Limb-Flare Prediction

(and...beyond-limb flare prediction) with a

4π Full-Heliosphere Forecasting Framework

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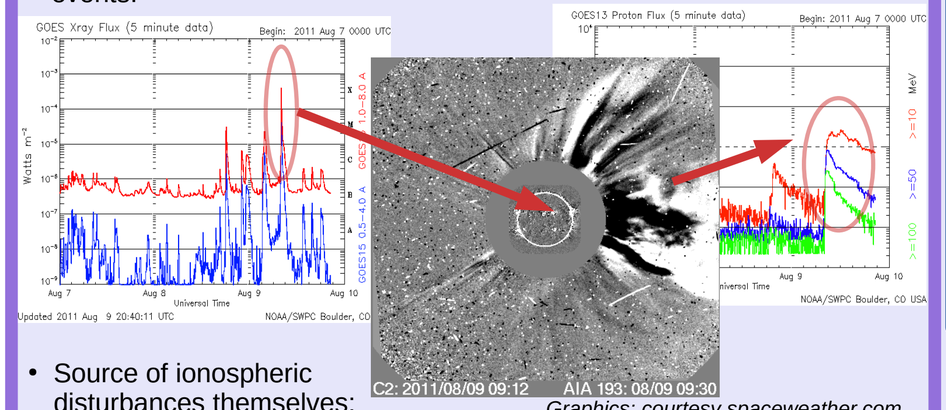
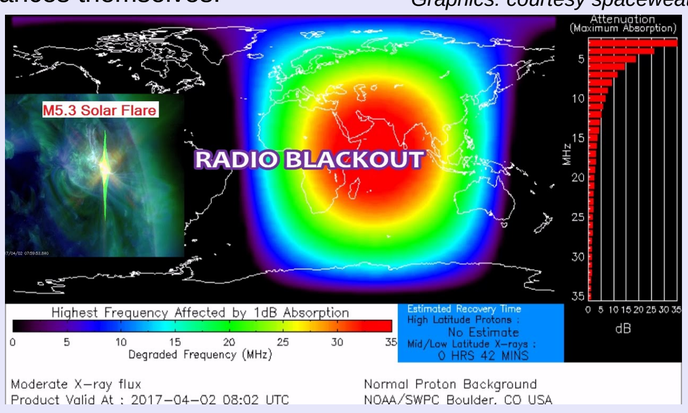
MOTIVATION:

- Flares are the "initiating" or "reference" events for many space weather phenomena.
- *Causally* related to Coronal Mass Ejections, Solar Energetic Particle events.



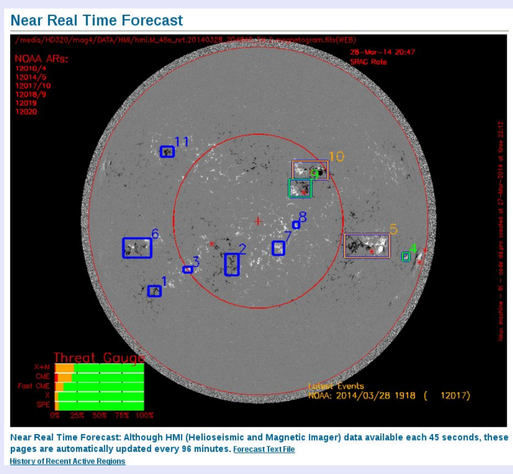
- Source of ionospheric disturbances themselves:

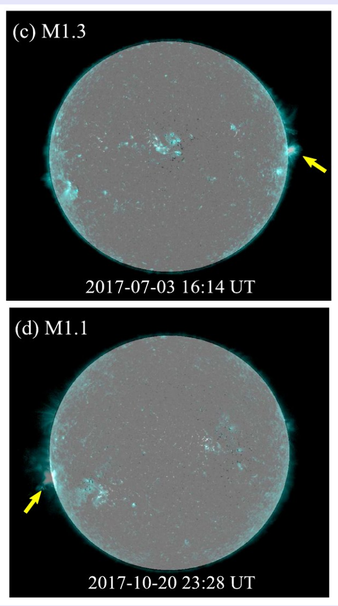
Graphics: courtesy spaceweather.com



Known Operational Failure Mode: Limb Flares & "4π Forecasts"

- Most prediction methods *miss* predictions for flares near, at, or just beyond the solar limb.





