Imperial College London

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Operational Forecasting of Ground Effects Using the Gorgon MHD Model

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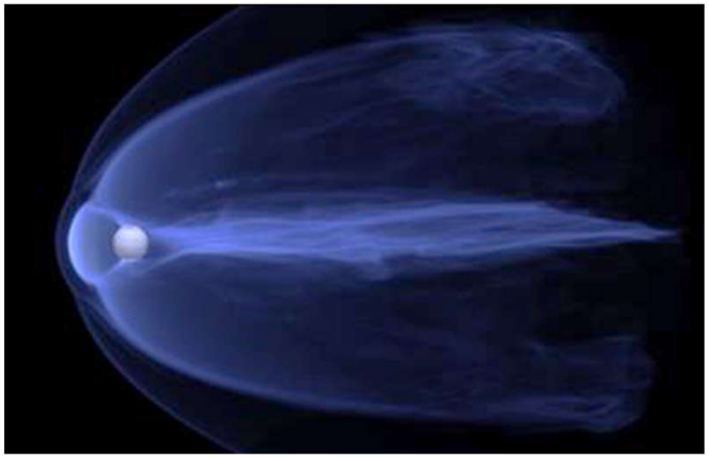
UKRI Natural Environment Research Council
Science & Technology Facilities Council
esa

Increasing Our Resilience to Severe Space Weather

- Global magnetohydrodynamic (**MHD**) **simulations** of the magnetosphere can provide **accurate and actionable predictions** of geomagnetic activity **faster than real-time**

- These physics based models can be driven with:
  - Live upstream L1 monitor data,
    e.g. ACE/DSCOVR (~30 min lead time)
  - Forecasts from first-principles heliospheric model,
    e.g. EUHFORIA (2-3 day lead time)



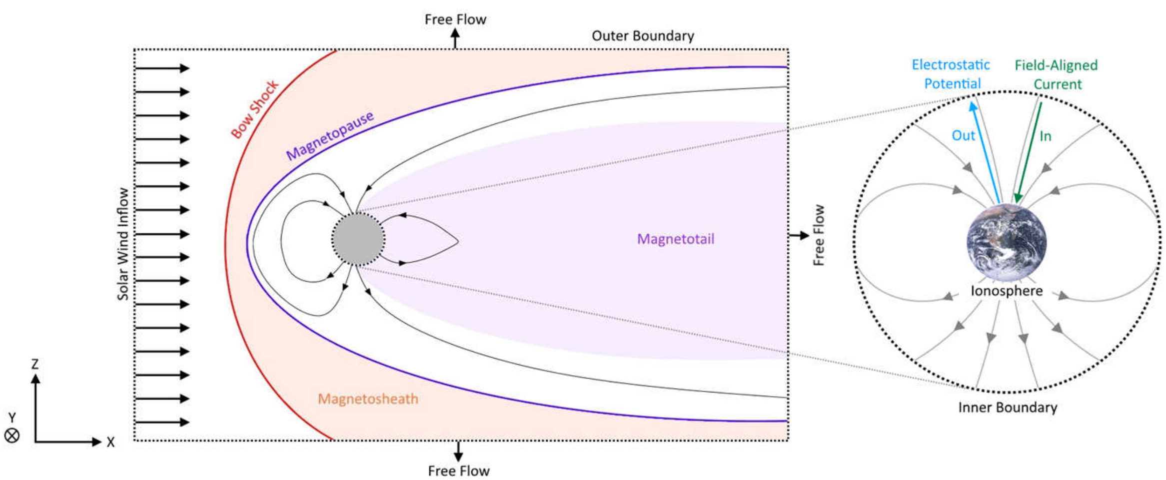
- Recently, the Gorgon MHD model has been optimised for real-time global magnetospheric forecasting as part of:
  - SWIMMR Activities in Ground Effects (**SAGE**) project
  - ESA's Virtual Space Weather Modelling Centre (**VSWMC**)
  - ESA **P3-SWE-XLV** '*3D MHD Modelling of the Earth's Magnetosphere*', in collaboration with UiB

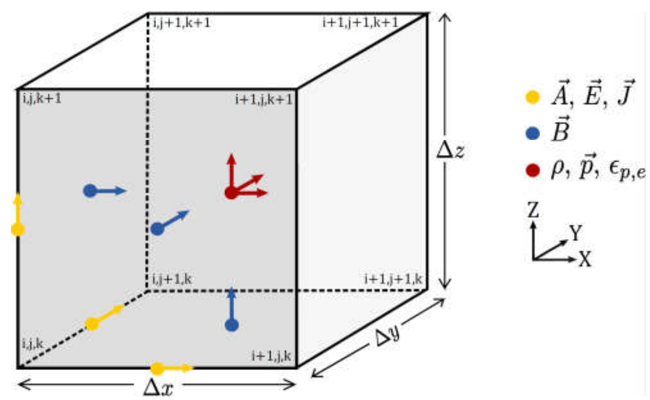
Image Credit: Nvidia GPU rendered visualisation, J. W. B. Eggington

Gorgon MHD Code – An Overview

- Explicit, Eulerian formulation of resistive MHD equations on 3D Cartesian grid (Ciardi + 2007)
  - Satisfies $\nabla \cdot \boldsymbol{B} = 0$ to machine precision via vector potential and staggered grid variables

- Split dipole implementation with previous applications for Earth and Neptune magnetospheres (Mejnertsen + 2016, 2018, 2021, Eggington + 2020, 2022a,b, Desai + 2021a,b)
  - Magnetosphere-ionosphere coupling captured as inner boundary condition via thin-shell model

