Attitude Independent Magnetometer Calibration in the Earth's Parking Orbit

AIMC

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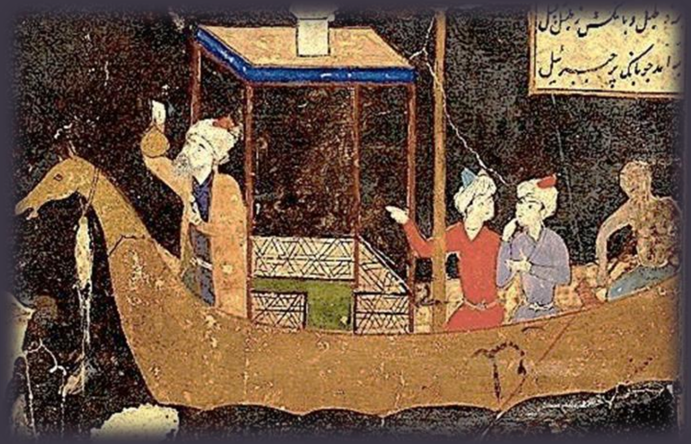
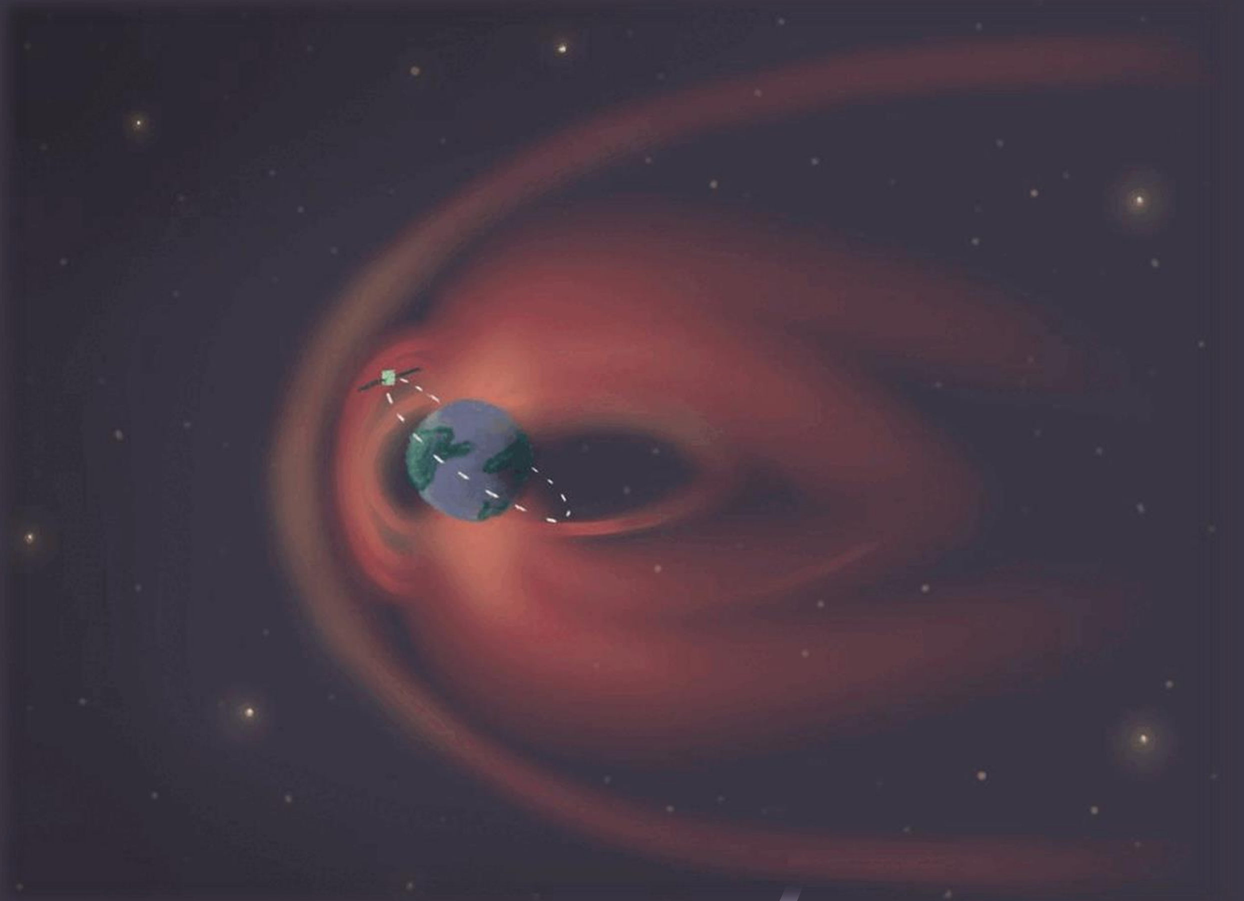


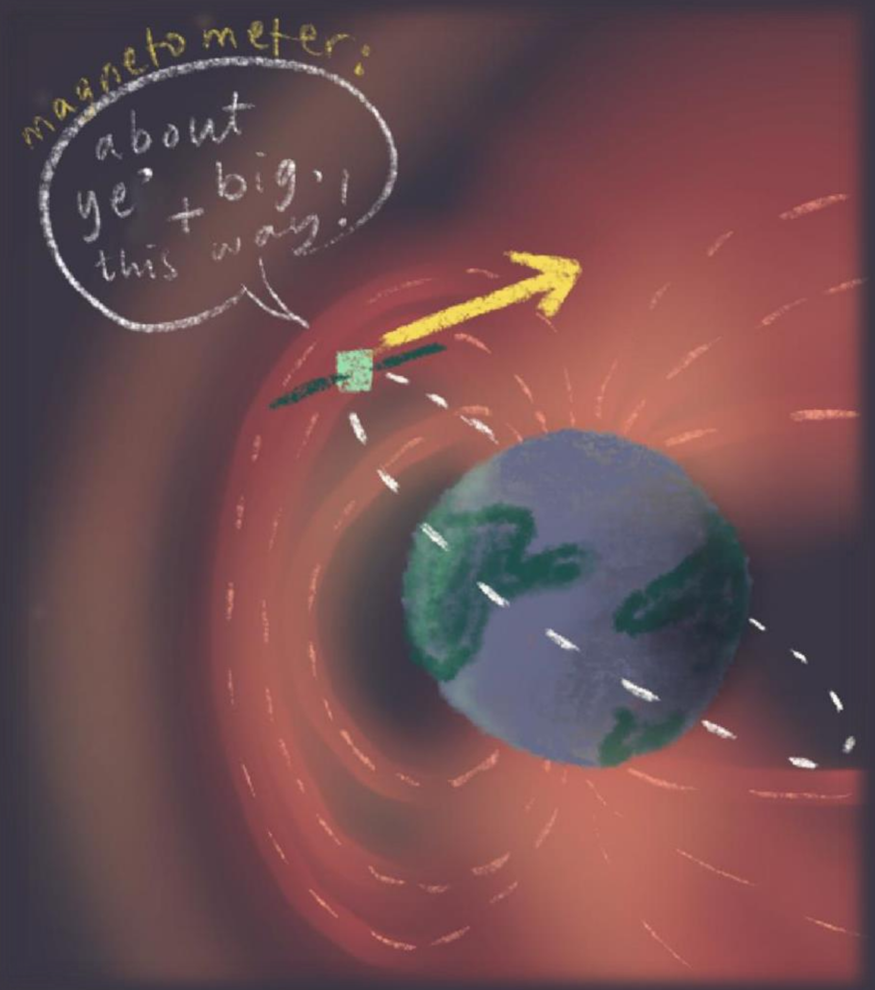
Classical problem in navigation:
Where are we ***headed***?