LEFT: Example flare forecasting method (MAG4); regions inside red circle are "most reliably" predicted, no predictions are provided for regions near (or beyond) the visible limb.
RIGHT: Examples of recent medium-sized limb flares, *both of which* caused ionospheric disturbances & HF outages.

From Park+2020.

However

- X-rays can heavily impact the ionosphere, even when the Active Region is partially occulted.
- West-limb flares can produce Earth-directed SEPs.
- **Space weather predictions are soon needed for non-Earth solar system locations (*e.g.*, Mars).**

Limb-flare / 4π Forecast Challenge:

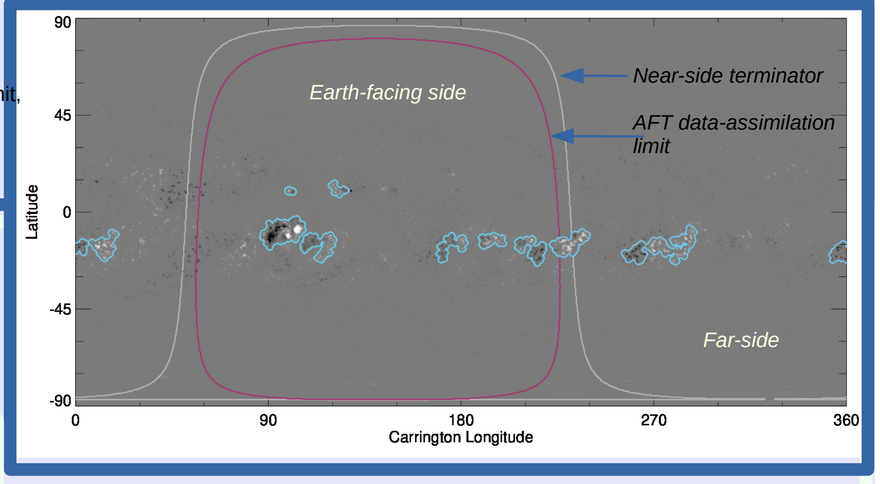
- **Correctly predict flares at ±90º +/- 30º Stonyhurst longitude**
- **Develop 4π ("full-Heliosphere") flare forecast capability.**

Limb Flares & 4π Forecasts: Basic (initial) Approach: Forecasting based on Carrington-grid Magnetic Field characterization.

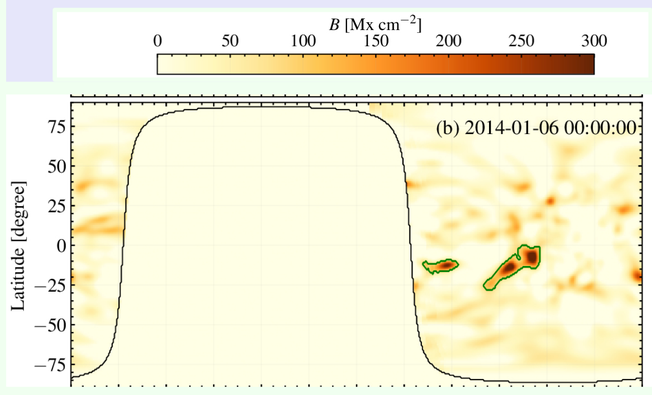
- Advective Flux Transport (AFT) model (Upton & Hathaway 2014) produces 4π solar photosphere magnetic field maps
  - Data from Earth-facing HMI B_{los} is assimilated (hourly) and an estimate of Br is produced.
  - AFT solves the radial component of the induction equation, evolving the system every 15 minutes:
    - **Br:** radial magnetic field
    - **U**: horizontal flows including convective and axisymmetric (differential rotation, meridional circulation)
    - **S term**: magnetic source term (new flux emergence)
    - **η term**: (numerical) diffusivity term

$$\frac{\partial B_r}{\partial t} + \nabla \cdot (\vec{u} B_r) = S(\theta, \phi, t) + \eta \nabla^2 B_r$$

Example frame from AFT showing surface flux, solar limb (near/visible-side is image-center), the AFT assimilation limit, and identified active regions (from Jha+2025).
Here, only near-side data from HMI is assimilated ("default" or "baseline" mode).