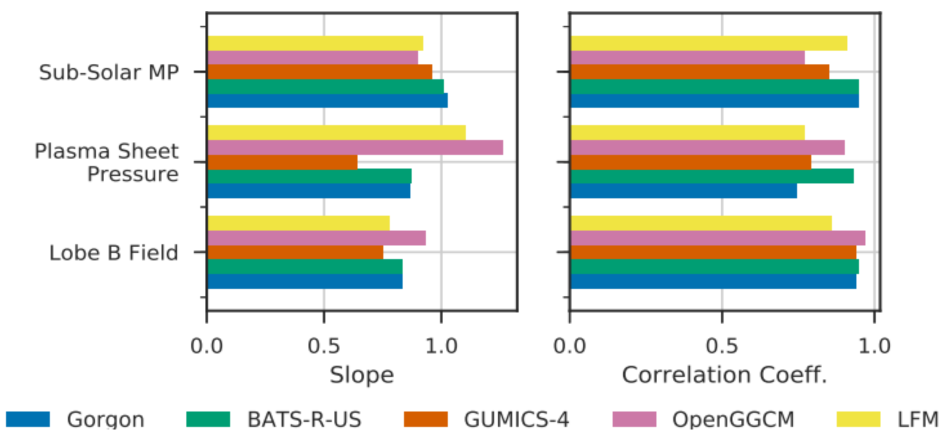




Gorgon MHD Code – Model Details and Operational Setup

Parallelised Fortran, with faster than real-time performance on ~200 CPUs at ICL, KUL and UK Met Office

- Input:
  - Solar wind parameters, Earth dipole and rotation axis orientations
- Output:
  - Magnetospheric and ionospheric grid variables over time
  - Benchmarks (R_{MP}, CPCP, Joule heating, ground **B-field**, etc)
  - Visualisations via '**Gorgon Tools**' Python package



Operational Gorgon Setup	
Domain	X = [-24, 66] R_E, Y = [-40, 40] R_E, Z = [-40, 40] R_E, uniform 0.5 R_E grid resolution, 3 R_E inner boundary
Field	Dipole strength and latitude taken from IGRF data covering 1900-2025
Ionosphere	Thin-shell model with empirical conductances (solar EUV, auroral + polar cap contributions)
Solar Wind	Measured (e.g. DSCOVR/OMNI) or modelled (e.g. EUHFORIA) L1 data with Earth's diurnal rotation imposed

Data credit: Gordeev + 2015

Gorgon MHD Code – Integrating Particles

- Test particle simulations run in parallel with Gorgon (Desai + 2021)
- Electromagnetic forces are calculated for particles using the time-evolving Gorgon MHD fields
- Direct application in radiation belt modelling within the SWIMMR SatRisk project through delivery of "extreme event" look-up database to the MET Office
- Future work to self-consistently include particle contributions

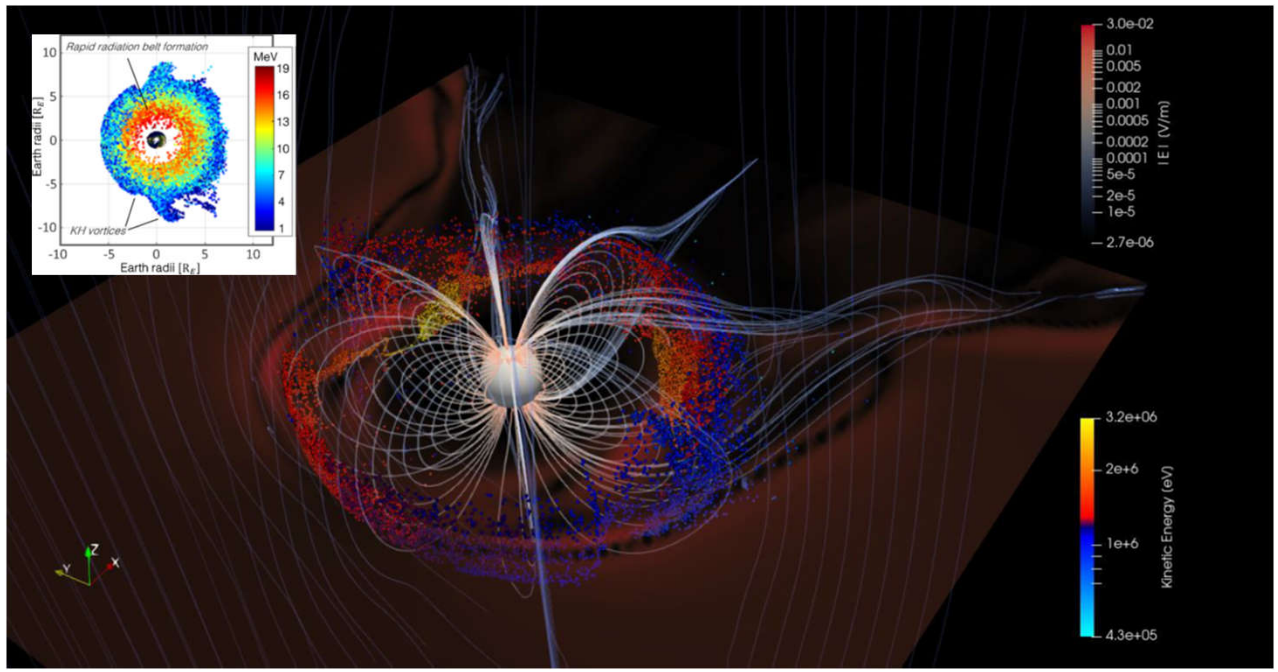
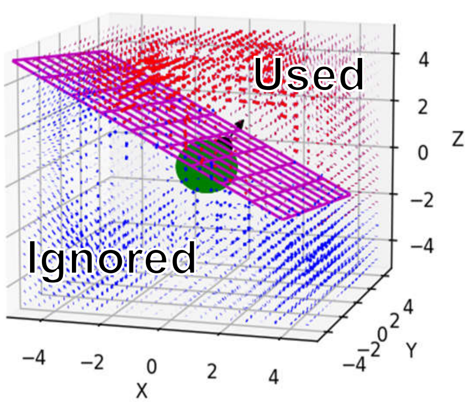
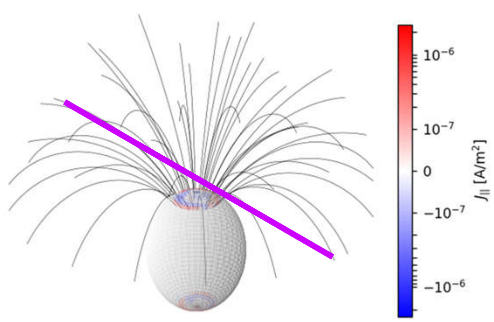


