Topical Discussion Meeting Report

UTILISATION OF REAL-TIME SOLAR WIND DATA FOR FORECASTING: CHALLENGES AND POSSIBLE SOLUTIONS

Conveners: Norah Kwagala (Univ. of Bergen), Andy Smith (UCL/MSSL) (online), Joseph Eggington (Imperial College London)
Date – Time – Room: Thursday 27/10/2022, 11:30-12:45, Air
Nr of participants: 65 (40 in-person, 25 online)

Objective of the TDM

With the increased need for operational space weather forecasting, there has similarly been an increase in reliance on real-time solar wind data from L1 monitors. Due to the location of these monitors in the upstream solar wind, the propagation time needed for solar wind plasma to reach Earth after measurement can directly translate to a lead-time on forecasts (if the models using this input data run fast enough). In contrast to general modelling with post-processed science-quality data, using unseen raw real-time solar wind data for forecasting comes with additional challenges (examples include down-link delays, data gaps, monitor availability, differences in monitor calibration/location and forecasted solar wind propagation to Earth or the bow shock). In many cases model performance is adversely affected and/or cumulative delays impact the usefulness of the forecast. This topical discussion meeting aims to explore challenges in using raw real-time solar wind data in the context of operational space weather forecasting and ultimately move towards pragmatic operational solutions. Contributions and perspectives are encouraged from across the field, whether it be to identify new challenges from an end-user perspective or to present existing real-time data cleaning pipelines and next-generation instrumentation.

Some Discussion Highlights

Research to Operations Lessons from SWIMMR - Andy Smith, *UCL/Univ. of Northumbria, UK (online)*

Data gaps and differences in data values are the main issues when comparing NRT and Science solar wind data from L1. In the case of the former, interpolation up to 5 mins greatly increases the amount of continuous data available to models. There was interest in the best technique to use for such interpolation. In terms of data values, it is critical that training is done on representative data, i.e., NRT data when the aim is forecasting using NRT. Having an archive of such historic NRT in needed, and there was interest in the data archive associated with a recent paper (https://doi.org/10.1029/2022SW003098).

Real time solar wind data: potential pitfalls - Edmund Henley, *UK Met Office (online)*

Using a recent paper by Loto'aniu et al 2022 (https://doi:10.1029/2022SW003085) to illustrate issues arising from data gaps, a couple of example pitfalls seen in operational models run by the Met Office were highlighted. These included the operational Ovation model crashing due to a longer data gap in L1 data (shorter data gaps in previous runs also causing issues hadn't been noticed). A recommendation in this regard is testing with good, canned datasets representative of extreme data gaps or failovers. Similar issues were seen with the DRAP model, where brief model crashes when GOES was in eclipse had also been missed. Recommendation for exposing and reviewing model uptime/runtime logs to identify such issues. Within L1 data products it was noted that sparser, slower, warm solar wind conditions are not well characterised by DSCOVR, triggering failover to ACE. A complication is that multiple velocity components are only present for DSCOVR – where the L1 data has failed over to ACE only speed is present. For operationalising Geospace at the Met Office, this required assuming $v_x=|v|$ during failovers to ACE. Interpolation is an additional consideration, similar to the work presented by Andy Smith, with care needed on restarts regarding any backfilling which may have occurred since, potentially modifying earlier L1 data. Further care should be taken regarding doubled-up DSCOVR and ACE entries, with identical timestamps. There was a question around the usability of data flags in the real-time data – whether these can be used to identify poor data, and their reliability. A response from Doug Biesecker is that they may not be reflective of data quality, but there is always some criterion in the data chain that triggers the data flags.

Input parameters, lead time and real time data: solar wind to Kp - Peter Wintoft, *IRF, Sweden*

Various implementations of the IRF Lund Kp prediction models using solar wind data were presented. The current version is available at https://www.spaceweather.se/forecast/kp (with a lead time of a bit over 3 hours (dependant on solar wind speed) and using both magnetic and plasma data). It is noted that Kp is sensitive to sub 3-hour variations. As a result, significant improvements are seen when using high time cadence solar wind data (https://doi.org/10.1051/swsc/2017027). To mitigate the effect of bad solar wind data showing up as spikes, especially in real time data, a 5 min medium filter gives additional improvements. Further analysis was presented using various different input data sets, i.e., ACE, DSCOVR and OMNI testing sets. It should be noted that the models were trained on ACE Level 2 data and testing on DSCOVR data, this provides insights to the generalisation capabilities. Although results are similar, there was definite sensitivity to which training set was used and whether the dataset included bad solar wind data (i.e., produces definite Kp outliers). With the increase of prediction lead-time to up to the 3 hours used there is of course some loss in correlation, but the prediction remains useful (https://doi.org/10.1029/2018SW001994). There was further interest in coupling the IRF Kp prediction model with forecasted EUHFORIA solar wind data (question from Anwesha Maharana), I.e., increasing the lead-time significantly without needing time-shifting of the actual prediction model.

RTSW Data Utilization at NOAA Geospace Model - Doug Biesecker*, NOAA, USA*

Real-time data use within the context of the NOAA Geospace model was presented. It was noted that the low bit rate of ACE has an effect on processing and results in bad data, especially SEP events. DSCOVR has data issues, but for different reasons, e.g., mistakes in electronics cabling. Both space craft use Faraday cups, and Parker Solar Probe actually used same one and but noticed a problem so tightened it and fixed. A lot of person hours are needed to maintain the data stream and modelling effort. Within the Geospace framework, if there are is a 15 minute or longer gap, the model restarts. Analysing output of the predicted Kp and Dst values, effects of these restarts and bad data are seen. In particular, data gaps create overestimation of Kp and Dst and density spikes in real-time solar wind data similarly is linked to overestimation. The follow on SWFO mission (launching 2025) will address multiple aspects of these shortcomings, with increased sensitivity, error bars and correction factors from forward modelling. There is an additional plan to introduce the 'best' real-time solar wind data dynamically (currently no threshold and done manually by forecasters). There were questions around which data stream is best to use, but the best follow up would be with Jeff Johnson who is the current lead.

Solar wind modelling for Space Weather forecasting with EUHFORIA - Anwesha Maharana, *KU Leuven, Belgium*

Coupled physics-based coronal and heliospheric simulations provide a forecasting capability for solar wind modelling, early warning high-speed streams and SIRs crucial for CME, SEP predictions and magnetic connectivity. CME arrival and impact forecasting is done using flux rope propagation with respect to solar wind (spheromak andFRi3D model). In the Virtual Space Weather Modelling Centre (VSWMC), a configuration is established to create a chain of models, for example the coronal model boundary condition provides the input to the heliospheric model, which in turn can feed into empirical or magnetospheric models that compute global ground indices (Dst, Kp, Dso). This type of coupling can provide early warnings of geoeffectiveness of solar storms faster than using the real time solar wind data, in order to get sufficient time for mitigation. Additional application of predicted solar wind is with a particle transport model called Paradise, which is coupled to the EUHFORIA heliospheric domain. This was shown in the context of Parker Solar Probe and STEREO-A observations and integrated SEP events.

Solar wind forecasting models: global models vs. point in situ measurements - Rui Pinto, *IRAP OMP, France*

Global models and in-situ measurements were contrasted. Main goal is the use multiple and non-uniform input data in a robust and unified modelling environment. This can be showcased using MULTI-VP to drive to HELIO1D/EUHFORIA models, which can then be coupled to the Salammbô radiation belt model or a neural-network predicting Kp at Earth. Details of the coronal model include a purely radial flowing solar wind using the data driven MULTI-VP model (https://doi.org/10.3847/1538-4357/aa6398). Using different magnetogram sources results in quite different properties. Similarly, using the same magnetogram one can employ different extrapolation methods, such as PFSS or PFSS+SCS as done in the WSA model. Synthetic coronagraphs show displacements versus reality. To get an improved result or validation, the extrapolation methods are ranked based on HCS position and then further using in-situ properties of polarity and wind speed (there are other evaluation criteria available). Using this reduced ensemble size an ensemble weighted mean of a 21-point grid about subsolar line (not quite LOS angle but conceptually similar) are used to account for spatial and temporal uncertainties (which besides having error bars also has the best agreement with OMNI). The high variability between neighbouring solar wind streams is real feature of the solar wind at L1 not just model weakness – and this makes validation using single point observations challenging. An alternative is to validate the global models at coronal heights or offer multi point strategies.

Planned Real Time Data from NOAA's SWFO Mission and Dynamical Stability of Global Magnetospheric MHD Models - Dimitrios Vassiliadis, *NOAA, USA*

The SWFO L1 mission aims to deliver the next generation of in-situ solar wind measurements. Coronal imagery (white light intensity), interplanetary magnetic field and wind speed are prioritised, along with additional standard solar wind parameters such as density, temperature etc. As part of the product generation and distribution program, data products will include error bars and better flags in comparison to previous L1 data. Feedback on existing data products or requests for additional end-user products are welcomed as they are being designed currently. Furthermore, data will be available for immediate use and archived. There were some questions/requests about the availability of documentation. Looking at the dynamical stability of global magnetospheric models (SWMF and OpenGGCM) when encountering interplanetary magnetic field impulses (as may be the case with bad L1 data), a study was done with G. Toth (SWMF), L. Rastatter (CCMC) and J. Raeder (OpenGGCM). In this study, impulses (of various amplitudes) perturbed a baseline solar wind input to models (which both included the RCM inner magnetosphere model). The linear response was short and near immediate, with a convection timescale of 10-20 min. The peak ground perturbation was directly proportional to the impulse amplitude but was short-lived in general. The non-linear response was however seen much later, with a long tail-loading timescale 4 hours. In this case, perturbations were independent of impulse amplitude. Opposite polarities relative to baseline are suggestive of flux loading and unloading. A paper reporting these results is in preparation.

Main Conclusions of the Meeting

- Care must be taken when developing models with science data, this will not be representative of real-time data (i.e., particularly for data driven models)
    - More generally models are sensitive to training data and bad quality data
- Canned representative real-time data with gaps and failovers should be used, and runtime/uptime logs should be used to track model performance
    - Ideally make use of recognised software patterns/standards for runtime logs, with tuneable levels of reporting, e.g., ranging from diagnostic to critical
- Using high cadence solar wind data can significantly improve low cadence outputs
- Future L1 mission will include improvements in raw real-time data (sensitivity, range, correction factors etc) and how it’s packaged (error bar, data flags etc)
    - Feedback and/or requests for SWFO data products are welcomed
- Physics-based heliospheric models provide advanced lead-time with improvements on B_z and other critical parameters – can be used as a first estimate in the face of real-time data issues
- Variability of solar wind streams at L1 is a real feature of the solar wind and either driving models or validating them using a single point measurement is not ideal
- Ensemble modelling of heliospheric models may provide a better contextual picture of L1 dynamics
- Interplanetary magnetic field impulses, indicative of L1 uncertainty and/or bad data, influence global magnetospheric model stability
    - Short-term linear effect proportional to impulse amplitude
    - Long-term non-linear effects independent of impulse amplitude

Annexes

Below are the slides presented during the TDM.

