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Isolating internal secular variation in Geomagnetic Virtual Observatory time series using Principle Component Analysis

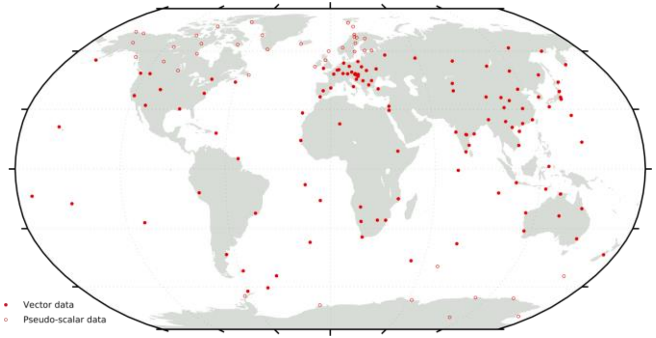
DTU Space
National Space Institute

British Geological Survey

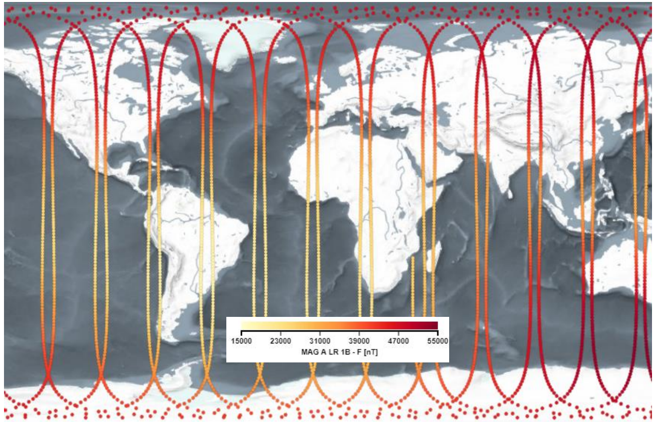
Geomagnetic Virtual Observatories (**GVO**): what and why?

- Ground observatories (**GO**) provide high-resolution magnetic time series, but at sparse spatial sampling
- Satellite missions provide global data, but with no direct way to observe time variations – generally must fit model to data first
- The GVO method converts satellite observations to a spatial grid of time series
- From time series, we can calculate time derivatives – the variations of magnetic field sources, particularly that of the core field (secular variation, **SV**), useful for studies of core physics and dynamics

Ground observatory locations



1 day Swarm A data



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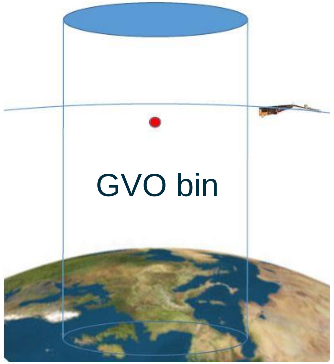
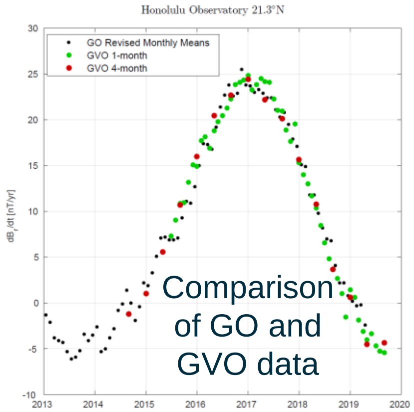
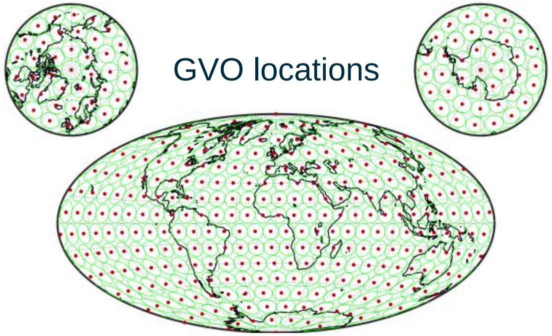
Geomagnetic Virtual Observatories (**GVO**): how?