Image Credit: R. T. Desai (ravindra.desai@warwick.ac.uk)

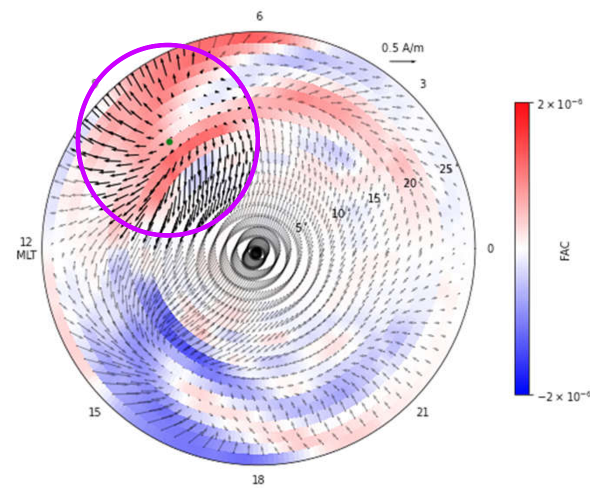
Gorgon MHD Code – Estimating the Ground Geomagnetic Field

- Capability to estimate ground magnetic field in-line, in parallel:
  - Explicit Biot-Savart integration (Rastatter + 2014) with line-of-sight masking
  - High-cadence (1 min) prediction for arbitrary test stations, e.g., gridded input to BGS geoelectric field model within SAGE project context



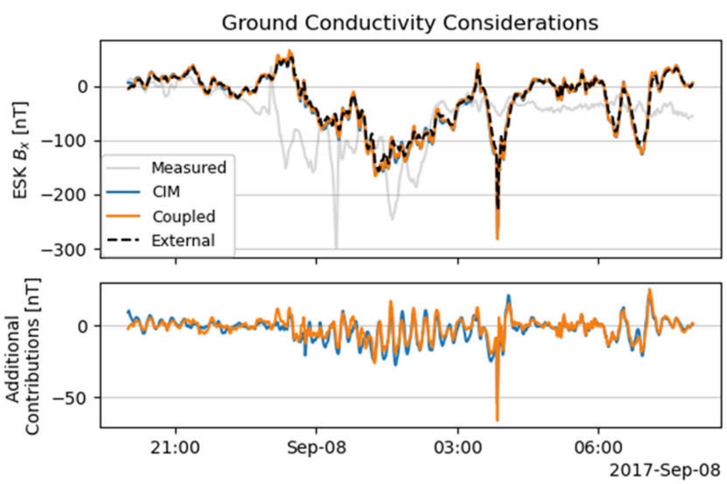


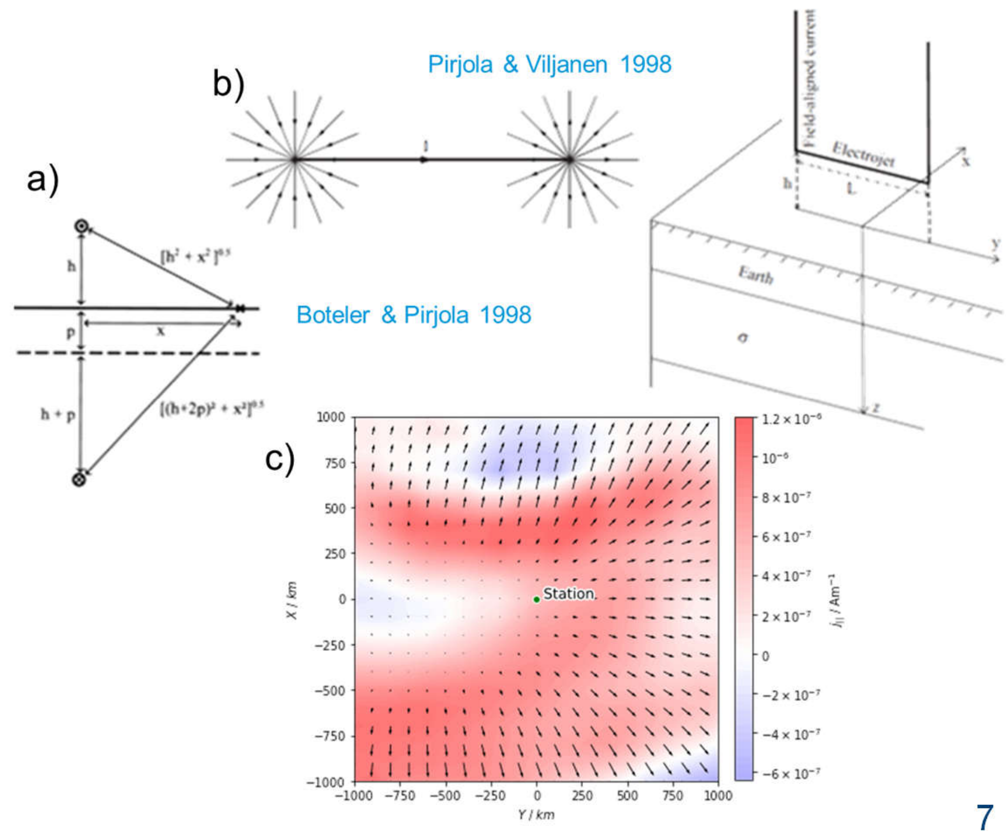
*Field-lines solely for visualisation.