Introduction and Agenda (Norah Kwagala, Univ. of Bergen, Norway)

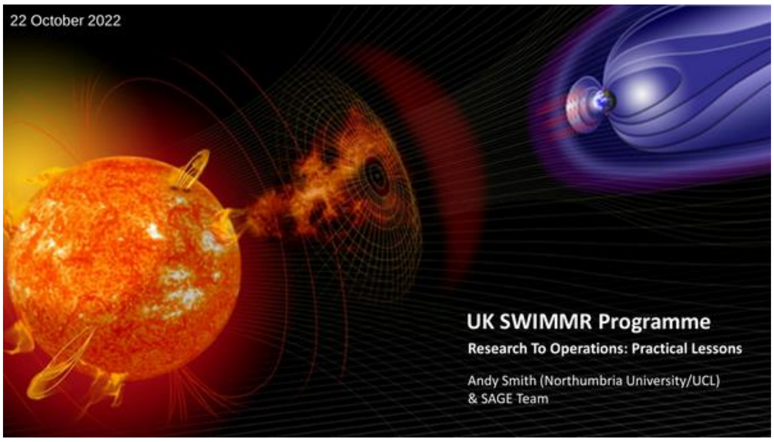
TOPICAL DISCUSSION MEETING - UTILISATION OF REAL-TIME SOLAR WIND DATA FOR FORECASTING: CHALLENGES AND POSSIBLE SOLUTIONS

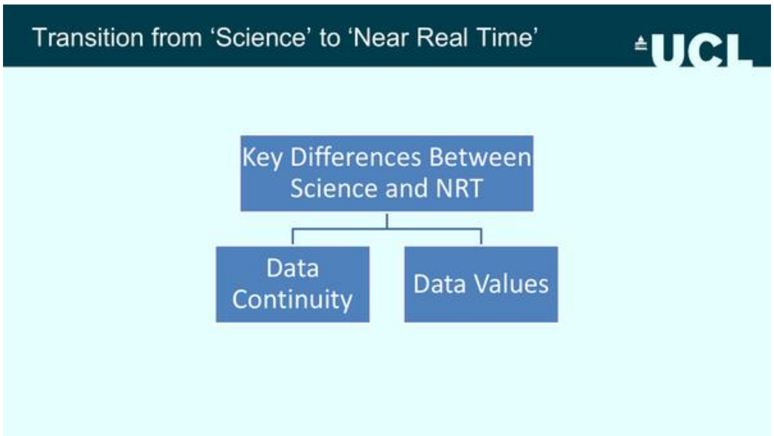
Chairs:
Norah K Kwagala, University of Bergen, Norway
Joseph Eggington, Imperial College London, UK
Andy Smith, Northumbria University, Newcastle, UK (online)

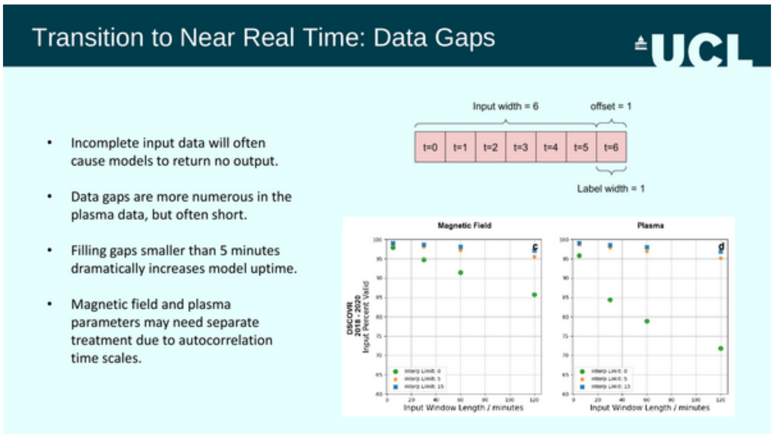
Highlights

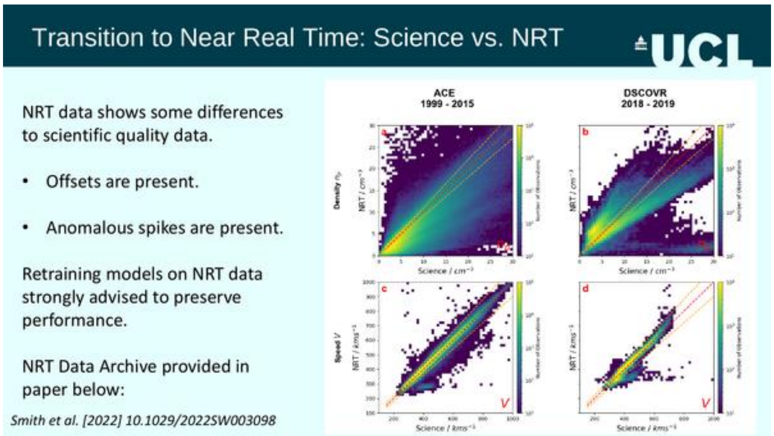
- Research to Operations - Lessons from SWIMMR - *Andy Smith (online)*
- Real time solar wind data: potential pitfalls - *Edmund Henley UK Met Office (online)*
- Input parameters, lead time and real time data: solar wind to Kp - *Peter Wintoft IRF, Sweden*
- RTSW Data Utilization at NOAA - Geospace Model - *Doug Biesecker NOAA, USA*
- Solar wind modelling for Space Weather forecasting with EUHFORIA - *Anwesha Maharana, KU Leuven, Belgium*
- Solar wind forecasting models: global models vs. point in-situ measurements - *Rui Pinto, IRAP OMP, France*
- Planned Real-Time Data from NOAA’s SWFO Mission and Dynamical Stability of Global Magnetospheric MHD Models - *Dimitrios Vassiliadis NOAA, USA*

Research to Operations – Lessons from SWIMMR (Andy Smith, UCL/Univ. of Northumbria, UK)









Real-time Solar Wind Data: Potential Pitfalls (Edmund Henley, UK Met Office)

Real-time solar wind data: potential pitfalls

Edmund Henley, Met Office
ESWW 2022

Real-time solar wind data: data gap/failover pitfall

Validation of the DSCOVR Spacecraft Mission Space Weather Solar Wind Products

Paul T. M. Loto'aniu[1,2], K. Romich[1,2], W. Rowland[2], S. Codrescu[1,2], D. Biesecker[3,4], J. Johnson[1,5], H. J. Singer[5], A. Szabo[4], and M. Stevens[6]

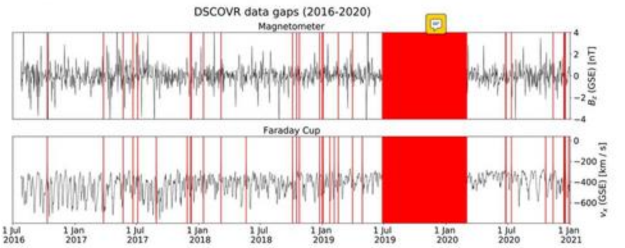


Figure 3. Visualization of Deep Space Climate Observatory (DSCOVR) magnetometer B_z component (top) and Faraday Cup solar wind v_x component (bottom) data, showing date ranges for which DSCOVR data were available for this study. The red regions represent dates for which <75% of the available data are useable.

doi:10.1029/2022SW003085

- Real-time solar wind data has various challenges which scientists using science-grade datasets (e.g. OMNI) often don't encounter
- Dev using science-grade data easier, but can be a R2O barrier when trying to operationalise models later
- Nice overview of some issues in Loto'aniu et al 2022, comparing DSCOVR real-time vs science-grade ACE & WIND
- Basic issue: data gaps & failovers
- Big 2019 DSCOVR data gap <<< took out our insufficiently-tested Ovation nowcast – code broke on ACE failover, these ~rare, & runs are high cadence, so we hadn't spotted breakages in earlier shorter failovers.
- Lesson: need good canned data tests!

Data gap pitfall elsewhere: GOES eclipses & DRAP

```
:> head -13 ./OSPO/GOES-16-SPRING-2022-Eclipse.txt ospo.noaa.gov/Operations/GOES/eclipse.html
-----------------------------------------------------------------------------------------------
| GOES-16 Eclipse Information: 2022/01/25 11:00:00 UTC ||||||||||||||||||||||||||||||||||||||||
-----------------------------------------------------------------------------------------------
|<>| ECLIPSE PHASE |     ENTRY  TIME      |      EXIT TIME       | DURATION | ECLIPSING BODY |<>|
-----------------------------------------------------------------------------------------------
|\ |   PENUMBRA     2022/02/26 05:05:22   2022/02/26 05:22:13     16.85        EARTH       | /|
| \|   PENUMBRA     2022/02/27 05:00:25   2022/02/27 05:08:48      8.37        EARTH       |/ |
| /|   UMBRA        2022/02/27 05:08:48   2022/02/27 05:18:26      9.64        EARTH       |\ |
|/ |   PENUMBRA     2022/02/27 05:18:26   2022/02/27 05:26:49      8.37        EARTH       | \|
|\ |   PENUMBRA     2022/02/28 04:56:55   2022/02/28 05:02:23      5.46        EARTH       | /|
| \|   UMBRA        2022/02/28 05:02:23   2022/02/28 05:24:30     22.12        EARTH       |/ |
| /|   PENUMBRA     2022/02/28 05:24:30   2022/02/28 05:29:58      5.46        EARTH       |\ |

                         services.swpc.noaa.gov/json/goes/primary/xrays-3-day.json
# 3rd eclipse: 2022-02-28T04:56:55 - 2022-02-28T05:29:58
:> sed -n "3896,3933p;3934q" $PROCESSED_PRIMARY | sed 's/"observed_flux".*/.../'
{"time_tag": "2022-02-28T04:55:00Z", "satellite": 16, "flux": 1.7540683927563805e-07, ...
{"time_tag": "2022-02-28T04:56:00Z", "satellite": 16, "flux": 1.6702753669051162e-07, ...
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{"time_tag": "2022-02-28T05:06:00Z", "satellite": 16, "flux": 0.0, ...
```
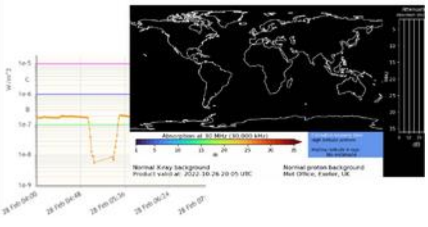
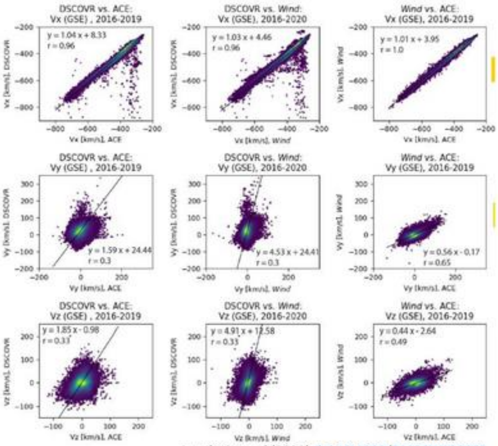

- Different/similar data gap issue with DRAP
- High cadence model runs, of model with naturally low output if x-ray flux is low. So hadn't spotted issues during short GOES-16 (primary) eclipses in fall & spring
- Penumbra -> x-ray flux low -> DRAP too low
  Umbra -> x-ray flux = 0 -> DRAP crashes
- Lesson: review model uptime/logs! DevOps?



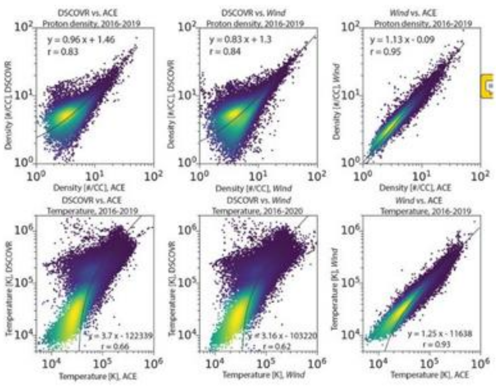
Real-time solar wind data: bad data pitfall



Loto'aniu et al (2022) doi:10.1029/2022SW003085

- Same Loto'aniu et al (2022) paper also nicely illustrates some issues with the plasma parameters (B ~OK)
- "Slow, warm & sparse" solar wind conditions: DSCOVR struggles to characterise plasma parameters accurately (hence some failovers to ACE)
- DSCOVR "waterfall": can (rarely) get large range of Vx at low ACE/WIND Vx
- Note the odd slopes on Vy & Vz
- *Note real-time ACE only has speed*
- Density & temperature spreads worse

Real-time solar wind data: bad data pitfall



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Loto'aniu et al (2022) doi:10.1029/2022SW003085

services.swpc.noaa.gov/json/rtsw/rtsw_wind_1m.json

time_tag: "2022-10-25T13:00:00"
active: true
source: "DSCOVR"
proton_speed: 408
proton_temperature: 80429
proton_density: 5.14
proton_vx_gse: -407.6
proton_vy_gse: 11.8
proton_vz_gse: 13.5
proton_vx_gsm: -407.6
proton_vy_gsm: 16.7
proton_vz_gsm: 6.5
proton_sample_size: 7
alpha_speed: null
alpha_temperature: null
alpha_density: null
alpha_vx_gse: null
alpha_vy_gse: null
alpha_vz_gse: null
alpha_vx_gsm: null
alpha_vy_gsm: null
alpha_vz_gsm: null
alpha_sample_size: null
max_convergence_flag: 0
max_data_flag: 0
max_error_count_flag: 0
max_processing_flag: 0
max_range_flag: 0
max_sample_count_flag: 0
max_telemetry_flag: 0
overall_quality: 0
▶ 1817: {…}

Real-time DSCOVR has velocity components absent from real-time ACE.