- ESA Swarm DISC Level2 GVO product

- Bin data within a 700km radius cylinder, over sampling period (e.g. 1, 4 month)
- Remove estimate of core field from data in bin
- Fit a local cubic potential field to data residuals in bin
- Calculate potential at centre of bin in time and space
- Add back core field estimate
- Produce grid of 300 equidistant GVO for each sample period
- Sample-by-sample internal/external field spherical harmonic analysis to separate field sources





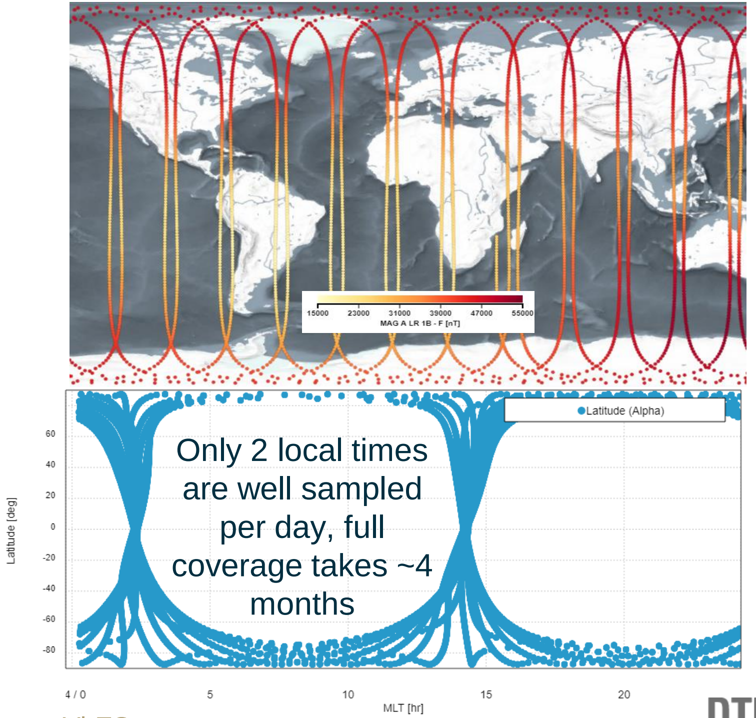


Hammer et al, EPS, 2021

Isolating core field SV from GVO

- For ESA Swarm DISC GVO product, we applied two approaches in the processing chain to isolate the core field:
  - Quiet time data selection, 4 month time sampling, to capture robust long-term core field SV
  - No data selection, Principle Component Analysis (**PCA**), 1 month time sampling, to capture rapid internal and long-period external variations
- 4 month sampling required to achieve sufficient data density when data selection is applied, and to average out local time (**LT**) biases caused by slow precession of polar satellite orbits (~4 months for full LT coverage with Swarm)
- PCA approach provides alternative that retains data density without data selection, separates field sources, and allows correction of LT sampling biases
- PCA can be applied for satellite missions with long LT procession rates (e.g. Ørsted, CryoSat-2), without losing resolution in time or space

1 day Swarm A data



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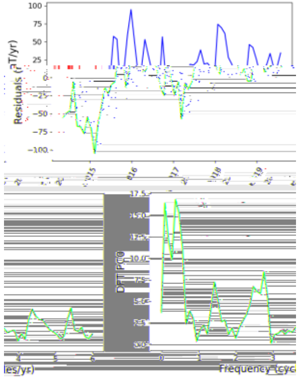
Principle Component Analysis (**PCA**) of GVO SV