Gorgon MHD Code – Including Induced Contributions

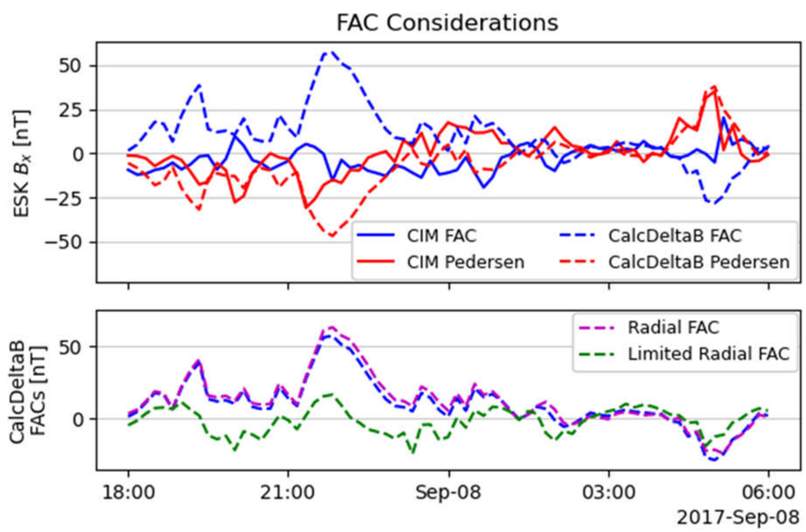
- Induced current contribution modelled through complex image method (CIM)
- Includes ionospheric currents and **implicit** FACs
- Generalisation to explicit current integration through equivalent current (i.e., Fig. a)





Gorgon MHD Code – Model Diversity

- Model diversity in estimating the ground geomagnetic field gives a fuller picture



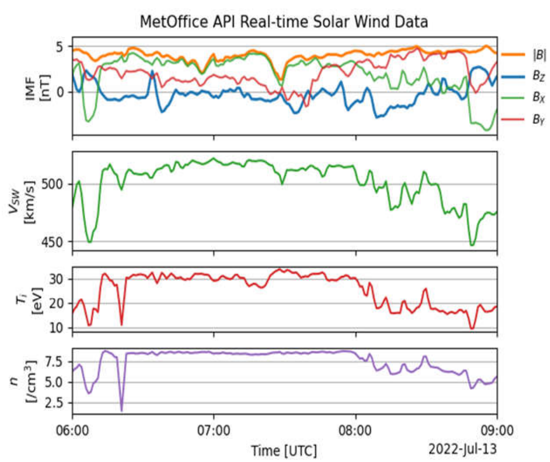
	CalcDeltaB	CIM
Contributions	Magnetosphere, FACs, ionosphere	Ionosphere, nett FACs on grid
FACs	Dipolar, line-of-sight	Vertical
Extent	Full simulation domain, spherical coords, line-of-sight	Stereographic projection with 1000km^2 grid
Induced Current	Simplified CIM coupling using equivalent current	Explicit inclusion of ionospheric and FAC contributions

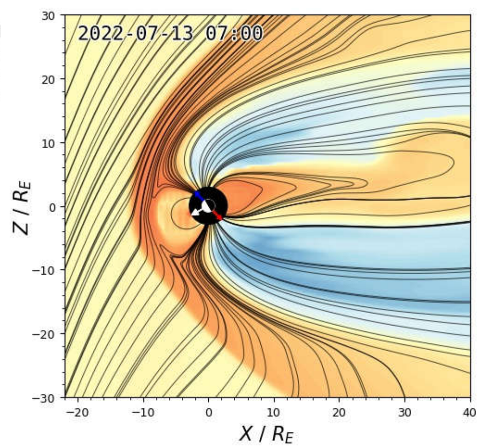
Gorgon @ Met Office: Real-Time Data Example

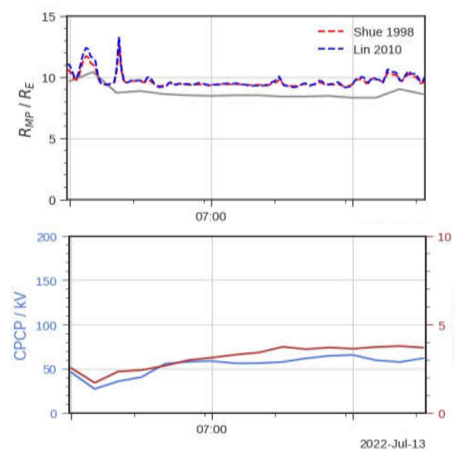
Ingest real-time L1 solar wind data via Met Office API (5 min bursts)

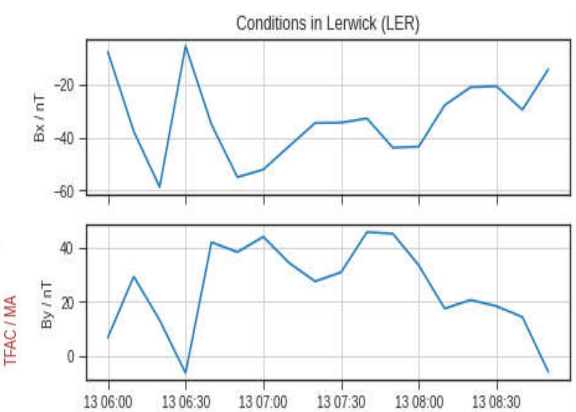
Run Gorgon with L1 data, output gridded and in-line processed data (e.g. ground **B-field** @ 1-min)

Transfer to SWIMMR AWS environment for post-processing and coupling to downstream models



