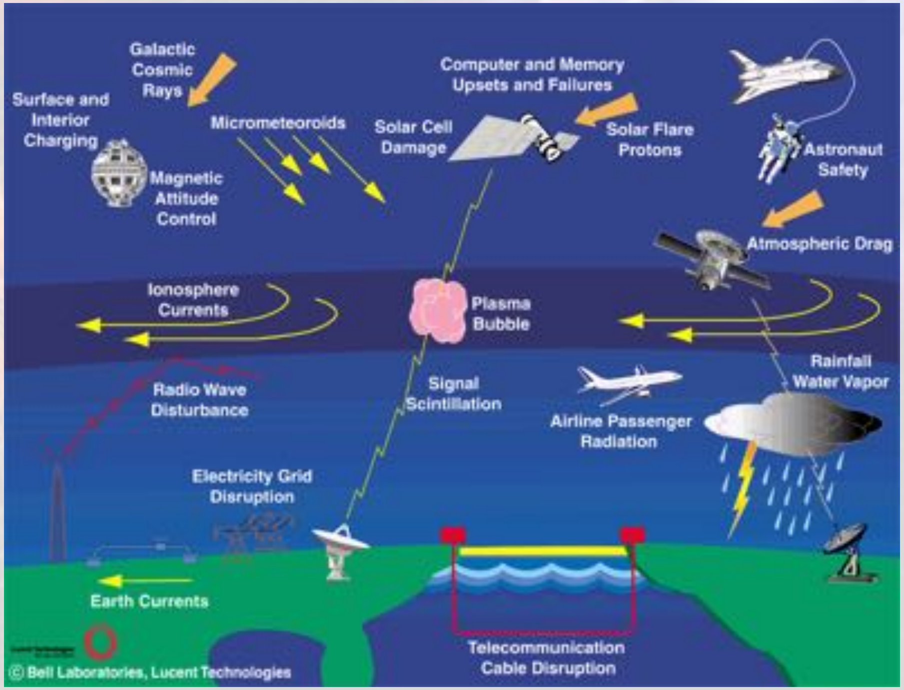
Probabilistic model for heliospheric propagation of CMEs: DBEMv2 web application

J. Čalogović[1], M. Dumbović[2], B. Vršnak[1], M. Temmer[2], A. Veronig[2], T. Žic[3], L. M. Mays[4], I. Piantschitsch[2]

1. Hvar Observatory, Faculty of Geodesy, University of Zagreb, Croatia
2. Institute of Physics, University of Graz, Austria
3. Faculty of Engineering, University of Rijeka, Croatia
4. NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

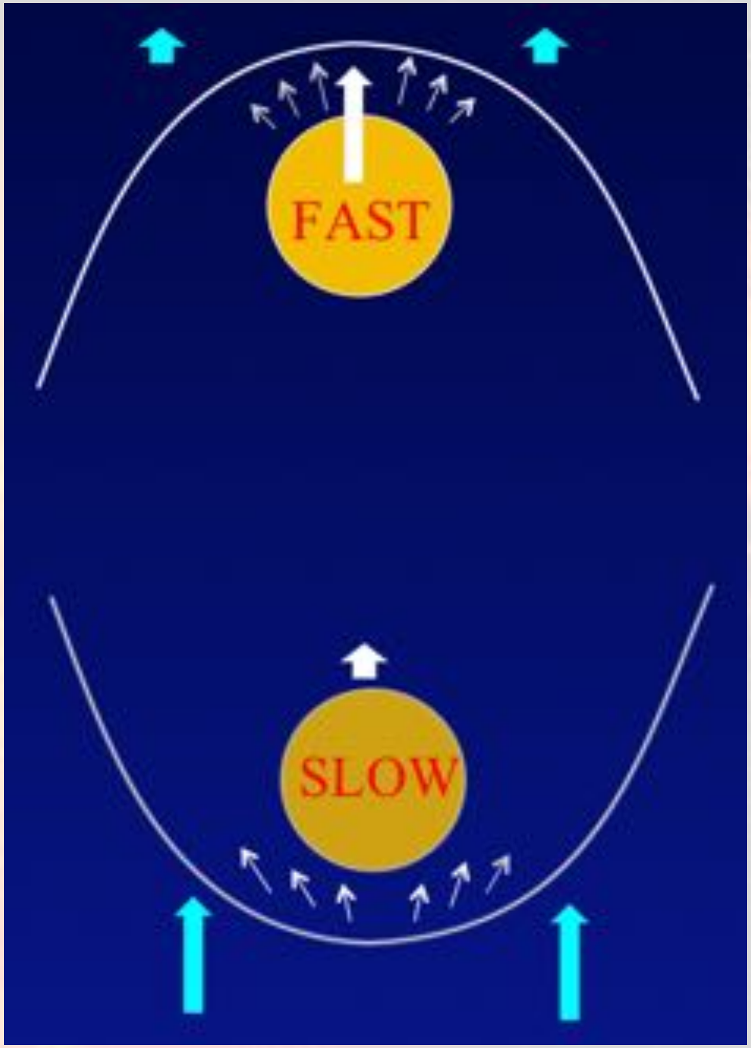
Heliospheric propagation models are important for space weather forecasting