North
(a reference vector)

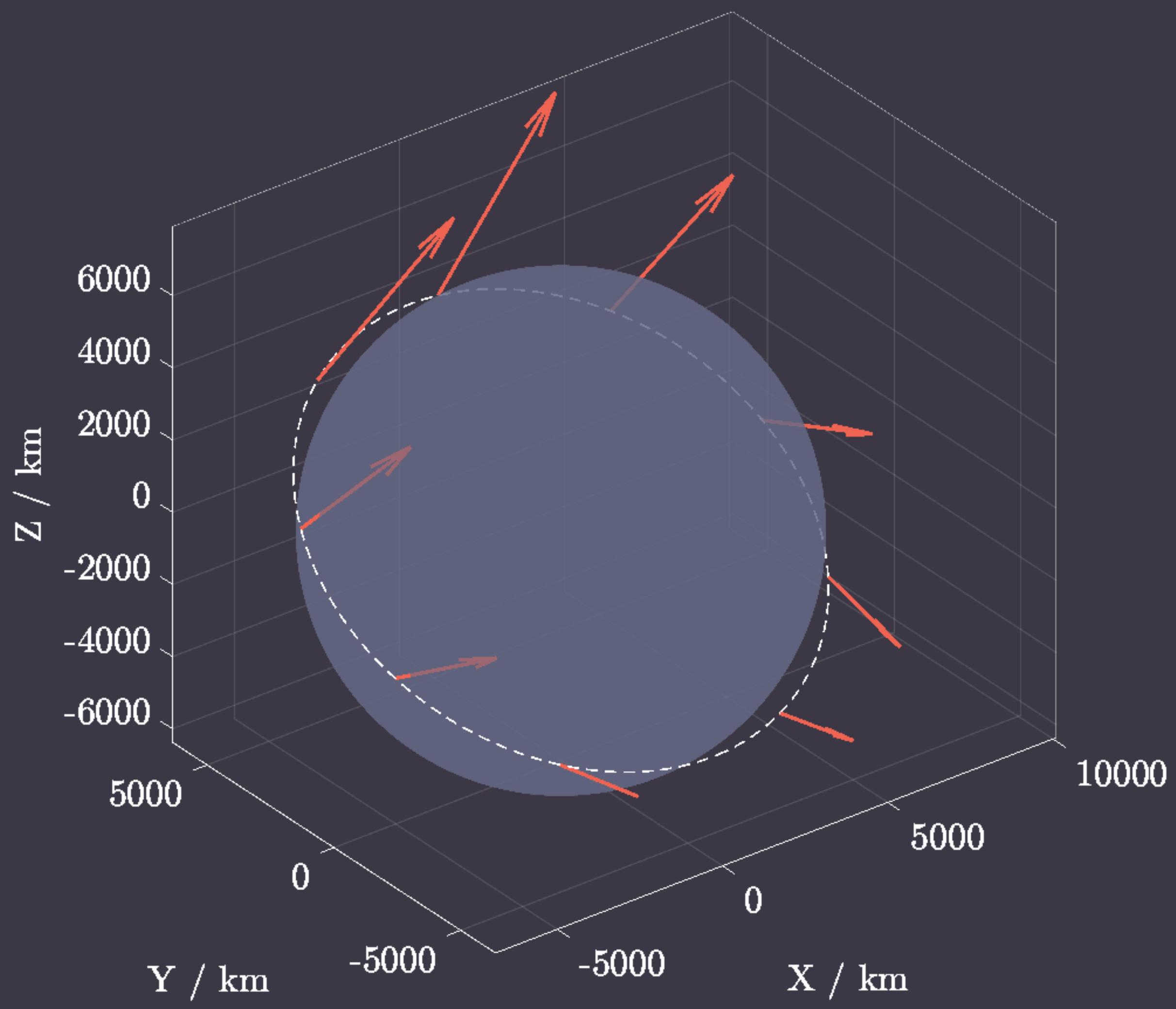
Compasses navigate in 2D (Earth's surface) using the geomagnetic field.

Spacecraft also need a reference to navigate in 3D, and also exploit the geomagnetic field.





Inform of geomagnetic field
strength *and* 3D direction,
like 3D compasses!

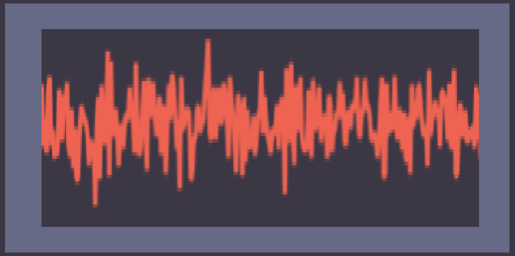


True Magnetic Field (IGRF) along the
Earth's parking orbit every 10 minutes

Magnetometer Calibration

Two manufacturing defects:

- Noisy measurements
- Non-orthonormal magnetometer axes



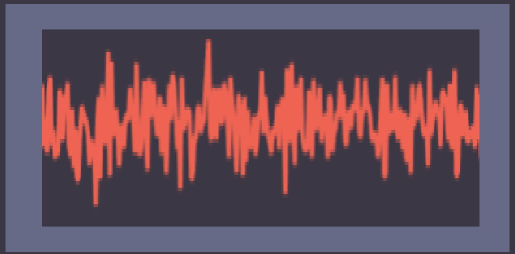
Error propagates in measurements.

Calibration compensates for this.

Goal of Calibration

- Find bias *compensation* to add to reading of each component.

Fix this! →



$$\boldsymbol{b}_{\boldsymbol{true}} = [\boldsymbol{b}_1 \ \boldsymbol{b}_2 \ \boldsymbol{b}_3]^{\mathrm{T}}$$

- Realign the magnetometer axes…
  - Find the orthonormality *compensation* matrix (symmetric 3x3).

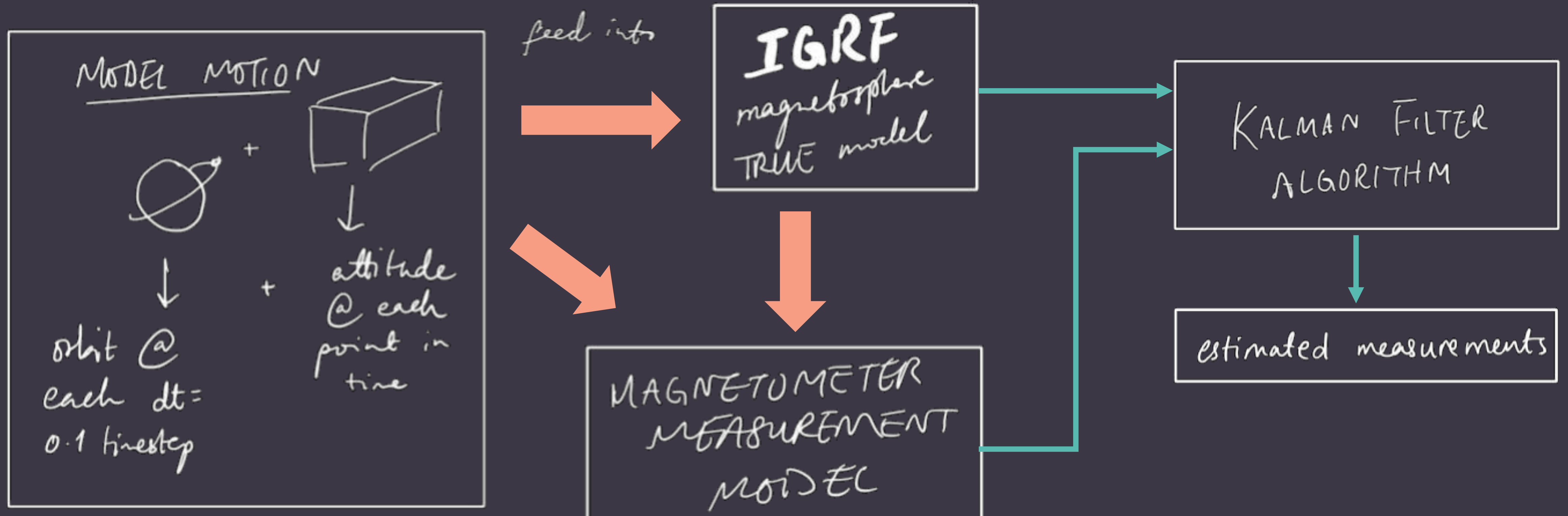
→

$$\boldsymbol{D} = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{12} & D_{22} & D_{23} \\ D_{13} & D_{23} & D_{33} \end{bmatrix}$$

EKF for AIMC

- Current goal for modern-day spacecraft is:
  - ***onboard*** and
  - ***autonomous*** calibration
  - in ***real-time***
  - ***without ground support****

My EKF 4 AIMC Algorithm



EKF Algorithm

Time Update ("Predict")