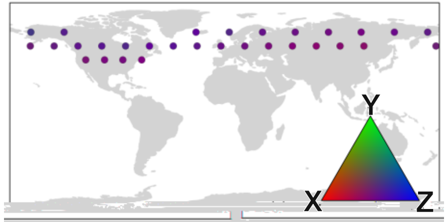
- We provide an update to the MagPySV software (Cox et al 2018, EPS), to process GVO data as well as GO data
- Remove estimate of core field from GVO to get detrended residual time series
- Calculate time derivative (annual differences SV) of residual time series
- Separate GVO locations into magnetic latitude activity zones – poles, auroral ovals, mid- to low-latitudes
- Calculate covariance matrix of GVO residual vector time series in each zone
- Calculate Principle Components (**PC**) of each zone's covariance matrix
- Characterise PC by spatial orientation, time-correlation to magnetic activity indices, frequency content
- Identify and remove unwanted PC, here the most significant few PC
- Add back removed core field estimates to remaining residuals, integrate SV back to main field

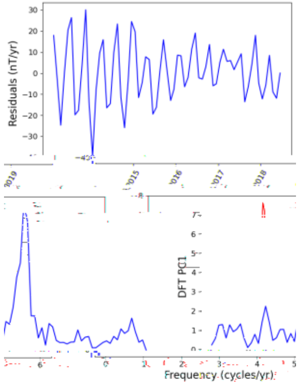
Example for Swarm in Northern auroral zone

1. Eigenvalue spectrum indicates most significant PCs



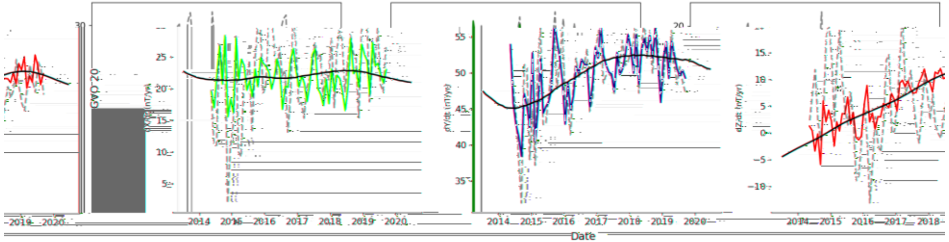
2. 1st PC has strong long-period signal, in X and Z, correlation of 0.73 with AE-index





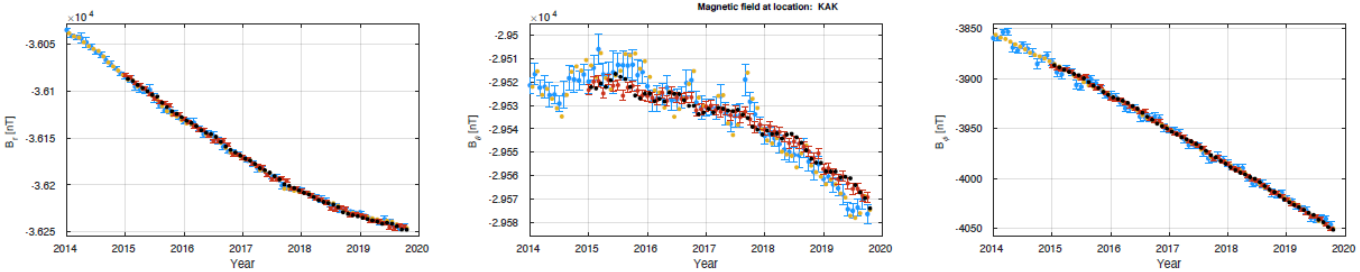
3. 2nd PC has strong ~4.2 month signal, with complex spatial pattern, uncorrelated to any activity index

