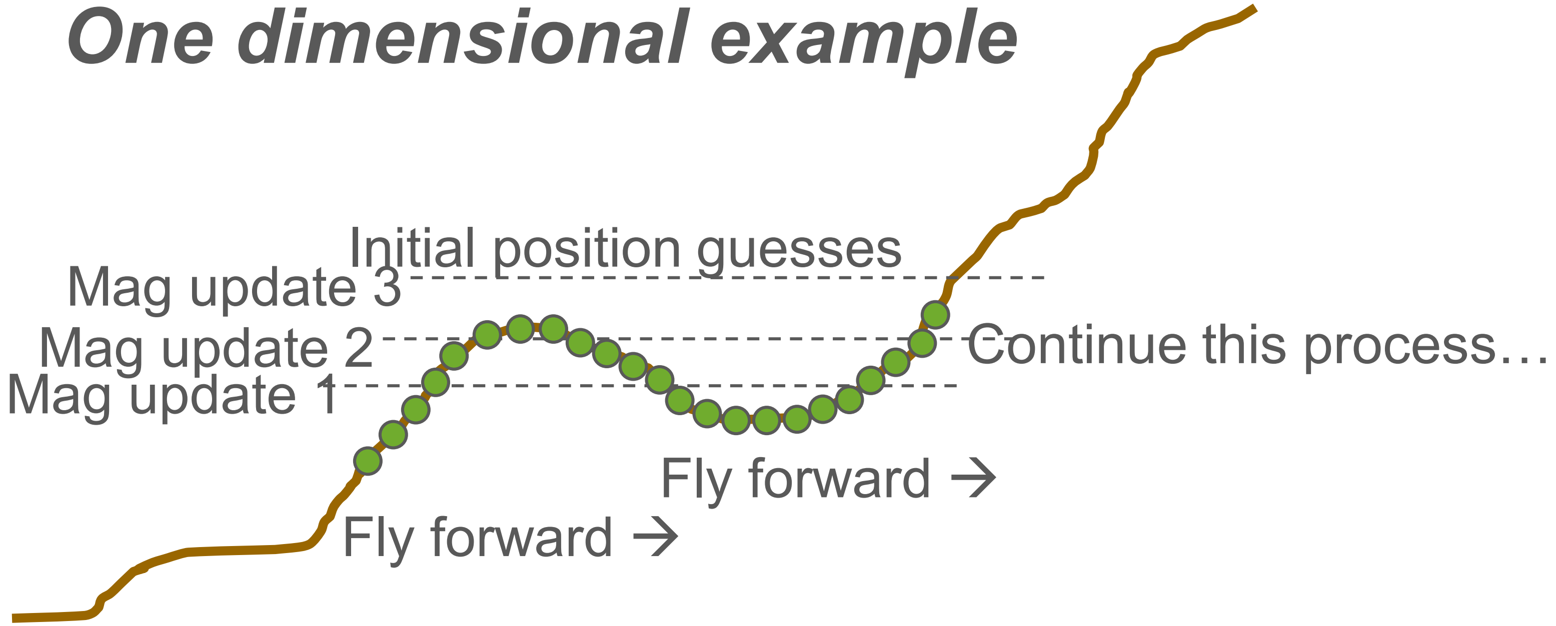
MagNav Measurement Equation

Map-Matching Techniques

- **There exists a long history of map-matching algorithms that originated with terrain following**
  - TERCOM – heuristic based, match a sequence of measurements to a terrain map
  - SITAN – EKF, sequential filter using terrain maps as a measurement function
- **Modern algorithms outperform these techniques**
- **The current proposed and flight-test proven technique is that of a Rao-Blackwellized particle filter, sometimes called a marginalized particle filter**
- **Current RBPF approaches are nearly achieving the Cramer-Rao Lower Bound on real datasets**