(1) Project the state ahead

$$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_{k-1}$$

(2) Project the error covariance ahead

$$P_k^- = AP_{k-1}A^T + Q$$

Measurement Update ("Correct")

(1) Compute the Kalman gain

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$$

(2) Update estimate with measurement z_k

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-)$$

(3) Update the error covariance

$$P_k = (I - K_k H)P_k^-$$

Initial estimates for $\hat{x}_{k-1}$ and P_{k-1}

Calibration Scenarios

- Scenario 1: constant true bias vector
  - Usual case in calibrations

$$\boldsymbol{b}_{true} = [\mathbf{3000\ 5000\ 6000}]^{\mathrm{T}}$$

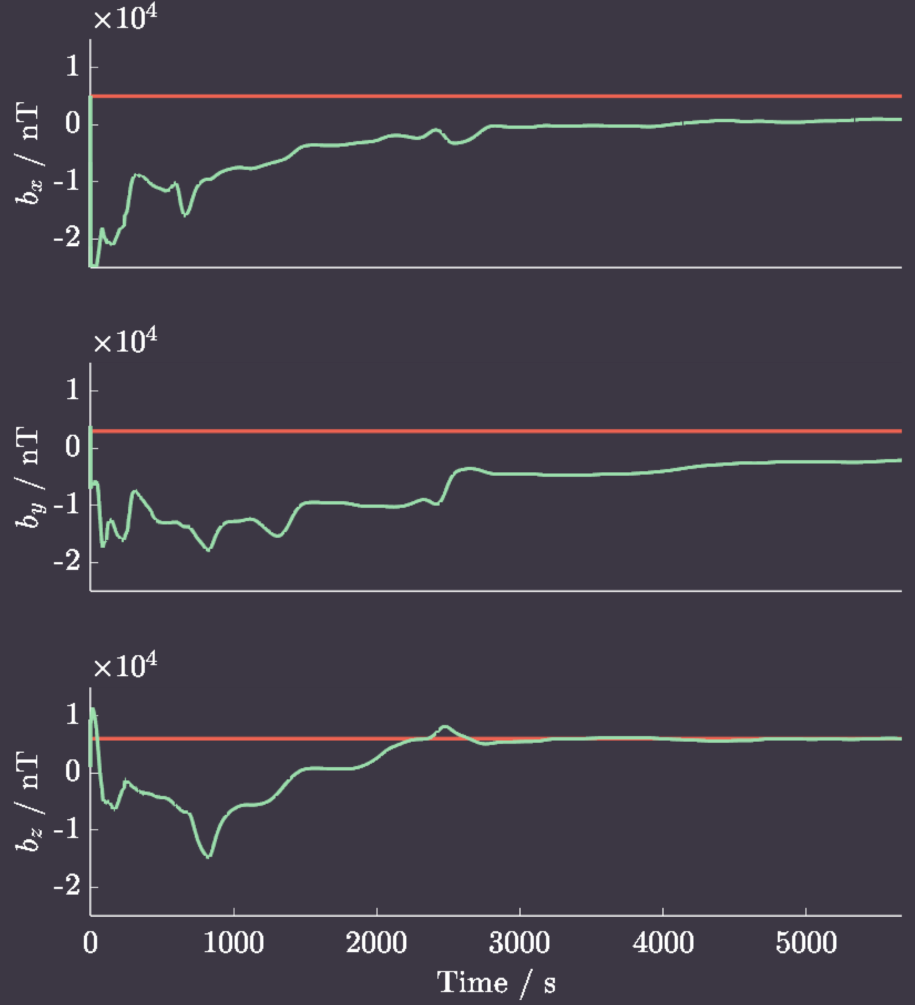
- Scenario 2: time-dependent true bias vector
  - Arises when interference with magnetometer due to other onboard electronics

$$\dot{\boldsymbol{b}}_{true} = \boldsymbol{v}_{TAM,bias}$$

where $\boldsymbol{v}_{TAM,bias}$ can be modelled by a Gaussian distribution with a standard deviation of 300 nT/s

Results: Scenario 1

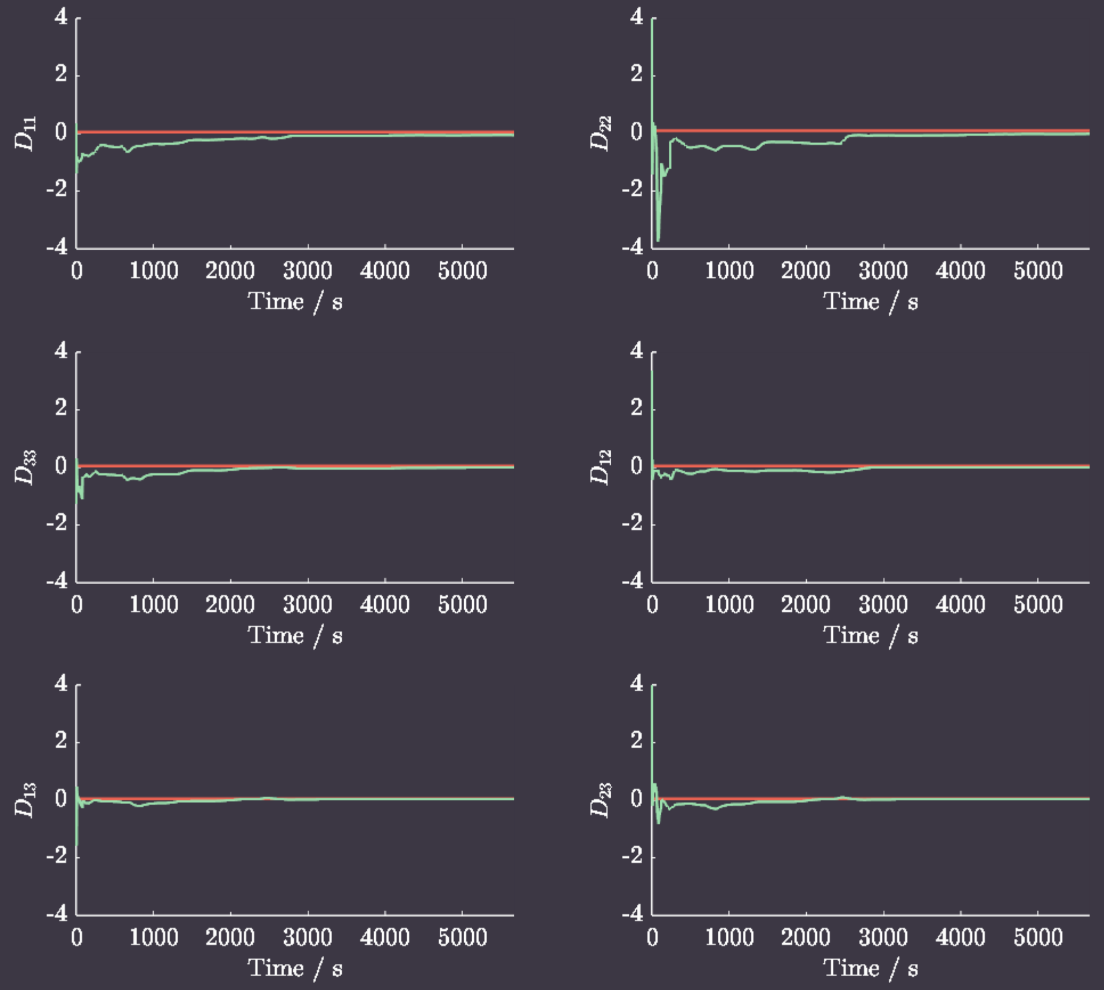
True and Estimated Bias Vector Components



