On the drag parameter of ICME propagation models

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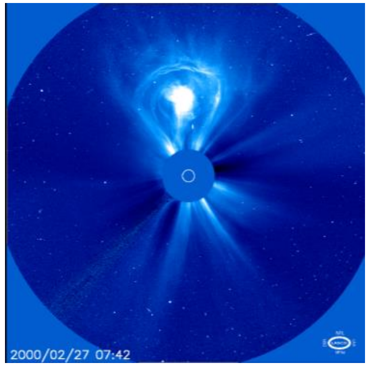
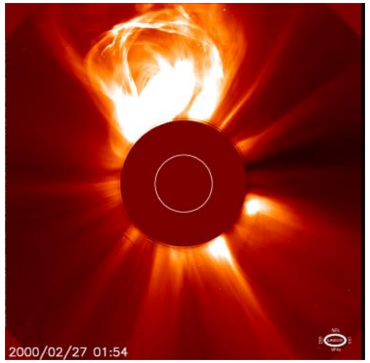
Introduction





Coronal Mass Ejections (CMEs) are violent phenomena of solar activity responsible for major Space Weather effects, and the main cause of geomagnetic storms. For this reason, the prediction of the time of arrival of an Interplanetary Coronal Mass Ejections (ICME) at 1AU is one of the primary subjects of the space-weather forecasting.

As critical as the forecast accuracy is the knowledge of its precision, i.e.: the error associated to the estimate, for which it is required to run multiple simulations to produce a distribution of possible ICME arrival times and speeds. While numerical heliospheric models are currently efficient in simulating a single CME propagation, running simulations for ensemble of N > 10^3 events, as required for a proper sampling of the parameter space, is still not affordable due to the large time involved, ranging from tenth of minutes to several hours per single event.

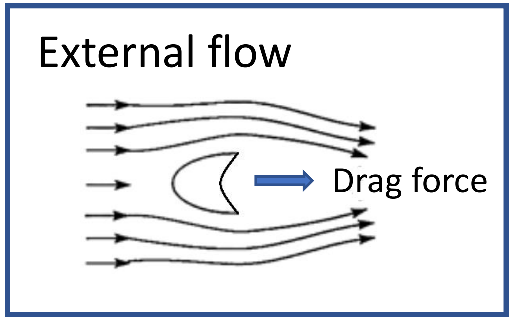
The use of simplified model as the Drag-Based Model by introducing probability distributions, rather than exact values, as input parameters allows Multiple runs using uncertainty ranges for the input values can be performed in almost real-time, within a few minutes. [..]

For this purpose, a proper definition for the distributions of the model parameters is required to improve forecast accuracy, and is mostly based on the statistics collected from past events.

The Drag-Based Model

The Drag-Based Model assumes the dynamics of ICME propagation is governed mainly by its interaction with the ambient solar wind, which exerts a drag force analogous to that experienced by a body immersed in a fluid:

$$\frac{d^2r}{dt^2} = -\gamma\left(\frac{dr}{dt} - w\right)\left|\frac{dr}{dt} - w\right|$$



where *r* is the heliocentric distance, *γ* is the **drag parameter**, and *w* is the **radial solar wind speed.** A constant value of *w* and *γ* allows to obtain analytical solutions.

(Vrsnak et al. 2012)

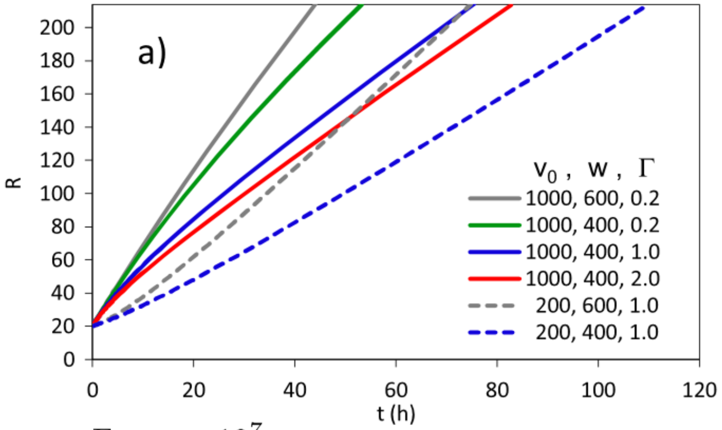
$$r(t) = \pm\frac{1}{\gamma}\ln\left[1 \pm \gamma(v_0 - w)t\right] + wt + r_0$$