When failover to ACE occurs, may need to account for this.

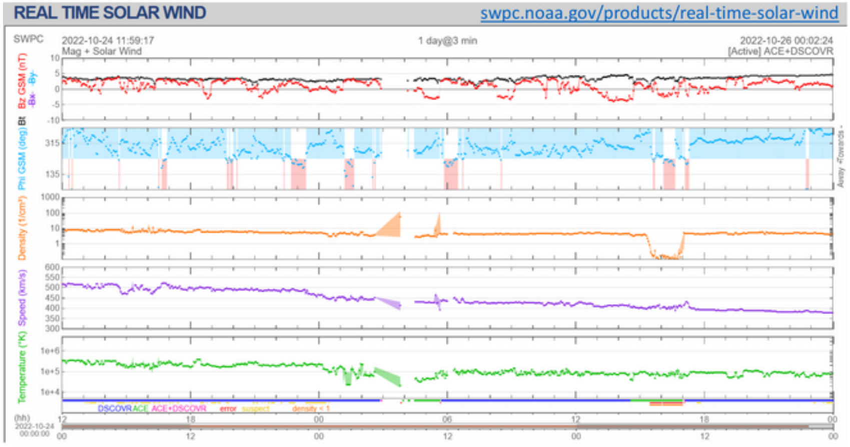
My current one for Geospace at ACE failovers:
Vx = -1 * speed
Vy = 0
Vz = 0

time_tag: "2022-10-25T15:00:00"
active: false
source: "ACE"
proton_speed: 403.1
proton_temperature: 87972
proton_density: 3.99
proton_vx_gse: null
proton_vy_gse: null
proton_vz_gse: null
proton_vx_gsm: null
proton_vy_gsm: null
proton_vz_gsm: null
proton_sample_size: 1
alpha_speed: null
alpha_temperature: null
alpha_density: null
alpha_vx_gse: null
alpha_vy_gse: null
alpha_vz_gse: null
alpha_vx_gsm: null
alpha_vy_gsm: null
alpha_vz_gsm: null
alpha_sample_size: null
max_convergence_flag: 0
max_data_flag: 0
max_error_count_flag: 0
max_processing_flag: 0
max_range_flag: 0
max_sample_count_flag: 0
max_telemetry_flag: 0
overall_quality: 0
▶ 1594: {…}

Note there are data quality flag entries in real-time data feeds

time_tag: "2022-10-25T15:13:00"
active: false
source: "ACE"
proton_speed: null
proton_temperature: null
proton_density: null
proton_vx_gse: null
proton_vy_gse: null
proton_vz_gse: null
proton_vx_gsm: null
proton_vy_gsm: null
proton_vz_gsm: null
proton_sample_size: null
alpha_speed: null
alpha_temperature: null
alpha_density: null
alpha_vx_gse: null
alpha_vy_gse: null
alpha_vz_gse: null
alpha_vx_gsm: null
alpha_vy_gsm: null
alpha_vz_gsm: null
alpha_sample_size: null
max_convergence_flag: 0
max_data_flag: 2
max_error_count_flag: 0
max_processing_flag: 0
max_range_flag: 0
max_sample_count_flag: 0
max_telemetry_flag: 0
overall_quality: 2
▼ 1581:

Real-time solar wind data: mitigations



For model testing, worth ensuring you have canned data sets which at least include data gaps and failovers.

More?
Bad data?
Backfilling?

Can more use be made of the data quality flags?

Shared canned data sets?

Real-time solar wind data: mitigations

- Careful: there can be “doubled-up” ACE & DSCOVR entries between failovers!

Input Parameters, Lead-time and Real-time Data: Solar Wind to Kp (Peter Wintoft, IRF, Sweden)

Input parameters, lead time, and real-time data: Solar wind to Kp

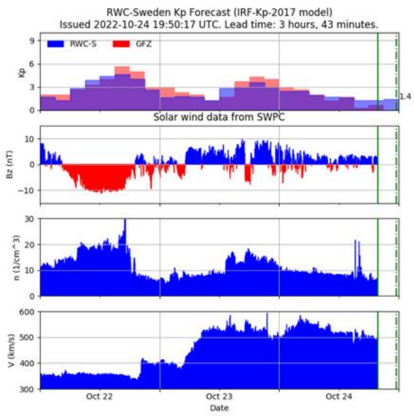
Peter Wintoft
Swedish Institute of Space Physics

1

Peter Wintoft, peter@lund.irf.se

IRF Kp predictions

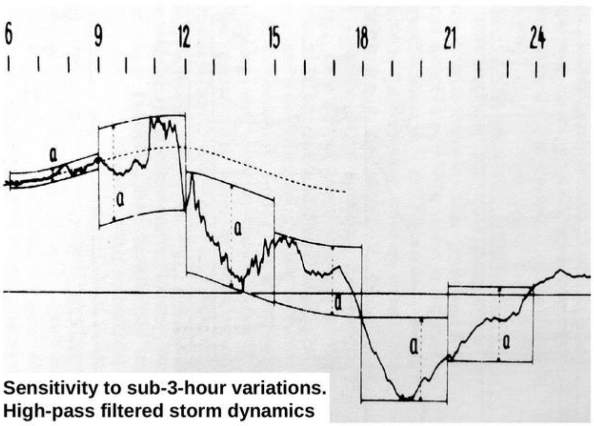
https://www.spaceweather.se



2

Peter Wintoft, peter@lund.irf.se

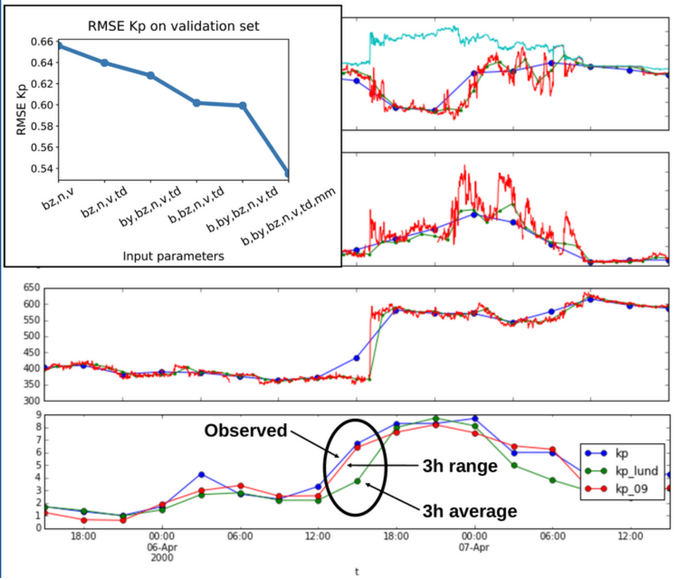
The Kp index



- **Sensitivity to sub-3-hour variations.**
- **High-pass filtered storm dynamics**

Derivation, meaning, and use of geomagnetic indices, P. N. Mayaud, AGU, 22, 1980.

3



5-minute median filter

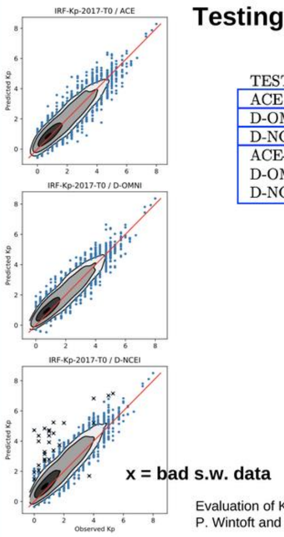
Table 4. RMSE and CORR for predicted *Kp* using ACE Level 2 data (L2) and ACE real-time data (RT) as inputs for the period 1 April 2011 to 1 March 2013. Coverage indicates whether samples corresponding to timestamps of the L2 or RT set have been used in computing RMSE and CORR. Median indicates whether the 5-minute median filter to *n* and *V* has been applied.

	Model	Input	Coverage	Median	RMSE	CORR
1	IRF-*Kp*-2017	L2	L2	False	0.49	0.92
2	IRF-*Kp*-2017	RT	L2	True	0.51	0.91
3	IRF-*Kp*-2017	RT	RT	True	0.59	0.89
4	IRF-*Kp*-2017	RT	RT	False	0.65	0.86
5	IRF-*Kp*-2017-h3	L2	L2	False	0.54	0.91
6	IRF-*Kp*-2017-h3	RT	L2	True	0.56	0.90
7	IRF-*Kp*-2017-h3	RT	RT	True	0.73	0.85
8	IRF-*Kp*-2017-h3	RT	RT	False	0.75	0.84

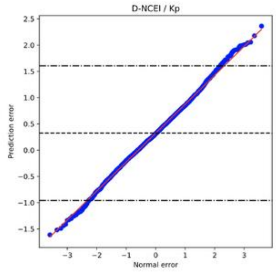
Forecasting Kp from solar wind data: input parameter study using 3-hour averages and 3-hour range values
P. Wintoft, M. Wik, J. Matzka, and Y. Shprits
Journal of Space Weather and Space Climate 7 A29 (2017)

Peter Wintoft, peter@lund.irf.se

Testing on independent datasets



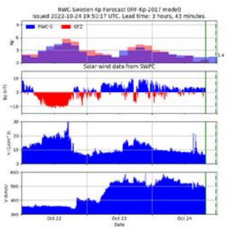
	BIAS	RMSE	CORR	R2
TEST	-0.050	0.559	0.915	0.834
ACE	0.058	0.533	0.916	0.835
D-OMNI	0.164	0.534	0.922	0.834
D-NCEI	0.325	0.639	0.915	0.763
ACE-BIAS	-0.000	0.530	0.916	0.837
D-OMNI-BIAS	-0.000	0.509	0.922	0.850
D-NCEI-BIAS	-0.000	0.551	0.915	0.824

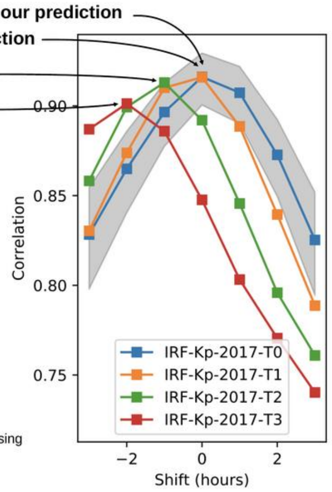


Evaluation of Kp and Dst Predictions Using ACE and DSCOVR Solar Wind Data,
P. Wintoft and M. Wik, Space Weather 16 1972-1983 (2018)