4. Removal of these 2 PC accounts for ~75% of variance, and removes significant external and LT bias content

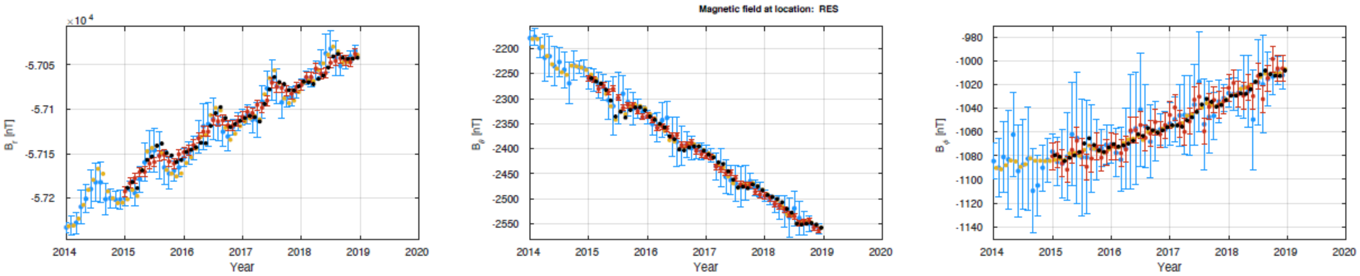


Results for Swarm vs. ground data

Kakioka (KAK), Japan, 36.232N, 140.186E



Resolute Bay (RES), Canada, 74.690N, 265.105E

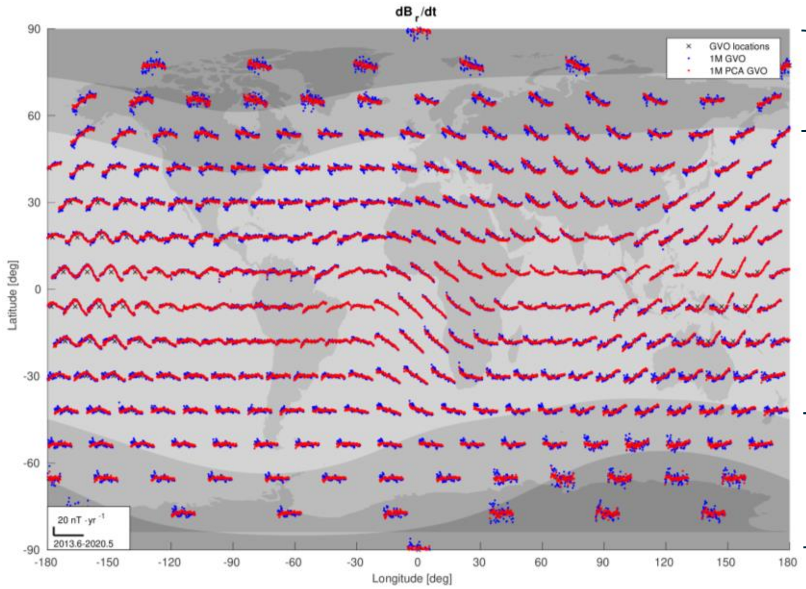


- GVO observed field (±σ)
- GVO core field (±σ)
- GO observed field
- GO core field

Hammer et al, EPS, 2021

Global results for Swarm AD

- Different external signals dominate in different magnetic latitude regions
- Local time effect seen at all latitudes but spatial manifestation depends on orbit track orientation