$$v(t) = \frac{v_0 - w}{1 \pm \gamma(v_0 - w)t} + w$$

$r_0 = r(t = 0) \simeq 20R_\odot$

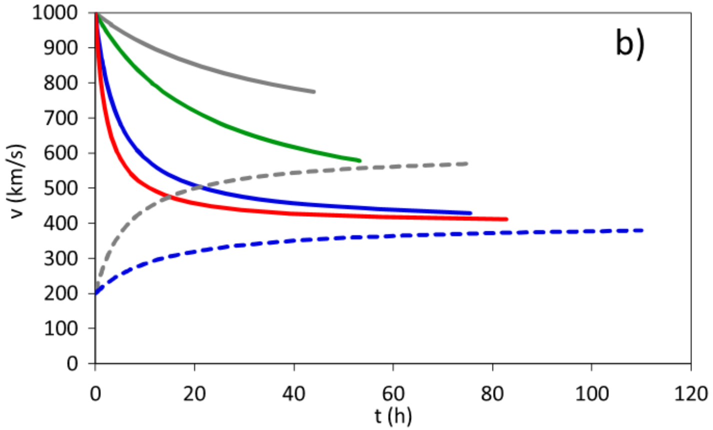
$v_0 = v(t = 0)$

$\pm$ acceleration/deceleration regime



$\Gamma = \gamma \times 10^7$

R in solar radii



The Probabilistic Drag-Based Model

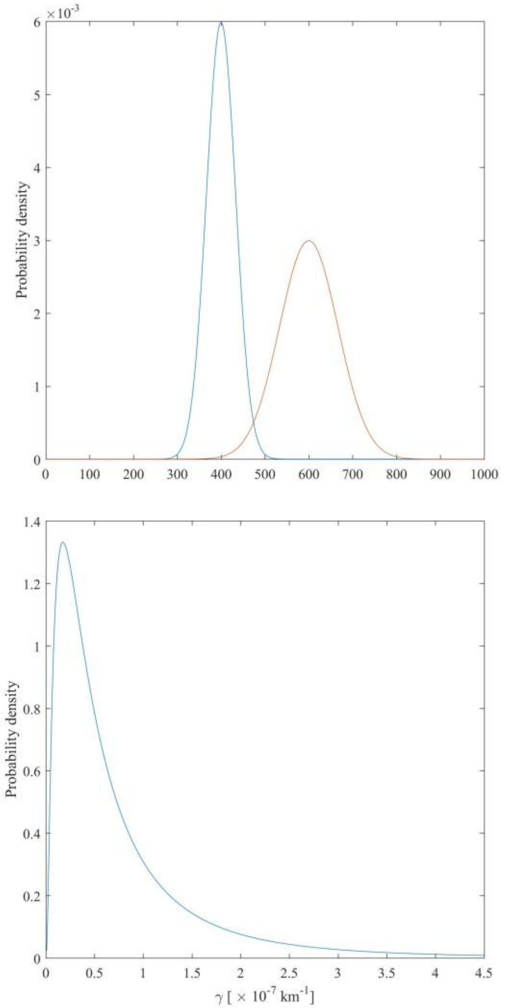


Figure 1. PDFs adopted for the solar wind (left) and the drag parameter (right) in the P-DBM.

The DBM can be employed to compute ICME transit time and arrival velocity at the target distance

r_0 initial distance
v_0 initial speed
d target distance
w solar wind speed
γ drag parameter

ICME transit time T
Impact speed at target distance v_d

Initial position and speed of an ICME are known from measurements, but *γ* and *w* generally aren't. Thus we employ PDFs for these two parameters to generate values of initial conditions and parameters [*r0* , *v0* , *γ* , *w*] to evolve through the DBM. Two distributions for the solar wind speed are possible, accounting for a slow or a fast solar wind accompanying the ICME. This approach is called the "Probabilistic-DBM" (Napoletano et al. 2018), which transforms through the DBM the PDFs associated to the inputs into PDFs for the outputs. Figure 2 shows the distribution of the computed transit time for an ICME obtained generating 50000 values of initial conditions and parameters [*r0* , *v0* , *γ* , *w*] from the respective PDFs.

