Predicting heliospheric propagation of CMEs with probabilistic Drag-Based Ensemble Model (DBEM)

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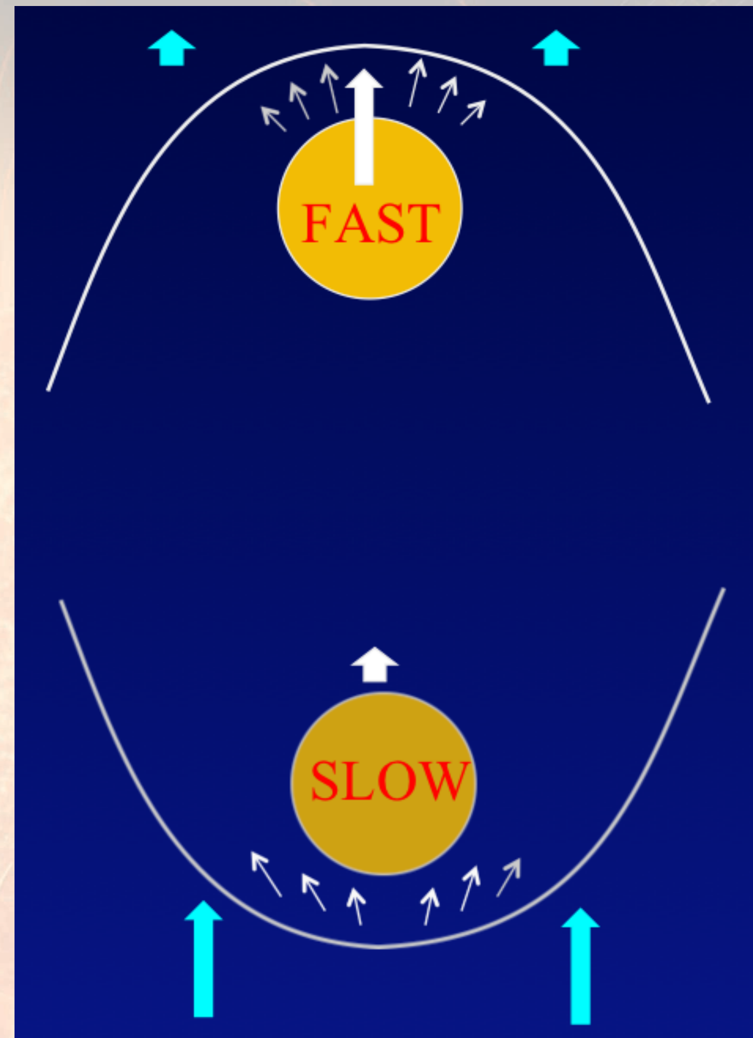
Drag-Based Model (DBM)



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

- CME 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 CME and solar wind – the drag is larger for broader, low-mass CMEs 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
- Uses CME cone geometry with "flattening" (leading edge of CME deforms gradually with time where CME flanks move faster than CME apex)

- **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)

Ensemble modelling

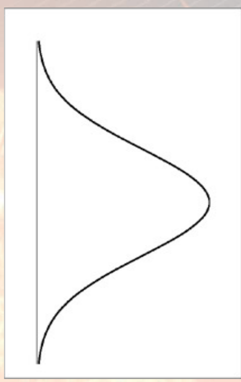
Input

Parameter 1 (eg. γ)

value 1

value 2

value x



Parameter x

Value 1

value x

Multiple DBM model runs (DBEM)