Peter Wintoft, peter@lund.irf.se

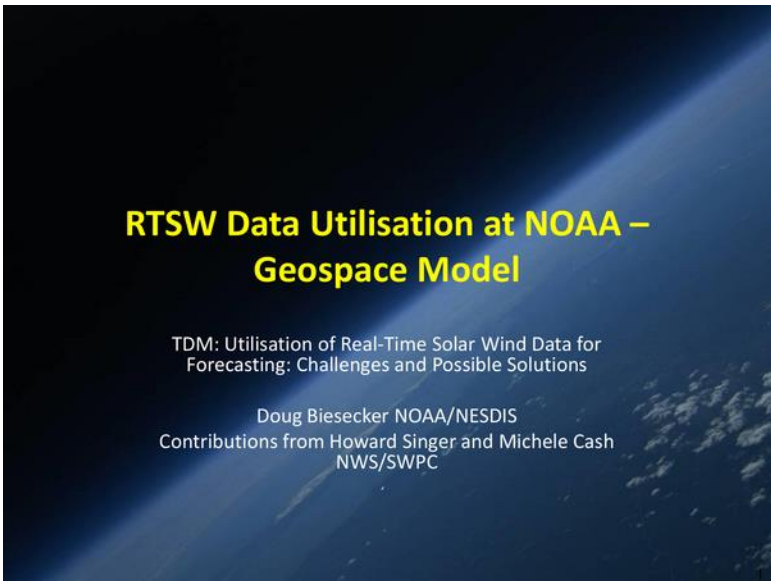
Prediction lead time

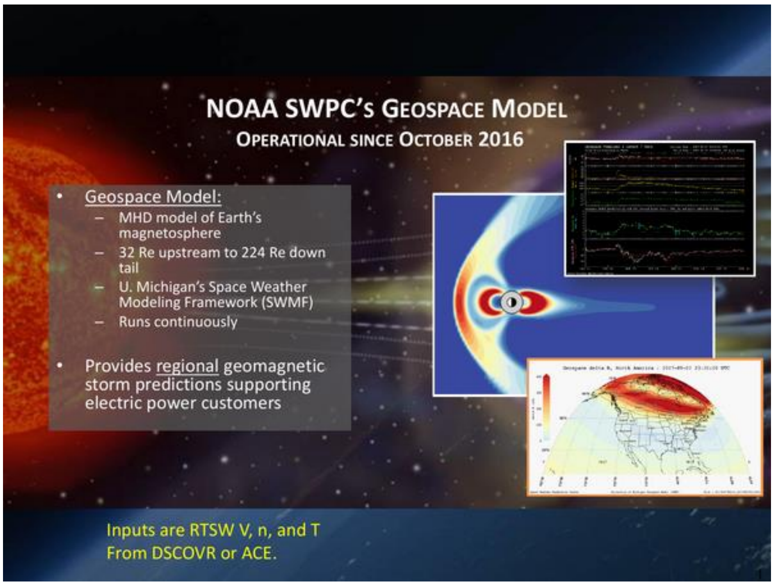


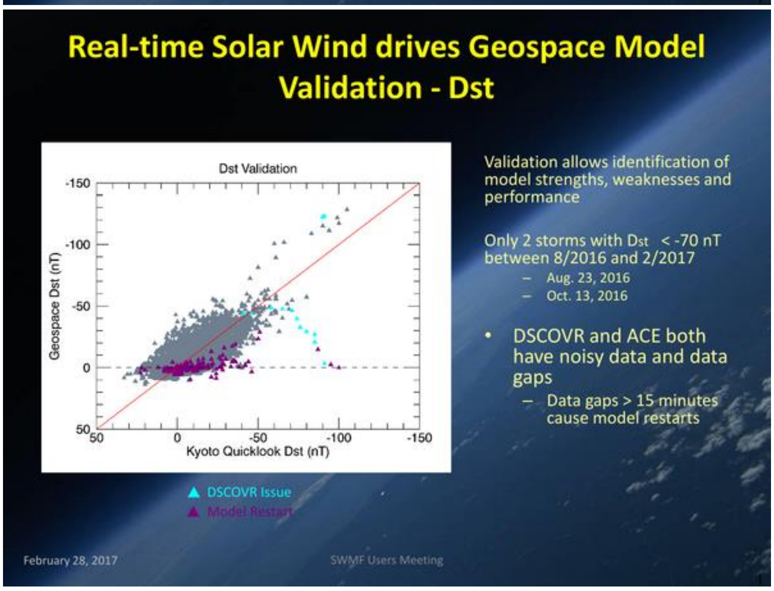


Evaluation of Kp and Dst Predictions Using
ACE and DSCOVR Solar Wind Data
P. Wintoft and M. Wik
Space Weather 16 1972-1983 (2018)

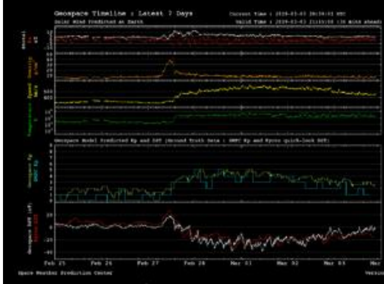
RTSW Data Utilization at NOAA Geospace Model (Doug Biesecker, NOAA, USA)







RTSW Data Gaps Cause Overestimates of Model's Kp Prediction



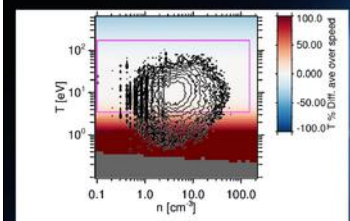
Feb 25 – Mar 4 2019
good model data agreement

Mar 8 – Mar 11 2018
model over-predicts Kp and Dst activity

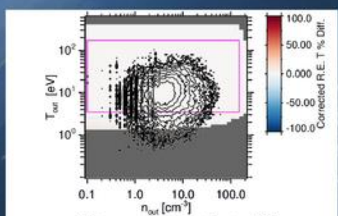
RTSW Density Spikes Cause Overestimates of Model's Kp Prediction

How we are solving these problems at the source

- Ensuring data meet accuracy requirements
  - NOAA SWFO-L1 Solar Wind Plasma Sensor (SWiPS)
    - Launch Feb 2025
    - Requirements: $200 < V < 2500$ km/s (±10%); $0.1 < n < 150$ cm^{-3} (±10%); $0.04 < T < 2$ MK (±10%)
    - Forward modeling shows it will fail to meet accuracy requirements over whole range
      - Implementing correction factors determined from the forward model
- Reducing the gaps in real-time data
  - NOAA SWFO-L1 and NASA IMAP I-ALiRT
    - Providing redundant real-time data streams to NWS/SWPC
    - Plan is to automatically select 'best' RTSW data
      - Currently, SWPC forecasters toggle between ACE and DSCOVR as needed



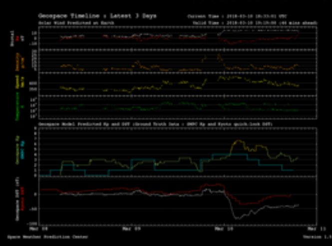
For wind speed 400-600 km/s



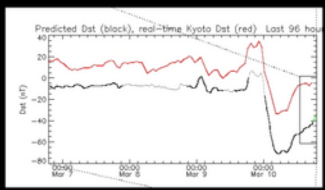
After correction that will be applied in real-time

BACKUP SLIDES

Operations to Research – Event Analysis
March 8 – March 11 2018



March 8- 11, 2018 - Geospace Model good model data agreement

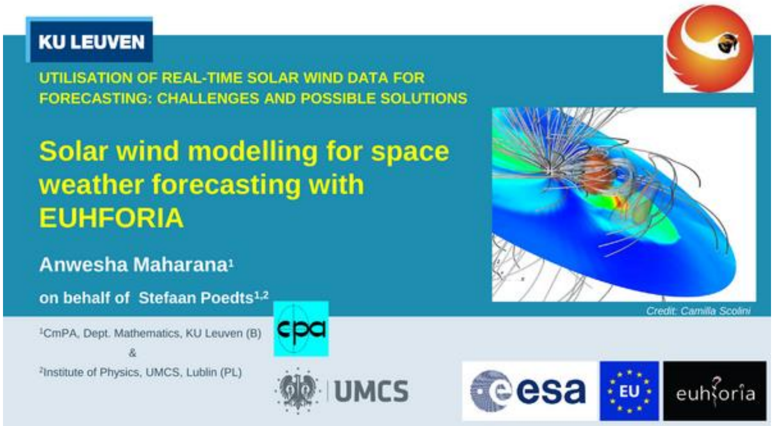


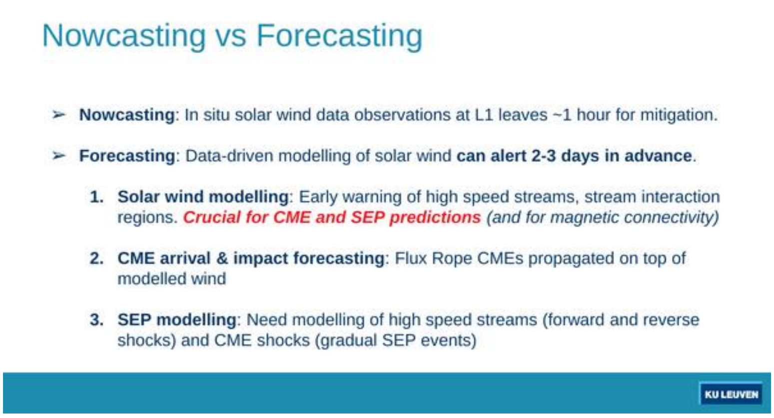
March 8- 11, 2018 - Li and Temerin Model

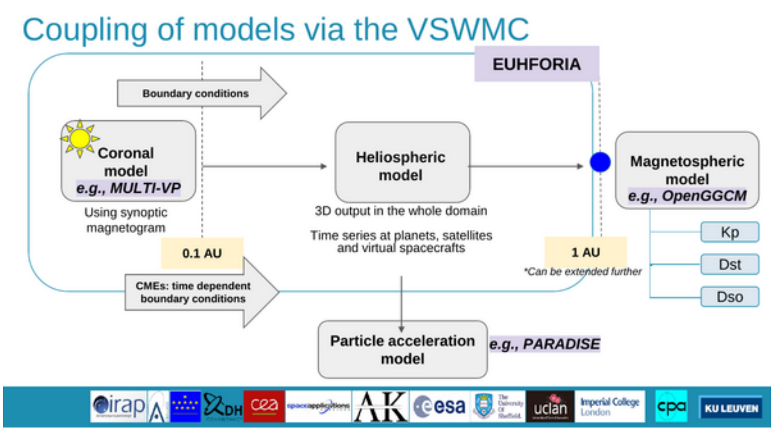
- Geospace Model appears to over-predict activity
  - On 3/10 Kp ~ 4, but model predicts about 7⁻ and Dst quick look ~ -39 but model predicts ~ -70
- Xinlin Li's real-time forecast of Dst, based on Temerin and Li (2002, 2006) empirical model, shows similar results
- Therefore, in this case, it may be that the solar wind input may be the problem rather than the model, but why? Needs further evaluation.

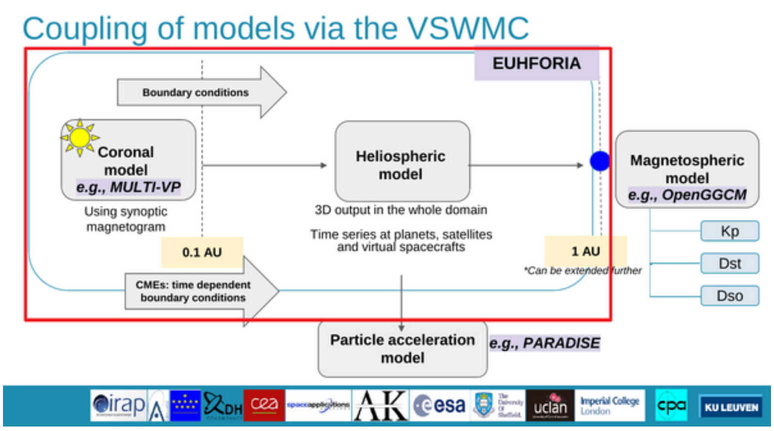
Bad Solar Wind Density and Velocity Cause Overestimate of Model Kp Prediction

Solar wind modelling for Space Weather forecasting with EUHFORIA (Anwesha Maharana, KU Leuven, Belgium)





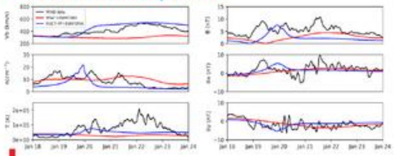


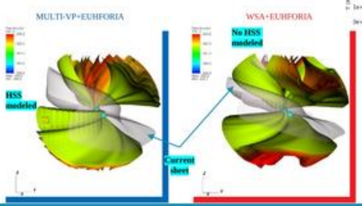


1. Improving solar wind modelling

MULTI-VP coupled to EUHFORIA heliosphere

HSS bulk speed at Earth as modeled by WSA+EUHFORIA (red) and MULTI-VP+EUHFORIA (blue) for 6 days of forecasting. Both runs have been conducted with the GONG synoptic magnetogram taken on 2018-01-17T23:14. The MULTI-VP+EUHFORIA output captures the real HSS while this is not the case for the WSA+EUHFORIA.

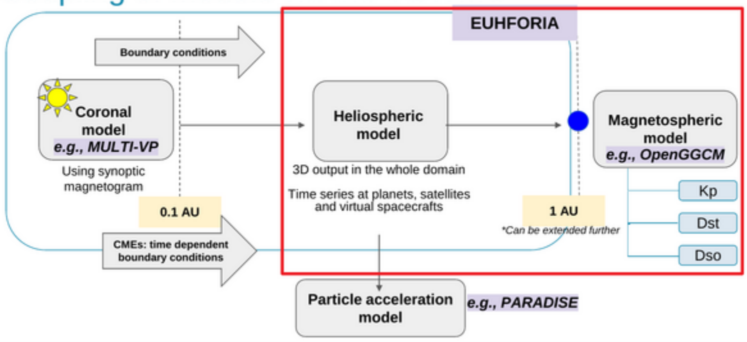




3D visualizations of the structures produced by WSA+EUHFORIA and MULTI-VP+EUHFORIA throughout the inner heliospheric domain. The heliospheric current sheet is indicated in grey while the colorful isosurfaces represent solar wind speeds between 520 and 600 km/s. Earth is shown in light blue color.