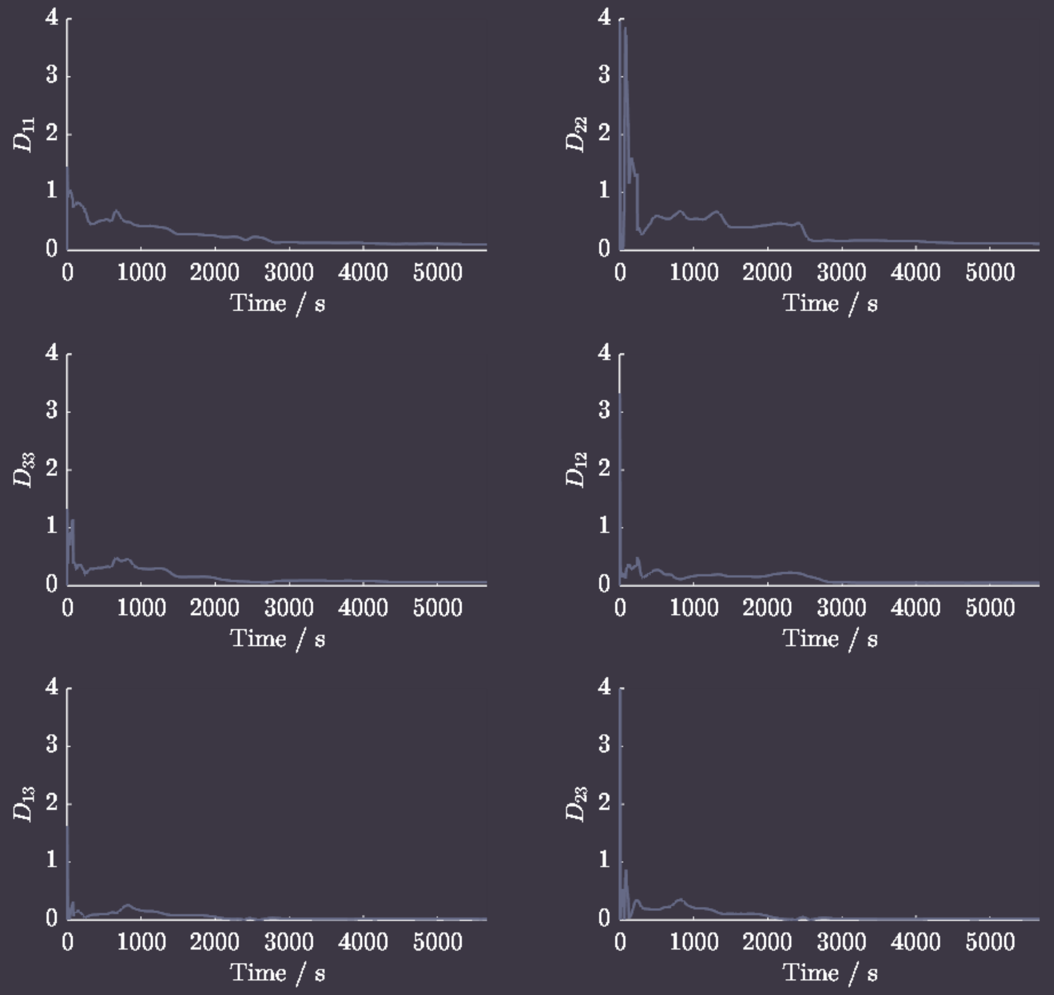
Error in Estimated Bias Vector Components