- CME/ICMEs major drivers of solar wind disturbances and geomagnetic storms
- Prediction of CME/ICMEs propagation in the heliosphere – important task for space weather forecasting



- Various models are used for space weather forecasting:
  - purely empirical/statistical methods
  - kinematical-empirical methods
  - analytical (M)HD-based models (**DBM**)
  - numerical MHD-based models (ENLIL)

Drag-Based Model (DBM)



Cargill et al., 1996; Vršnak and Žic, 2007; Vršnak et al. 2013

- Beyond about 20 solar radii the MHD "aerodynamic" drag (a_d) caused by the interaction of CME with solar wind, becomes the dominant force

$$a = \cancel{a_L - g} + a_d$$

$$a_d = -\gamma(v-w)|v-w|$$

Equation of motion

- ICME dynamics is governed by interaction with (ambient) solar wind (w)
  - fast CME ($v > w$) → deceleration
  - slow CME ($v < w$) → acceleration
- Drag parameter (γ) depends on characteristics of both ICME and solar wind – the drag is larger for broader, low-mass ICMEs in a high-density (slow) solar wind
- If w and γ constant there is analytical solution

Drag-Based Model (DBM)

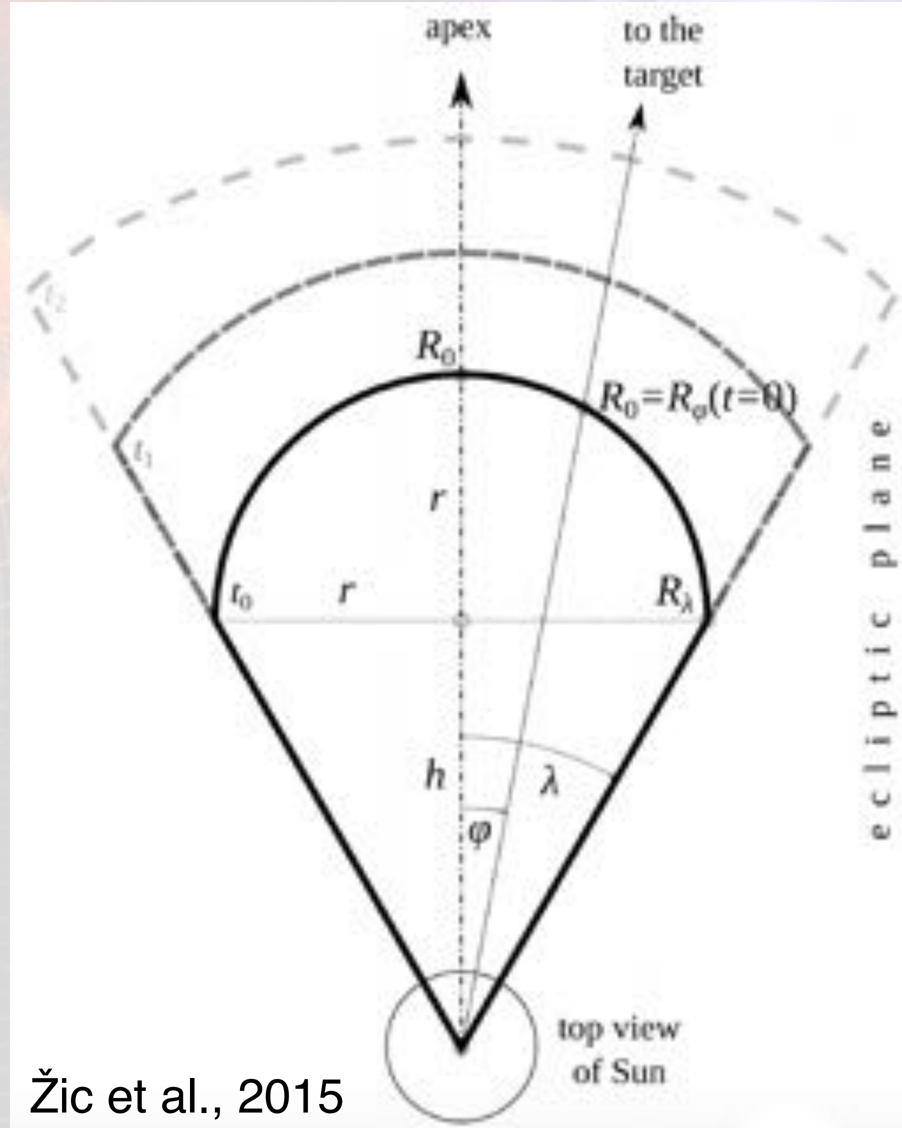
- Simple analytical model for heliospheric propagation of CMEs to predict the arrival time and speed of CME at any given target in the solar system

