STEREOCat Speed de-projection of SEP-Related CMEs

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Abstract.

Particles accelerated to high energies by solar eruptive phenomena can reach the Earth moving along the interplanetary magnetic field lines. We use a list of 156 SOHO ERNE 20 MeV solar energetic particle (SEP) events from solar cycle 24 (2009–2017) with identified solar origin (e.g. flares and CMEs). The aim of this study is to evaluate the 3D parameters of SEP-related CMEs and estimate if they can give us a better insight of SEP production than the previously used 2D velocities. The 3D kinematic properties of the CME set are explored using observations from STEREO SECCHI and SOHO LASCO coronagraphs based on the STEREOCat analysis tool.

Introduction

CMEs are changes in coronal structure including appearance and ejection of bright formation of plasma that can be observed at various wavelengths (white-light, soft X-ray, EUV, etc.). Usually their speeds are estimated in the plane of the sky (which is a projection of their real velocities) and have typical values in the range between 20 and 2000 km s^{-1}. Occasionally it may reach values up to 3500 km s^{-1} [*Chen P. F.*, 2011]. The mean CME speed varies between 300 km s^{-1} (near solar minimum) and 500 km s^{-1} (near maximum of the solar cycle) [*Yashiro S., et al.*, 2004].

CME parameters are important part of all CME propagation models as initial conditions. Such models help to estimate the CME path and arrival time at various locations, which requires precise evaluation of CME parameters.

Solar energetic particles (SEPs) are the in situ observed electrons, protons and ions of solar origin that were accelerated by processes taking place at solar eruptive phenomena and propagated through the interplanetary space to spacecraft outside Earth magnetosphere. SEP events constitute an important space weather component that carry technological and biological risks [*Pulkkinen T.*, 2007; *Semkova J., et al.,* 2018]. Mitigation procedures start with an improved forecasting of the phenomena that involves better knowledge on their connection to solar eruptive events. Generally, when quantifying the relationship between SEP intensity and solar flare flux and CME speed, one used Pearson correlation analysis. Apart from selected event cases described by *Park et al.* [2017], only SOHO/LASCO CME projected speeds were used previous papers. In this study, we expand the sample size by covering solar cycle 24.

Data

CMEs are visible in white light as bright structures moving away from the Sun in coronagraphs. The best observations of CMEs nowadays are provided by SOHO and STEREO missions. For the analysis performed in this study, we used data from the following coronagraphs:

- Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) COR 2 on board both the STEREO Ahead & Behind spacecraft (FOV – out to 15R$\odot$).
- Large Angle and Spectrometric Coronagraph (LASCO) C3 – SOHO with FOV 3.7÷32R$\odot$ above the solar limb.

The analysis presented in this study is done using the StereoCat tool. Related SEP events are explored using data from SOHO/ERNE ~20 MeV energy channel.

The aim is to estimate "true" 3D velocities of SEP-related CMEs and compared it with 2D speeds, provided by SOHO LASCO CME Catalog.

Results

a) Velocity distributions of SEP-related CMEs

A list of 156 solar energetic particle (SEP) events was obtained for the period of solar cycle 24 (2009–2017). All events were associated with CMEs and 112/156 events were also linked with solar flares.

We estimated the "true" velocities of SEP-related CMEs with STEREOCat tool, which allows common measurements using only 2 spacecraft data at once. Depending on visibility of eruptions by different instruments we made measurements with all possible combinations of telescopes. 41/156 CMEs were observed simultaneously by the 3 instruments and we estimated 3 values for their 3D speeds (STEREO A + LASCO C3; STEREO A + STEREO B; LASCO C3 + STEREO B). Since no STEREO Ahead data is available for the period 2014 July–2015 November and after October 2014 STEREO Behind is out of order, measurements for 28/156 events observed in this periods are impossible. 8/156 CMEs are only observed simultaneously by STEREO B and C3 (in the period of STEREO A data gap) and in other 9 cases the only possible combination includes STEREO A and C3 data (after communications with STEREO B dropped down).

Finally, we have 64 measurements by the pair STEREO A and LASCO C3, 56 calculations by STEREO A and STEREO B and 53 – by LASCO C3 and STEREO B. We plotted the distributions of the 3D velocities by each pair (Figure 1a, b, c) as well as the distribution of 2D velocity quantified by LASCO CME Catalog (Figure 1d).

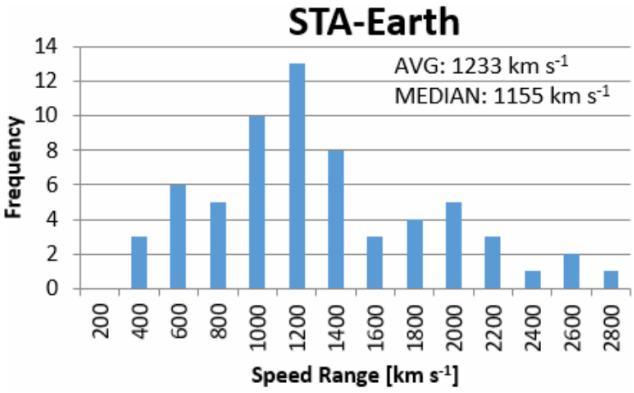
The average and median velocities in each case show that we have similar values from the 3 different combinations of instruments that estimate 3D speeds (average velocities between 1220 and 1273 km s^{-1} and median velocities 1148–1156 km s^{-1}), but they differ from the values obtained by the 2D sample (average and median speeds, 1003 km s^{-1} and 928 km s^{-1}, respectively).