Results: Scenario 1

True and Estimated Correction Matrix Components

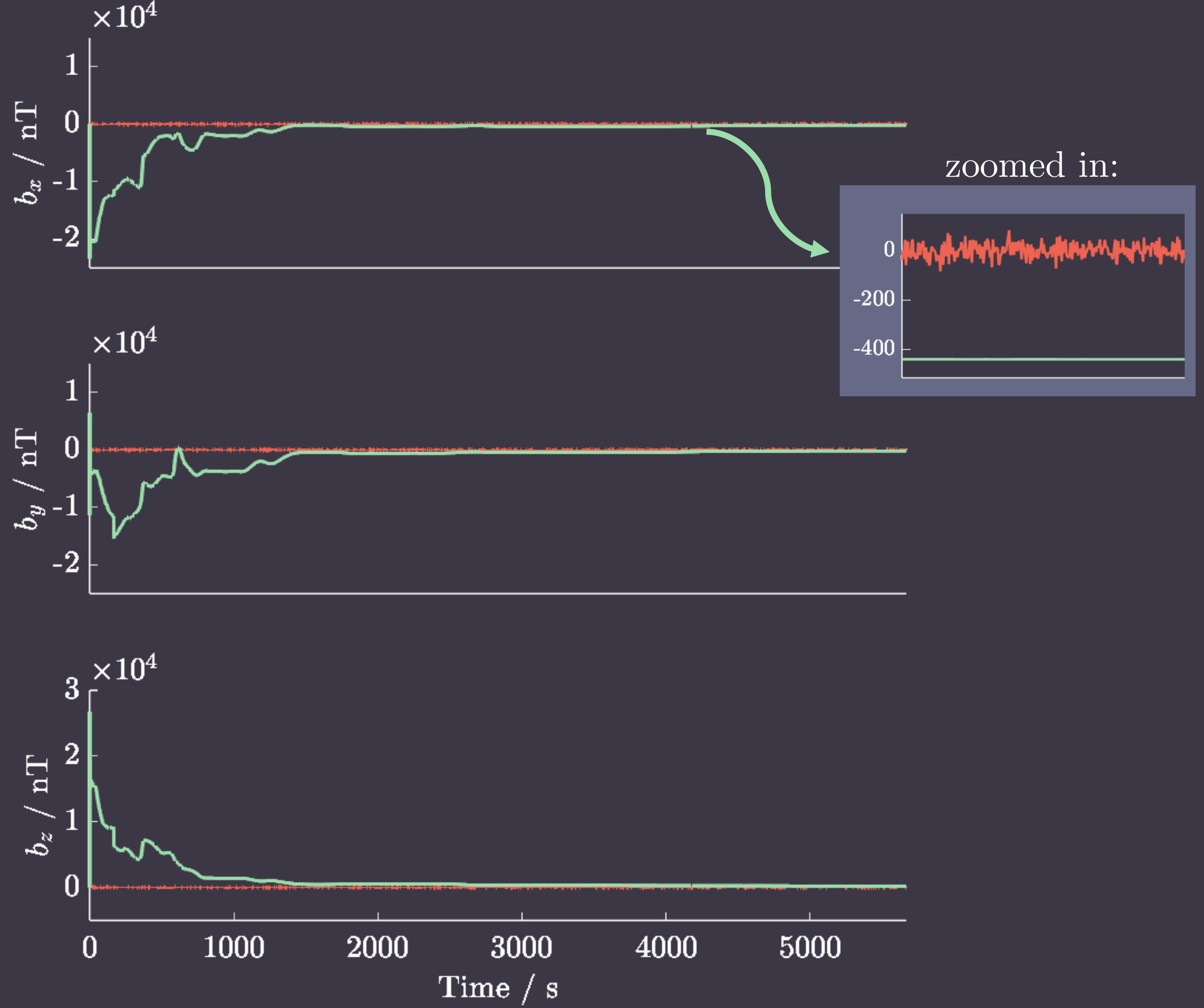


Error in Estimated Correction Matrix Components

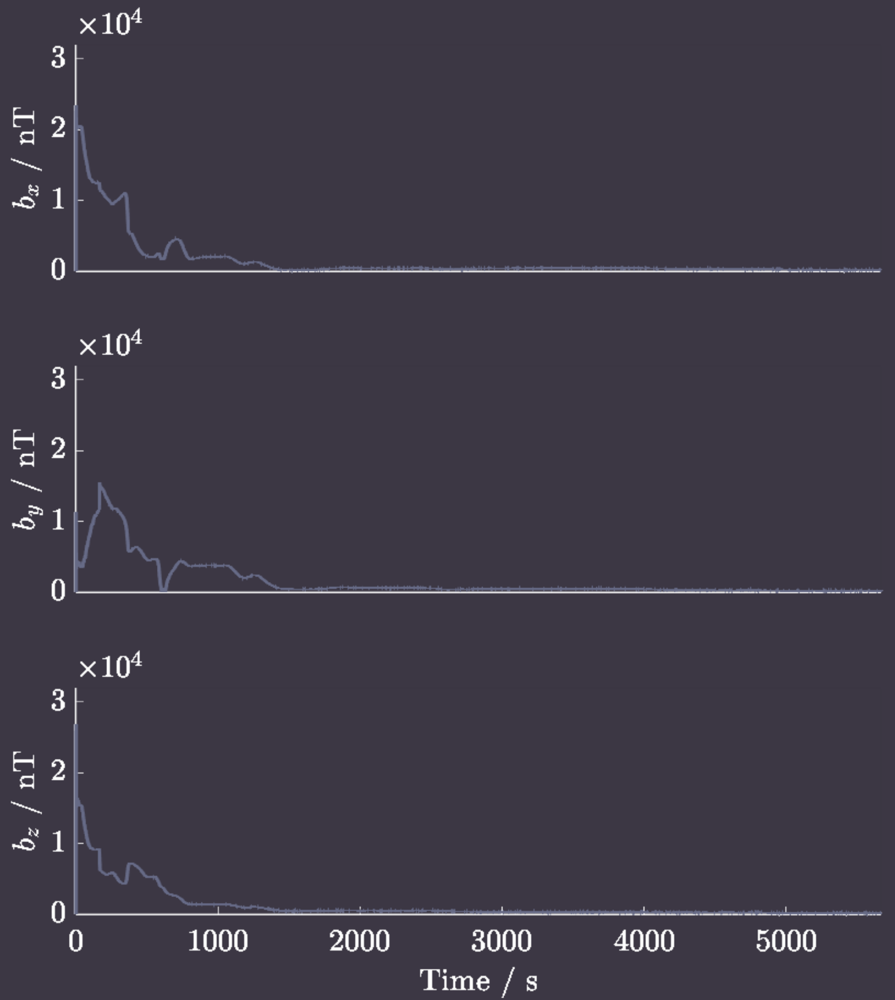


Results: Scenario 2

True and Estimated Bias Vector Components