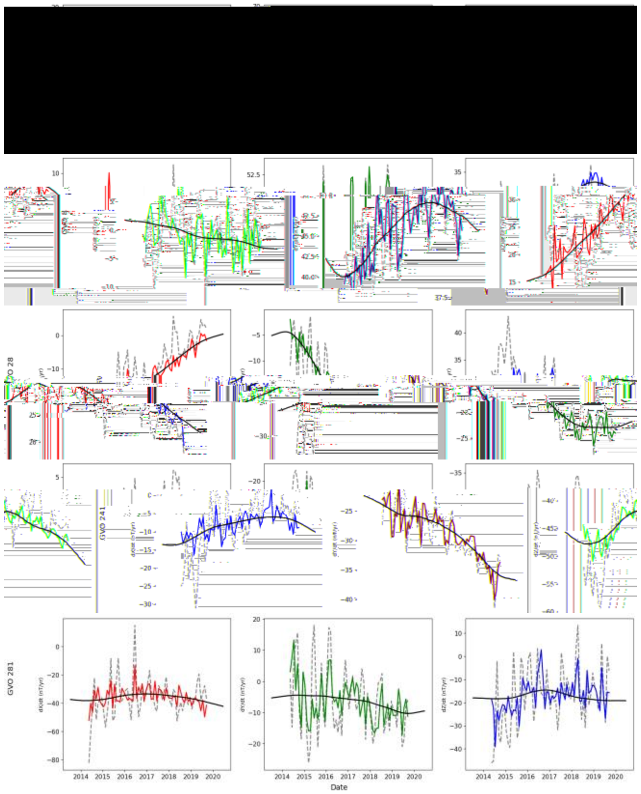


External fields mostly in Z

External fields mostly in X

External fields mostly in Z

X Y Z



North polar

North auroral

Mid-latitudes

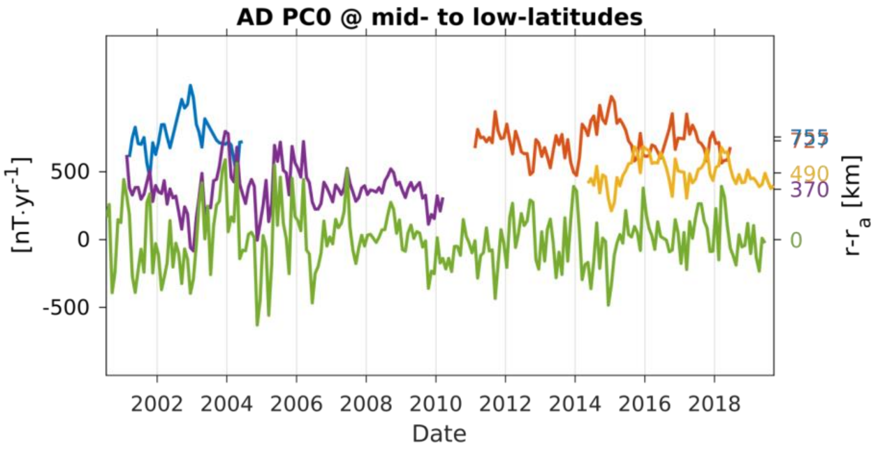
South auroral

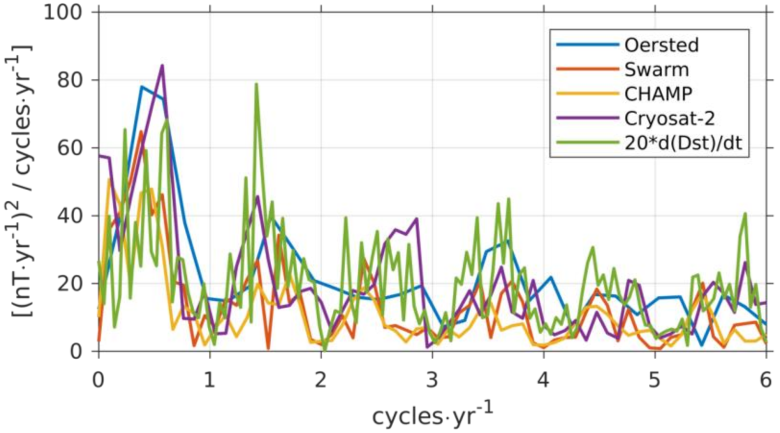
South polar

DTU

BGS

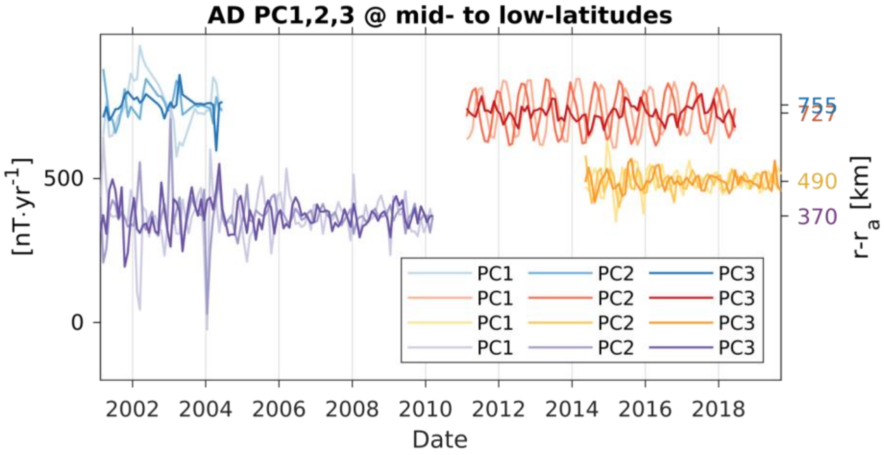
Application to GVO for other missions – ring-current