- **Advantages**
  - simple and robust
  - very fast (one run << 1 sec) compared to numerical MHD models (e.g. ENLIL)

- **Disadvantages**
  - doesn't give the best results in complex heliospheric environment (eg. CME-CME interactions, w and γ aren't constant)

DBM CME geometry

- Uses CME cone geometry with CME leading-edge flattening
- Solar wind speed (w) is radially dependent w(R) and γ is also function of radial distance γ(R)
- each CME leading-edge segment propagates independently → the initial cone geometry flattens



Žic et al., 2015

Ensemble modelling

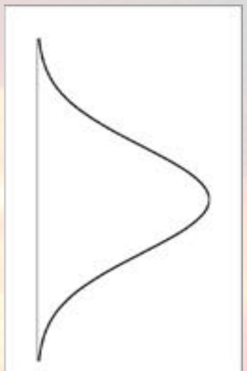
Input

Parameter 1 (eg. γ)

value 1

value 2

value x



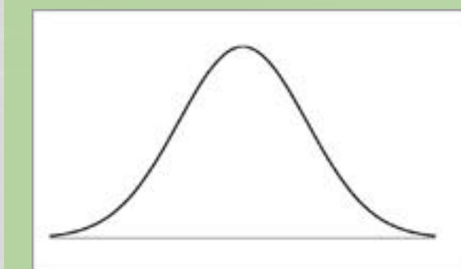
Parameter x

Value 1

value x

Multiple model runs (DBEM)

Set of results



allows to calculate the confidence intervals of arrival times and impact speed (parameter uncertainties are quantified)

Drag-based Ensemble Model (DBEM)

- Recently, the DBM code was rewritten to **python** (modular design)
- Optimizations and improvements in the code → new version of DBM runs up to 200 times faster
- Parallelization of code that supports multi thread (CPU) calculations (up to 1000x faster)

- Each DBEM input parameter can be defined as list of parameters (eg. multiple observations of the same event)

Example for input parameters for CME on 6 Feb 2013

Member ID	date & time	Latitude	Longitude	Half-Width	Speed
1	2013-02-06 03:15	30	-25	38	1226
2	2013-02-06 03:07	30	-35	38	1300
3	2013-02-06 02:42	33	-28	28	1389
4	2013-02-06 02:37	30	-20	27	1436
5	2013-02-06 02:40	30	-26	43	1460
6	2013-02-06 02:39	30	-24	36	1474
7	2013-02-06 02:37	33	-19	28	1536
8	2013-02-06 03:01	39	-33	43	1387
9	2013-02-06 02:40	30	-26	22	1460
10	2013-02-06 02:52	35	-30	27	1430
11	2013-02-06 02:44	34	-25	30	1470
12	2013-02-06 02:54	40	-28	30	1441
*	2013-02-06 02:41	30	-26	30	1460

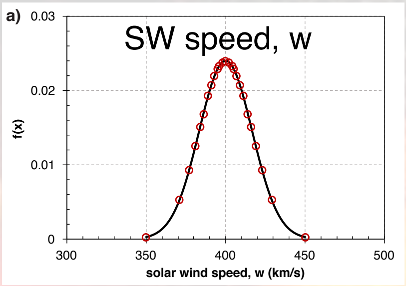
DBEM with ensemble and synthetic measurements

Dumbović et al., ApJ, 2018

INPUT

Ensemble of CME measurements:
$T_1, v_1, \phi_1, \lambda_1$
$T_2, v_2, \phi_2, \lambda_2$
…
$T_n, v_n, \phi_n, \lambda_n$