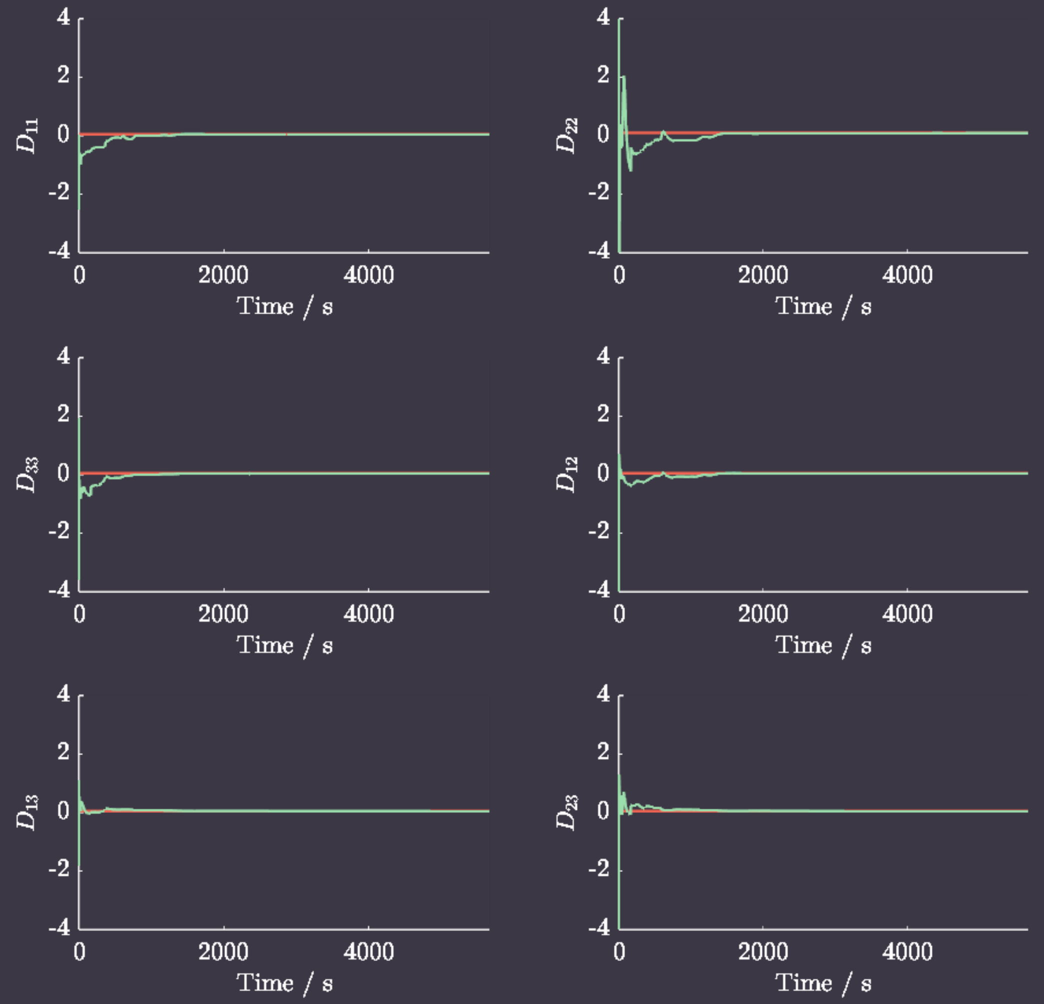


Error in Estimated Bias Vector Components

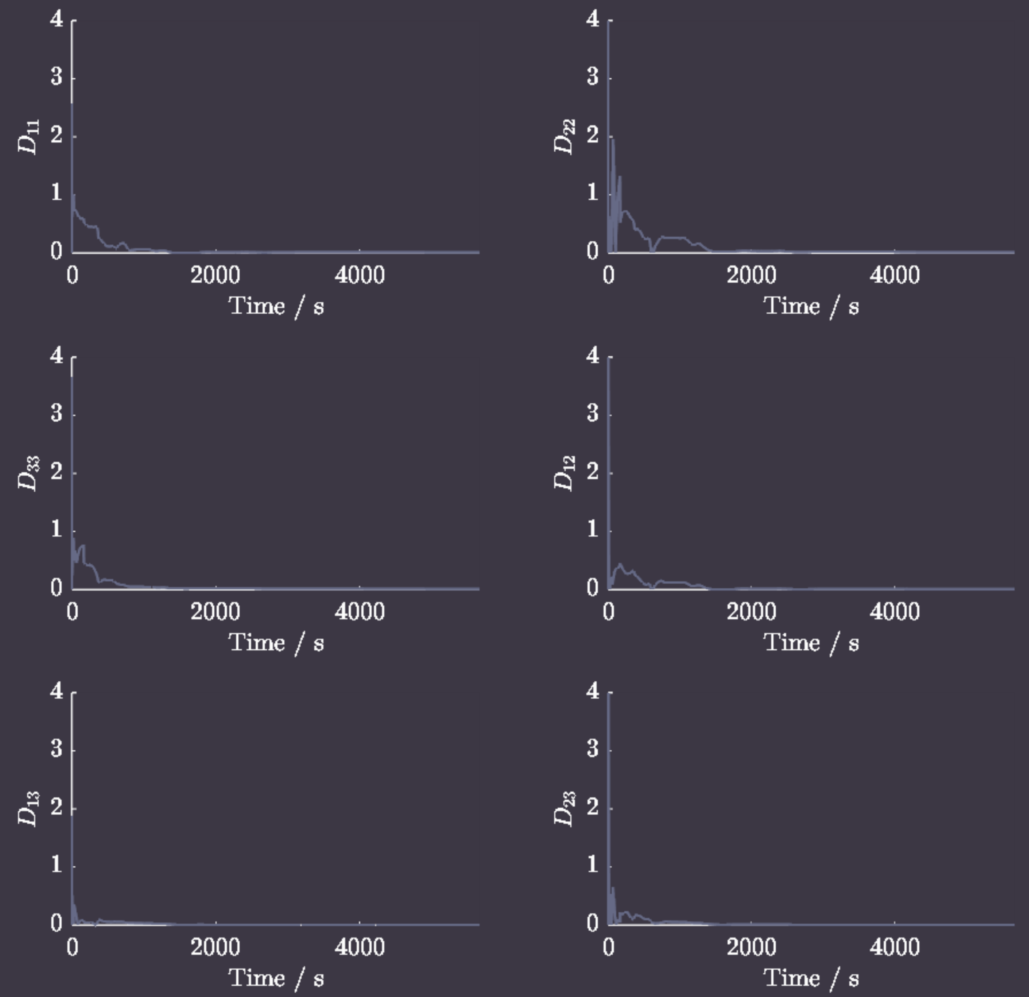


Results: Scenario 2

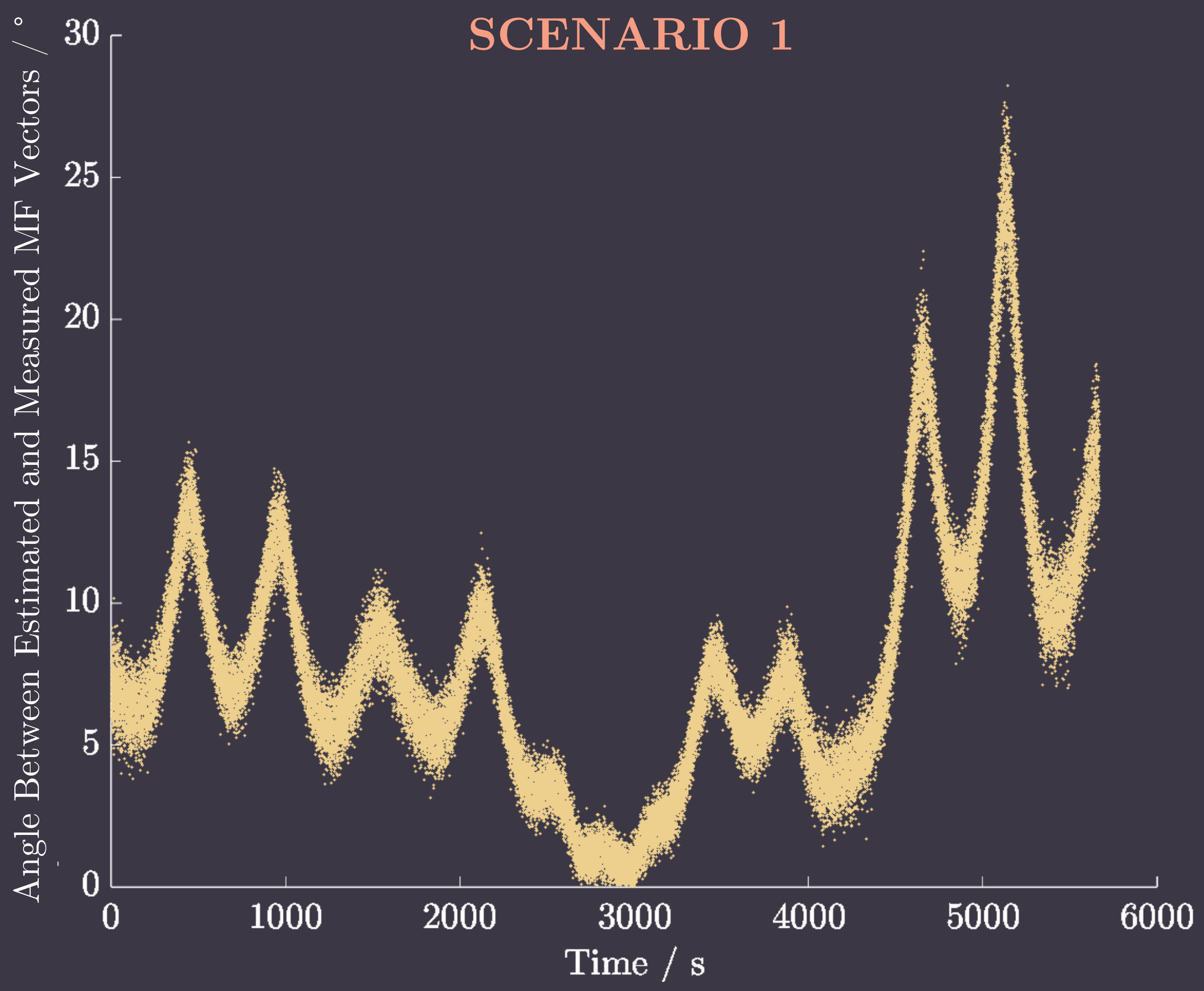
True and Estimated Correction Matrix Components