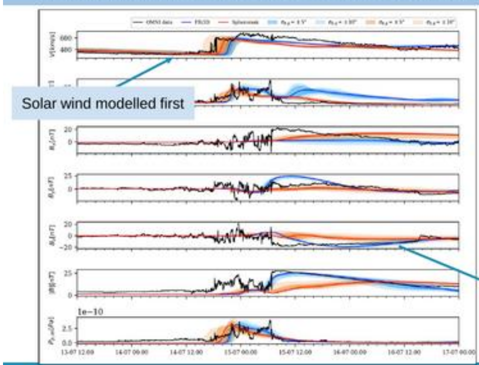
Source: Samara et al. 2021

Coupling of models via the VSWMC



2. CME arrival forecasting + geoeffectiveness prediction

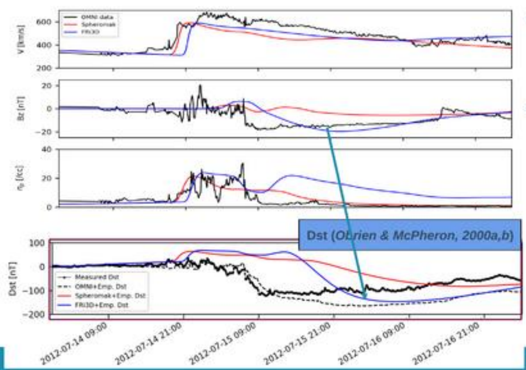
ICME predictions at Earth



- FRi3D arrival time is similar to Spheromak: ~3h delay than observed arrival
- FRi3D enhances the predictions of **B** and B_z by around 37% and 76% as compared to spheromak.
- Prolonged magnetic field enhancement reproduced by FRi3D

Maharana et al, ASR, 2022

2. CME arrival forecasting + geoeffectiveness prediction



- Using modelled solar wind plasma properties at Earth, empirical geomagnetic indices are computed.
- Solar wind - Dst coupling formula **(Obrien & McPheron, 2000a,b)**

$$\frac{d}{dt}Dst^* = Q(t) - \frac{Dst^*}{\tau}$$

$$Dst = Dst^* + a\sqrt{P_{dyn}} - b$$

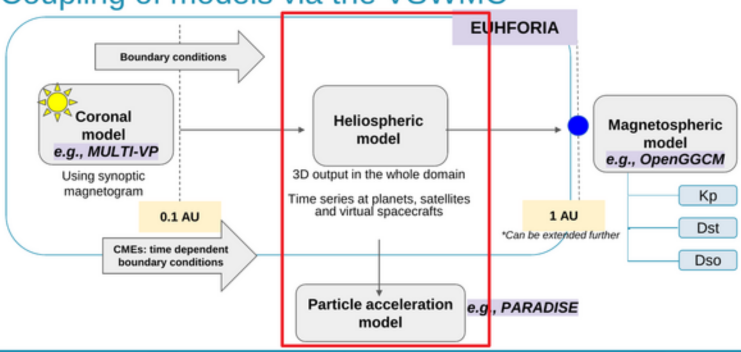
Quiet condition:

$$Dst(t=0) = 0.0$$

Improved minimum Bz modelled by FRi3D predicts the minimum Dst

Maharana et al, 2022

Coupling of models via the VSWMC



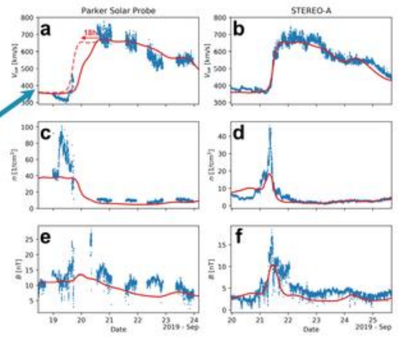
3. SEP modelling

Credit: Nicolas Wijsen

PARADISE
PSP CASE study

Comparison between the proton solar wind speed (a-b), density (c-d), and magnetic eld magnitude (e-f) observed (blue dots) by PSP (left) and STEREO-A (right) with the EUHFORIA simulation results (red solid lines).

The dashed line in panel a shows the simulated HSS onset observed at STEREO-A shifted earlier in time by 1.77 days (Allen et al. 2021) to account for corotation.



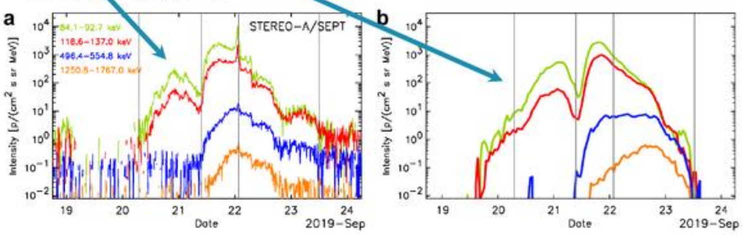
Source: Wijsen et al. 2021

3. SEP modelling

Credit: Nicolas Wijsen

Integrated SEP models: PSP CASE study

Observed (left) and **simulated** (right) omni-directional ion intensities at STEREO-A. The vertical lines indicate the onset time of the SIR (stream interaction regions) event (Sep 20 09:00 UT), the stream interface (Sep 21 09:30 UT), the developing reverse shock (22 Sep 01:35 UT), and the stop time of the SIR event (23 Sep 12:00 UT).



Source: Wijsen et al. 2021

THANK YOU! EUHFORIA is also available in euhforiaonline.com

Acknowledgements: EU H2020 project **EUHFORIA 2.0** *(Project 870405)* + ESA project ITT AO/1-10125/19/NL/HK (Heliospheric Modelling Techniques)

Some references:

J. Pomoell and S. Poedts: "EUHFORIA: EUropean Heliospheric FORecasting Information Asset", *J. of Space Weather and Space Climate*, **8**, A35 (2018). DOI: https://doi.org/10.1051/swsc/2018020

S. Poedts: "Forecasting space weather with EUHFORIA in the Virtual Space Weather Modeling Centre", *Plasma Physics and Controlled Fusion*, **61**, 014011 (6pp) (2018). DOI: 10.1088/1361-6587/aae048

N. Wijsen, A. Aran, B. Sanahuja, J. Pomoell, S. Poedts: "The effect of drifts during the decaying phase of SEP events", *Astron. Astrophys.*, **634**, A82 (2020). DOI: 10.1051/0004-6361/201937026

N. Wijsen, A. Aran, J. Pomoell, S. Poedts: "The Interplanetary Spread of Solar Energetic Protons Near a High-Speed Solar Wind Stream", *Astron. Astrophys.*, **624**, A47 (2019). DOI: 10.1051/0004-6361/201935139

Other references: **EUHFORIA web page**: euhforia.com/

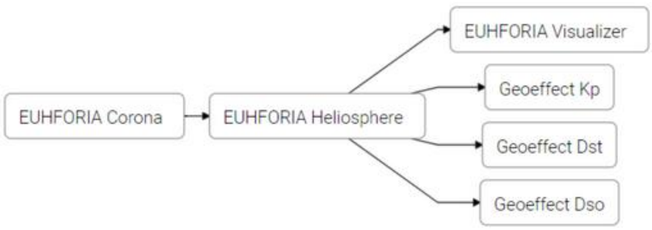
Coupling of models via the VSWMC

- **New 'trend'** in space weather modelling
- **Enables *better* predictions**
  - Example: MULTI-VP + EUHFORIA Heliosphere
    - *Better capturing of HSSs due to improved coronal model (Multi-VP vs WSA)*
  - Example: EUHFORIA + PARADISE (SEP model)
    - *Using (EUHFORIA) simulated IMF instead of Parker spiral*
    -
- **Enables *earlier* predictions/warnings**
  - Example: EUHFORIA + OpenGGCM/Gorgon/GUMICS
    - *replacing L1 data by synthetic/simulated data three days ahead*
    - *Enables forecasts 2-3 days ahead instead of nowcasts!*

Nowcasting vs forecasting

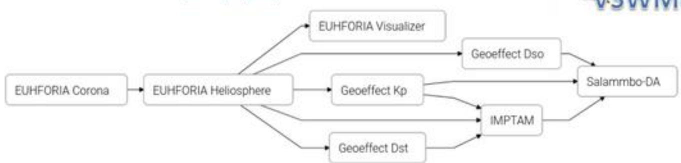
Most used model chain (via CLI)