n inputs

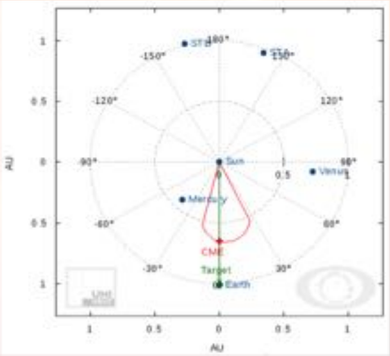


Synthetic values for:
w_1, γ_2 / w_2, γ_2
…
w_m, γ_m

m x m inputs

RUNS

nm^2 combinations (ensemble members)
nm^2 DBM runs

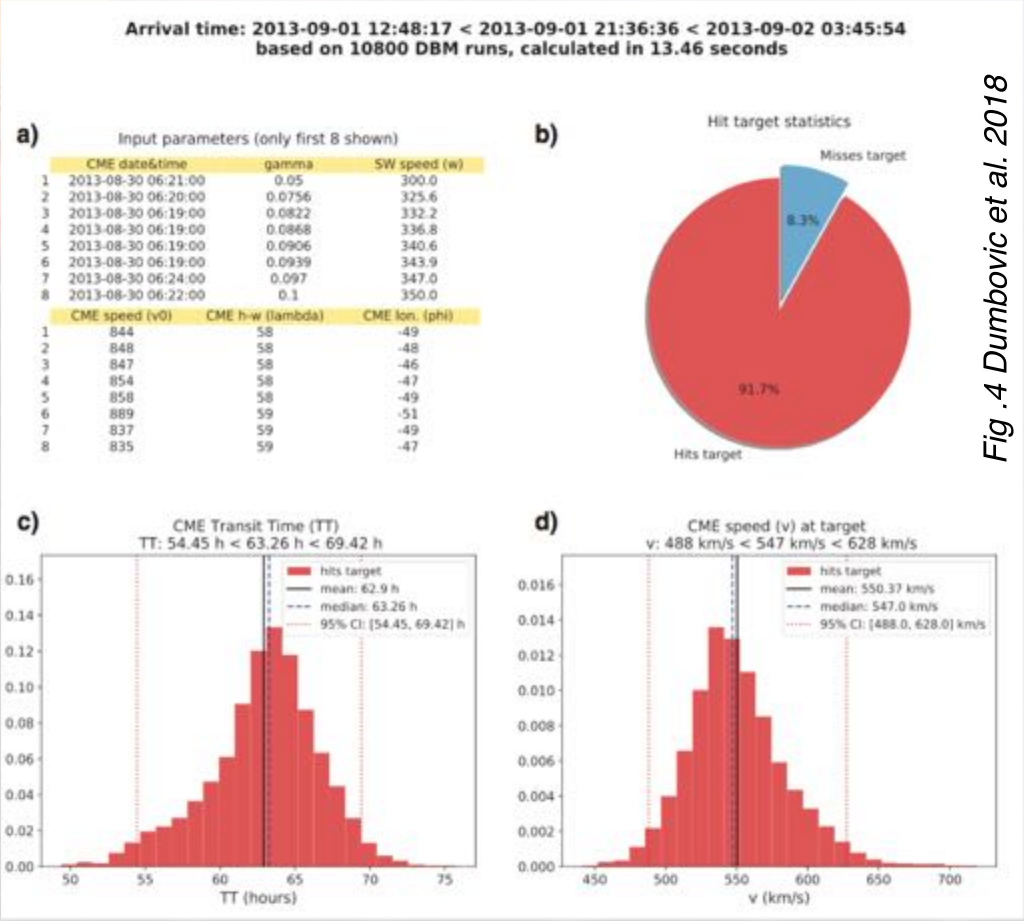


2D DBM (*Žic et al., 2015, ApJ*)

- hit or no hit
- transit time
- arrival time
- arrival speed

Ensemble modeling applied to Drag-based Model (DBM, *Vršnak et al., 2013, SolPhys*)

DBEM OUTPUT



	CME date&time	gamma	SW speed (w)
1	2013-08-30 06:21:00	0.05	300.0
2	2013-08-30 06:20:00	0.0756	325.6
3	2013-08-30 06:19:00	0.0822	332.2
4	2013-08-30 06:19:00	0.0868	336.8
5	2013-08-30 06:19:00	0.0906	340.6
6	2013-08-30 06:19:00	0.0939	343.9
7	2013-08-30 06:24:00	0.097	347.0
8	2013-08-30 06:22:00	0.1	350.0

	CME speed (v0)	CME h-w (lambda)	CME lon. (phi)
1	844	58	-49
2	848	58	-48
3	847	58	-46
4	854	58	-47
5	858	58	-49
6	889	59	-51
7	837	59	-49
8	835	59	-47