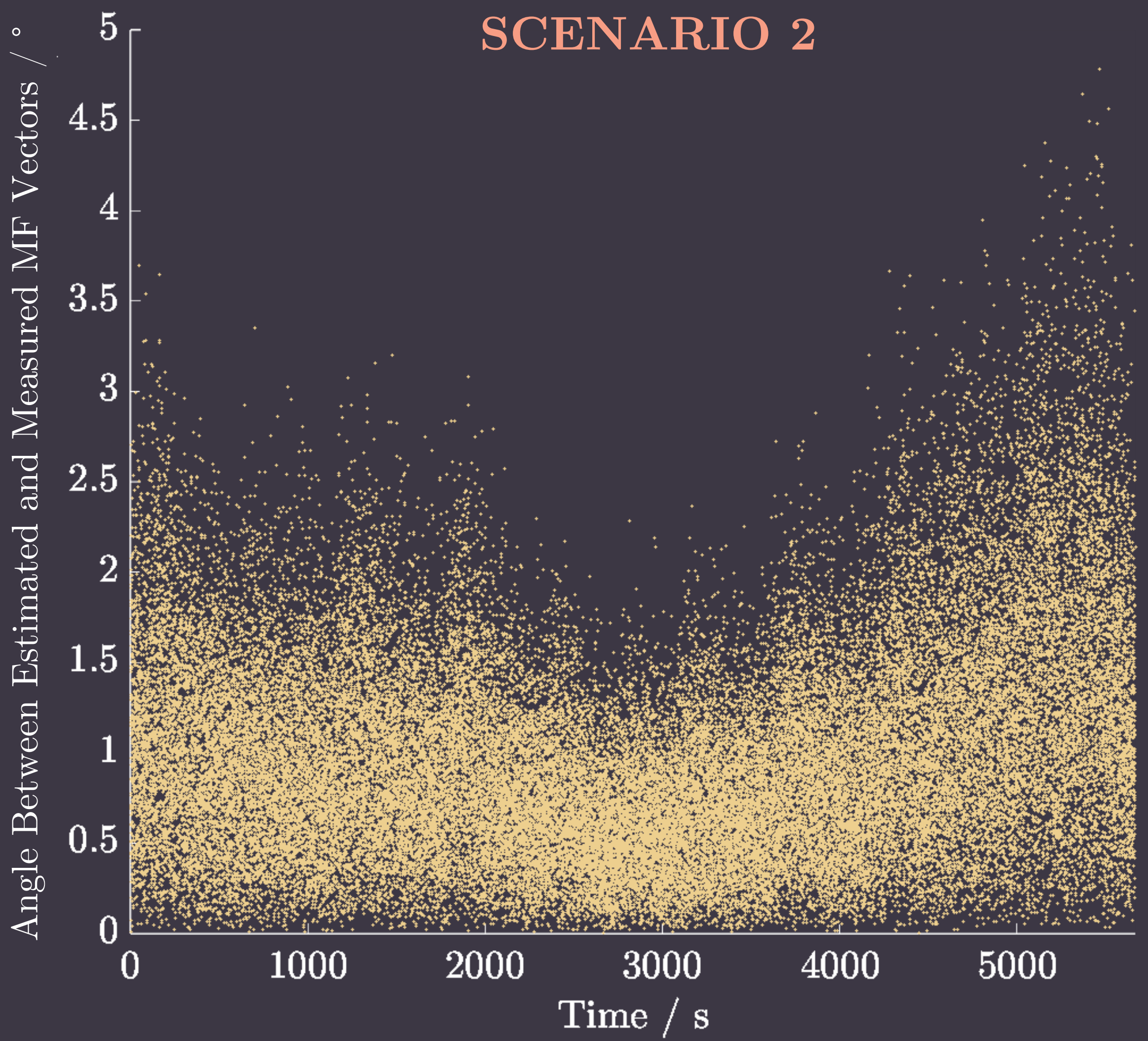


Error in Estimated Correction Matrix Components



Angle Residuals





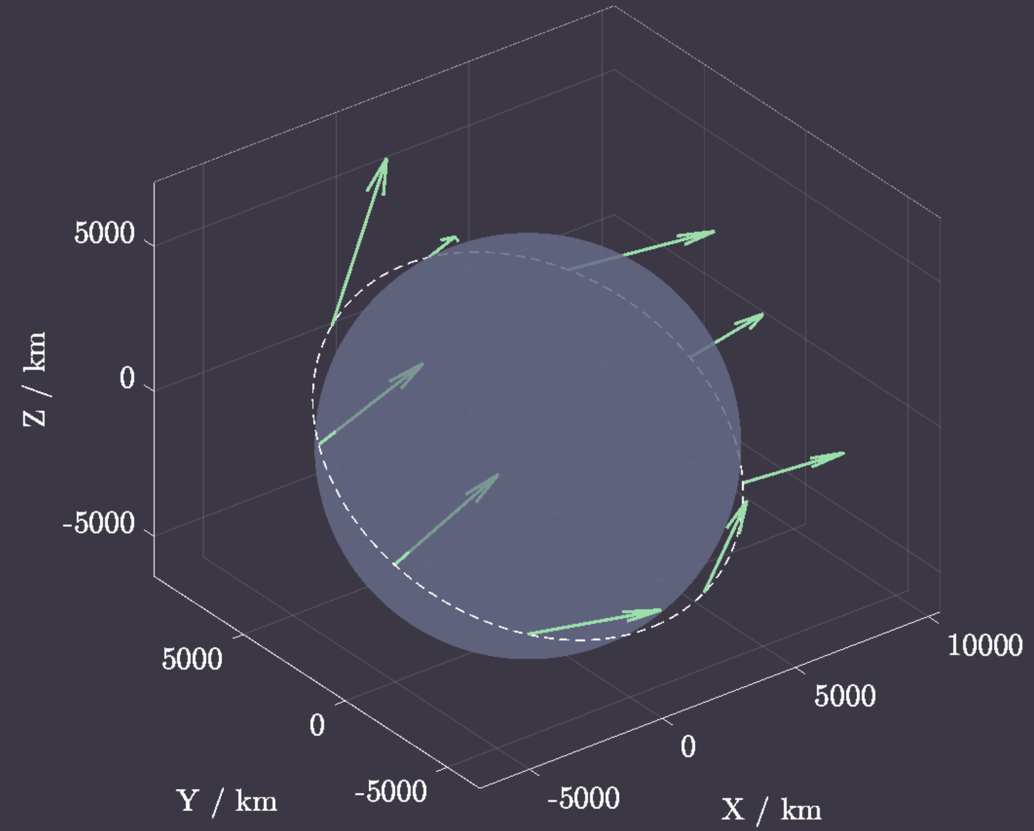
Results Summary (Vanilla)

RMS	b_x (nT)	b_y (nT)	b_z (nT)
Scenario 1	6323	8400	5815
Scenario 2	3553	3100	2677

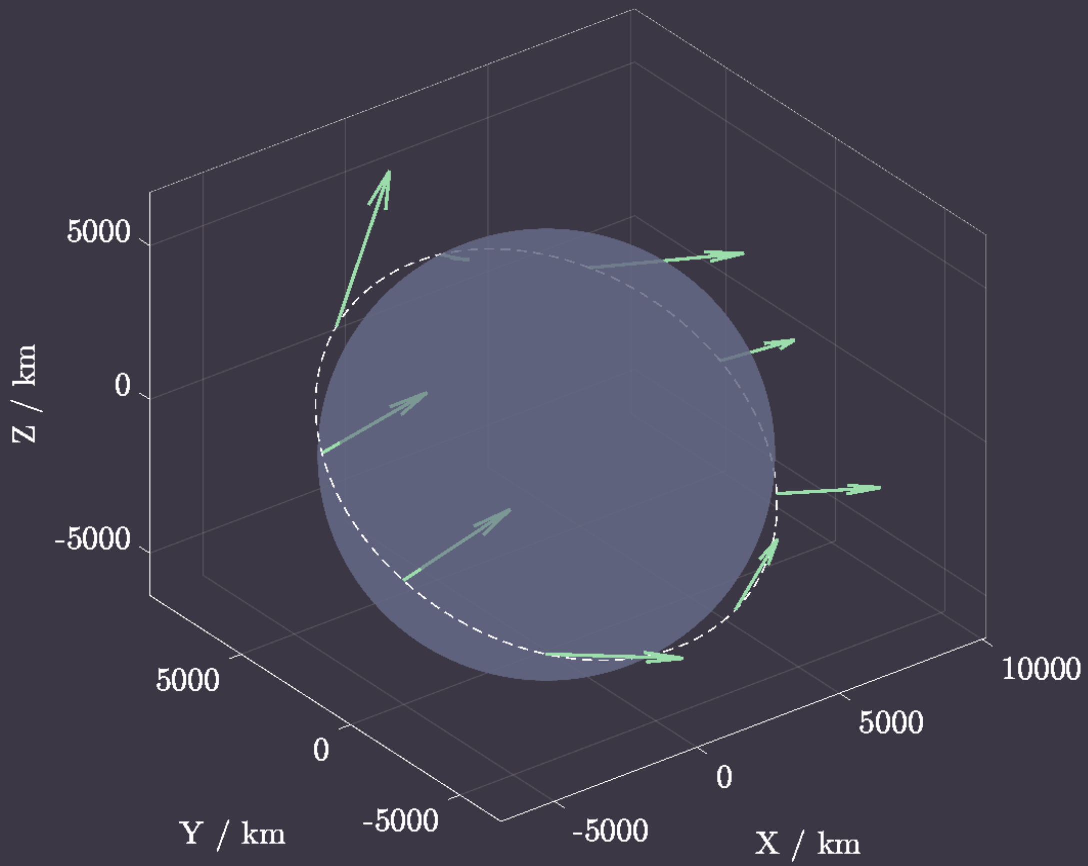
RMS	D_{11}	D_{22}	D_{33}	D_{12}	D_{13}	D_{23}
Scenario 1	0.2765	0.4235	0.1721	0.1046	0.0603	0.1198
Scenario 2	0.1421	0.2310	0.1295	0.0839	0.0676	0.1001

RMS	B_x (nT)	B_y (nT)	B_z (nT)
Scenario 1	22836	19810	21093
Scenario 2	20443	19190	20157

Visualizing the Measurements



Scenario 1 TAM Measurements
every 10 minutes



Scenario 2 TAM Measurements
every 10 minutes

Parameter Tuning (bonus)

We can improve the results of our simulation by:

1. Tuning the initial parameters
2. Tuning the covariance matrix guess
3. Using a different true magnetic field model

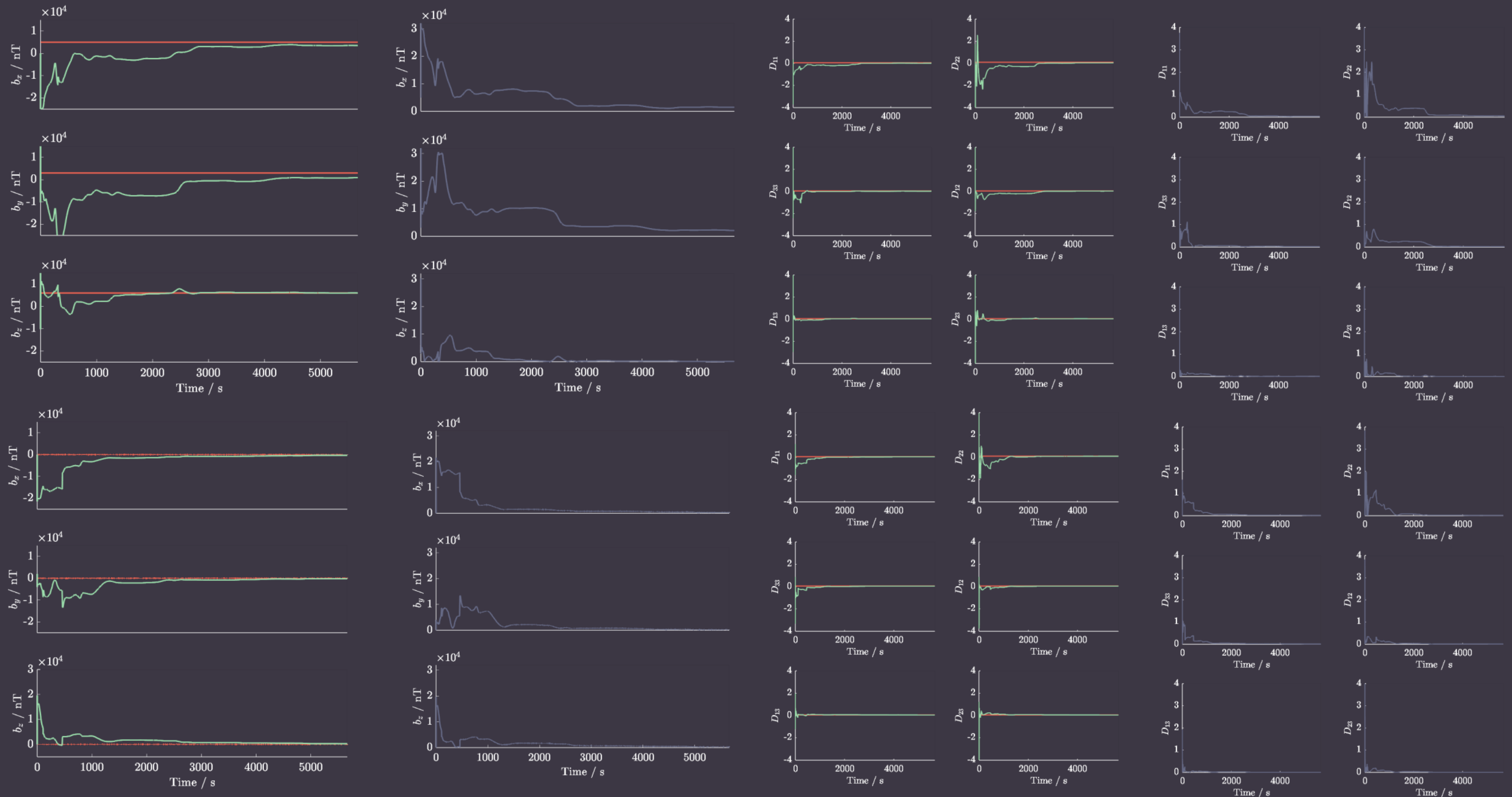
In case 3: IGRF → WMM

```
for i = 1:Nsteps
        [Btrue(i, :), ~] = wrldmagm(LLAorbit(i, 3), LLAorbit(i, 1), ...
        LLAorbit(i, 2), decyear(2024,11,22));
end
```