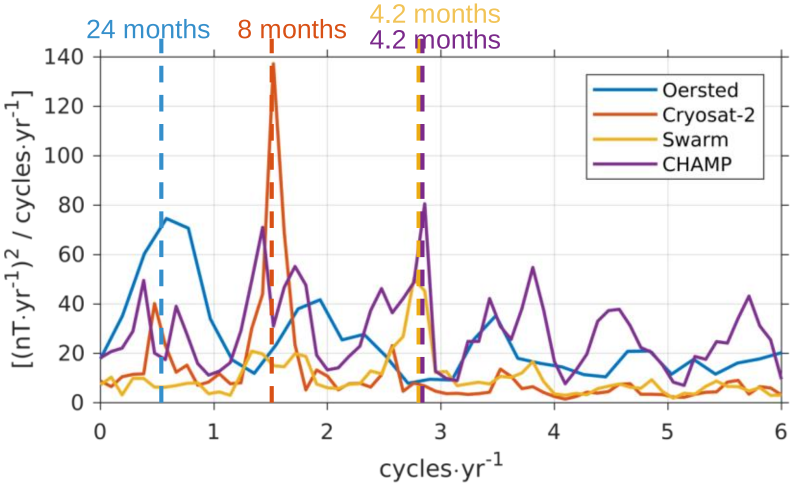




- At mid- to low-latitudes, the dominant PC for all missions is oriented roughly North-South
- This PC is strongly correlated (c=0.63 to 0.79) to the rate of change of the Dst-index
- We attribute this signal to magnetospheric origin, predominantly axial dipole
- This PC accounts for 39% (Ørsted) to 70% (Swarm) of variance in the residuals
- Note: sign of PC is arbitrary and signals can be correlated or anti-correlated