VSWMC



New RB-Fan (ESA project) models added

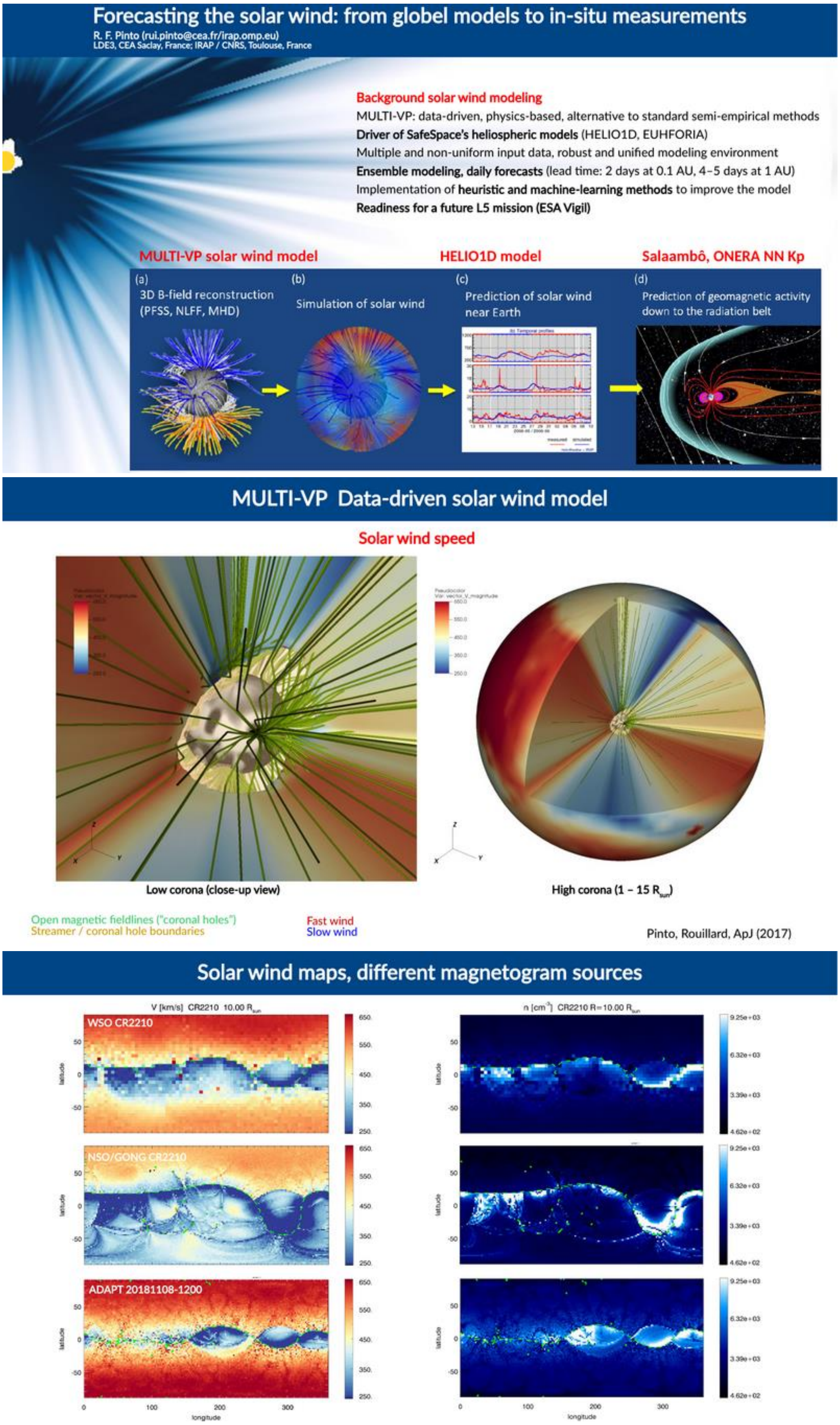
VSWMC



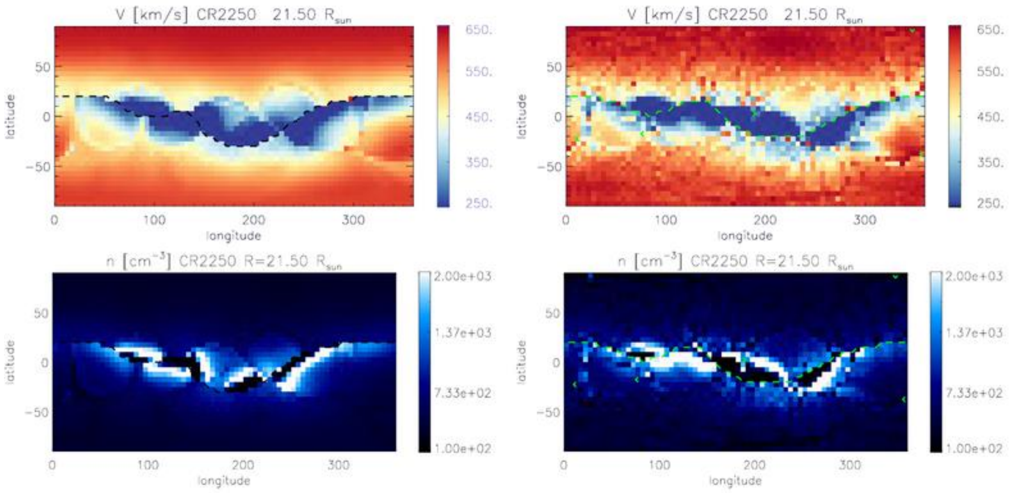
Simulation of **Euhforia + Indices + IMPTAM** (+ Salammbo)

- Euhforia + Indices run on HPC cluster in KU Leuven
- then IMPTAM runs in FMI, we monitor the run and receive the IMPTAM results
- Then we send Kp, Dso, and IMPTAM results to ONERA where Salammbo is ran (outside the VSWMC)

Solar Wind Forecasting Models: Global Models vs. Point In-situ Measurements (Rui Pinto, IRAP OMP, France)

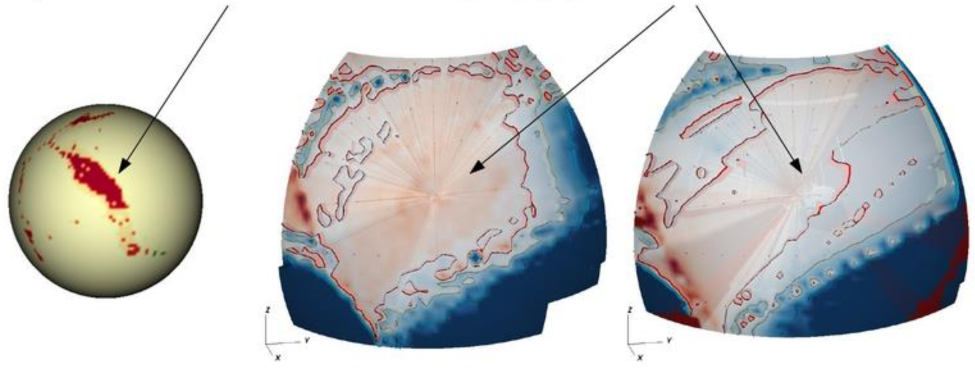


Solar wind maps, different magnetogram sources



MULTI-VP, same magnetograms, different extrapolations methods

Case-study with low-latitude coronal hole + **corresponding high-speed stream**



Based on **ADAPT/GONG** magnetogram

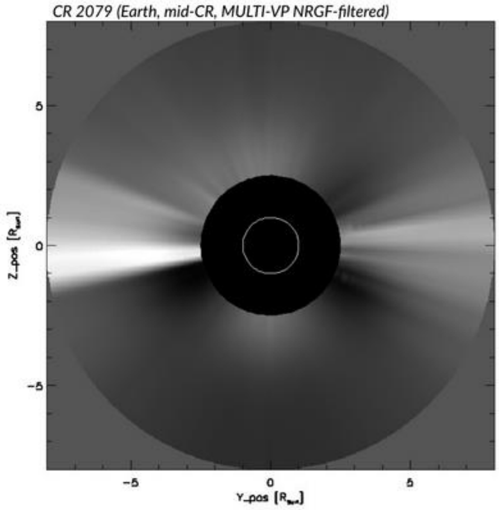
Using standard PFSS

Using PFSS+SCS (WSA)

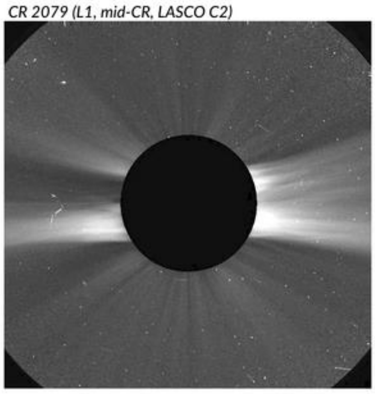
ISSI Team **Magnetic Open Flux And Solar Wind Structuring Of Interplanetary Space** (https://www.issibern.ch/teams/magfluxsol/)

MULTI-VP synthetic coronography

CR 2079 (Earth, mid-CR, MULTI-VP NRGF-filtered)

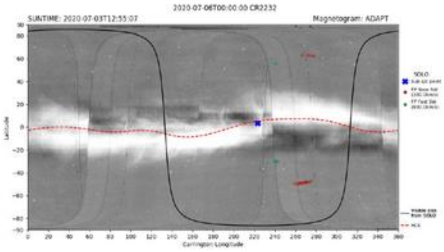


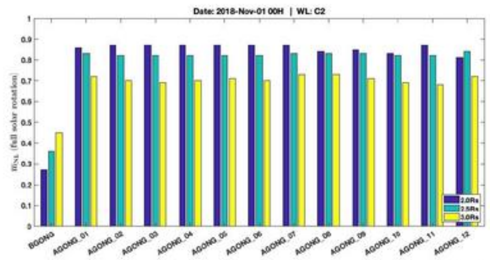
CR 2079 (L1, mid-CR, LASCO C2)



Diagnostics for validation and/or ensemble reduction

Evaluation criteria based on global mag field topology:
. rank **magnetogram + extrapolation parameter combinations** based on **HCS position vs. white-light** bright band



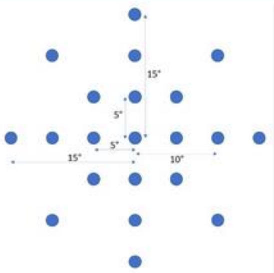


(Poirier et al, 2021)
http://connect-tool.irap.omp.eu/

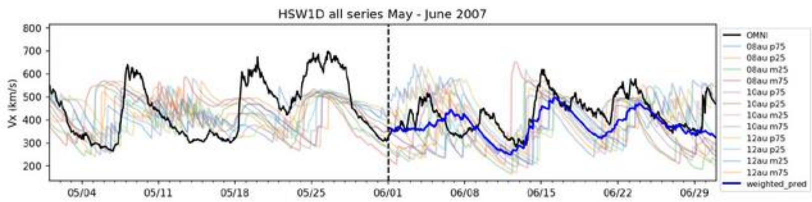
Evaluation criteria based on in-situ properties:
. rank **magnetogram + extrapolation parameter combinations** based on in-situ **polarity and wind speed**

Other criteria?
. compare to observed coronal features, types of wind stream vs. source, abundances, particle detection?

Ensemble forecasting using positional uncertainty



To account for spatial and temporal **uncertainties** of SW propagation, we implement a **21 grid point** with the sub-Earth point at the centre.



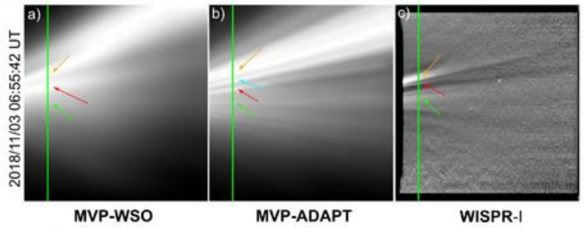
Conclusions

Global sola rphenomena, global models → forecasting
. Looking for a needle on a haystack

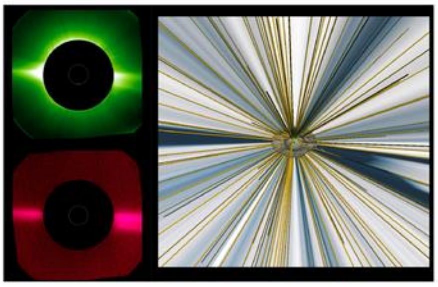
Validation, calibration
. usually based on direct comparison to “point” spacecraft measurements
. high variability b/w neighbour wind streams is a real feature of the solar wind at L1 (not just a modelling weakness)

What can we do?
. direct validation/calibration at coronal heights (PSP/SolO data)?
. other multi-point strategies
. use remote-sensing of the corona to help constraining models/model errors

Validation using remote-sensing



Synthetic MULTI-VP white-light
Parker Solar Probe/WISPR FoV
(Poirier et al, 2020)



MULTI-VP comparison with first
Solar Orbiter/Metis images
(June 2020)

(Pinto et al, *in prep*;
Pinto & Rouillard, 2017)

In the future: continuous monitoring

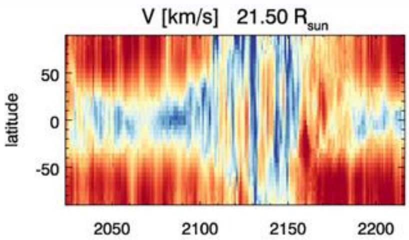
L1 (SoHO/LASCO)

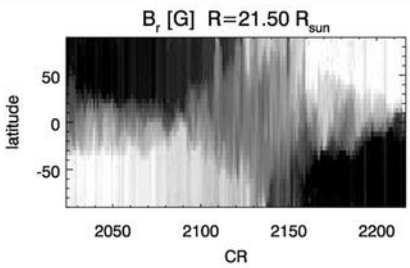
STEREO/COR

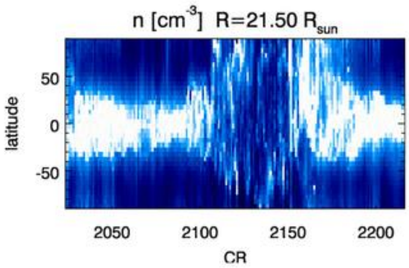
L5 (Vigil)

both imagery and in-situ validation
ahead of Earth

Long-term analysis with historical data





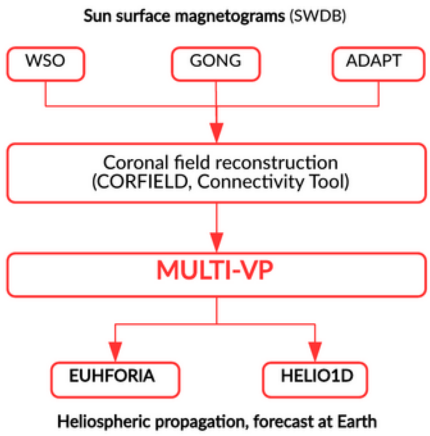


Long term time-series of full MULTI-VP runs
based on WSO synoptics maps,
currently covering almost a full 22 yr cycle.