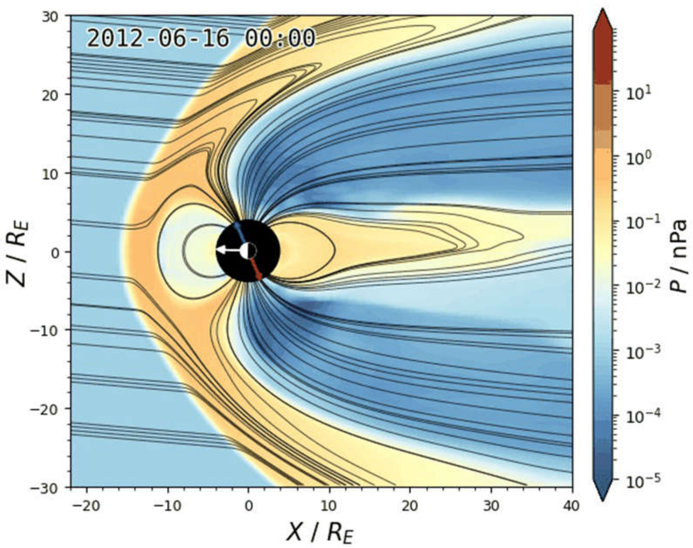


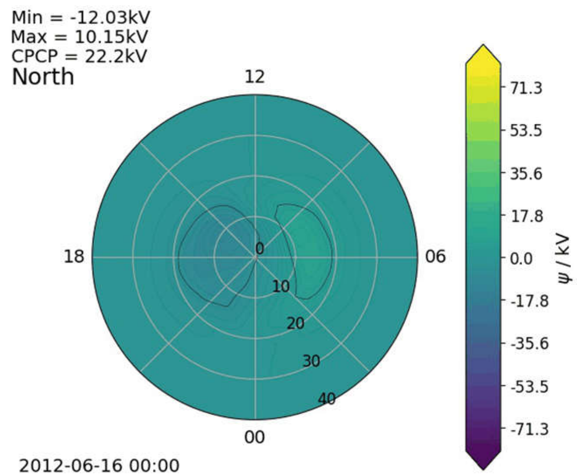


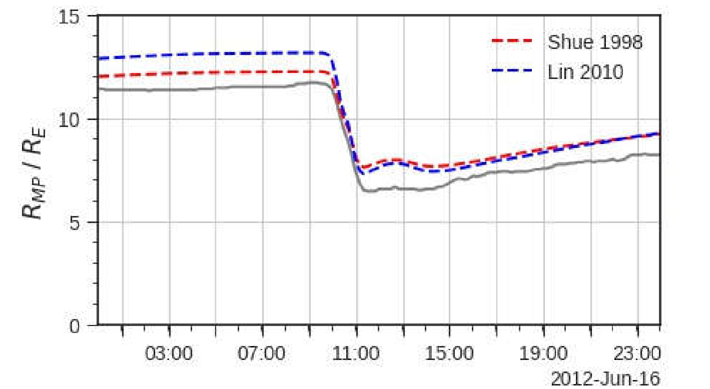


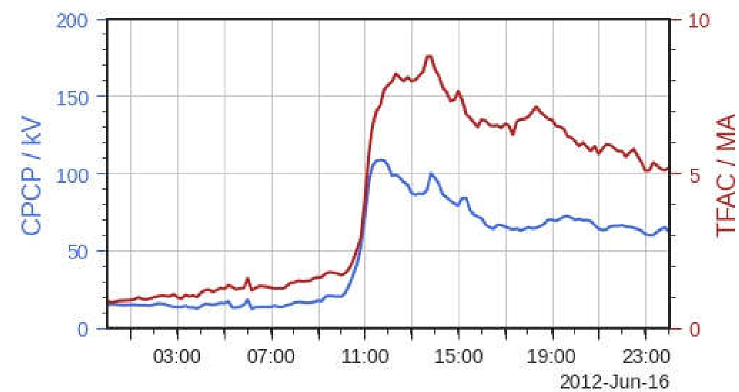
EUHFORIA-Gorgon: Simulated CME Impact

- Example within VSWMC deployment, coupled to upstream EUHFORIA model
  - Strong compression of magnetosphere, same trend as empirical models
  - Sharp growth in ionospheric parameters after impact, gradual drop-off