Application to GVO for other missions – local time bias

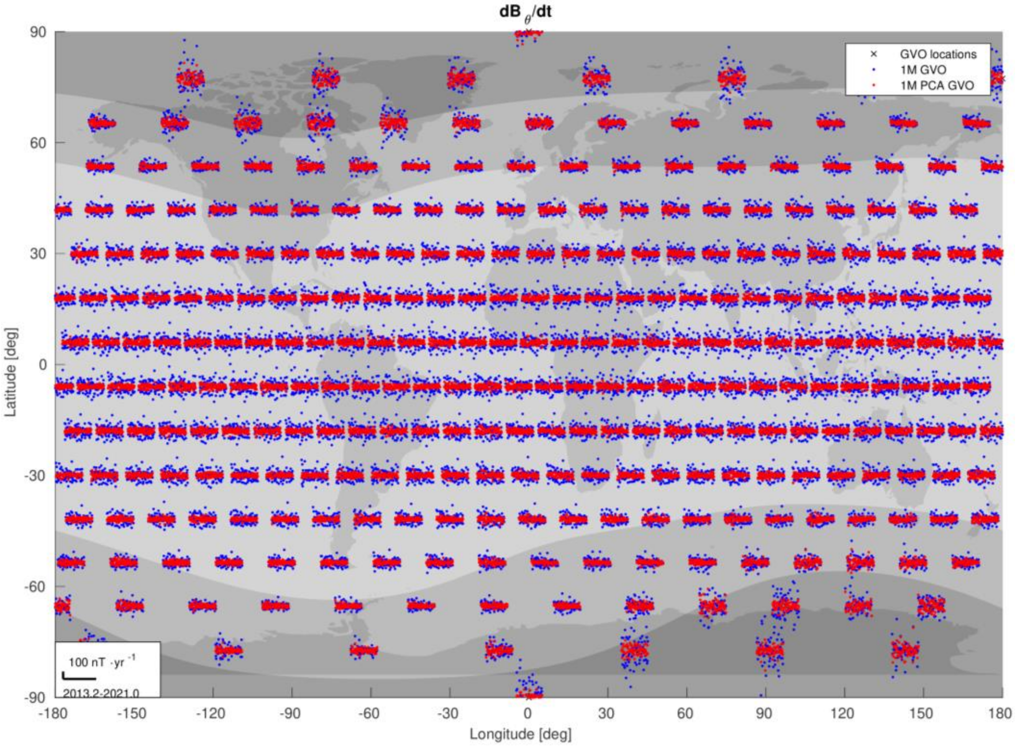




- At mid- to low-latitudes, second most significant set of 3 PC for all missions are spatially complex, varying by region
- These PC do not correlate strongly with any magnetic activity indices
- Frequency content peaks at LT precession rate of each mission
- We attribute these signals to local time sampling biases
- These PC account for 15% (Swarm) to 42% (CryoSat-2) of variance in the residuals, agreeing with magnitudes of frequency spectra
- Note: sign of PC is arbitrary and signals can be correlated or anti-correlated

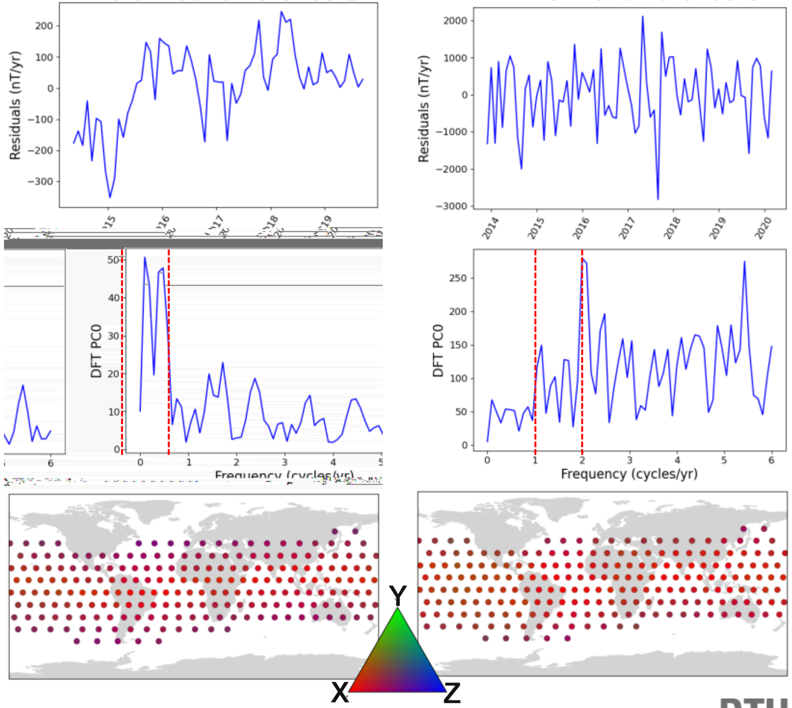
Application of PCA to first-differences SV

PCA correction of Swarm monthly first difference SV



1st PC annual difference SV

1st PC first difference SV



- Annual difference SV can't resolution sub-annual external field signals, first difference SV can
- For both SV types, primary contamination is southward dipole of magnetosphere
- Both SV types strongly correlated to d(Dst)/dt

Summary

- Geomagnetic Virtual Observatories provide a compact distillation of global satellite data in which time variations can be directly analysed, in an accessible form for a non-expert user base
- Principle Component Analysis can be applied to GVO secular variation to separate major components of internal and external field sources, and to remove local time sampling biases without reducing time or space resolution
- Our results show the method can be successfully applied to Ørsted, CHAMP, CryoSat-2 and Swarm GVO data sets, robustly identifying common external signals in each, and mission specific local time signals
- Applying PCA to monthly first differences allows us to isolate sub-annual external signals which cannot be sampled in annual difference SV
- Future work will be to apply method fully for monthly-first-difference GVO secular variation for all missions, and to assess applying PCA directly to main field time series