Map-Based PF Algorithm

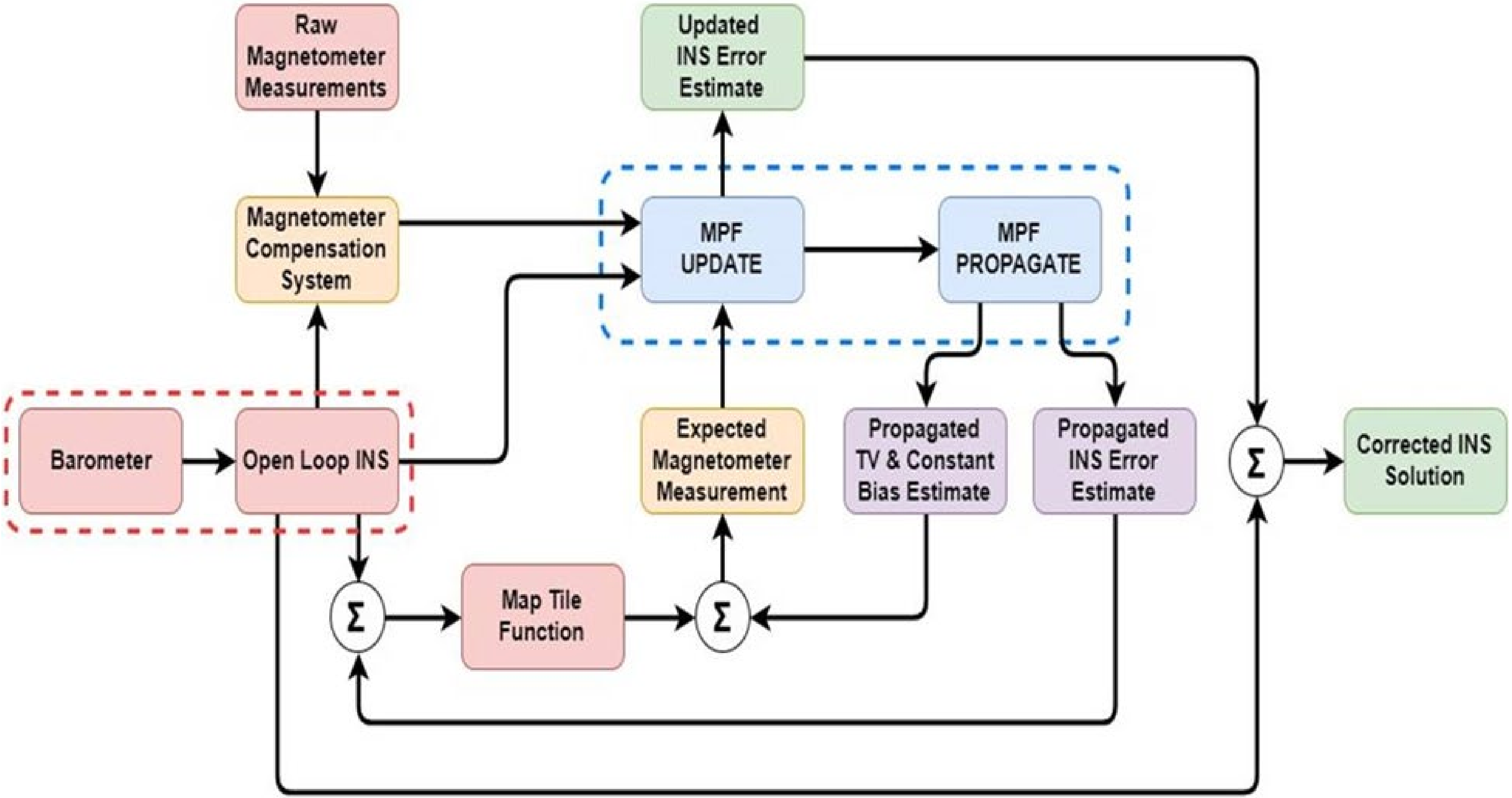
One dimensional example



INS Integration

- Magnetic navigation benefits from being combined with inertial navigation systems
- Conceptually, the use of an INS allows the navigation system to “coast” between periods of low magnetic variation
- The magnetic measurements are coupled with the inertial in such a way that INS errors are corrected by the magnetic measurements
- INS quality is a dominant variable in navigation performance and can make up for the decreased magnetic information at high altitudes or low velocities

Magnetic Navigation Algorithm



General Measurement Equation

$$M_3(lat, lon, h) = f_I^3(f_U(M_{h_0} + \delta M_{h_0}) + \delta U)$$

where:

M_{h_0} is the two dimensional grid of magnetic intensity values at height h_0

δM_{h_0} are the errors in the original map grid.

f_U is the upward continuation function which transforms M_{h0} to several discrete increasing altitudes, giving a three dimensional grid of values from the original two dimensional grid

δU is the error in the upward continuation transform

f_I^3 is an operation which returns a three dimensional interpolation function given a three dimensional grid of values

lat, lon are the latitude and longitudes at which the magnetic intensity is being evaluated

h is the altitude at which the magnetic intensity is being evaluated

$M_3(lat, lon, h)$ is a 3D interpolation function which returns expected magnetic intensity at a given latitude,

General Measurement Equation Cont'd

$$Z_t = M_3(lat, lon, h) + I(lat, lon, alt, t) + \delta I(lat, lon, alt, t) +$$

$$\delta C(\theta, \phi, \psi) + V(lat, lon, h, t) + H + b + w$$

where

Z_t is the raw measurement from the magnetometer at time t

$M_3(lat, lon, h)$ is the pre-computed 3D interpolation function which returns expected magnetic intensity

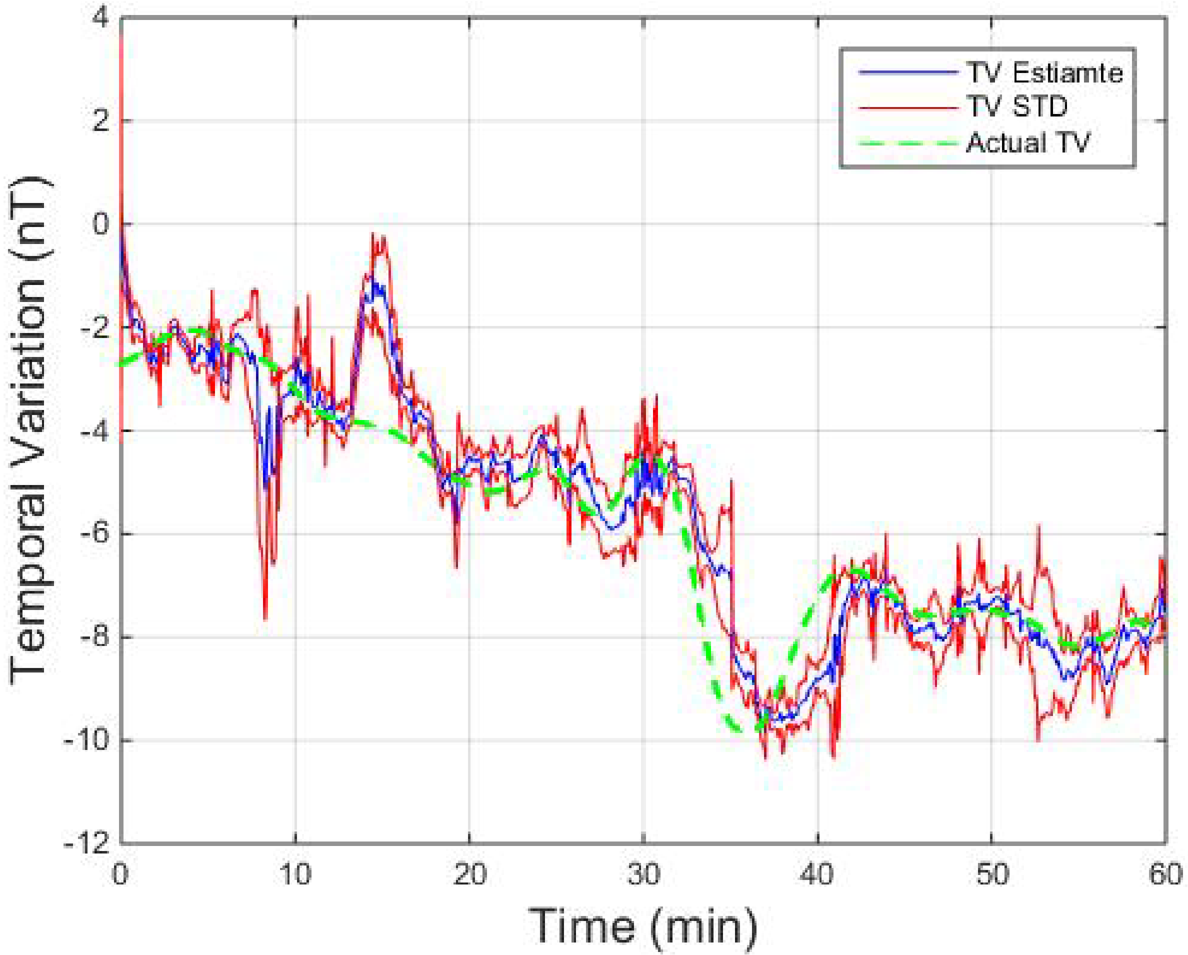
I is the IGRF model, which depends on both position and time

δI is the error in the IGRF model, which depends on both position and time

θ, ϕ, ψ are aircraft Euler angles

$\delta C(\theta, \phi, \psi)$ are platform effects remaining after compensation
$V(lat, lon, h, t)$ are the temporal variations, or space weather effects
H, b, w are sensor heading error, biases, and white noise errors