Fig .4 Dumbovic et al. 2018

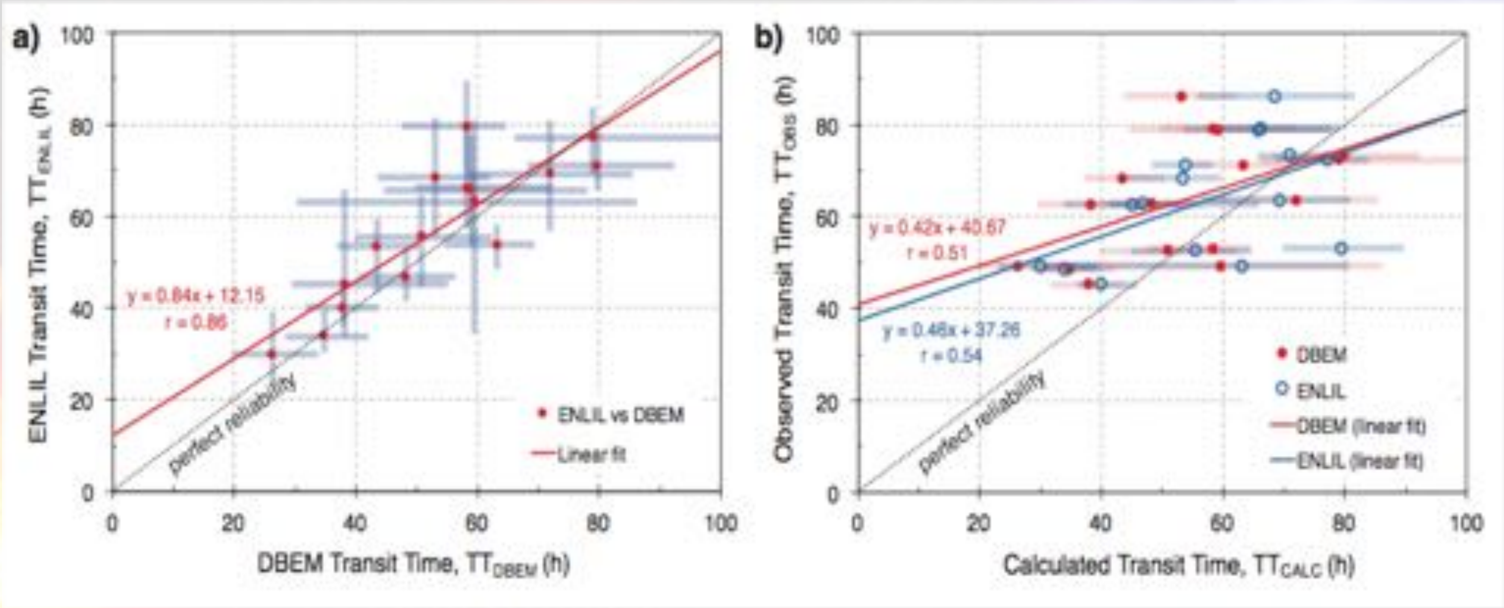
Performance and comparison with ENLIL

- Based on sample: *Mays et al., 2015, SolPhys*

- Both ENLIL and DBEM are not far away from the line of perfect reliability

TRANSIT TIME

Fig. 7 from Dumbović et al., 2018



RELIABILITY DIAGRAM

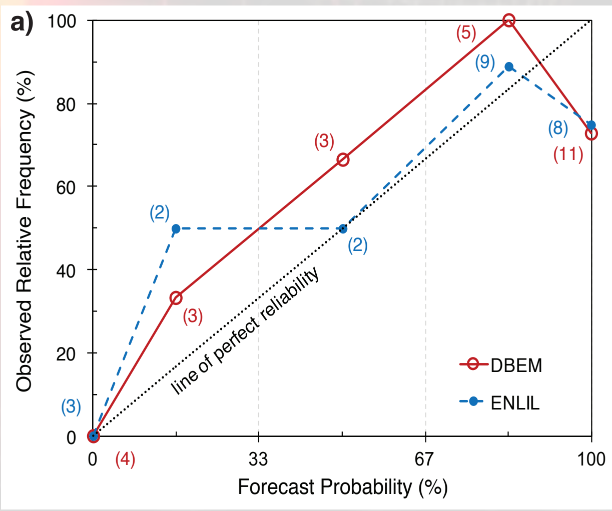


Fig. 5 from Dumbovic et al. , 2018

ARRIVAL SPEED

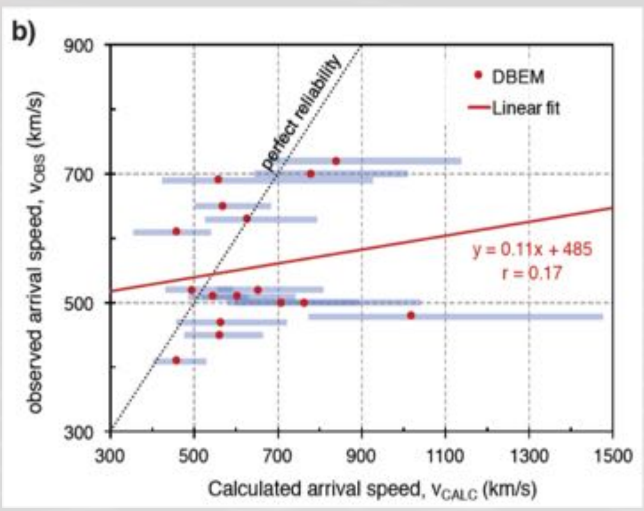


Fig. 8 from Dumbovic et al., 2018

Main points - DBEM

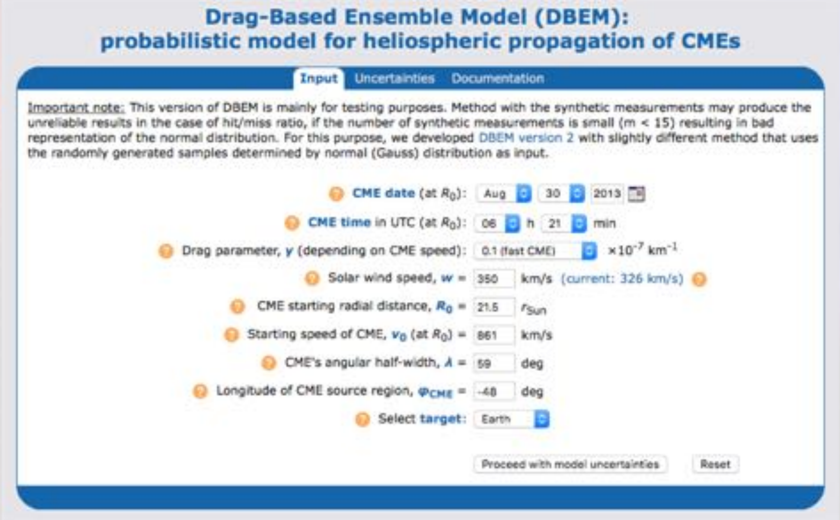
Dumbović et al., ApJ, 2018

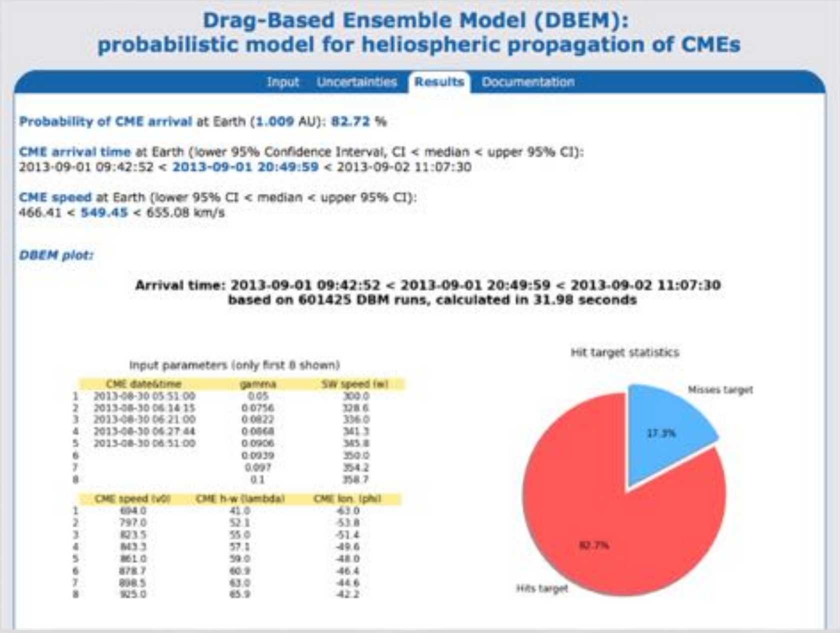
- Offers probabilistic forecasting of **CME hit chance**, **transit time** and **arrival speed** for different targets in solar system
- Reliable and simple model
- Runs **very fast** (more than 1000 DBM runs per sec on a single CPU)
- ENLIL and DBEM perform similarly
- Fast CMEs predicted to arrive too early for both DBEM and ENLIL
- Suitable for implementation as on-line (web) forecasting tool: **DBEMv1** and **DBEMv2** - ESA Expert Service Group for Solar & Heliospheric Weather (swe.uni-graz.at)

c) prediction errors for TT (h)	DBEM	ENLIL
mean error (ME)	-9.7	-6.1
mean absolute error (MAE)	14.3	12.8
root mean square error ($RMSE$)	16.7	14.4