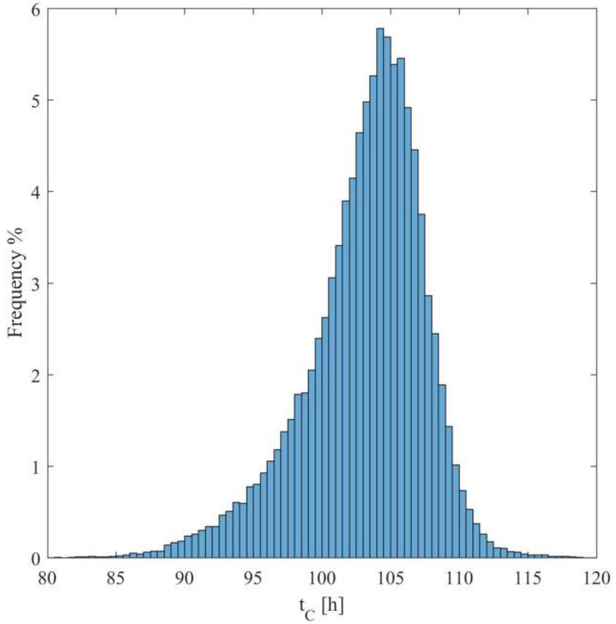


Figure 2. Distribution of the computed transit time obtained through the P-DBM with 50000 randomly generated initial conditions and parameters.

The Probabilistic Drag-Based Model

The P-DBM approach is an ensemble approach for computing ICME transit time and arrival velocity at the target distance together with a confidence interval incorporating our degree of knowledge about input quantities and parameters. The following Figures 3, 4 and 5 show a comparison between PDBM-predicted arrival times at 1AU and experimental values for a sample of 14 CME event for which a complete deprojection from coronagraph images and a safe association to in-situ signature were available (**Shi et al. 2015**).

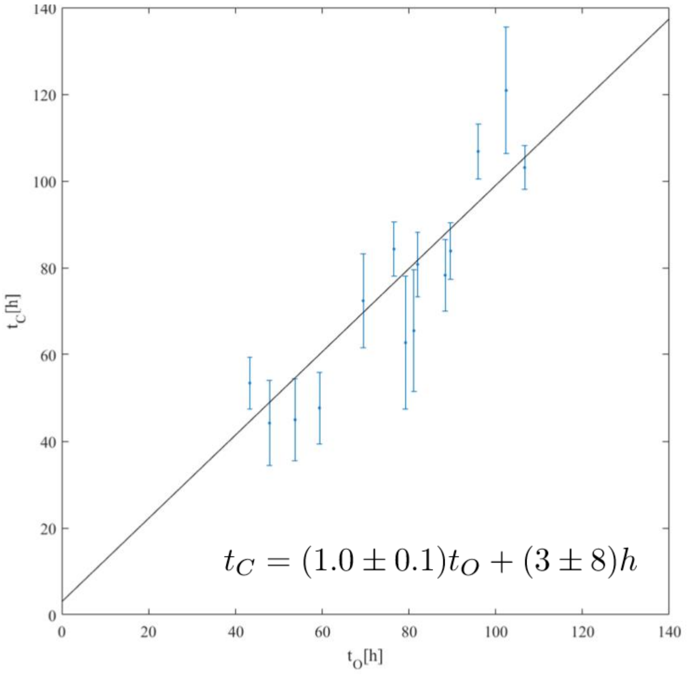


Figure 3: Plot of the computed travel times vs the observed travel times. The black line shows the linear best fit to the data.

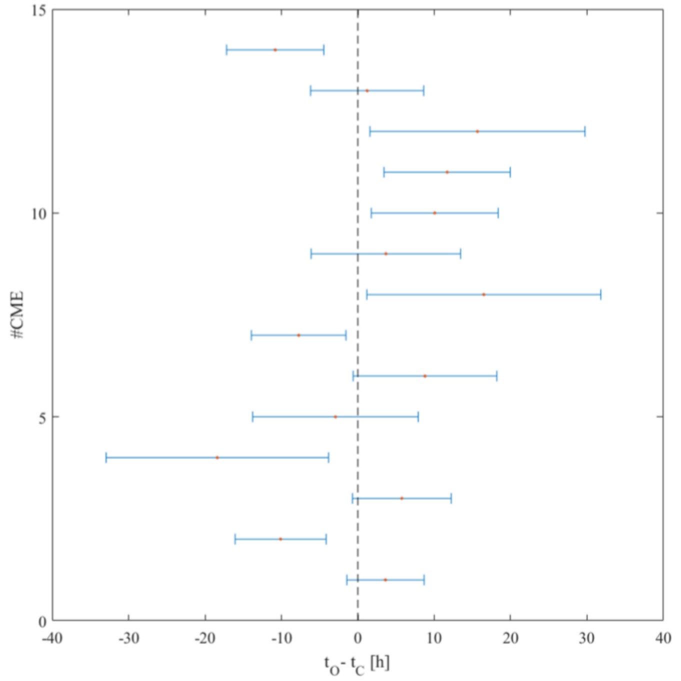


Figure 4: Plot of the time differences between prediction and observation. Events are piled vertically.