Temporal Variation Filter Observability



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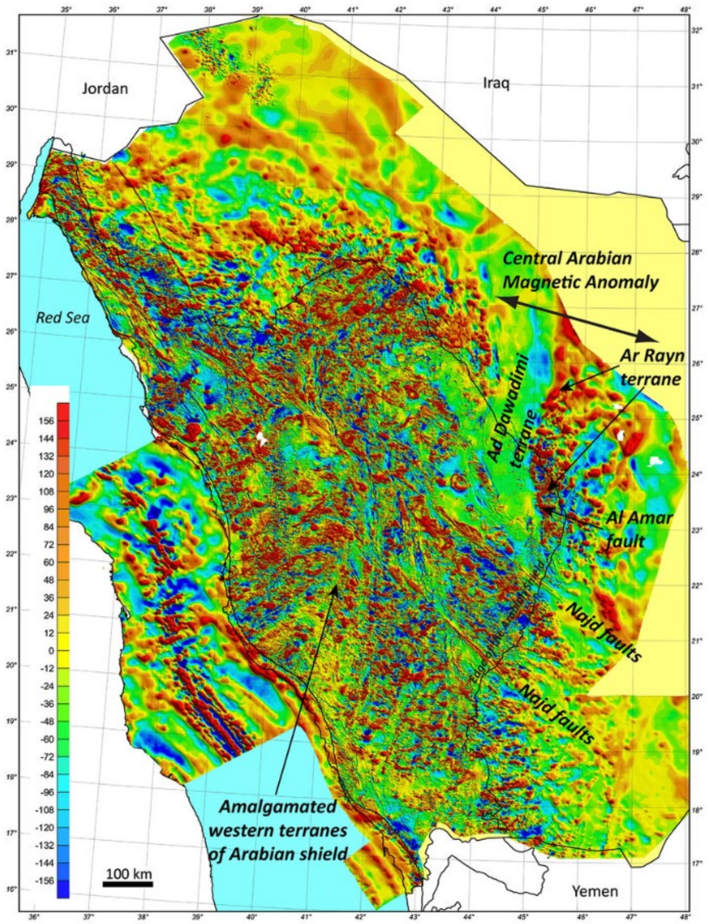
Maps and Models

Maps vs Models

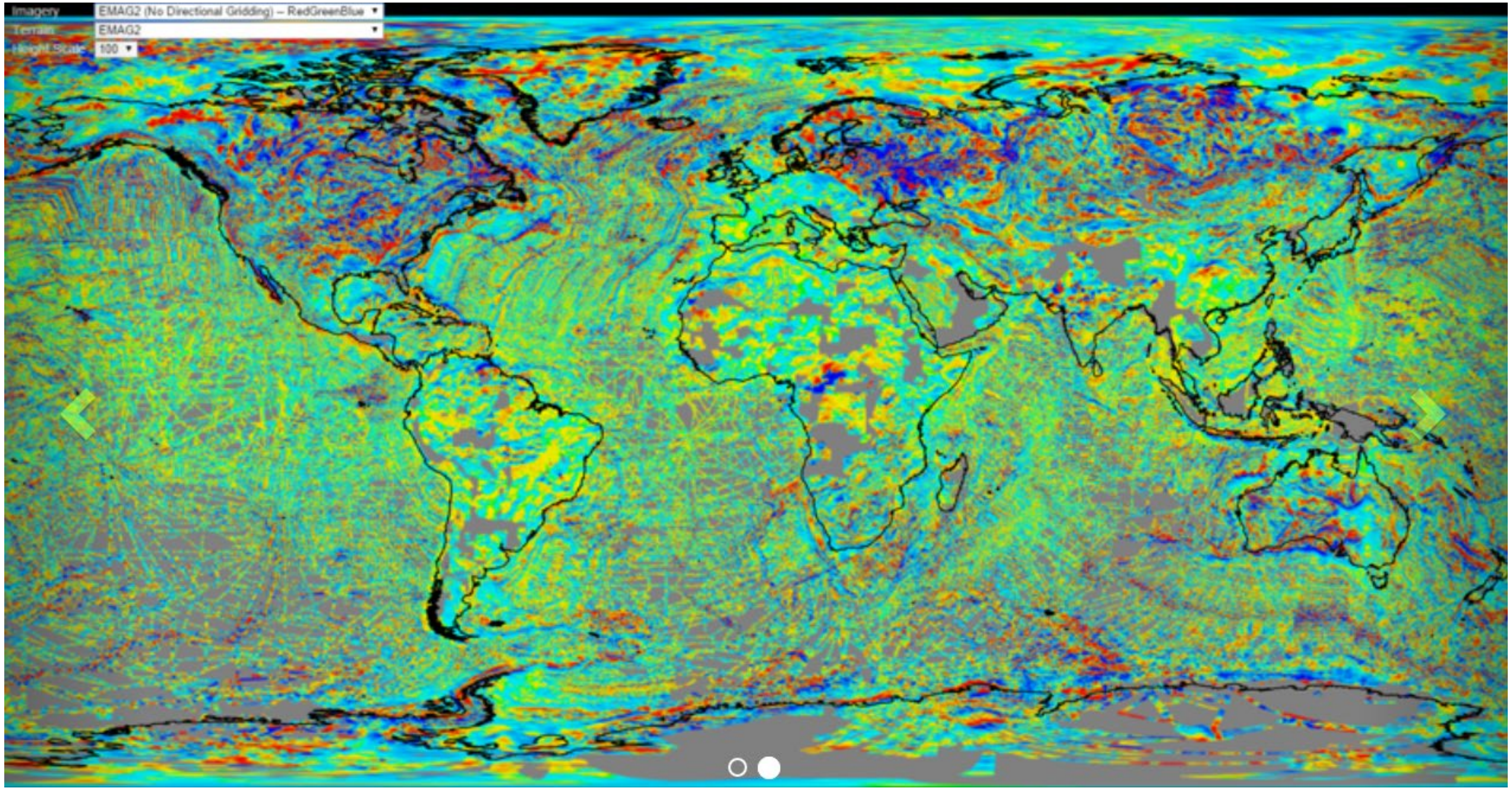
- **There are two main types of magnetic data**
  1. World or regional gridded map data (typically scalar data)
  2. Spherical harmonic world models (typically vector data)
- **There are important differences with regard to resolution, accuracy, and availability**

Regional Gridded Map Data

- **Typically scalar data, as this is what nearly all aeromagnetic surveys measure**
- **A fully-sampled regional map will typically be the most accurate magnetic data available**
  - Not all maps are fully sampled
  - Maps will become fully sampled when upward continued to their line spacing distance
- **Often leveled to arbitrary datums (do not match up with long wavelengths of Earth field)**