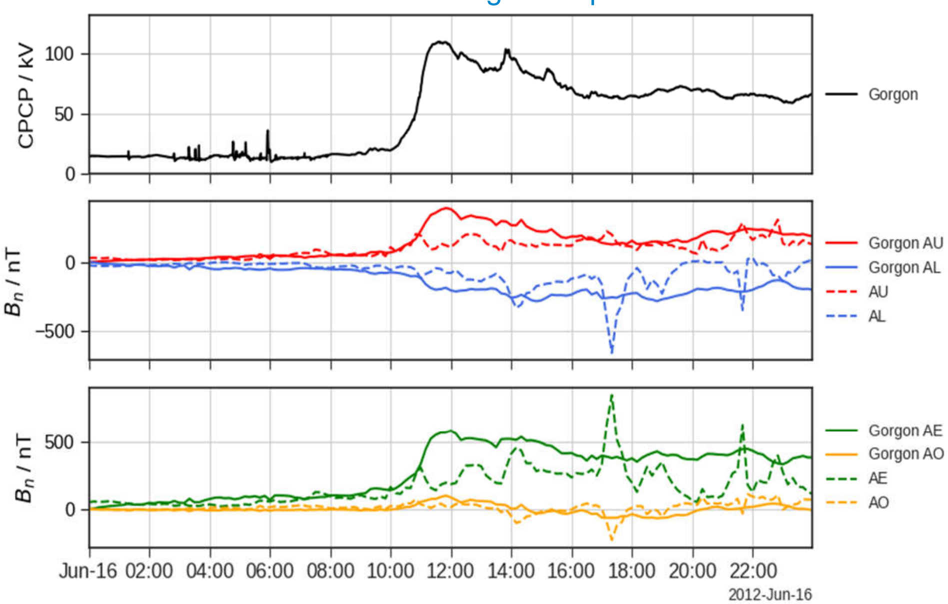




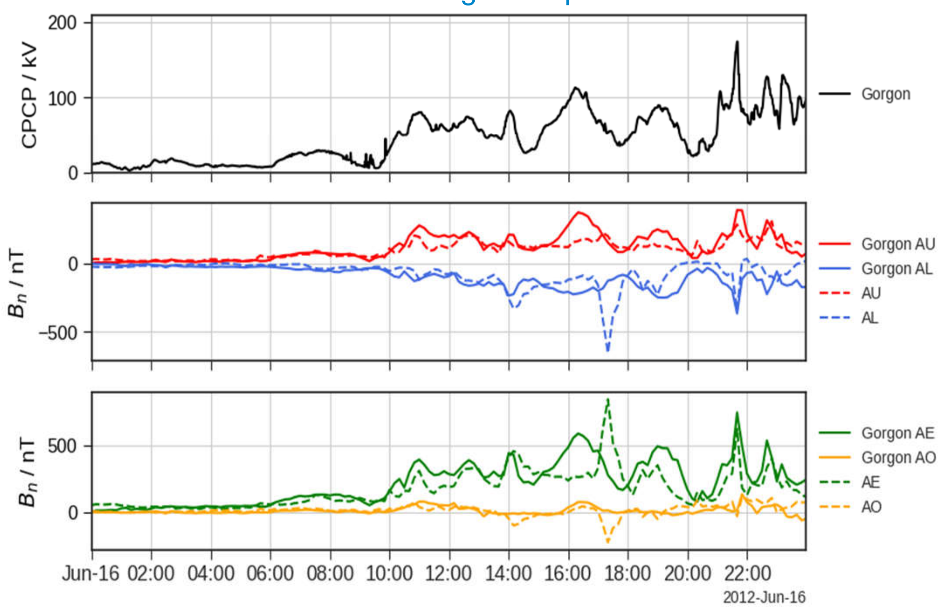
Gorgon Validation: CME Impact Ground Effects

- EUHFORIA predictions are intrinsically smoother, but agree with OMNI-driven Gorgon onset time and AE magnitude
- OMNI-driven Gorgon captures much of the shorter timescale behaviour seen in measured indices

EUHFORIA-Gorgon Output



OMNI-Gorgon Output

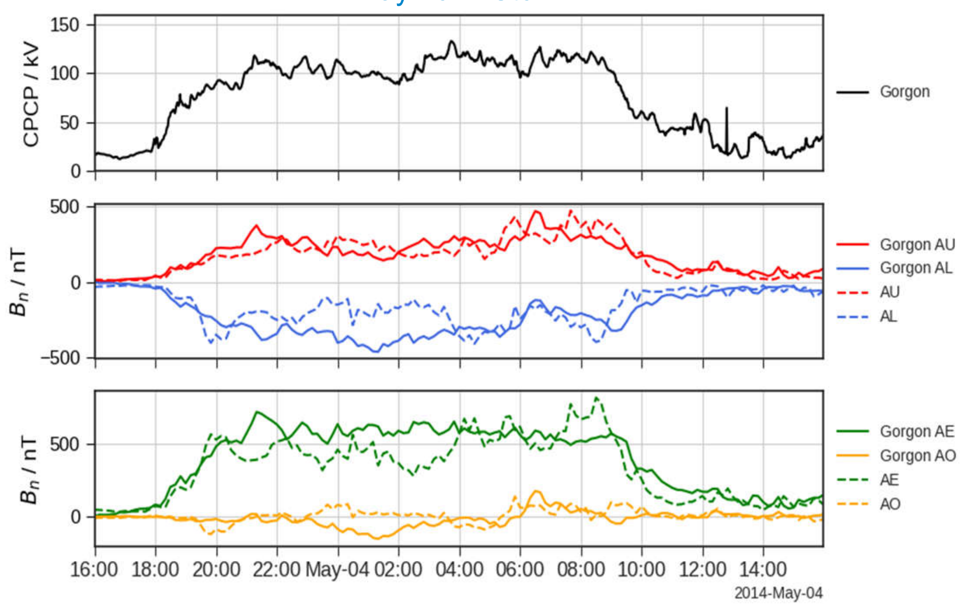


Data credit: WDC Kyoto U (indices)

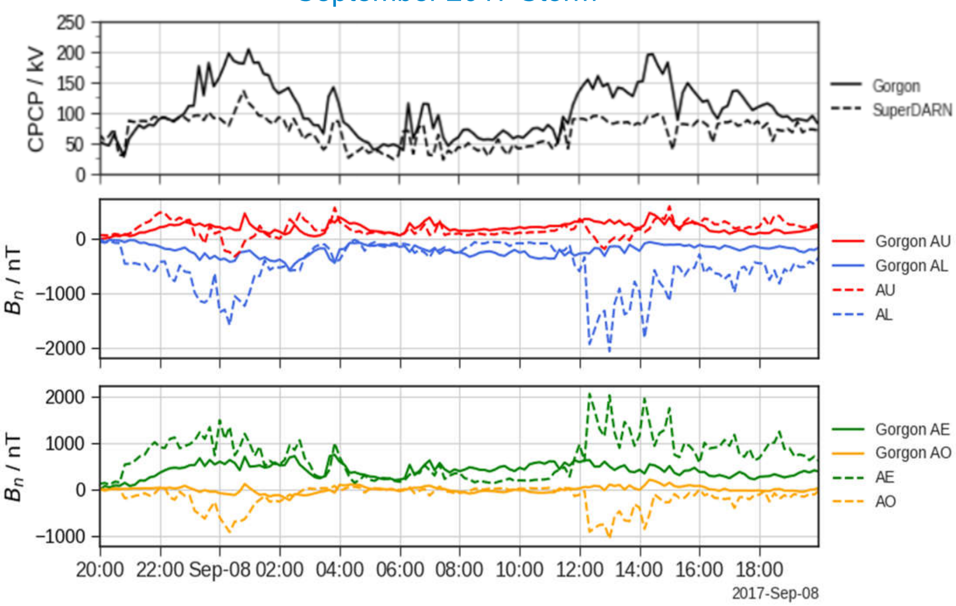
Gorgon Validation: Geomagnetic Storms Ground Effects