Set of results

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

DBEM - main points

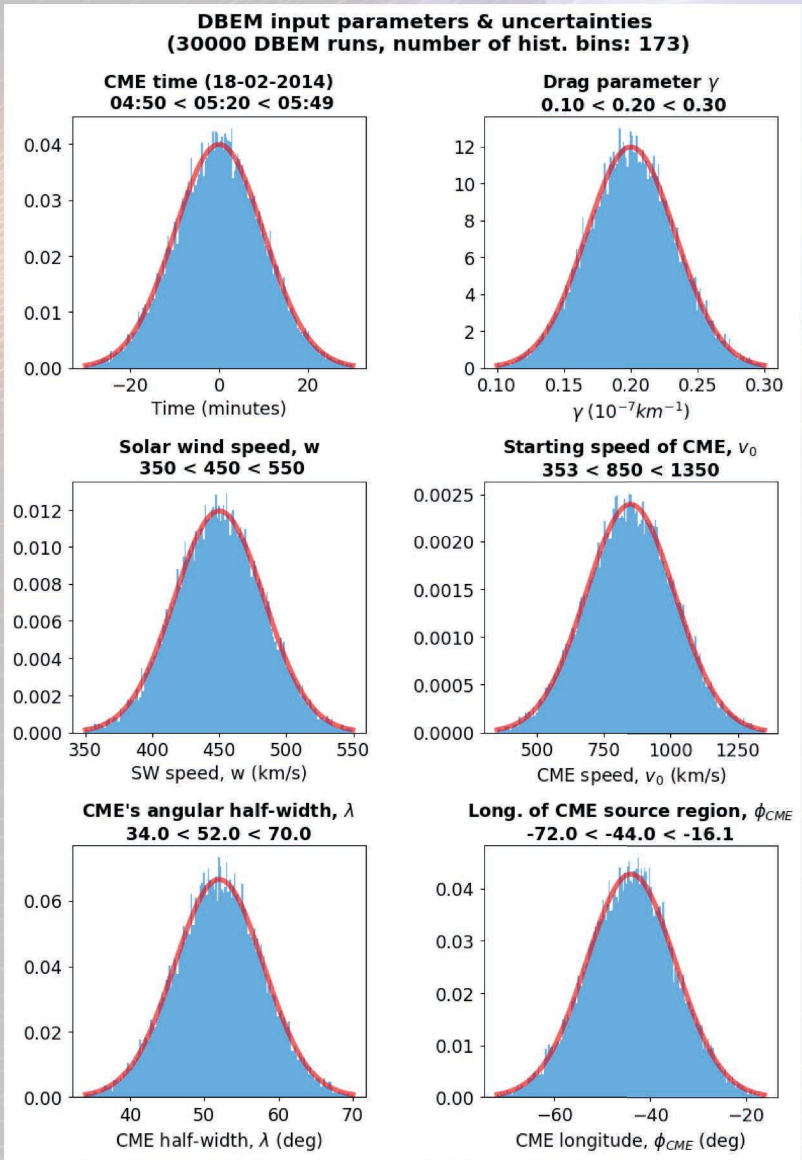
- Offers probabilistic forecasting of **CME hit chance**, **transit time** and **arrival speed** for different targets (planets and satellites) in solar system
- Reliable and simple model (written in Python)
- Runs **very fast** (more than 1000 DBM runs per sec on a single CPU)
- Comparisons show that ENLIL and DBEMv1 perform similarly
- Fast CMEs predicted to arrive too early for both DBEM and ENLIL
- Suitable as on-line (web) forecasting tool: **DBEMv25** implemented in **ESA Space Situational Awareness (SSA)** portal (**http://swe.ssa.esa.int/heliospheric-weather**)

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

Dumbović, Čalogović, Vršnak et al., ApJ, 2018

DBEMv2 (version 2) - input parameters

- For all 6 input parameters (CME time, starting speed of CME, drag parameter, solar wind speed, CME's angular half-width, longitude of CME source region) random values are generated in a range input ± uncertainty (3 σ) following a normal (Gaussian) distribution
- when compared to observations DBEMv2 performs slightly better than DBEMv1 with synthetic measurements (described in Dumbović et al ., 2018)



<u>Advantages:</u>

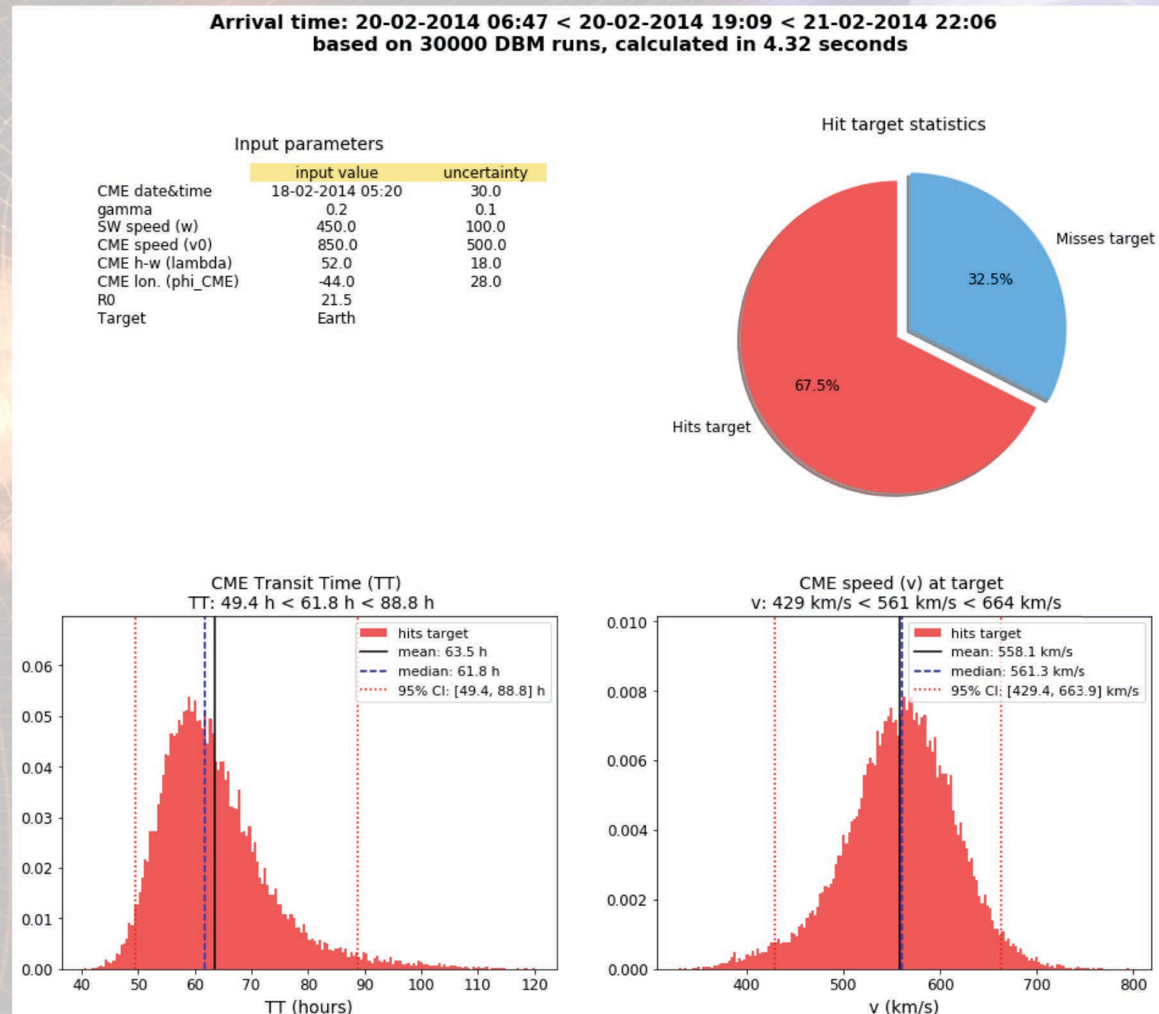
- input distributions better represented than in DBEMv1
- converges to stable results much faster than method with synthetic measurements
- allows lower number of DBM runs - **faster**
- user can choose the exact number of DBEM runs