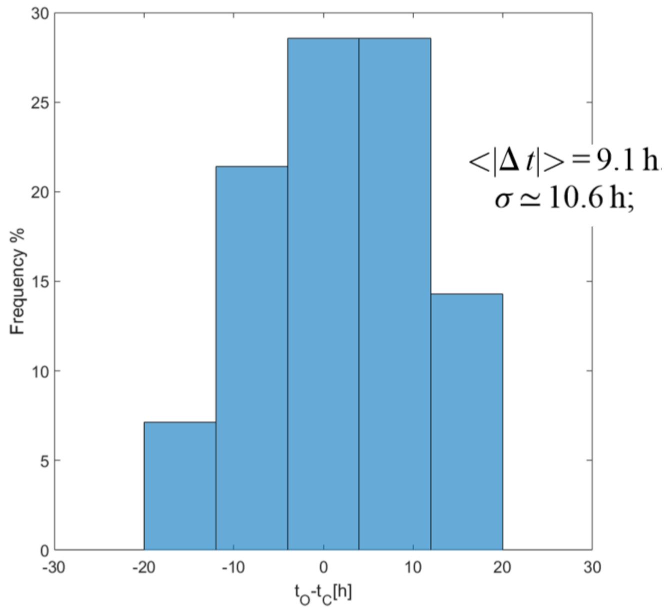


Figure 5: Histogram of the time difference between observed and PDBM computed arrival times.

Inversion procedure for parameters evaluation

Inversion of the DBM equations leaving as an unknown the drag parameter and the solar wind speed allows in principle to determine value of the DBM parameters for each event.

$$(r_0, v_0, t_{1AU}, v_{1AU}) \xrightarrow{\text{Inverse-DBM}} (w, \gamma)$$

Analytic inversion applied to events from Schwenn+2005 & Manoharan 2006 lists of events produced the distributions for the solar wind speed and drag parameter shown in Figure 6:

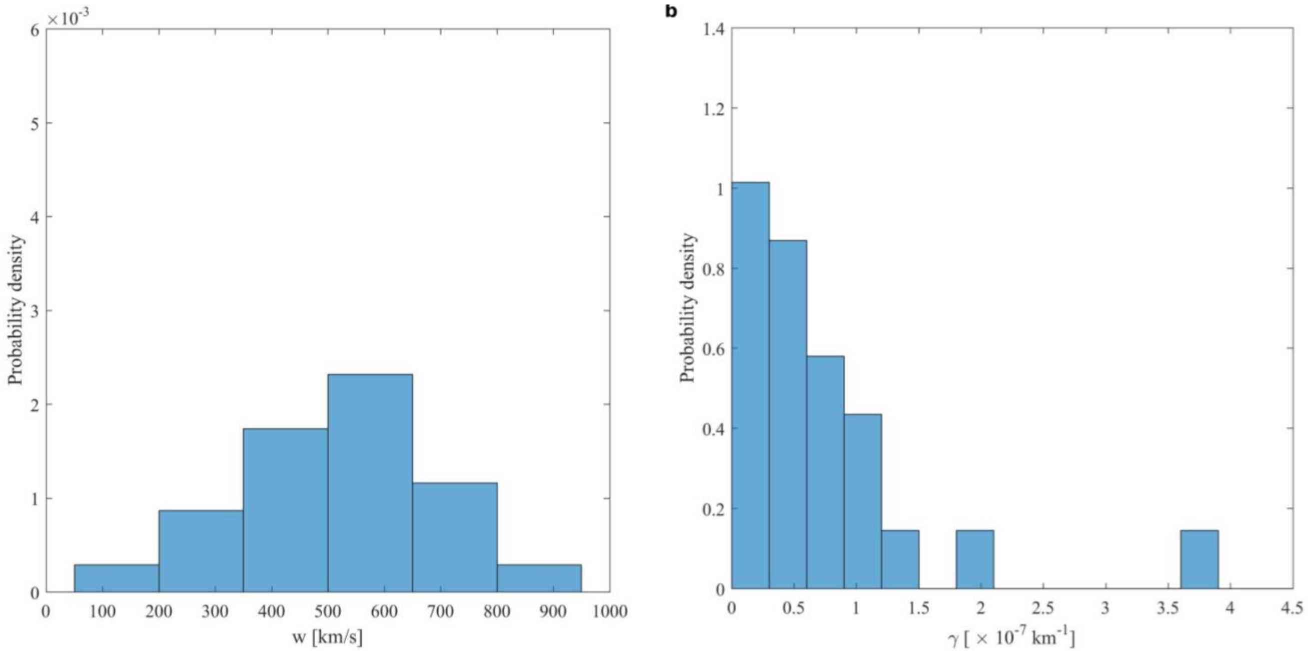


Figure 6: Solar wind speed and drag parameter distributions obtained applying analytic inversion to Schwenn+2005 & Manoharan 2006 lists of events.

$$F(w) = r_1 - r_0 - wT - \frac{(v_0 - w)(v_1 - w)\,T}{(v_0 - v_1)} \ln\left[1 + \left(\frac{v_0 - v_1}{v_1 - w}\right)\right] = 0$$

$$\gamma = \left|\frac{(v_0 - v_1)}{(v_1 - w)(v_0 - w)T}\right|$$

Inverse DBM equations, to solve for *w* and γ given CME initial speed, final speed and transit time (see Vrsnak+ 2012)

Towards a better definition of the parameter PDFs

It is not always possible to realized the analytic inversion of the DBM equation. We improve the input statistics by applying a statistical approach on the parameters' space to look for their distributions. Our starting point is a classical Bayesian framework: given a model parameters experimental data, from Bayes' theorem

$$p\,(\mathrm{Model}|\mathrm{Data}) \propto p\,(\mathrm{Data}|\mathrm{Model})p\,(\mathrm{Model})$$

then our goal is to sample a likelihood function of the parameters

$$\mathscr{L}\,(\mathrm{Model}) = p\,(\mathrm{Data}|\mathrm{Model}) \propto \exp\left(-\frac{\chi^2}{2}\right)$$

with χ^2 being a sum over data points i,

$$\chi^2 = \sum_i \frac{(\mathrm{Model}_i - \mathrm{Data}_i)^2}{\sigma_i^2}$$

In our specific case, (w, γ) are the model parameters and $(r_0, v_0, t_{1AU}, v_{1AU})$ the experimental data, and

$$\chi^2 = \sum_{j=1}^{N} \left[\frac{(T(\gamma, w) - T_j^{exp})^2}{\Delta T^2} + \frac{(v_1(\gamma, w) - v_{1j}^{exp})^2}{\Delta v_1^2} \right]$$

Is the prior function. We adopt a Monte Carlo Markov Chain algorithm to compute the parameters distributions in the (w, γ) space.