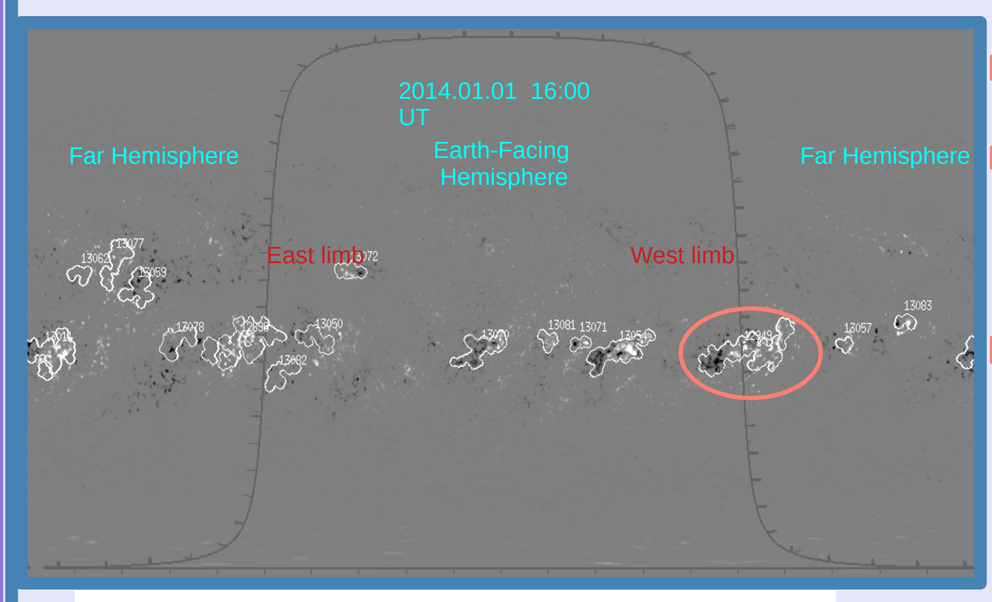
Adding "invisible" information: Far-Side Helioseismology



ABOVE: identification of GONG-based active regions on the far side for 2014-01-06T00:00 (the target).
Adopted ARs are based on size but also persistence before being considered "real", and incorporated into AFT.

- Far-side regions detected from ***Far-Side Helioseismology***
  - Global phase-shift maps from the Global Oscillations Network Group (GONG) [Harvey+1996; Jain+2021].
  - Regions identified based on phase- shift magnitude and persistence
  - Estimates of magnetic flux based on phase-shift strength, signal size (area). [Gonzalez-Hernandez+2007,2014,MacDonald+2015]
- Imported to AFT:
  - Informs *S(θ,φ, t):* new magnetic bipoles follow Hale's law and Joy's law
  - AFT is further "informed" with information on active region growth, *etc*.