b) Comparison between measured 3D and 2D velocities

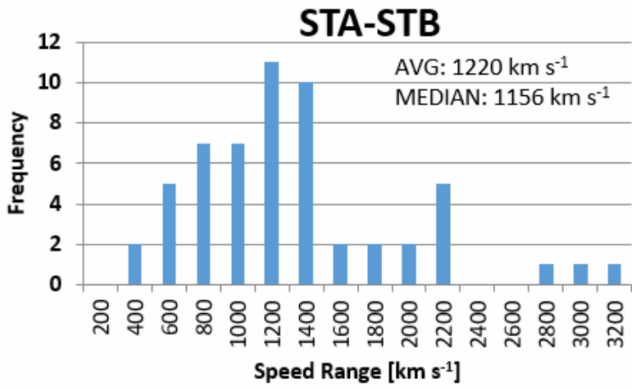
To compare the calculated velocities with LASCO 2D CME speeds we plotted the dependence and estimated Pearson product-moment correlation coefficient r for each plot (values are given in Table 1). The most powerful relation with 2D speeds seems to be with the velocities measured by STEREO A + LASCO C3 pair, although other pairs also show high positive correlation with 2D velocities. The uncertainties are calculated using bootstrapping method based on a sample of 1000 calculated correlations. Coefficients of determination (r^2) for each pair is also estimated and listed in Table 1.

Table 1. Pearson product-moment correlation coefficients r and coefficients of determination for 3D velocities measured by each pair of instruments with 2D LASCO speeds.

Pair of instruments	r	$r^2 \times 100$ [%]
STEREO A + C3	0.86±0.04	74
STEREO A + B	0.78±0.08	61
C3 + STEREO B	0.83±0.05	69



a)



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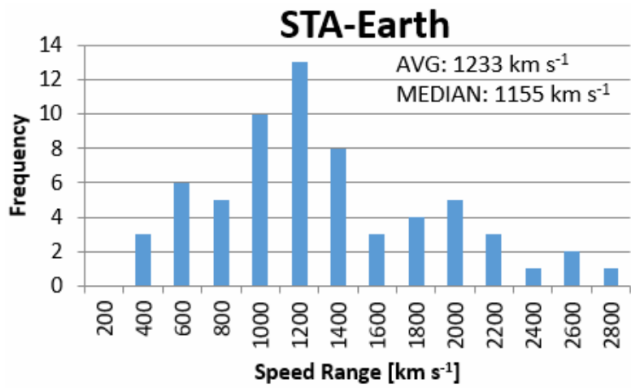

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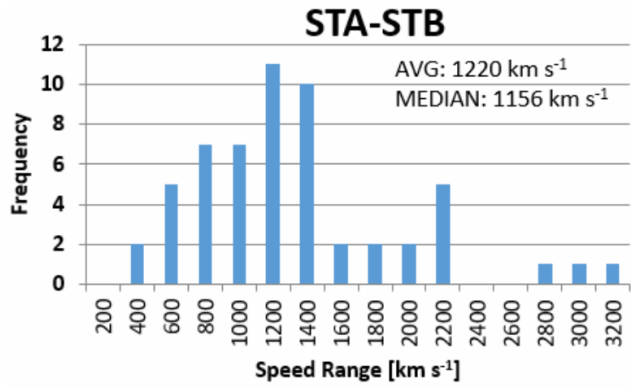

d)

Fig. 1 Distribution of the velocities of SEP-related CMEs according to the pair of instruments used for the measurements. STA denotes STEREO A, STB – STEREO B, Earth - SOHO.

Pearson correlation coefficient is also calculated to reveal a relation between a characteristic of SEP-related event (CME or flare) and peak intensity of SEP event, detected on 20 MeV by SOHO/ERNE. Results are listed in Table 2.

The highest correlation again is with 2D LASCO speeds, although STEREO A combinations with C3 and STEREO B also give close value.

Table 2. Pearson product-moment correlation coefficients r and coefficients of determination for relations of different properties (2D and 3D CME speeds, and flare class) with peak intensity of the associated proton event on 20MeV.

	Properties	No. of events	r	$r^2 \times 100$ [%]
20 MeV protons SOHO/ERNE peak intensity vs.	Flare class	112	0.42±0.07	18
	2D LASCO CME speed	156	0.55±0.05	30
	ST A+C3 CME speed	64	0.47±0.09	22
	ST A+ST B CME speed	56	0.47±0.11	22
	C3+ST B CME speed	54	0.42±0.11	18

Conclusions

We present a study of "true" 3D velocities of CMEs related with the SEP events from solar cycle 24.

Our results show that 3D speeds are in general larger than the SOHO/LASCO projected speeds. Correlation coefficients while using the 3D speed are smaller than those when using 2D speeds, although the differences are within the statistical uncertainty. Thus, LASCO CME speeds tend to overestimate the relevance of CMEs as the origin of SEP events, at least in a statistical sense.

Acknowledgment

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