<u>Disadvantages:</u>

- due to random input, it produces every time slightly different results - differences converge with increasing number of runs (differences are negligible for >10 000 runs)

DBEMv2 results

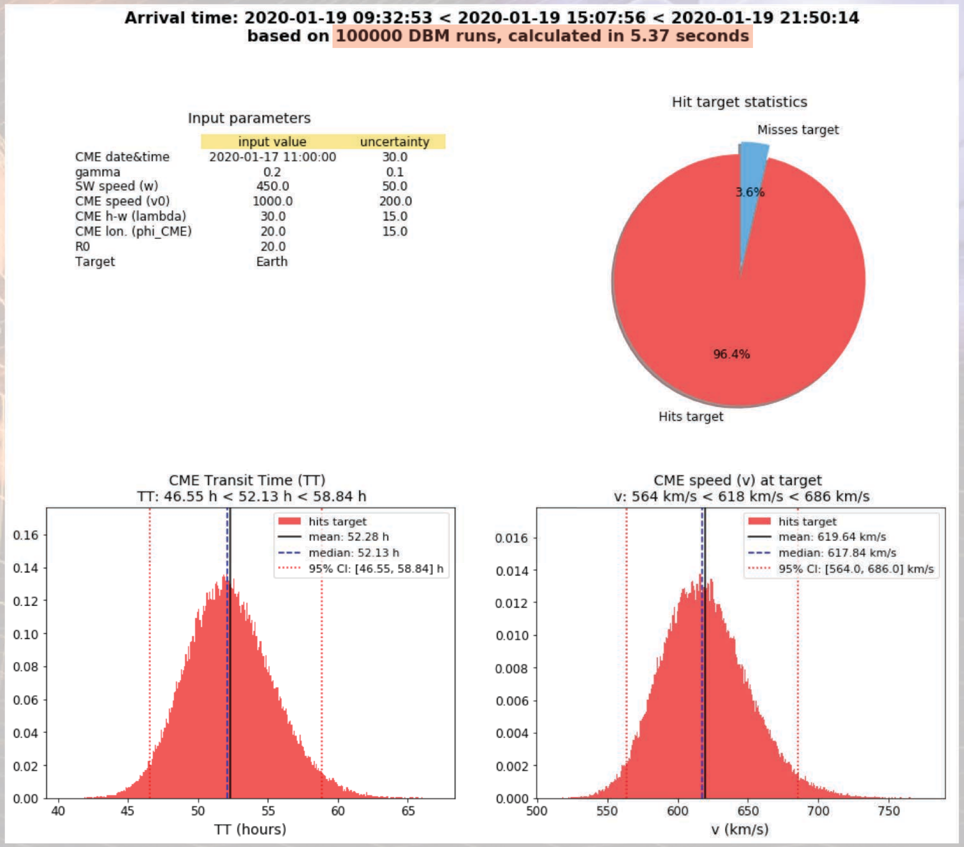
- More accurate hit/miss ratio due to better representation of normal distribution in uncertainty range
- Provides statistics (mean, min, max, StDev, CI) for all calculated parameters
- User can download all results in a zip file
- Integrated in **ESA SSA portal** as operational forecasting tool in the frame of the **[ESA Expert Service Group for Solar & Heliospheric Weather]**