Towards a better definition of the parameter PDFs

Fast wind events:
- Higher mean value
- Secondary peaks
- Lower drag parameter

Slow wind events:
- Sharp peak
- Higher drag parameter

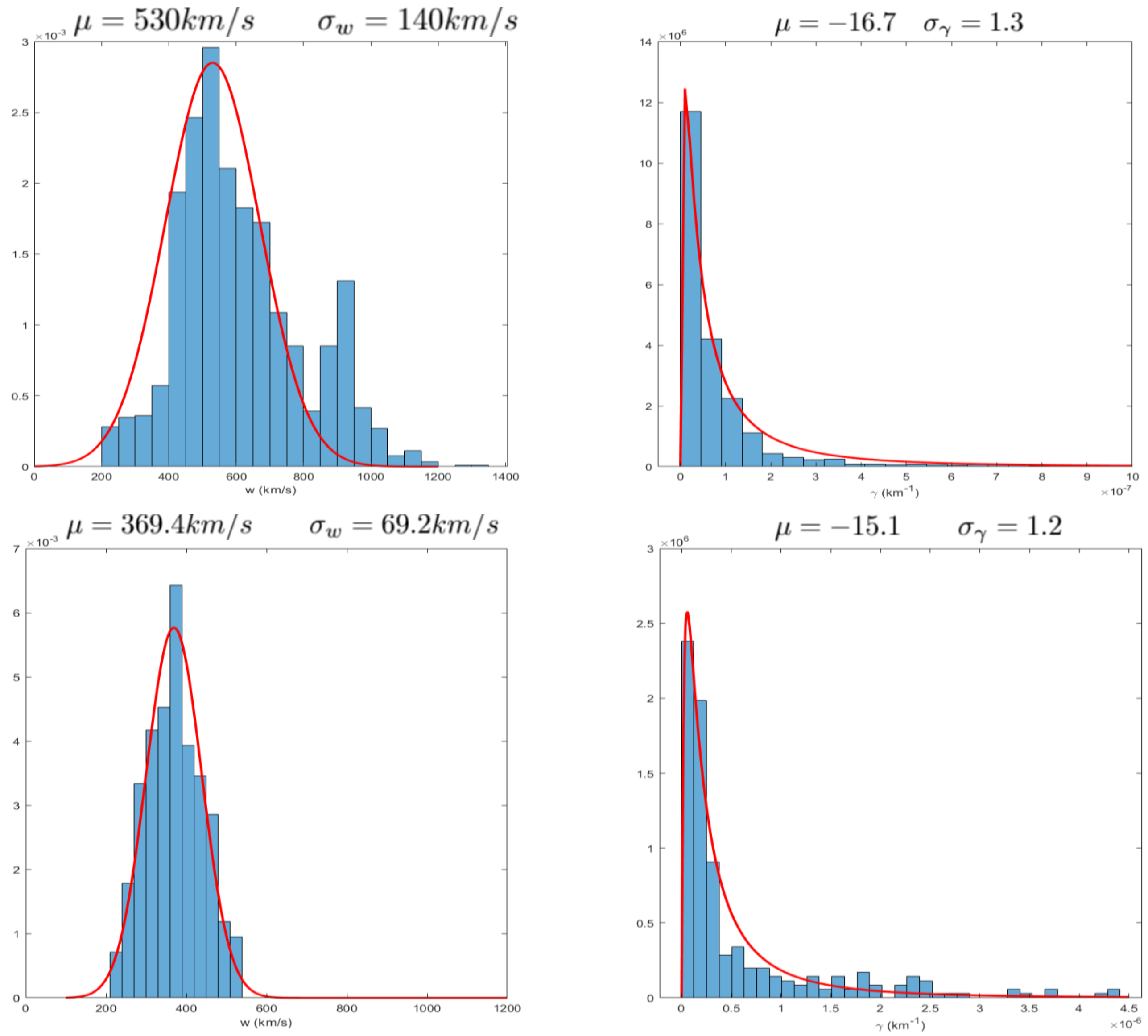


Figure 7: results for DBM parameters distributions obtained after MCMC statistical inversion technique.

Figure 7 shows the parameters distributions obtained through the MCMC inversion. Such results are certainly in agreement with the original distributions for the solar wind speed and drag parameter employed in the first version of the PDBM. In addition, these new PDFs suggest that the ICME is subject to a different order of drag in relation to the solar wind regime, with a generally higher and broader drag distribution for the slow wind case.

Testing the new solar wind and drag parameter PDFs

The previous distributions are now re-introduced in the PDBM and tested against an independent list of events. For this purpose, we employed the CME list compiled by Paouris and Mavromichalaki 2017, containing 214 well-associated cases of CME arrived at 1AU. Figure 8 shows results for the difference between the observed and computed arrival times (left) and arrival speed (right).