Parameterizing the 4π Active Regions



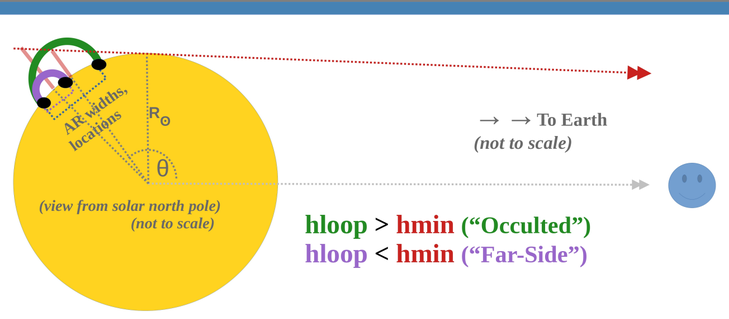
AFT_ID	2014010148
NEAR_VIS	1
ASSIMILATED	1
STONY_LAT	-16.1418
STONY_CMD	91.8202
MU	-0.015526
FLUX_TOT	1.48E+19
FLUX_NET	3.48E+18
BZ_MEAN	27.6533
BZ_STDEV	170.626
BZ_SKEW	-0.0309537
BZ_KURT	5.93677
GRAD_BZ_MEAN	6.91013
GRAD_BZ_STDEV	5.64238
GRAD_BZ_SKEW	1.31072
GRAD_BZ_KURT	4.53926
NL_AREA	2.89E+15
NL_FLUX_TOT	2.36E+17
GRAD_NL_BZ_MEAN	7.48793
GRAD_NL_BZ_STDEV	5.95202
GRAD_NL_BZ_SKEW	1.41477
GRAD_NL_BZ_KURT	2.09746
HCRIT	49.001
HWP_MEAN	-4.88526
HWP_STDEV	5.26846
HWP_SKEW	-1.25608
HWP_KURT	4.67471
HWP_AREA	2.51E+16
HWP_NL_AREA	1.36E+15
POWER_SLOPE	-3.3972

"Proof of Concept"

- Focus on two parameters "known" to be relevant for energetic events:
  - Total Magnetic Flux
  - Schrijver's "$\mathcal{R}$": magnetic flux near strong-gradient polarity-inversion lines [Schrijver 2007])

[c.f. Leka+2018 , 2019 on "DAFFS-G", near-real-time "backup" flare forecasting based on GONG B_{los} data]

- "Visibility" index: near side, far-side (fully) invisible), or "occulted" (near-limb or just-beyond) with likely-visible loops and SXR flares, *according to location and size of active region.*



LEFT: a simple model by which we label a beyond-limb region as "occulted" but from which X-ray flare radiation may be visible.

If the "size" of the AR implies visible coronal loops, **it is considered "occulted" for which a forecast is needed.** If not, it is fully invisible and *not* included in the statistics.

Regions at least partially outside the AFT assimilation window but with μ>0 are also considered "occulted", as most forecasting facilities cannot provide forecasts due to poor or unavailable data.

STATISTICAL METHODOLOGY

NWRA Classification infrastructure [Leka&Barnes 2007; Leka+2018, Barnes+2025 (in prep)]

- Multi-parameter NonParametric NonLinear Discriminant Analysis
- Statistical classification ("proof of concept" for forecasting)

TEST SET-UP:

- 24hr validity, C+, M+
- 3x/day sampling (independent parameter calculations, 8hr of evolution)
- 6.5 years of data: 2010.06.01 – 2016.12.30
- "region-by-region" and "full-disk" (sun-as-a-star) tests

Region-by-Region		
Sample Description	On-Disk Regions	Occulted Regions
AFT-ARs ("HMI Baseline")	23,485	4,825
C1.0+ flares	5,929	302
M1.0+ flares	1,012	67
AFT-ARs ("HMI + GONG ")	23,892	6,580
C1.0+ flares	5,923	522
M1.0+ flares	1008	127

Full-Disk		
Sample Description	# Samples	#C1.0+ Flares/ # M1.0+ Flares
AFT-ARs ("HMI Baseline")	6,911	3,895 / 950
AFT-ARs ("HMI + GONG ")	6,944	3,995/ 1002

EVALUATION: *Region-by-Region*

Difference in # "missed" events (over all) — *How many near- & beyond-limb events were successfully "forecast"* — *ROCSS evaluates the ROC curves, Brier Skill Scores (BSS) summarize Reliability plots*
0.0 = "no skill", 1.0 = "perfect"
(these are respectable)