http://swe.ssa.esa.int/heliospheric-weather

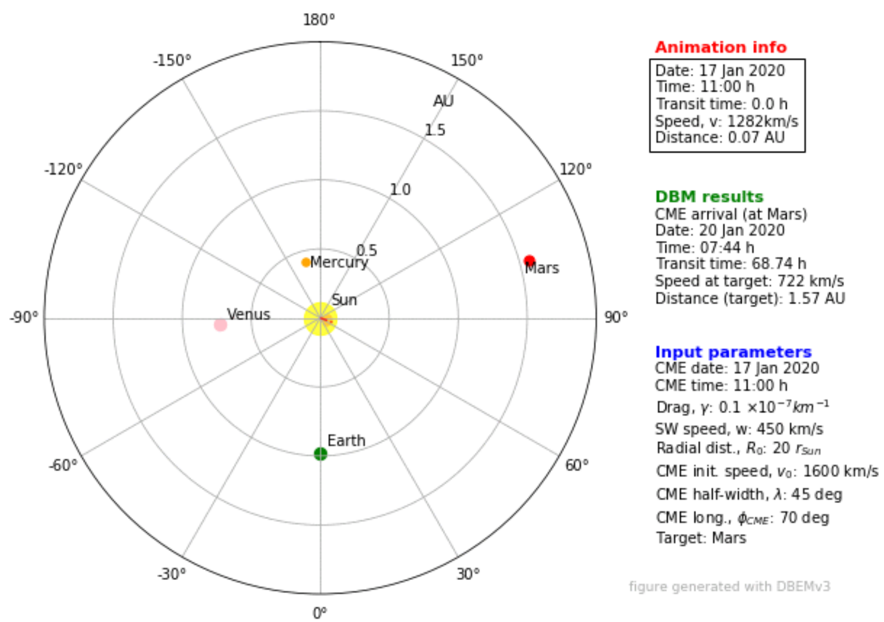
DBEMv25 - some recent improvements

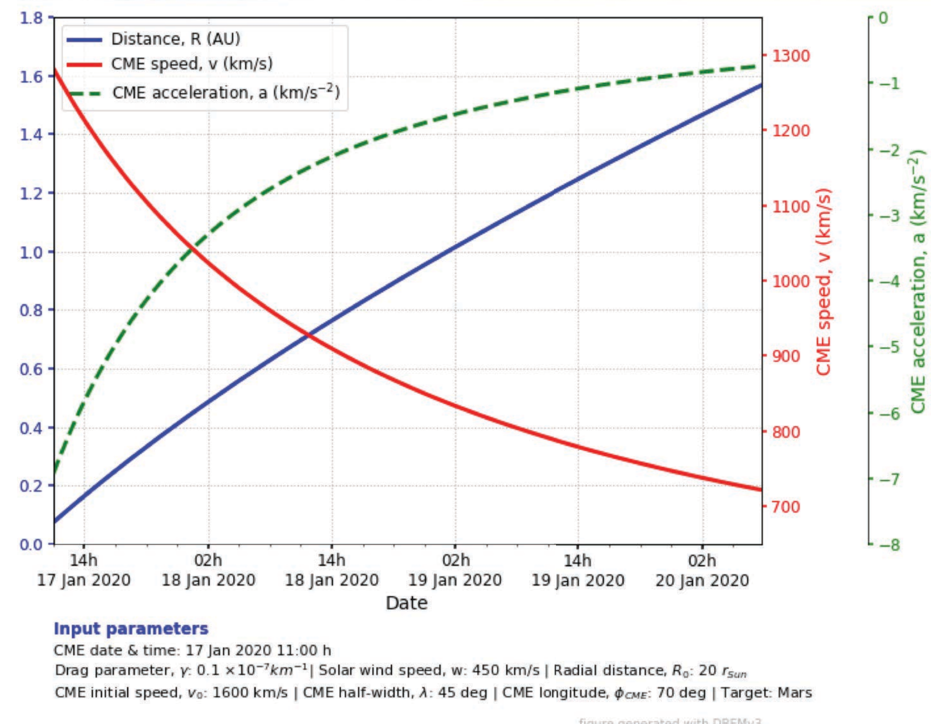
- Implementation of proper target movement (e.g. planets and satellites including Earth) during CME propagation (transit)
- Completely new routine for transit time (TT) calculation in DBM
- New ephemerides data employed (various new targets can be easily added - JPL's HORIZONS system https://ssd.jpl.nasa.gov/horizons.cgi)
- Parallelization of code and multi-CPU calculation support (e.g. calculates 100 000 DBM runs in less than 6 sec on 30/48 CPUs - Graz server)
- Added new targets (all planets, STEREO A & B, Solar Orbiter, Parker Solar Probe...)
- Some bug fixes