World Gridded Map Data

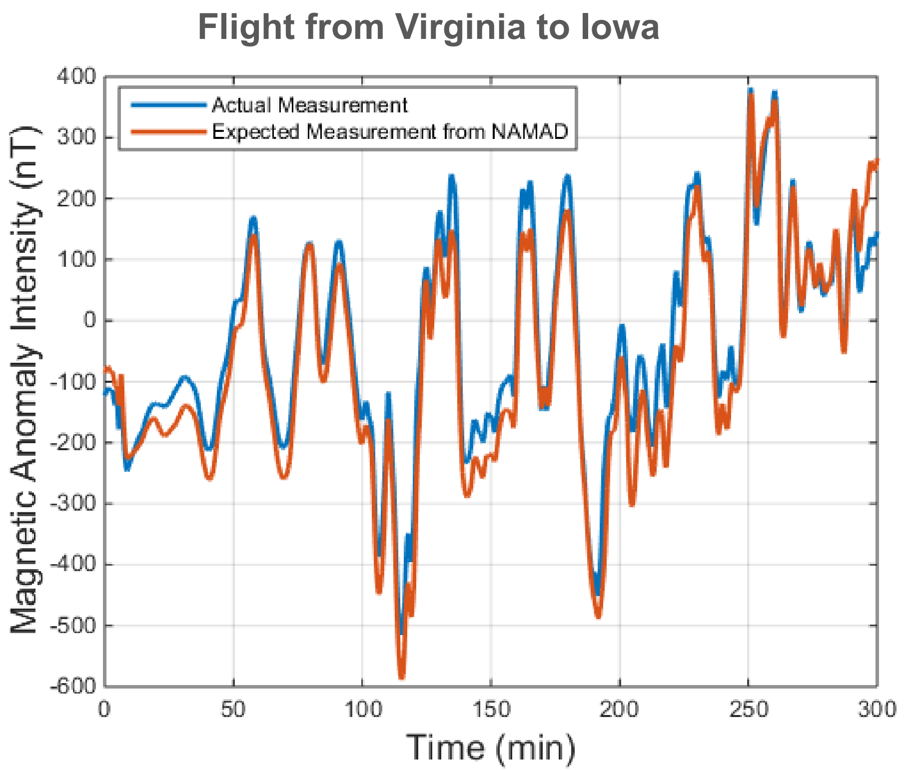


World Gridded Map Data

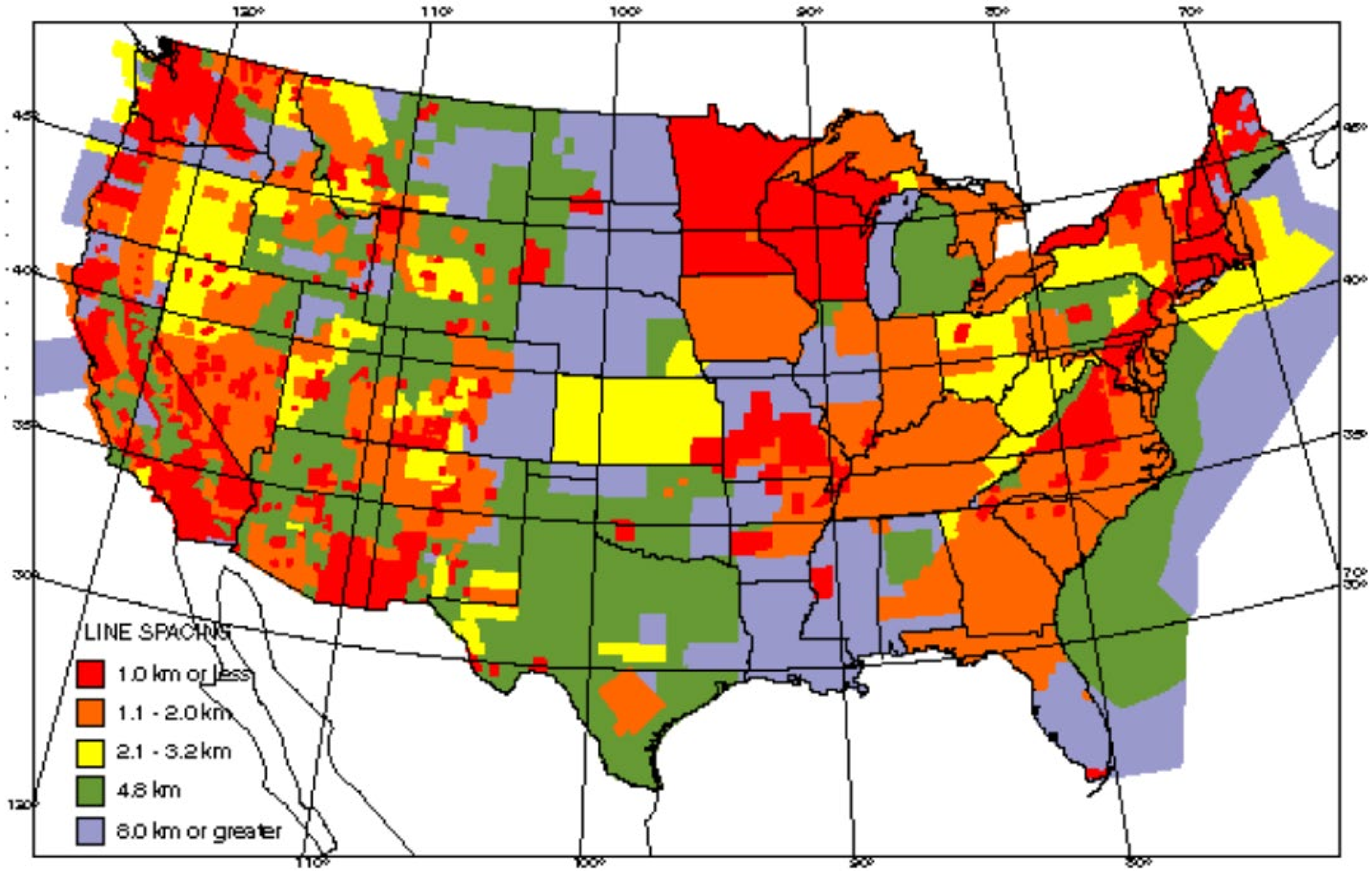
- **World gridded map data is created by merging both satellite data, ship-borne data, and aeromagnetic survey data**
- **Typically much lower resolution than regional maps**
- **Unavoidably there is varying:**
  - Resolutions
  - Data accuracy
  - Data availability (large holes)
- **Current world maps (such as EMAG2) throw out some high resolution data to create uniform resolution globally**
- **World models typically capture long wavelengths from satellite data and short wavelengths from aeromagnetic or shipborne data**