- **Severe 2017 storm:** cross polar-cap potential (CPCP) agreement with SuperDARN, AU captured better than AL
- **Moderate 2014 storm:** reproduces trends of auroral indices well, suggesting resolution and conductivity sensitivity

May 2014 Storm



September 2017 Storm



Data credit: M. Walach (SuperDARN), WDC Kyoto U (indices)

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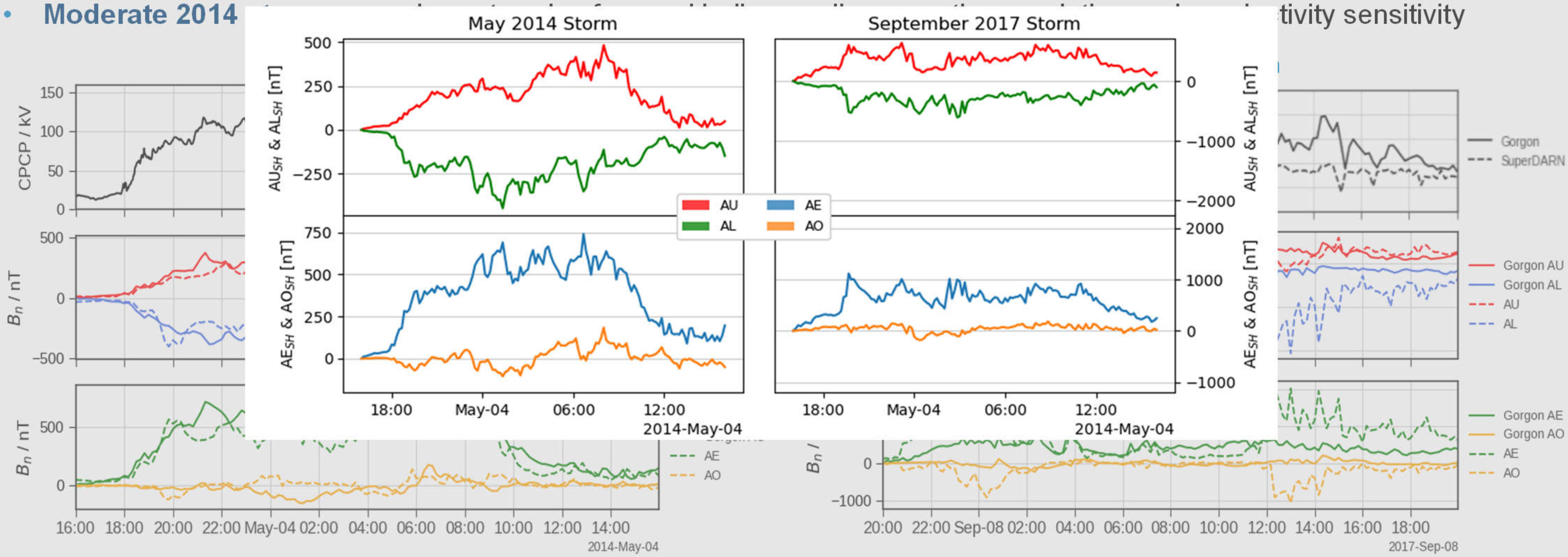

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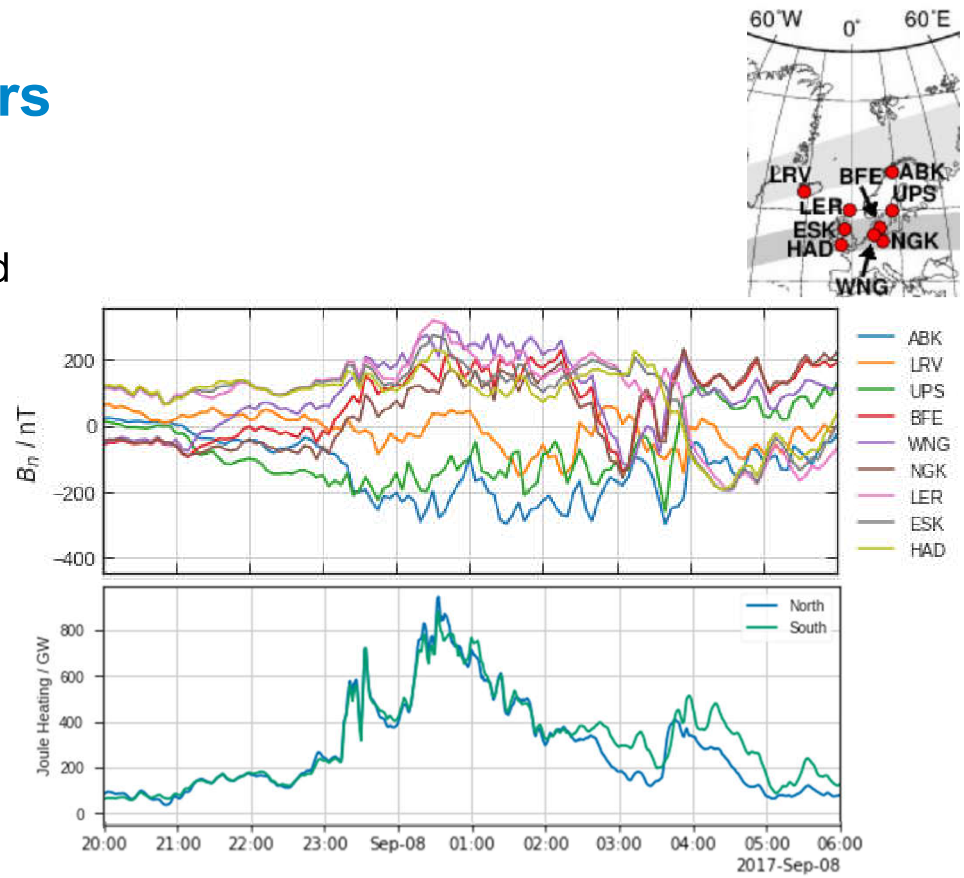
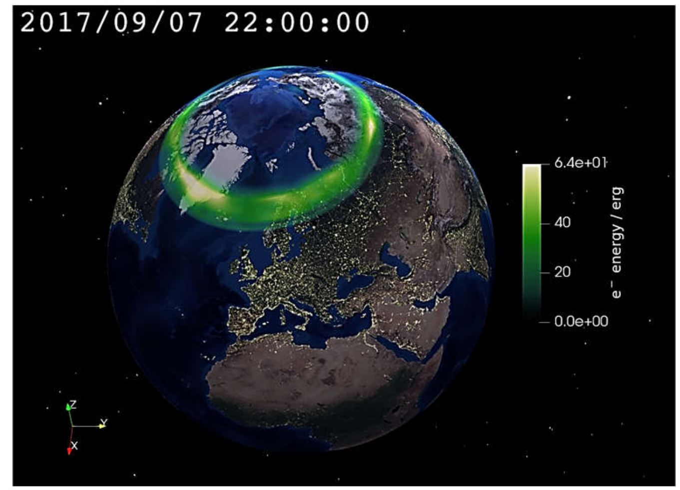
Tailoring Model Outputs for End-Users