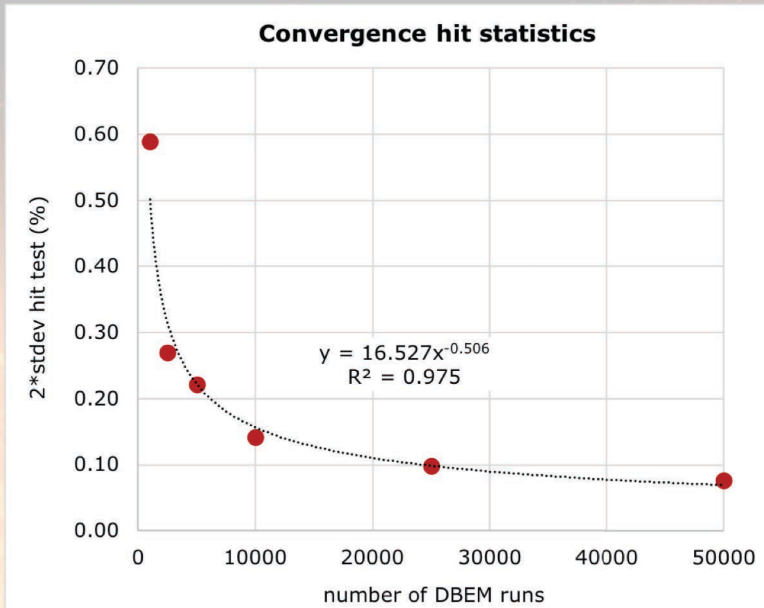
Development of DBEMv3

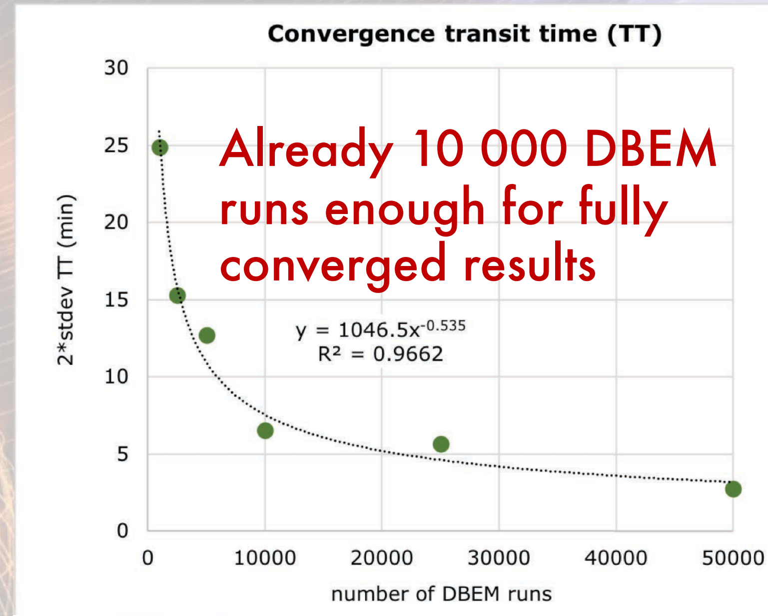
- Based on DBEMv25
- Complete integration of DBM web tool into DBEM together with DBM CME geometry & kinematic plot visualisations
- Graduated Cylindrical Shell (GCS) model option – calculates CME angular width from alpha, kappa, tilt (GCS parameters)