World Gridded Map Data

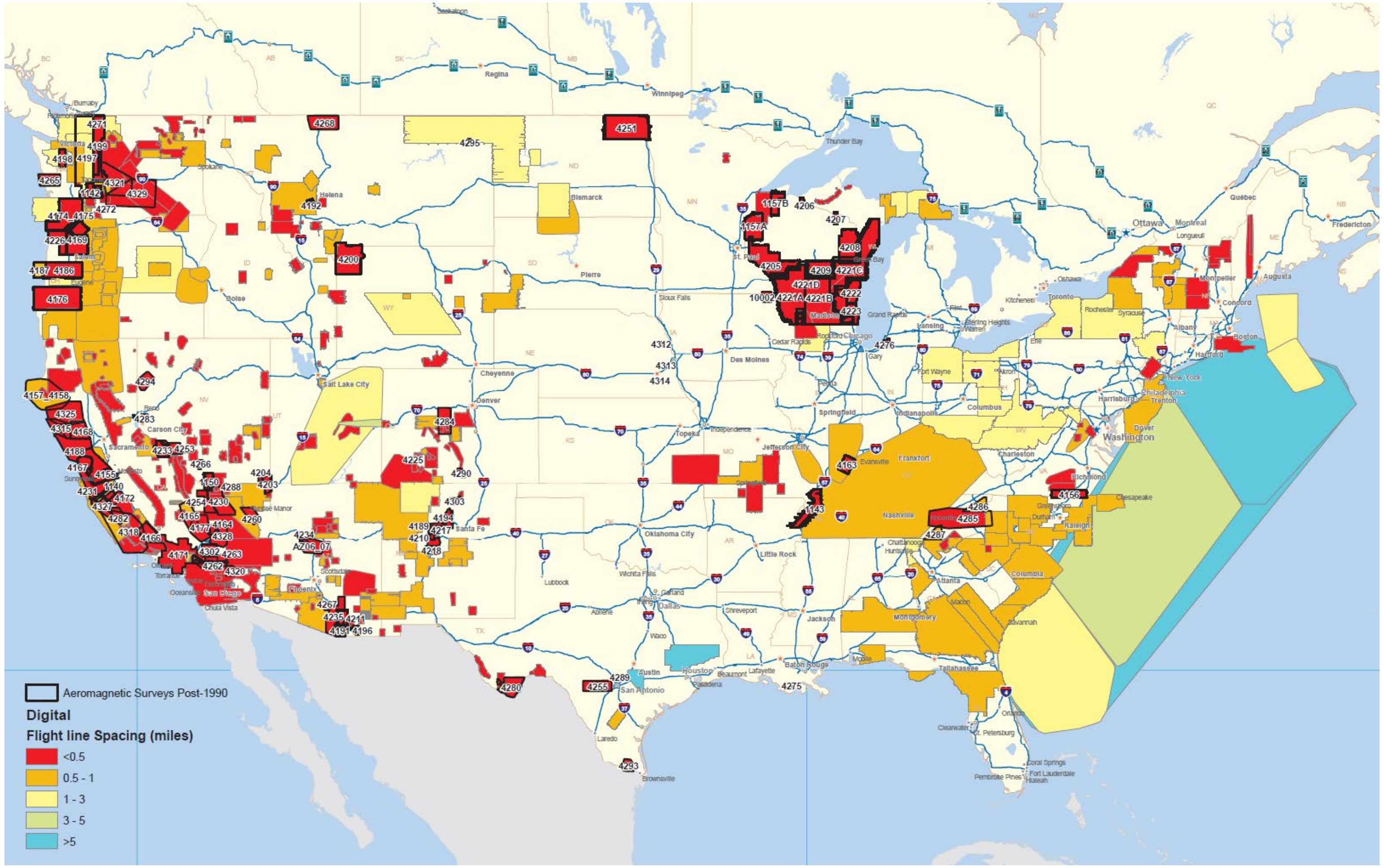
- Because global map products stitch together many smaller surveys, they are unable to capture long wavelengths
- Satellites can capture the longest wavelengths but wavelengths in between are difficult to capture



Map Quality and Availability



High Quality Surveys

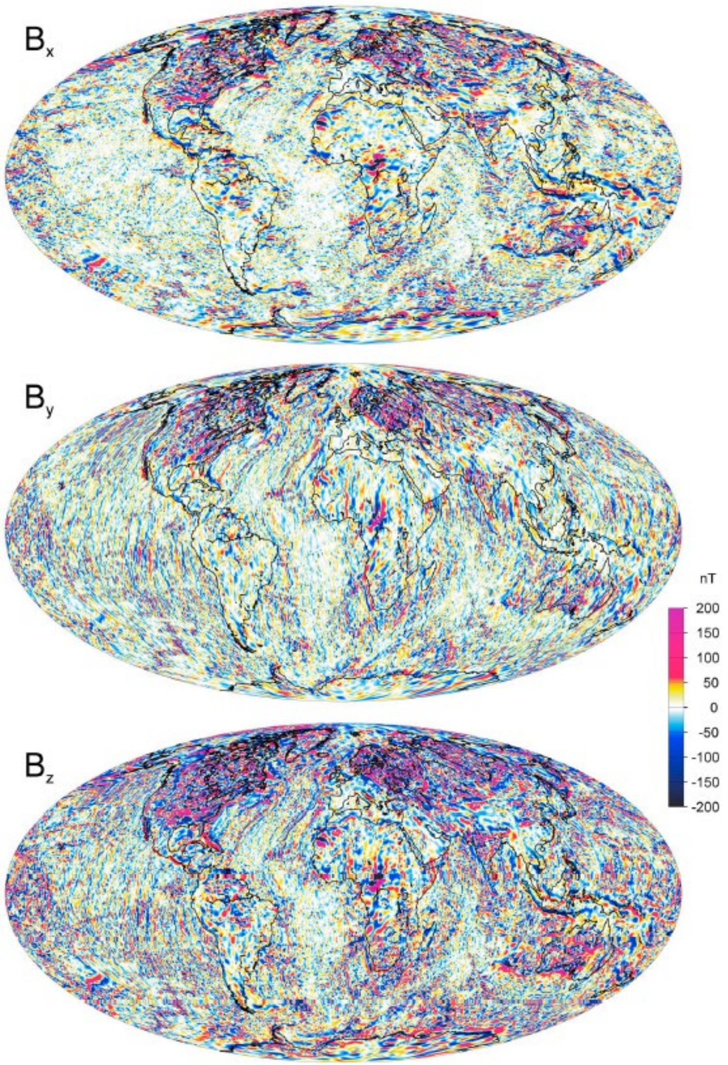


World Maps: What is Needed

- **Current global maps are useable for navigation but have widely varying data resolution, accuracy, and availability**
- **We need global map products which give**
  - The highest accuracy previously collected data which is available (no down-sampling)
  - Contain corresponding variance maps to describe trust in the map data
  - Allow the incorporation of new data easily into the map as we collect more data
- **Current world map products will benefit greatly from long-track data to resolve long-wavelength field components**