On-line DBEMv1 tool with synthetic measurements

- Needs as input only one CME measurement with estimated uncertainties
- Uses **synthetic measurements for all 6 input parameters** (T, v, ϕ, λ, w, γ)
- Needs certain number of synthetic measurements (m > 9) to perform reliably - large number of DBM calculations (slow)
- **DBEMv2** is faster and more reliable than DBEMv1



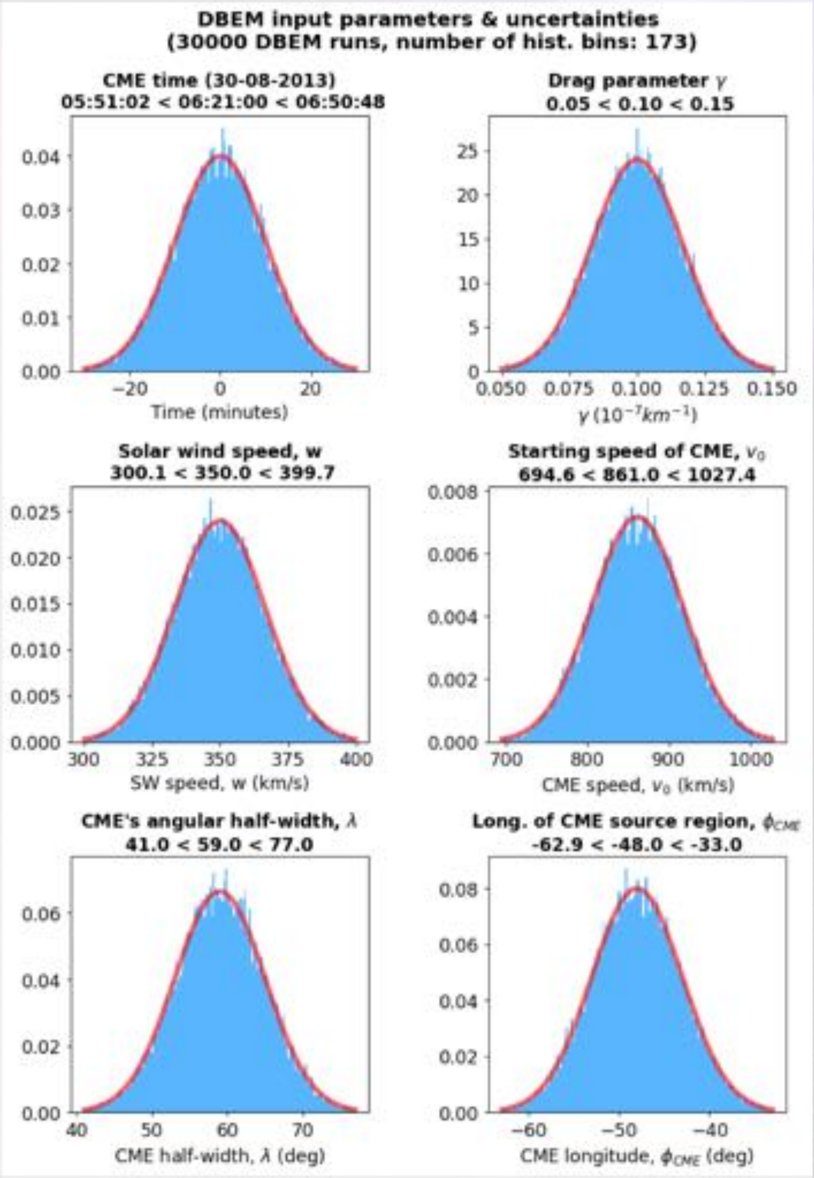


1. oh.geof.unizg.hr/DBEM
2. phyk039240.uni-graz.at:8080/DBEM

DBEMv2 (version 2) input parameters

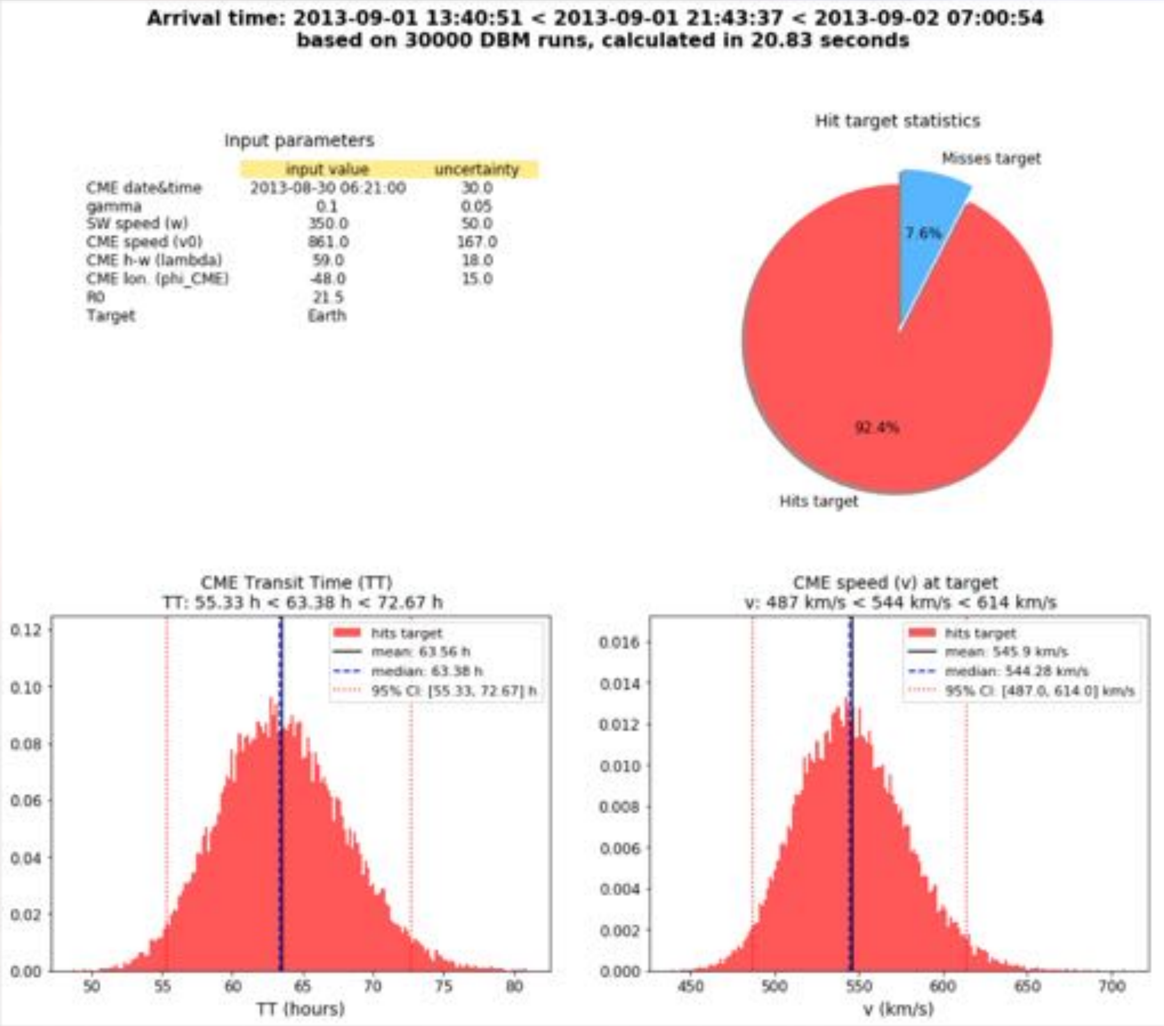
Čalogović et al., in preparation

- Same engine (software) as DBEMv1 with synthetic measurements, however different method is used for input uncertainties
- For all 6 input parameters (T, v, ϕ, λ, w, ɣ) random values are generated in a range input ± uncertainty (3 σ) following a normal (Gaussian) distribution
- <u>Advantages:</u>
  - input distributions are better represented than with DBEMv1
  - converges to stable results much faster than method with syn. measurements
  - allows lower number of DBM runs - **faster**
  - user can choose the exact number of DBEM runs
- <u>Disadvantages:</u>
  - due to random input, it produces every time slightly different results - differences converge with increasing nr. of runs (differences are negligible at >10 000 runs)



DBEMv2 results

- More accurate hit/miss ratio due to better representation of normal distribution in uncertainty range
- Provides statistics (mean, min, max, StDev, CI) for all calculated parameters
- User can download all results in a zip file
- Will be soon integrated in **ESA SSA portal** as operational forecasting tool in the frame of the **ESA Expert Service Group for Solar & Heliospheric Weather** (swe.ssa.esa.int/heliospheric-weather) -



DBEMv2 on-line tool

1. http://oh.geof.unizg.hr/DBEMv2
2. http://phyk039240.uni-graz.at:8080/DBEMv2

Thank you for your attention

We acknowledge the **ESA Space Situational Awareness** Programme's network of space weather service development activities, supported under **ESA contract number 4000113183/15/D/MRP**. We also acknowledge the support of the **Croatian Science Foundation** under the project 6212 „**Solar and Stellar Variability**“ (SOLSTEL).