$$< \Delta T >= -2.0h$$

$$\sigma_{\Delta T} = 16.7h$$

$$< \Delta v_1 >= -132.6km/s$$

$$\sigma_{\Delta v_1} = 88.0km/s$$

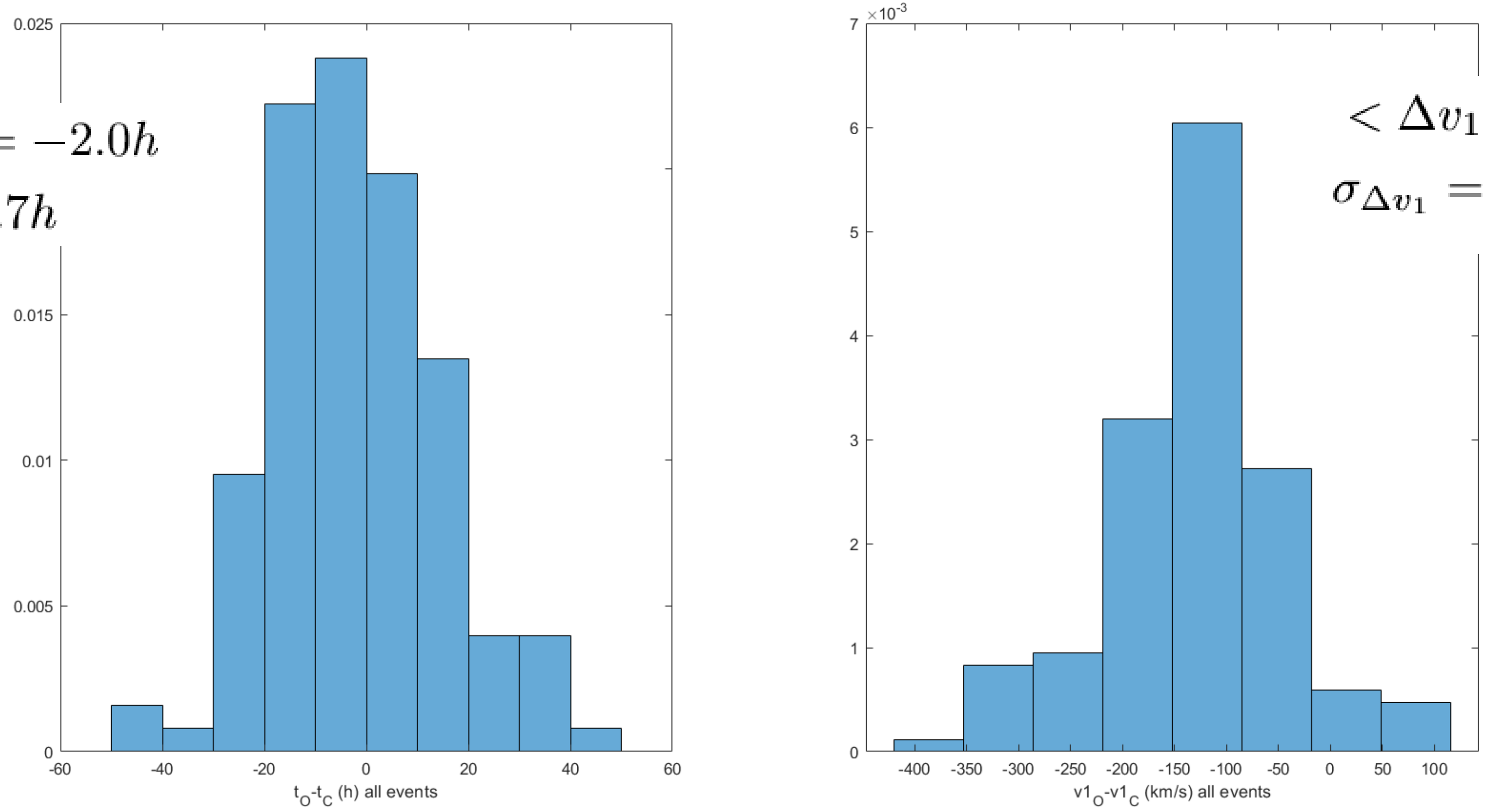


Figure 8: histograms for the difference between the observed and computed arrival times (left) and arrival speed (right).

Testing the new solar wind and drag parameter PDFs

Histograms in Figure 9 show the results from application of the PDBM to Paouris 2017’s list of events after separating between the fast and slow solar wind events. Differences between observed times and computed times (up) and observed arrival speed and computed arrival speed (down) are presented according to the solar wind regime employed in the PDBM computation.

Despite a systematic overestimation of the arrival speed in both cases, with no significant difference between the two speed distributions, it is clearly seen that the agreement between model prediction and observations is further improved when considering fast wind events alone.