Spherical Harmonic Models

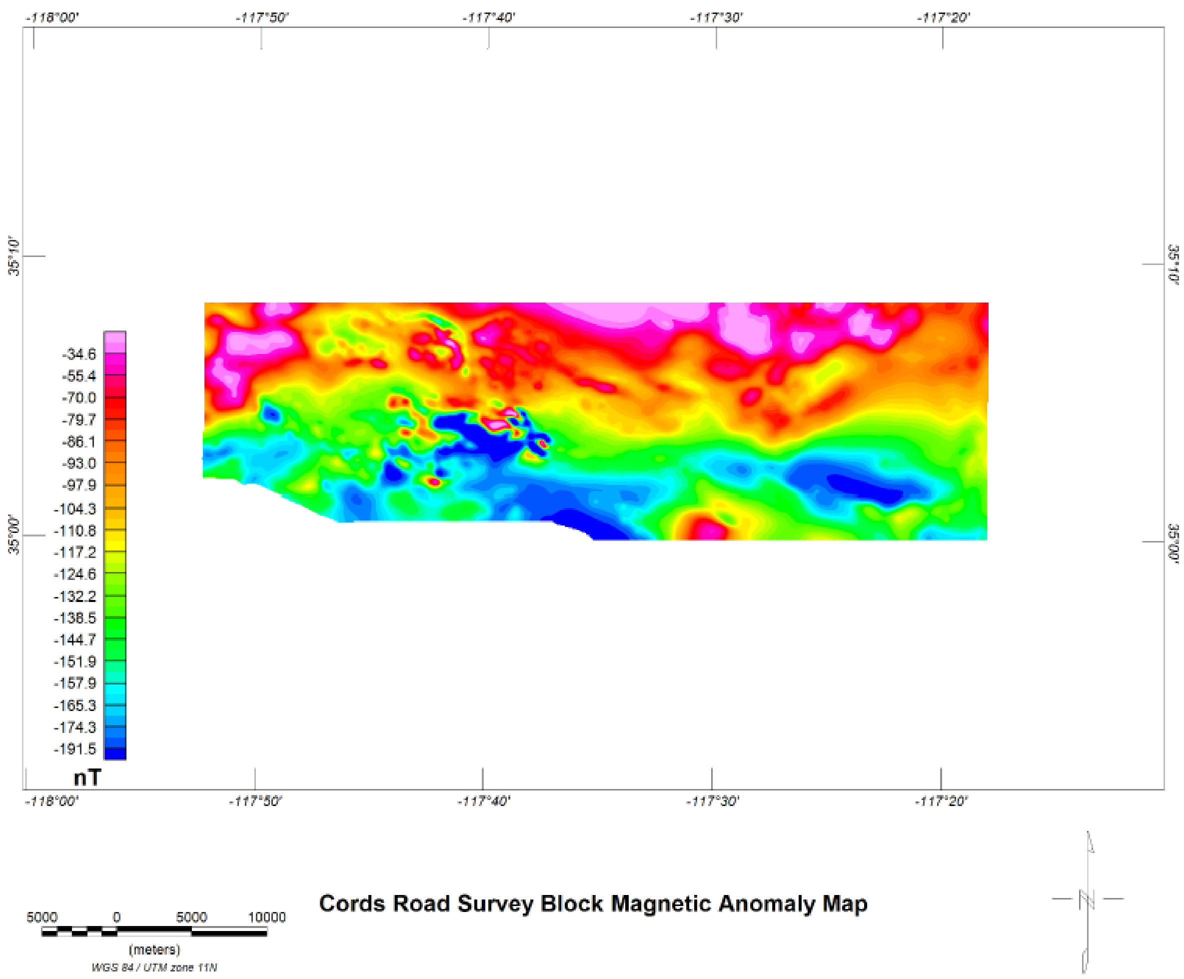
- **World-wide full vector field models exist**
- **The current highest accuracy model is the Enhanced Magnetic Model 790 produced by NOAA**
- **Vector models could potentially enable magnetic vector navigation**
- **These models are at much lower resolution than gridded map data**
  - 51 km wavelengths for EMM790
  - EMAG2 world grid has 2 arc-minute spacing (~4 km)
- **The additional information from using the full vector may somewhat mitigate the lower resolutions of the models**



DOD Magnetic Navigation Corridor

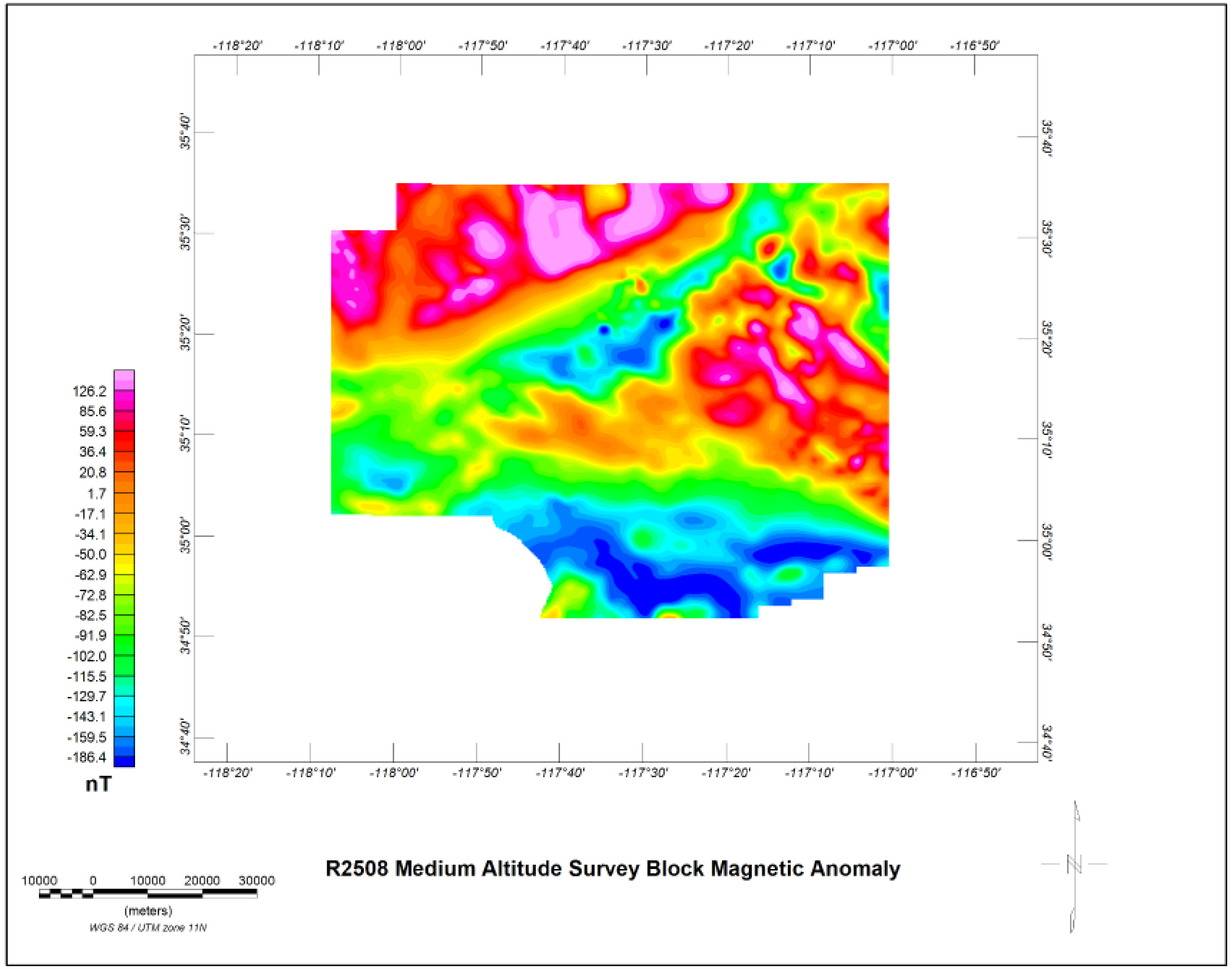
- In 2019 a large magnetic navigation testing corridor was created over Edwards AFB, CA
- This data is made freely available to any DOD contractors who are working on magnetic navigation
- The airspace is not difficult to fly in – a civilian Canadian company got permission to fly so US defense contractors should have no issues