← *Latitude – time (Carrington rotation) maps of V, n and B at 0.1 AU*

(Pinto, et al, *in prep*)

SWiFT: modular pipeline, data back-end



Ensemble modeling

Several data sources + variations in model parameters

Cover data + model uncertainties

Uniformisation of input + output data at database level

Modules are automated autonomously

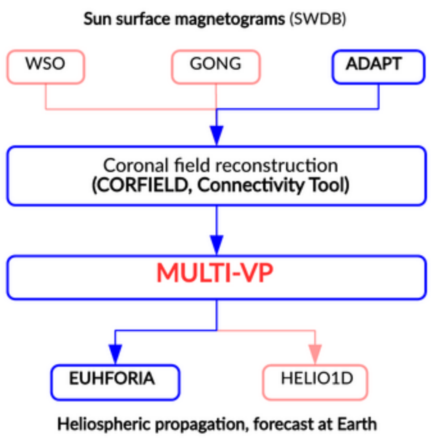
Each module:
- polls and outputs database to common database
- follows its own update cycle,
  spawns its own ensemble members
- checks "oldness" of available data, acts accordingly

Benefits

Robustness against data gaps and code crashes

Easier to manage, improve and update

SWiFT pipeline / MULTI-VP data-driven solar wind model



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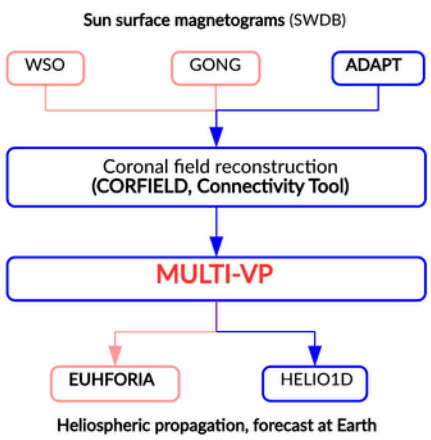

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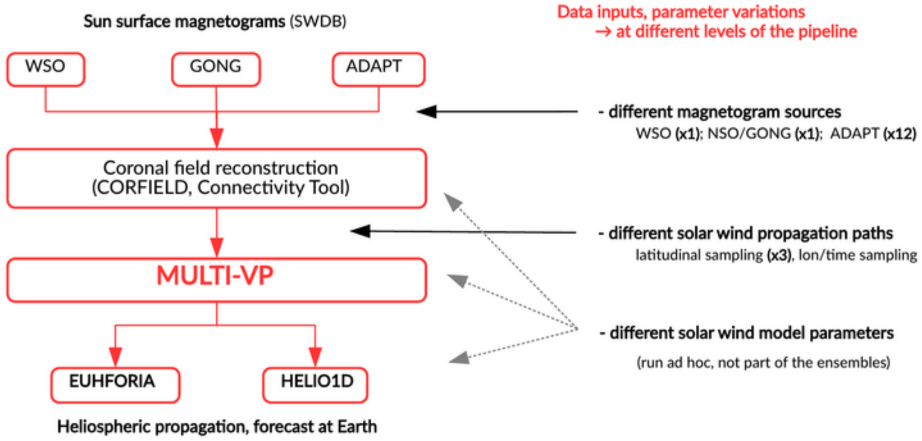
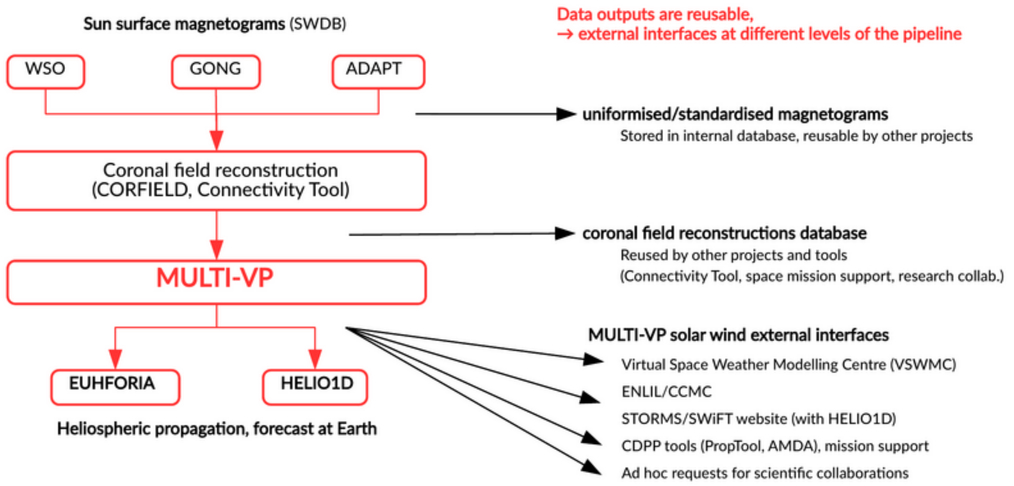
Easier to manage, improve and update

SWiFT: multiple inputs, multiple ensemble members

Data inputs, parameter variations
→ at different levels of the pipeline

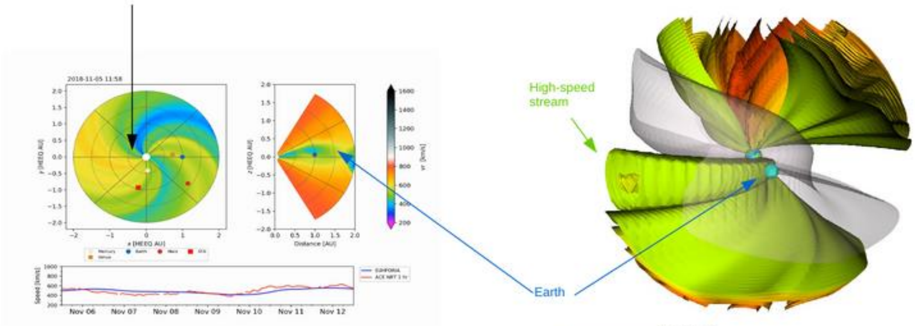


SWiFT: multiple output data products



Interfacing with EUHFORIA

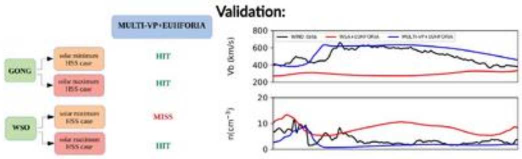
MULTI-VP (2D solar wind map of V, N, T, B at 0.1 AU) → EUHFORIA (0.1 – 2 AU)



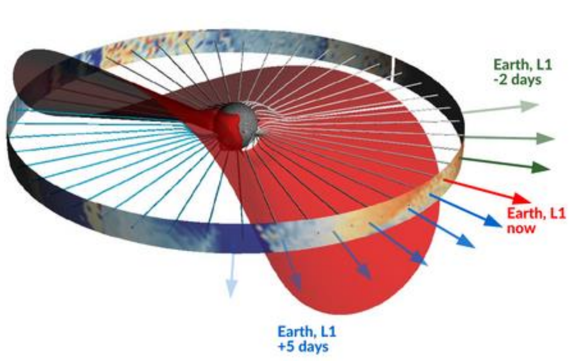
Improved background solar wind solutions:
- Better HSS forecasting
- More reliable ambient wind for CME propagation

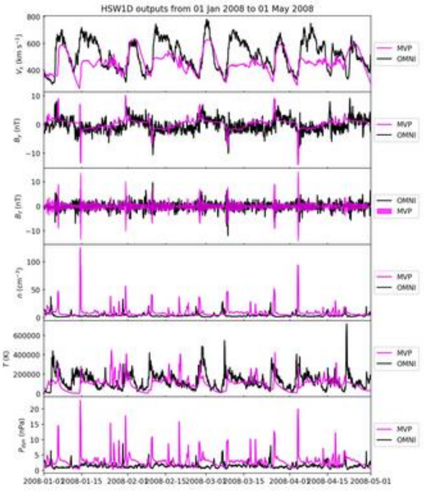
Samara, Pinto, et al (2021)

Validation:



Interfacing with HELIO1D: continuous solar wind forecasting



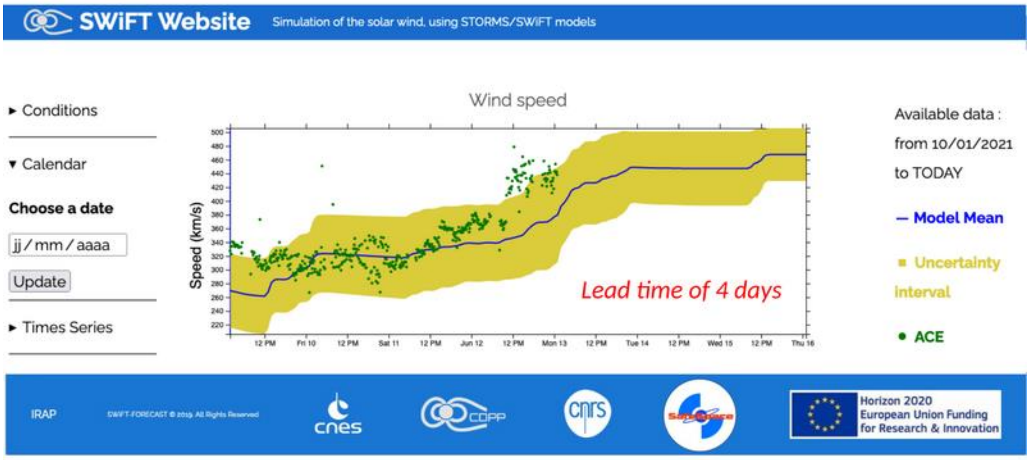


MULTI-VP (V, N, T, B time-series at 30 R_{sun})

↓

HELIO1D (output time-series at L1, Earth)

HELIO1D: daily forecast outputs



(http://swift.irap.omp.eu/)

Planned Real Time Data from NOAA's SWFO Mission and Dynamical Stability of Global Magnetospheric MHD Models (Dimitrios Vassiliadis NOAA, USA)

18TH EUROPEAN SPACE WEATHER WEEK

TDM: Utilisation of Real-Time Solar Wind Data for Forecasting: Challenges and Possible Solutions

Planned Real-Time Data from NOAA's SWFO Mission and Dynamical Stability of Global Magnetospheric MHD Models

National Environmental Satellite, Data, and Information Service

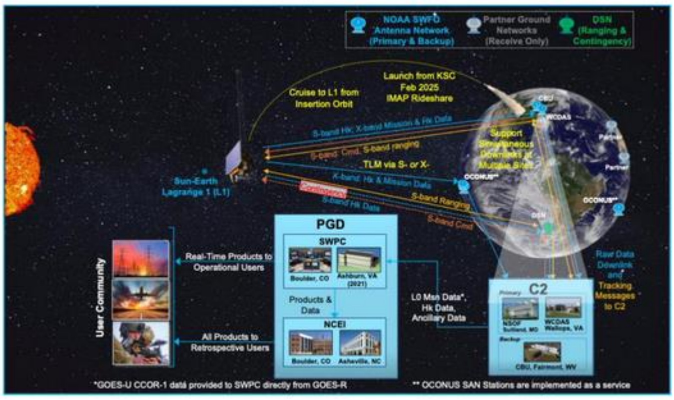
October 27, 2022

Dimitris Vassiliadis, Doug Biesecker, Nicholas Zaremba
NOAA/NESDIS

Space Weather Follow On Program: Overview

SWFO will provide solar and heliospheric observations as a continuation of NOAA's DSCOVR and NASA's ACE and SOHO operational capabilities.

- Coronal imagery: will provide situational awareness for long-term forecasting
- Solar wind and interplanetary magnetic field measurements will be used as inputs to magnetospheric models.
- Particle flux measurements will be used to improve estimates of the solar wind arrival time.



SWFO Program: Data Products

- SWFO data products include coronal imagery and solar wind measurements.
- Key Performance Parameters (KPPs) are the highest-priority products and include coronal white light intensity, solar wind speed, and interplanetary magnetic field.
- The Initial Operational Capability (IOC) of the SWFO Program is based on the generation of KPPs at Levels 1 to 3 and delivery to users.
- Higher-level products are planned at SWPC.

Space Weather Data Product	KPP
Coronal White Light Intensity	Y
Thermal Plasma Ion Velocity	Y
Thermal Plasma Ion Density	N
Thermal Plasma Ion Temperature	N
Vector Magnetic Field	Y
Suprathermal Ion Differential Flux	N
Dynamic Pressure	N

[SWFO Level 1 RD]

SWFO Program: Product Generation and Distribution

- SWFO PGD will enable the following products and space weather services:

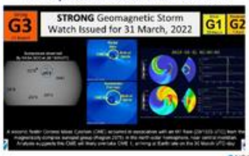
1. Processing of L0 datastreams into science products:

- Coronal images (SOHO LASCO/C3 → GOES-U CCOR-1, SWFO-L1 CCOR-2)

- Time series of solar wind plasma and magnetic field: DSCOVR FC, MAG → SWFO-L1 SWiPS, MAG as well as STIS

2. Immediate use of the products in providing situational awareness and in reliably driving real-time models. Thus the data will result in SpWx nowcasts and forecasts.