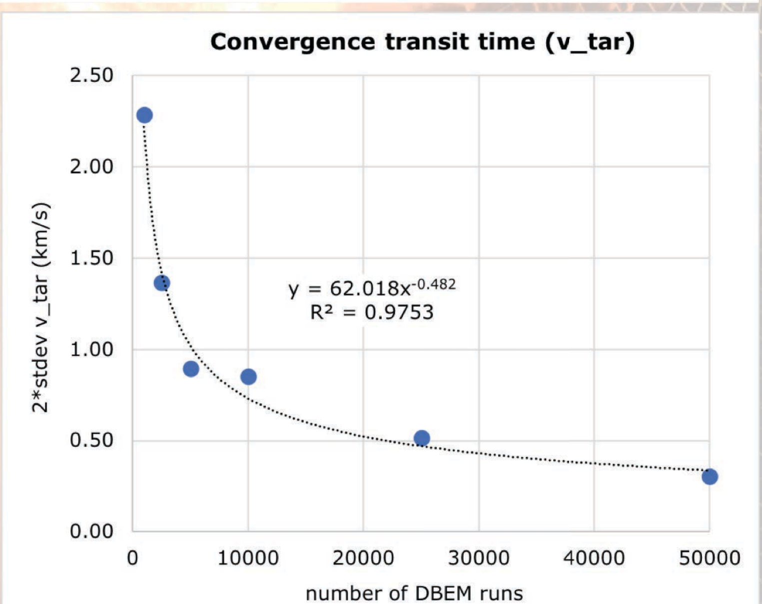


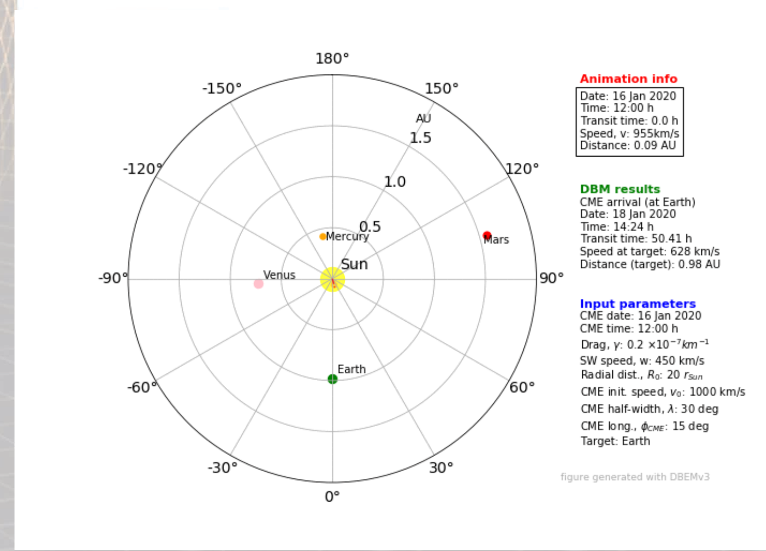


Convergence of DBEMv25 results







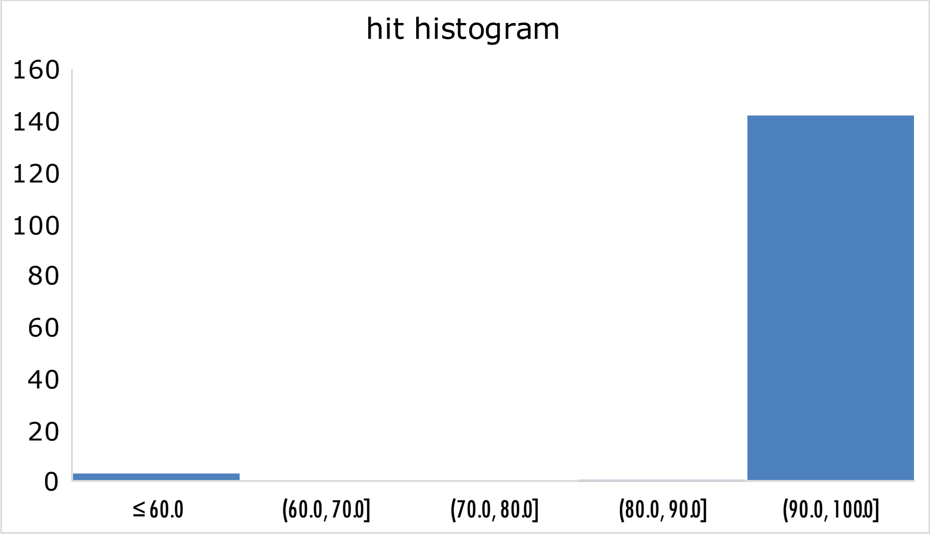


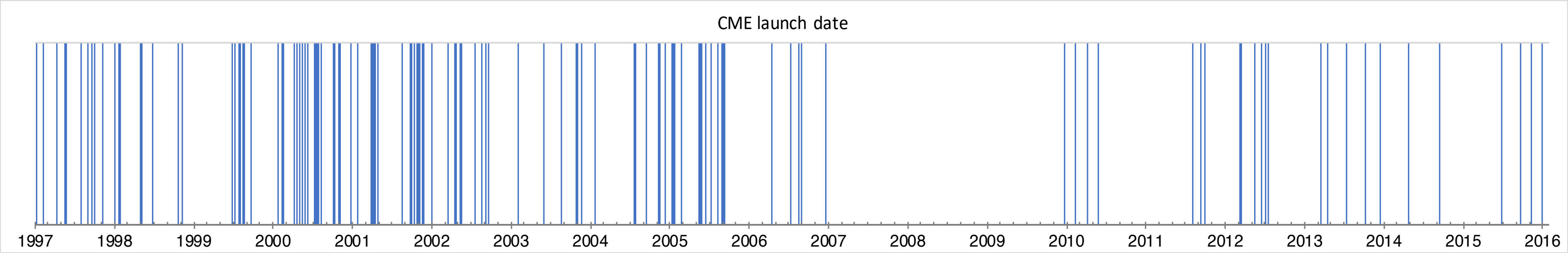
Based on 20 DBEM simulations with identical parameters

DBEMv25 evaluation with Richardson & Cane CME list (146 events)

DBEMv25 input parameters

- R0 = 20 Rs
- Number of DBM runs: 50 000
- CME start time: ± 30 min
- CME initial speed, v0: ± 10%
- CME half-width: ± 30 deg
- CME longitude: ± 10 deg
- Solar wind speed: 450 ± 50 km/s
- Gamma:
  - 0-600 km/s: 0.5 ± 0.1
  - 600-1000 km/s: 0.2 ± 0.075
  - >1000 km/s: 0.1 ± 0.05





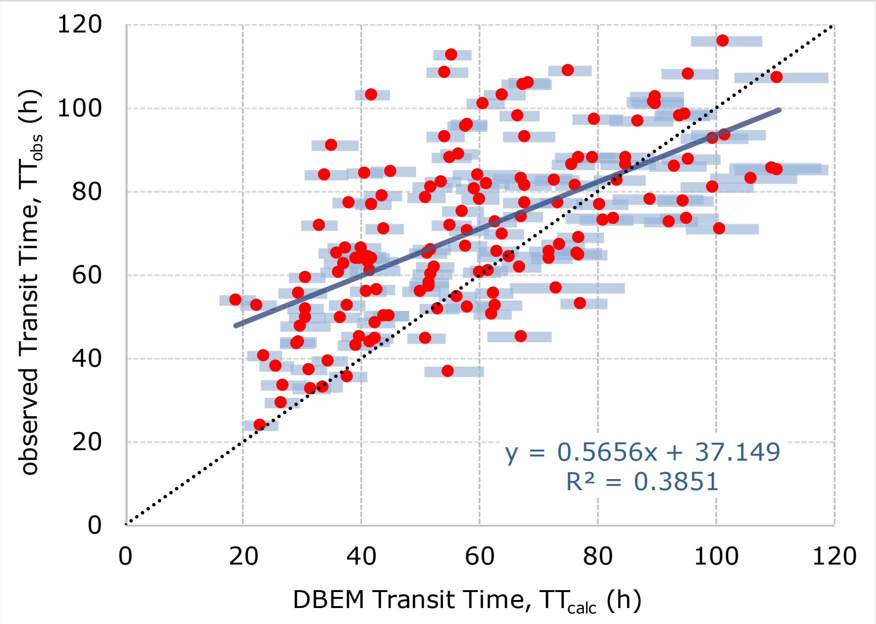
DBEMv25 evaluation (146 events)
Transit Time, TT