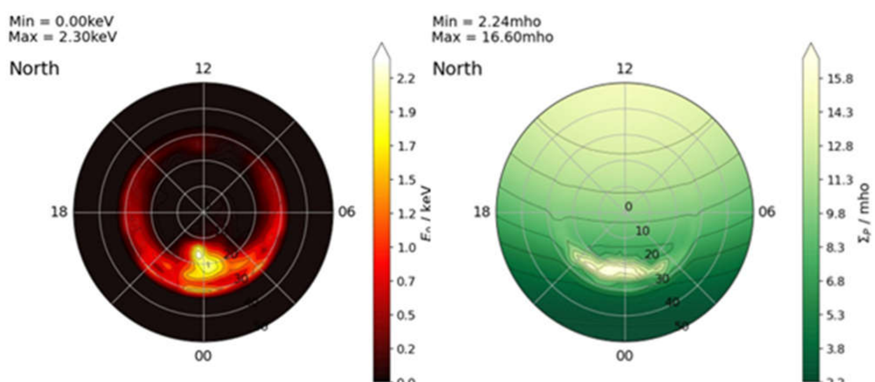
- Relevant **end-user** products include:
  - Ground **dB** and **dB/dt** at arbitrary stations (gridded or individual), separate current contributions and include optional induced subsurface current
  - Global **geomagnetic indices** (e.g. AE, Kp)
  - Potential to develop regional and/or normalised indices, e.g. “AEur”, “KEur”
  - **Joule heating** as proxy for satellite drag
  - Magnetospheric conditions (e.g. **magnetopause standoff distance**) and visualisations
  - Ionospheric conditions (e.g. **cross polar-cap potential**) and visualisations

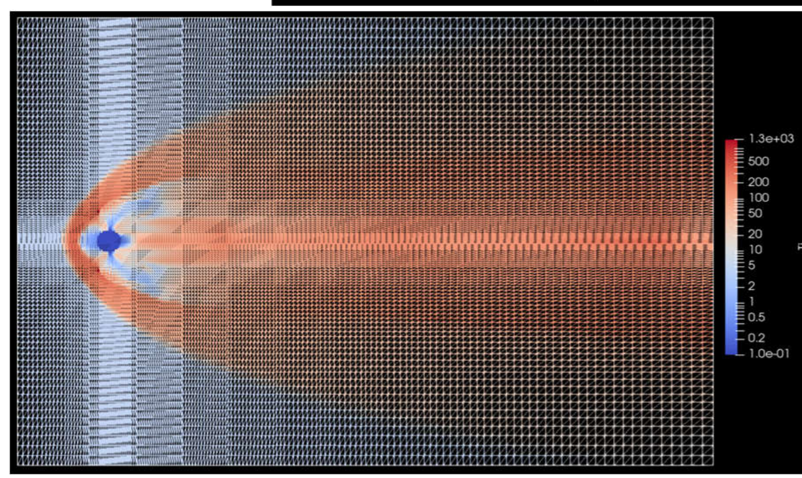


Ongoing Development: What's Next?

- Continuous validation of deployments allows operational testing to feed back into ongoing developments (**R2O2R**):
  - MHD-derived **conductance** from auroral precipitation,
    i.e., improved ionospheric and ground predictions
  - Optimisation of simulation **grid** (stretched and block-refined),
    i.e., improved accuracy and faster runtime
  - **Extension** to mid-latitudes regions (region 2 currents)







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Summary

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- **Gorgon has been adapted to simulate the global magnetosphere faster than real-time**
  - Allows for both modelled (e.g. EUHFORIA) and measured (e.g. DSCOVR) solar wind input to produce **continuous forecasts** of geomagnetic conditions
  - Simulations of past geomagnetic storms and case studies **reproduce key trends** in observed ionospheric and ground metrics
- A range of in-line and post-processed forecasting products **tailored to end-user needs** is being developed, e.g. local estimations, regional indices and global metrics