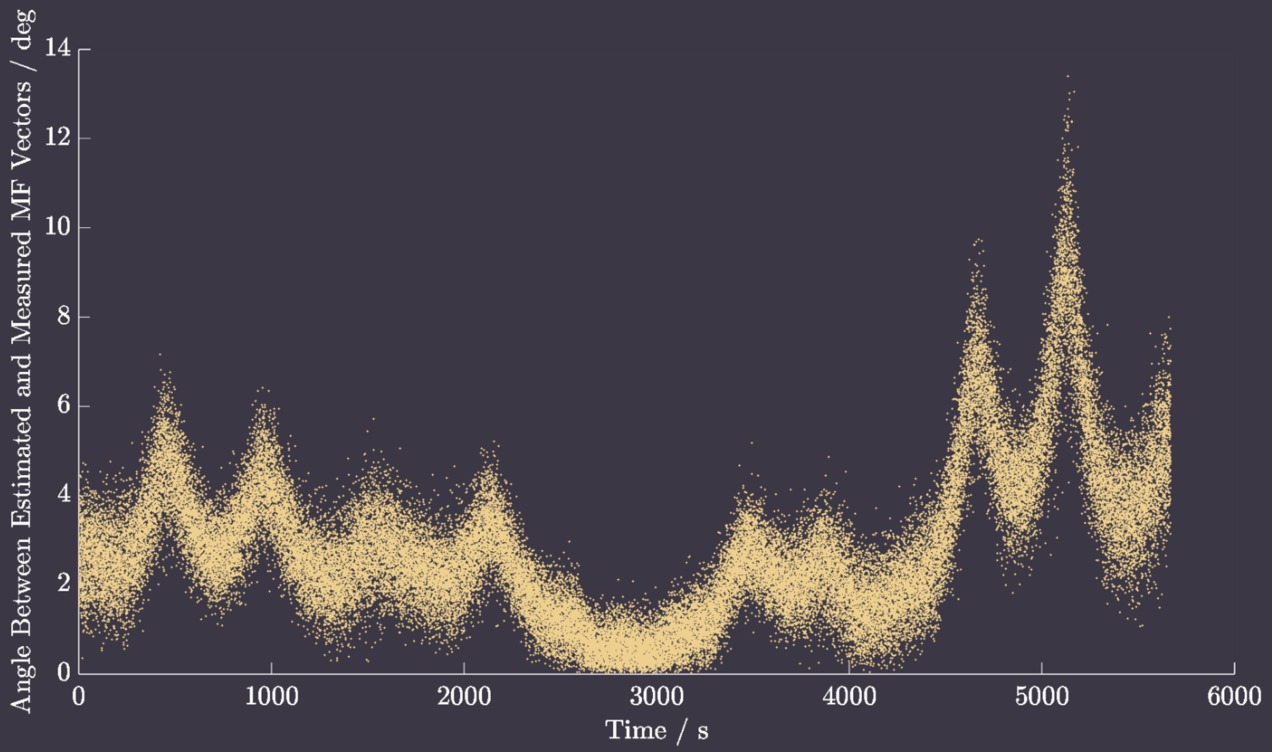
Employing WMM

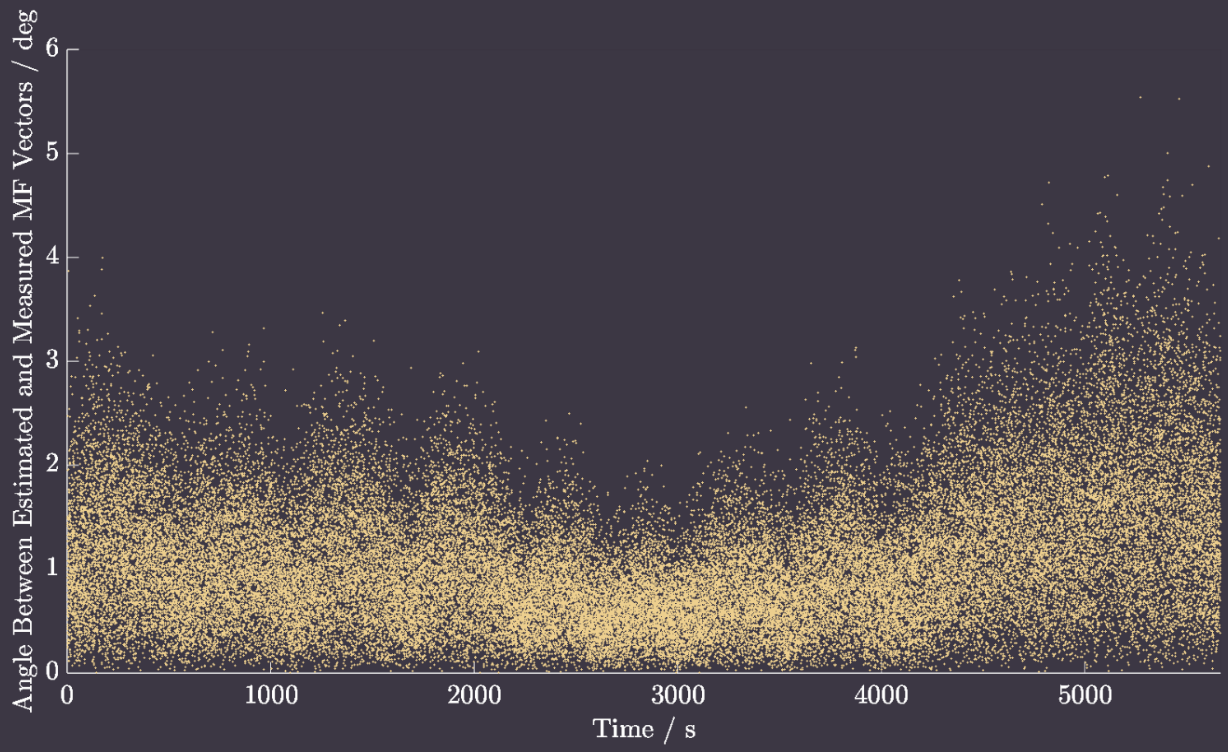
SCENARIO 1

SCENARIO 2



WMM angle residuals





Parameter Tuning - $\widehat{P}_0$

- Couldn’t find the time ☹

Parameter Tuning - b_{true_0}

- Couldn't find the time ☹

Thank You!