COORDS Road Survey



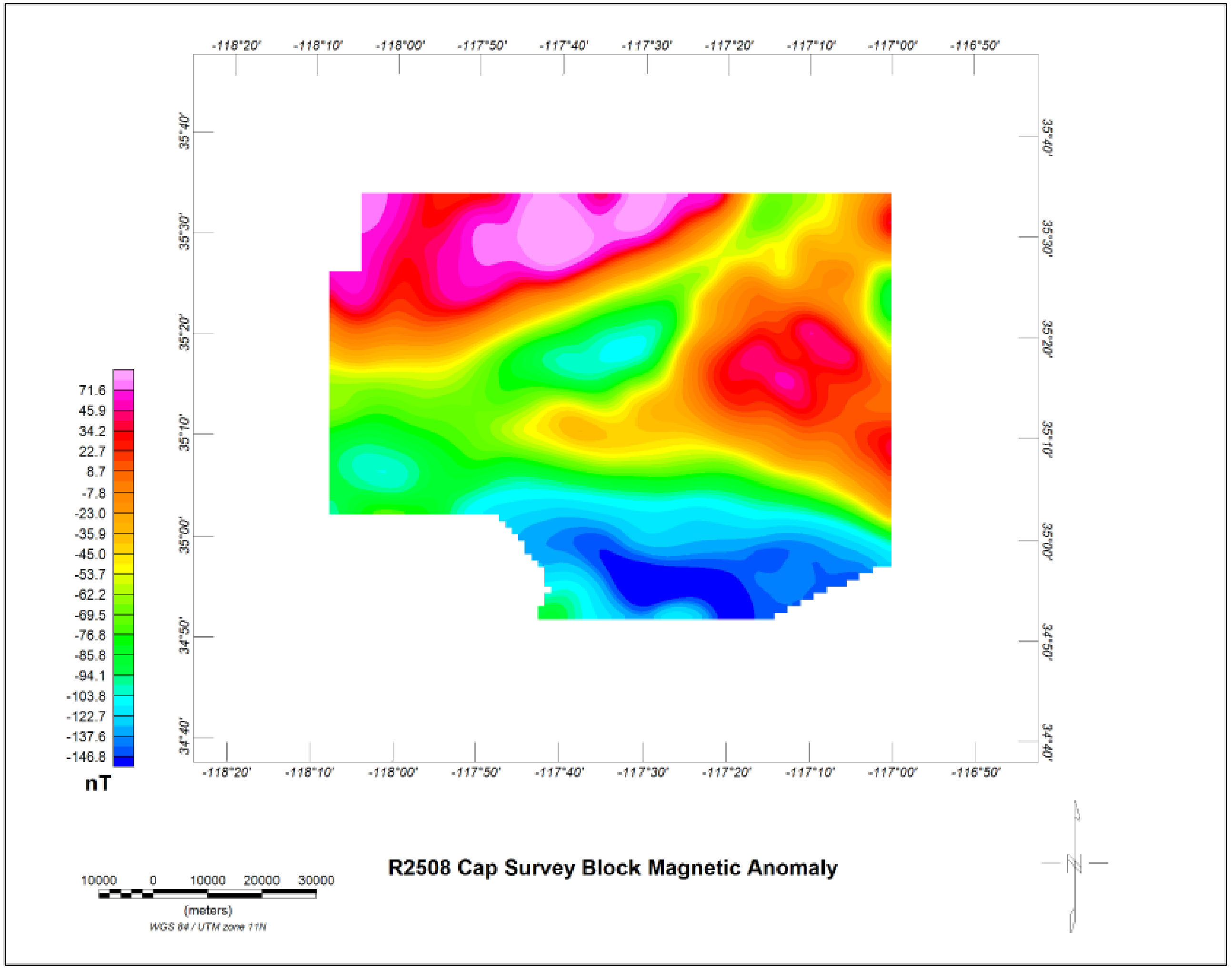
Cords Road Survey Block Magnetic Anomaly Map

Mid-Altitude Survey



R2508 Medium Altitude Survey Block Magnetic Anomaly

CAP Survey



R2508 Cap Survey Block Magnetic Anomaly

Conclusions

- **The issue of magnetic maps for navigation is complex, with many variables to consider**
  - Resolution
  - Availability
  - Altitude
  - Scalar/Vector, etc.
  - Variance information
- **In the long term there would need to be dedicated efforts to providing magnetic maps to the DOD for use in navigation**
- **Self-building models are a large enabler for creating a truly global navigation system**