Heliospheric model and forecast



Auroral model and forecast

3. Archiving of data to enable access by the science community and numerous other users.

(DSCOVR Data Portal → SWFO Science Center)

Solar Wind-Dependent Data Products at SWPC and NCEI

- The following is a selection of data products at NOAA's centers that are utilized by space weather users worldwide. Several of these products as well as specialized ones are provided to domestic and international partner forecast centers.
- Space Weather Prediction Center (SWPC):
  - Observations: Real-time solar wind (plasma and IMF variables); experimental products currently based on ACE and STEREO
  - Models: Geospace (global MHD) model, CTIPe, REFM, OVATION; validation of WSA Enlil
  - Summaries and Reports; Alerts/Watches/Warnings
- National Centers for Environmental Information (NCEI):
  - Observations: Retrospective solar wind (plasma and IMF variables: fc0, fc1, f3s, etc.; mg0, mg1, m1s, etc.)

Stability of Global MHD Models to IMF Impulses During a Storm

Dimitris Vassiliadis and Nick Zaremba
NOAA/NESDIS

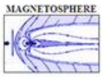
Acknowledgments: We thank L. Rastaetter, J. Raeder, and G. Toth for useful discussions.

National Environmental Satellite, Data, and Information Service

Global Magnetospheric Models at CCMC

Used two models:
1. The Open Geospace General Circulation Model (**Open GGCM**).
2. The Space Weather Modeling Framework (**SWMF**)

MAGNETOSPHERE

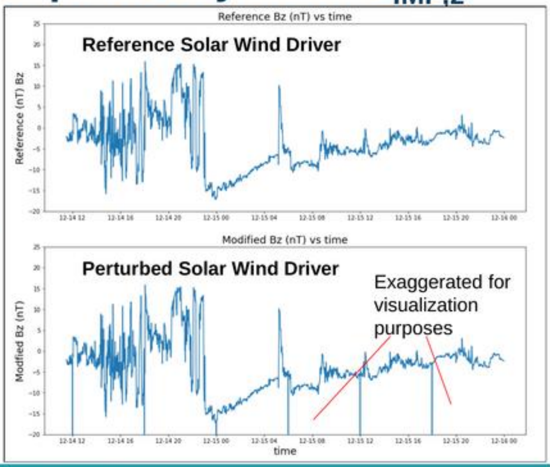


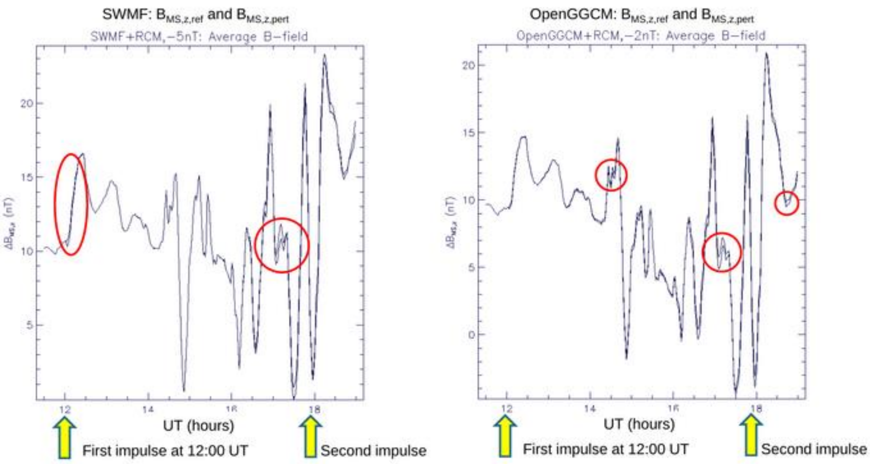
Global Magnetosphere:			
BATS-R-US	Dr. Tamas Gombosi et al.	CSEM	
SWMF/BATS-R-US with RCM	Tamas Gombosi et al., Richard Wolf et al., Stanislav Sazykin et al., Gabor Toth et al.	CSEM	
OpenGGCM	Joachim Raeder, Timothy Fuller-Rowell	Space Science Center, UNH	
GUMICS	Pekka Janhunen et al.	FMI	
CMIT/LFM-MIX	John Lyon, Wenbin Wang, Slava Merkin, Mike Wiltberger, Pete Schmitt, and Ben Foster	Dartmouth College/NCAR-HAO/JHU-APL/CISM	
Plasmasphere	Viviane Pierrard	IASB-BIRA	
WINDMI	W. Horton, M. L. Mays, E. Spencer and I. Doxas	Univ. of Texas at Austin	
Inner Magnetosphere:			
LANL*	Yiqun Yu, Josef Koller	LANL	
RCM	Stanislav Sazykin, Richard A. Wolf	Department of Physics and Astronomy, Rice University	
Fok Ring Current	Mei-Ching H. Fok	NASA, GSFC	
Fok Radiation Belt Electron	Mei-Ching H. Fok	NASA, GSFC	
CIMI	Mei-Ching H. Fok, Natalia Buzulukova	NASA GSFC	Bo[illegible] model oxyg[illegible]

Perturbed Interplanetary Field $B_{IMF,z}$

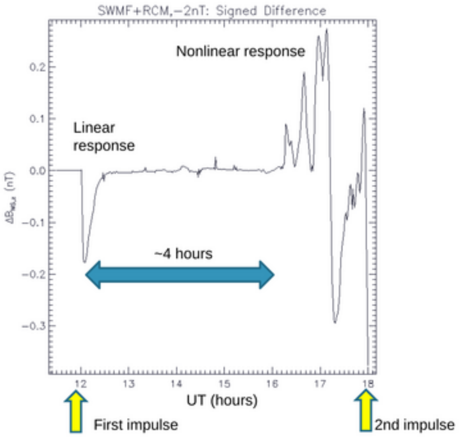
- We perturbed the $B_{IMF,z}$ component at 6-hour intervals beginning at 12:00 UT.
- In a series of runs, the $B_{IMF,z}$ was modified with the following impulse amplitudes:

$\delta B_{IMF,z}$ = -0.2, -0.5, -1, -2 and -5 nT.





- Time series of $\Delta B_{MS,z}$ over equatorial plane.
- Linear response:
  1. Immediate: SW convection timescale of 10-20 minutes
  2. Peak value $\Delta B_{MS,z,max}$ directly proportional to driver amplitude $\delta B_{IMF,z}(0)$
  3. Short-lived
- Nonlinear response:
  1. Storage release with time difference of ~4 hours (release at ~16:00 UT).
  2. Peak values appear to be independent of driver amplitude
  3. Opposite polarities indicative of flux loading and unloading
- Measure divergence rate after loading onset (16:00 UT).



Summary

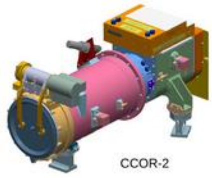
- The Space Weather Follow On program will provide upstream solar wind/IMF data, as well as coronal imagery, to replace the current capabilities of DSCOVR, ACE, and SOHO.
  - All instruments have a significant heritage from research payloads such as Rosetta/IPS, MAVEN/SEP, and STEREO/COR1-2.
- Products developed at NOAA SWPC and NCEI will be based on existing set as well as new products based on user needs.
  - *Feedback from users is welcomed as these products are being designed.*
- These data will be used to drive a large number of operational and research models. It is therefore important to properly understand the dynamical and stability properties of such models.
  - We examined the stability of two well-known MHD models, OpenGGCM and SWMF in several different scenarios. One set of scenarios included systematic changes in the IMF representing measurement uncertainties. The dynamical instability parameters, such as growth rate and saturation level, were measured [Vassiliadis, Zaremba, Rastaetter, Raeder, 2022, in preparation].

Backup

SWFO Program: Sensors

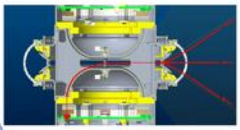
CCOR-1

Compact Coronagraphs (CCORs): Developed by Naval Research Lab (NRL), the telescope will be used to observe the solar corona and detect coronal mass ejections (CMEs) and other structures. CCOR-1 will fly on the GOES-U satellite and a nearly identical CCOR-2 on SWFO-L1.

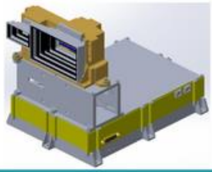


CCOR-2

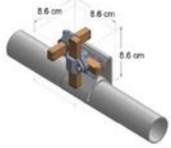
Solar Wind Plasma Sensor (SWiPS): Built by Southwest Research Institute (SwRI), it will measure properties of the solar wind plasma flowing past SWFO-L1, such as density, velocity, and temperature.

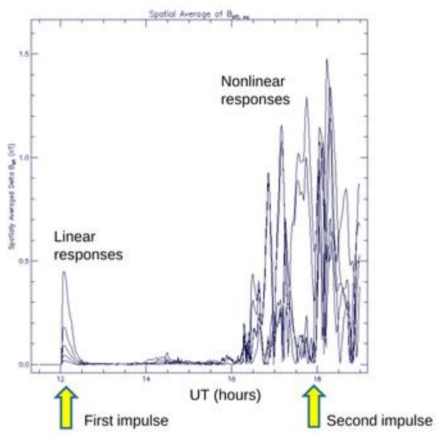


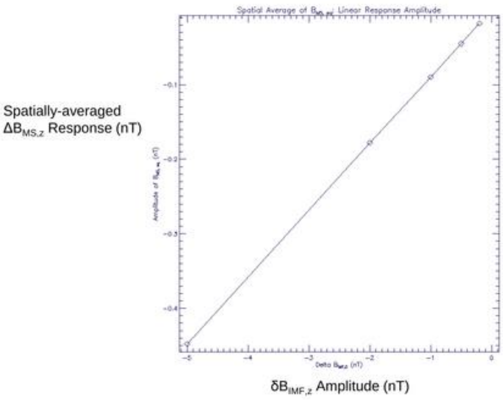
Suprathermal Ion Sensor (STIS): Developed by University of California, Berkeley, it will collect fast ions in the solar wind.

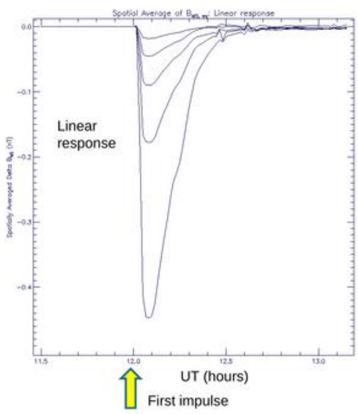


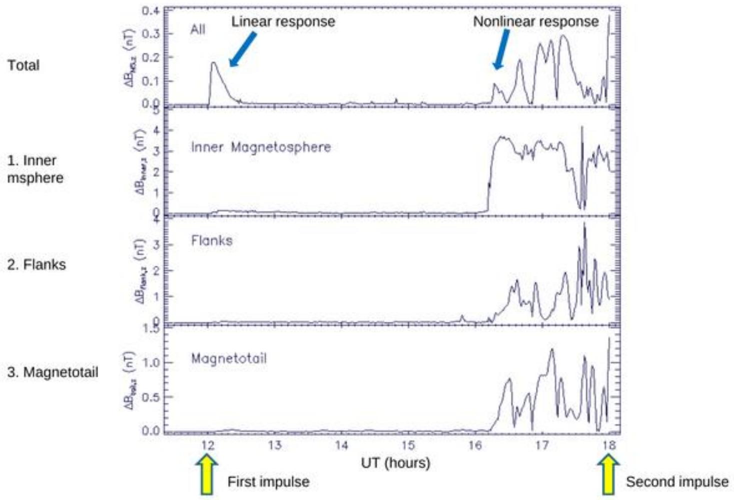
Magnetometer (MAG): Developed by the University of New Hampshire and SwRI, it will measure the magnetic field carried by the solar wind.











Regional Difference $\Delta B_{MS,z}$

- Identify regions where divergence is maximal:

1. Inner magnetosphere
2. Flanks
3. Magnetotail

We are not including the magnetopause/sheath effects.

- Define regions in the model domain (indicated by the highlighted shapes) where the model $\Delta B_{MS,z}$ response is measured in detail.