References and resources

- Cox, G. A., Brown, W. J., Billingham, L., & Holme, R. (2018). MagPySV: A Python package for processing and denoising geomagnetic observatory data. *Geochemistry, Geophysics, Geosystems*, 19, 3347– 3363. https://doi.org/10.1029/2018GC007714
- Hammer, M.D., Cox, G.A., Brown, W.J. *et al.* Geomagnetic Virtual Observatories: monitoring geomagnetic secular variation with the Swarm satellites. *Earth Planets Space* **73,** 54 (2021). https://doi.org/10.1186/s40623-021-01357-9

- MagPySV Python software: https://github.com/gracecox/MagPySV
- ESA Swarm and other mission GVO data sets, documentation and software at Swarm DISC GVO project webpage at DTU Space: https://www.space.dtu.dk/english/research/projects/project-descriptions/geomagnetic-virtual-observatories
- Data access, visualisation, virtual research environment for ESA Swarm mission: https://vires.services/

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THANK YOU

Any questions?
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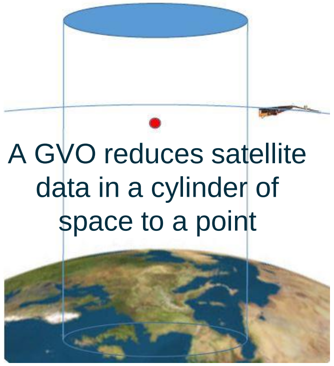
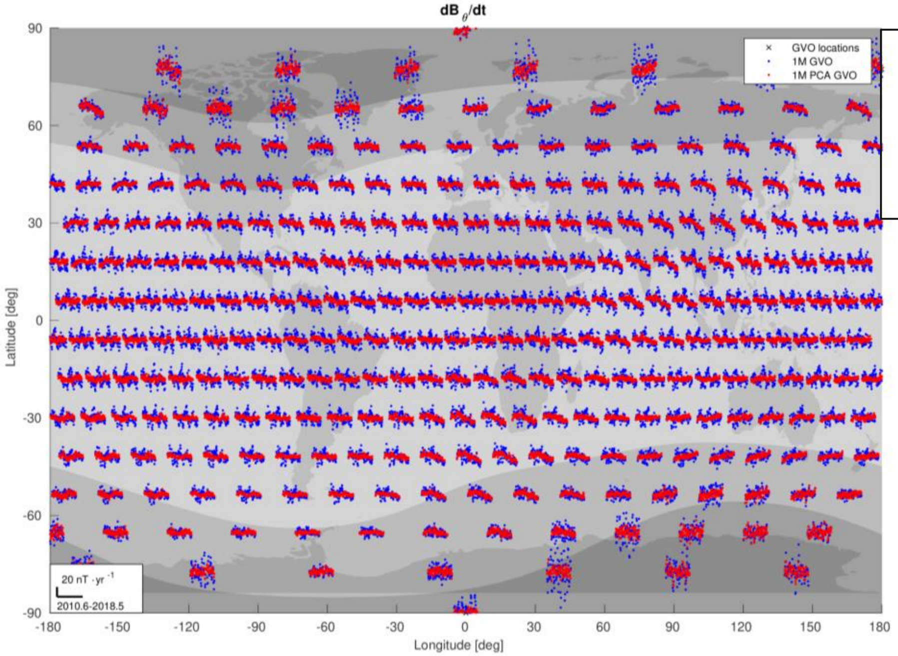
Isolating internal secular variation in **G**eomagnetic **V**irtual **O**bservatory time series using **P**rinciple **C**omponent **A**nalysis

- We apply the GVO technique to data from Ørsted, CHAMP, CryoSat-2 and Swarm satellite missions to produce easy to use globally gridded time series, spanning 2000 to present
- We use PCA to identify common external field signals and mission specific local time sampling biases in the GVO data, and remove them
- We produce data sets with isolated core field secular variation, while retaining 1 month resolution



A GVO reduces satellite data in a cylinder of space to a point



CryoSat-2 GVO secular variation

Observed field
Core field

Identified, orbit specific local time sampling biases