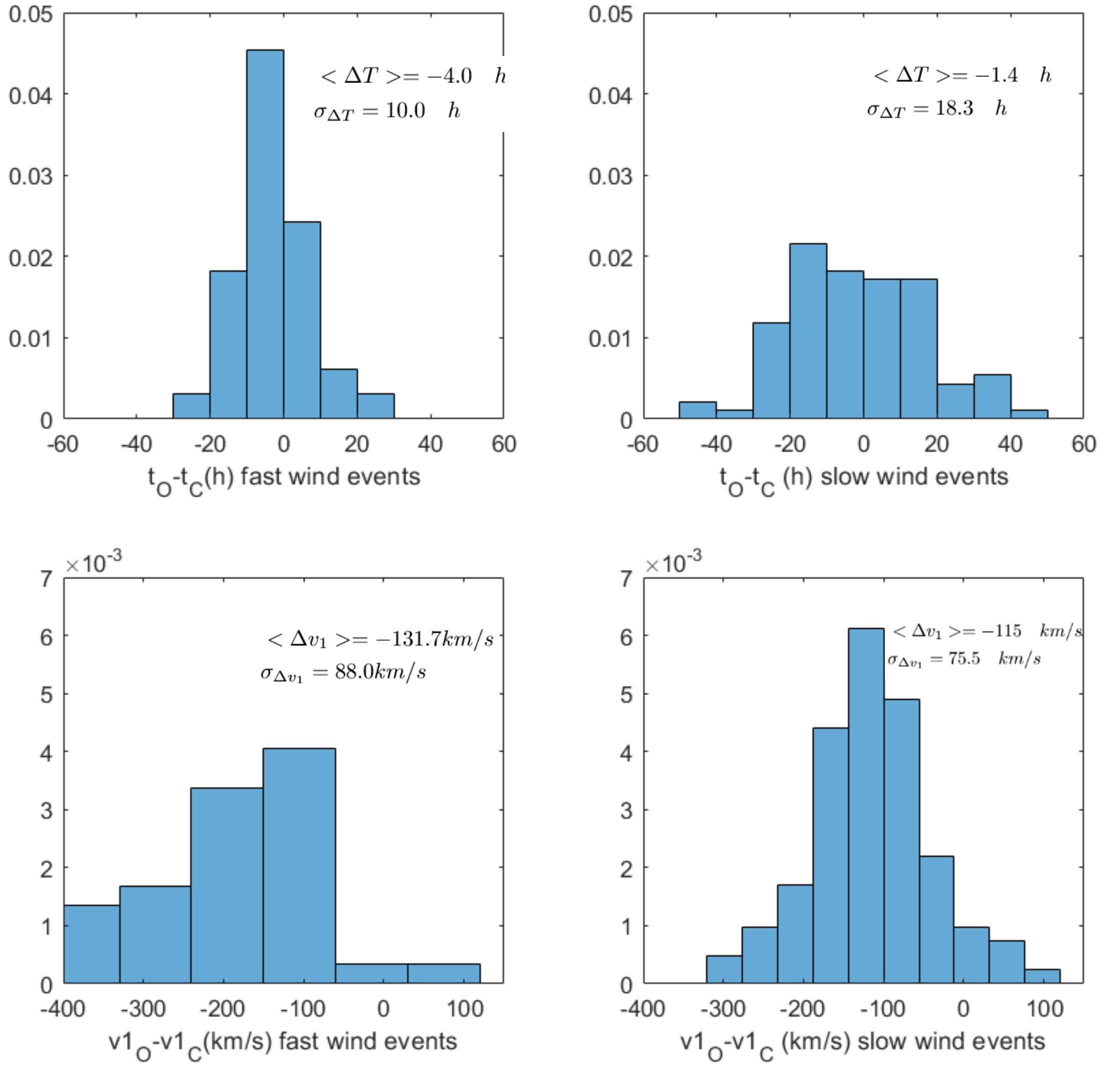


Figure 9: histograms for the difference between the observed and computed quantities separated respect to the solar wind regime.

Conclusions

- Simplified models offer a computationally efficient alternative to numerical model for the purpose of forecasting and involving several parameters which must be properly evaluated;
- A Monte Carlo approach to the DBM inversion for the parameters evaluation allows to enlarge and refine the statistics, enforcing our first assumptions for the solar wind distributions and providing a new result for the drag parameter distributions;
- Our results suggest that to improve the forecast accuracy, different distributions for the drag parameters are to be employed as a function of the solar wind regime the ICME is subject.

References

- **G. Napoletano, R. Forte, D. Del Moro, E. Pietropaolo, L. Giovannelli and F. Berrilli**: "*A probabilistic approach to the Drag-Based Model*", Journal of Space Weather and Space Climate (2018);
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- **B. Vrsnak et al**.: "*Propagation of Interplanetary Coronal Mass Ejections: The Drag-Based Model*", Solar Physics (2012).