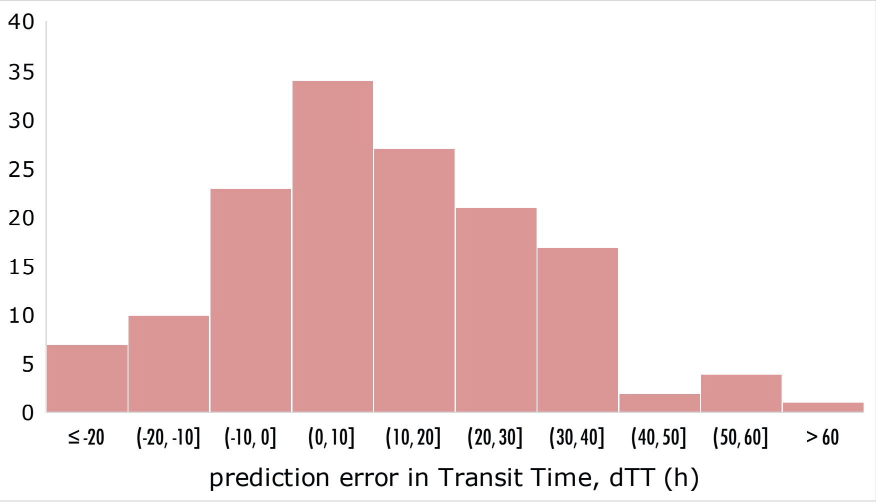
Prediction error in Transit Time, dTT

- Mean error: 11.3 h
- Mean absolute error: 17.3 h
- Max underestimated value: -29.9 h
- Max overestimated value: 61.1 h

- 50% events (50th percentile) dTT < 13.9 h
- 70% events (70th percentile) dTT < 22.9 h

- For slow CMEs TT is overestimated
- For fast CMEs TT is underestimated





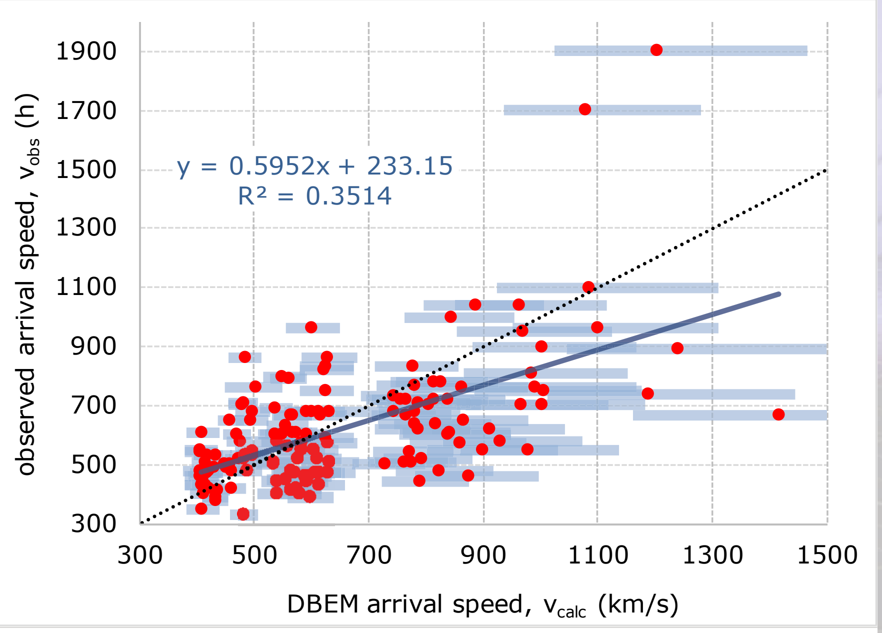
DBEMv25 evaluation (146 events)
arrival speed, v_{tar}

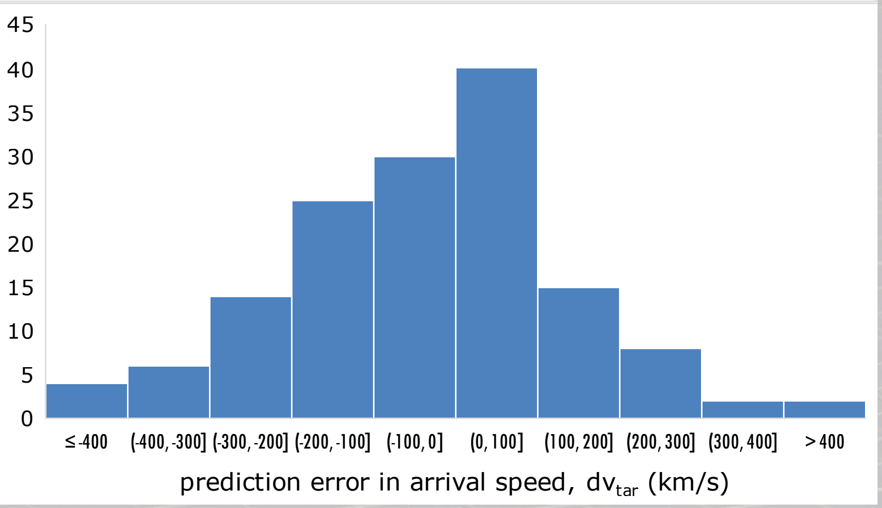
Prediction error in arrival speed, dv_{tar}