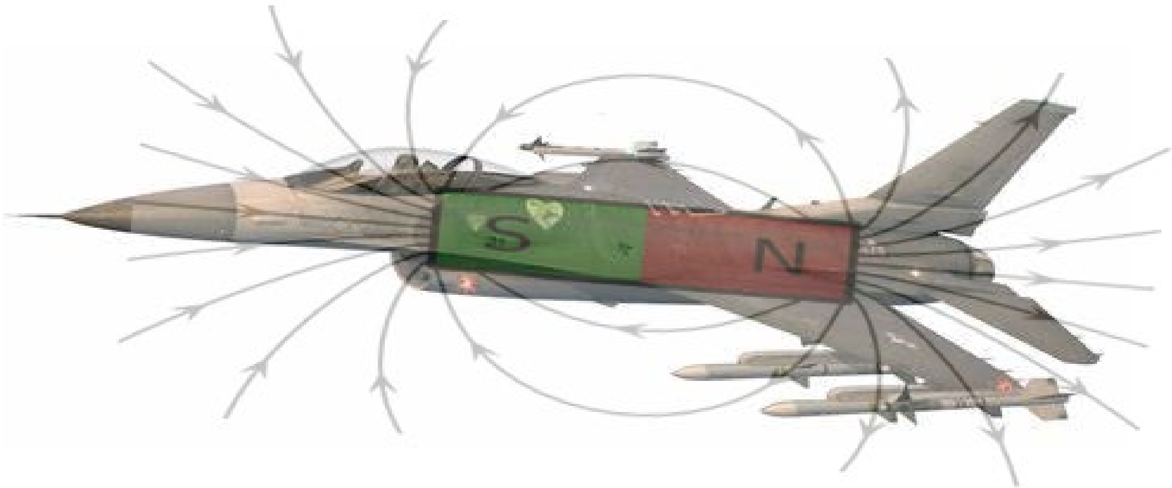
MAGNAV SEMINAR

Calibration

Attitude Coupling

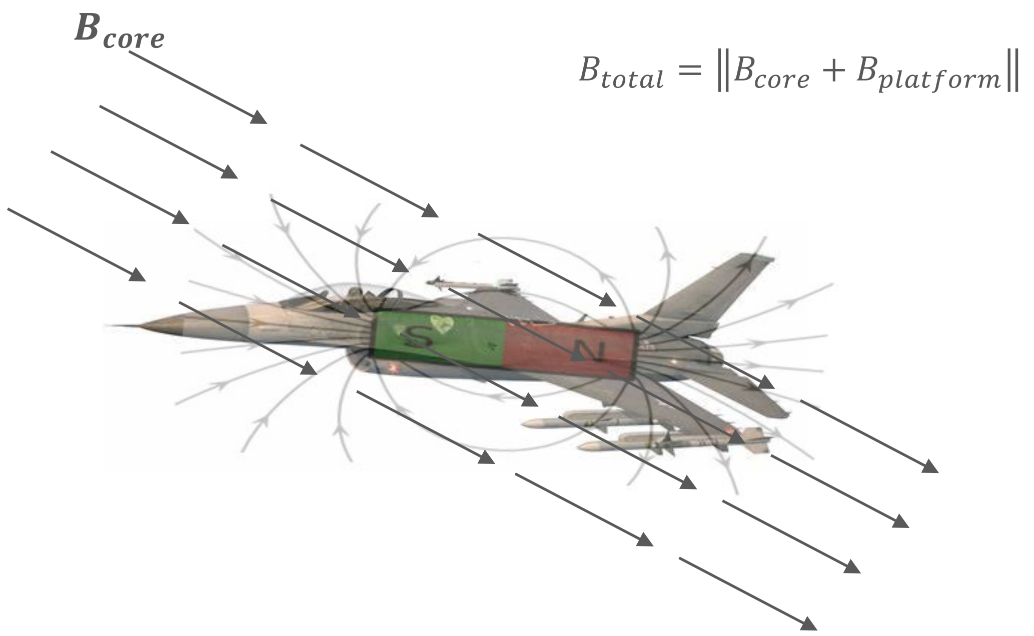
- **The problem:** ALL platform magnetic field effects are coupled to aircraft dynamics, even unchanging permanent magnetic fields of the plane

- **Why is this so?** Shouldn't a magnetic field "attached" to the platform have a constant effect on the sensor?



The Complete Picture

- We can't ignore the large external core field!
- Sometimes the core field constructively adds with the platform field, sometimes it deconstructively adds with the platform field
- Therefore all magnetic fields on the aircraft are a function of aircraft attitude

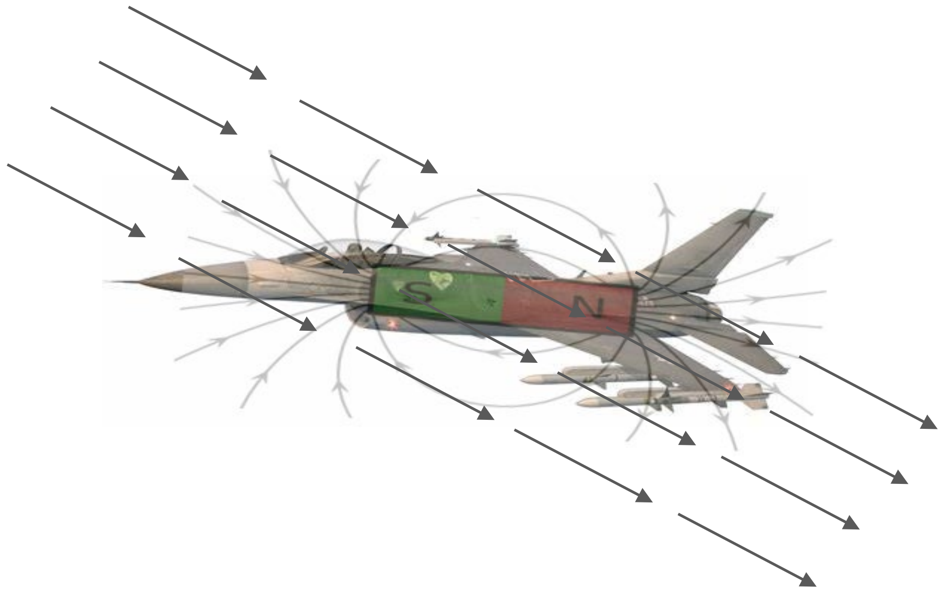


Types of Platform Magnetic Fields

- **Static Effects**
  1. Permanent Fields
  2. Induced Fields
  3. Eddy Currents
- **Temporal Effects**
  1. DC Shifts from electronics turn-on / turn off
  2. Communications equipment
  3. Control surfaces
  4. Fuel Pumps
  5. Lights
  6. Temperature Effects
  7. Engine

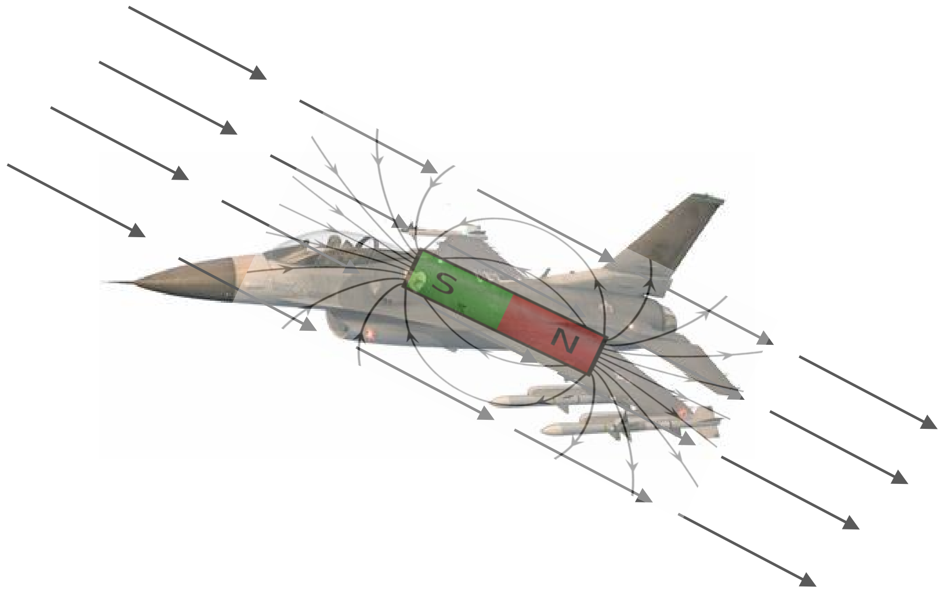
Static Effects: Permanent Fields

- For permanent fields the magnetic moments are attached to the frame of the aircraft



Static Effects: Induced Fields

- Induced magnetic moments stay aligned with the inducing field, in this case the Earth's core magnetic field



Static Effects: Eddy Currents

- Eddy current magnetic fields are induced in the aircraft as a function of how quickly it is rotating within the inducing field

- They are electrical currents which are generated to oppose the induced magnetic field of the aircraft (Len’s Law)