	Test	Event Definition	Climatology (R)	Δ(FN) (@$P_{th}=R$)	TP (Vis1) (@$P_{th}=R$)	ROCSS	ΔROCSS	BSS	ΔBSS
AFT Baseline	DISK	C1.0+	0.252		0	0.606		0.255	
	DISK+ OCCULTED	" "		-10	116	0.617	+0.011	0.264	+0.009
	DISK	M1.0+	0.043		0	0.676		0.161	
	DISK+ OCCULTED	" "		-26	34	0.734	+0.058	0.178	+0.017
AFT+GONG	DISK	C1.0+	0.248		0	0.574		0.232	
	DISK+ OCCULTED	" "		+31	155	0.584	+0.010	0.240	+0.008
	DISK	M1.0+	0.042		0	0.615		0.149	
	DISK+ OCCULTED	" "		-24	60	0.718	+0.103	0.151	+0.002

uncertainties ≈0.01 (C+) and ≈ 0.02 (M+) ; the Δ's are statistically significant, usually.

Many more examples in the paper.

EVALUATION:

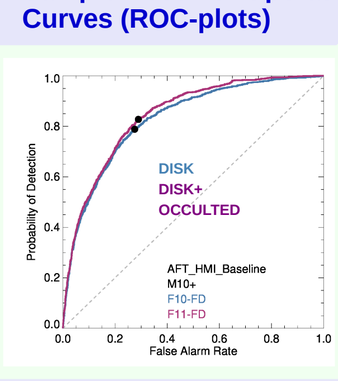
- Evaluate the system for improvement by comparing scenarios that *have*, vs. *do not have*, occulted-region information.
  - Case "**DISK**":
    - only-on-disk data used to "train"
    - beyond-limb forecasts ≡ 0.0 (penalized for missing occulted-region flares)

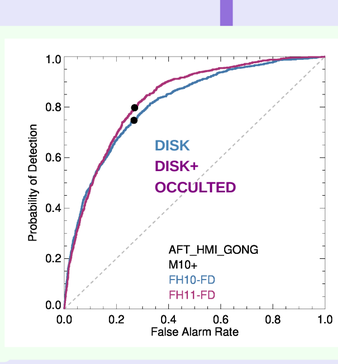
vs.

  - Case "**DISK+OCCULTED**":
    - on-disk *data* used to "train"
    - on-disk *and occulted regions* provide probabilistic forecasts
  - When necessary, a "probability threshold" is used that reflects the DISK-based event rates.
    - Occulted-region flares are likely under-counted. Flares physically know no location preference, so the on-disk event rate should be "universal".

EVALUATION: Sample Receiver Operation Curves (ROC-plots)

Many more examples in the paper.





ROC plots indicate performance over the full range of probability thresholds with ROCSS = 2*(area-under-curve)-1.0 = area above "x=y" line.
Of note here, there is a larger difference between **DISK** and **DISK+OCCULTED** for the AFT+GONG over the AFT Baseline.

EVALUATION: East- vs. West-Limb Flares: Does the Helioseismology help? *(YES!)*

- AFT by itself should improve West-limb flares preferentially.
- Imbalance Ratio for successful limb "hits" (correct event forecasts):
  $H = |\#East - \#West| / N = 0$ for balance.
- ***With* the helioseismology, H decreases, showing *improved East-limb forecasts*.**

East *vs* West "Occ" Success (Region-by-Region)

Test	Event Def.	Climatology	N_{East}	N_{West}	Imbalance (H)
AFT	C1.0+	0.252	8	108	0.86
AFT+seis.	C1.0+	0.248	45	110	0.42
AFT	M1.0+	0.043	2	32	0.88
AFT+seis.	M1.0+	0.042	24	36	0.20

BOTTOM LINE / SUMMARY

- We demonstrate a framework for full-heliosphere "4π" Solar Energetic Event Forecasting.
- Multiple levels of infrastructure were developed.
- Proof of Concept was evaluated against limb-flare forecasting failures with positive results.

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More details & results can be found at: Leka et al 2026, ***Space Weather***, doi: 10.1029/2025SWW004582