- Mean error: -30.3 km/s
- Mean absolute error: 139.3 km/s
- Max underestimated value: -746 km/s
- Max overestimated value: 695 km/s

- 50% events (50th percentile)
  dv < 102 km/s
- 70% events (70th percentile)
  dv < 162 km/s

- For slow CMEs v_{tar} is underestimated
- For fast CMEs v_{tar} is overestimated

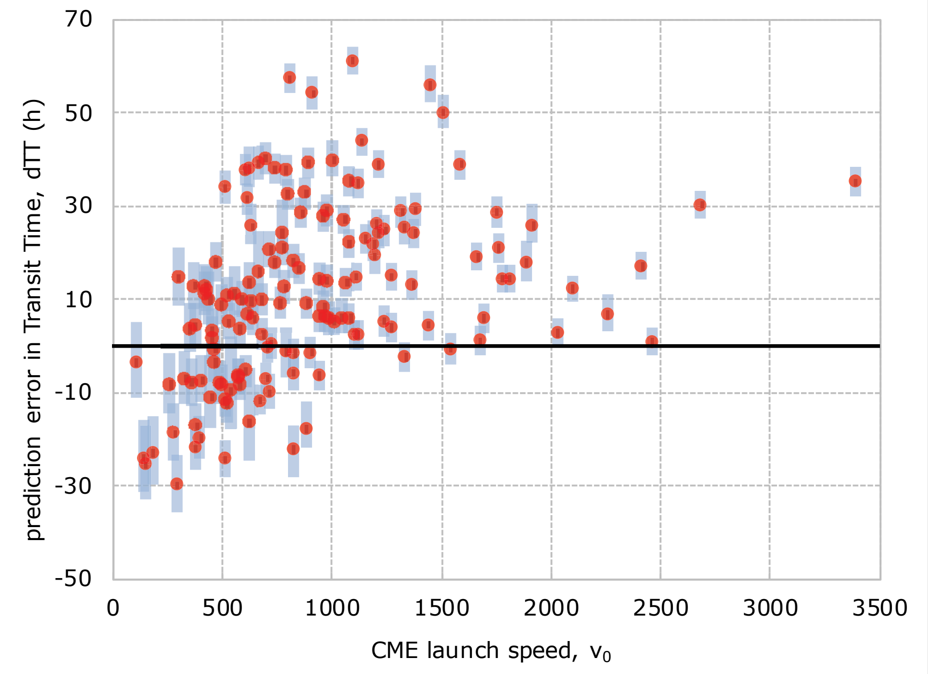




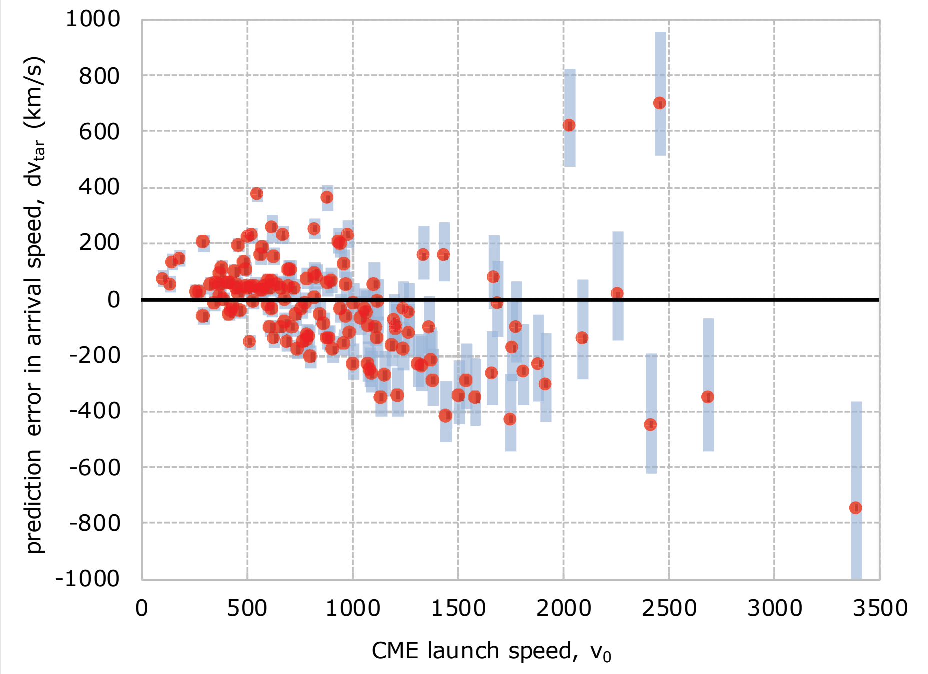
DBEMv25 evaluation (146 events)

prediction dependence of dTT & dv_{tar} on CME launch speed, v_0

error in Transit Time, dTT



error in arrival speed, dv_{tar}



Conclusions

- **Very fast** (up to 20 000 runs per sec), reliable and simple model
- Suited for a fast real-time space-weather forecasting
- Comparisons with numerical MHD models (ENLIL) show good accuracy of DBM at very low computational cost
- DBM performs better during the solar minimum than in the solar maximum, due to the complex heliospheric environment (eg. CME-CME interaction)
- DBEM can provide important information such as confidence intervals of CME arrival time and impact speed related to the input errors (observations)