TRAJECTORY ESTIMATION FOR FRESH IMPACTS ON MARS

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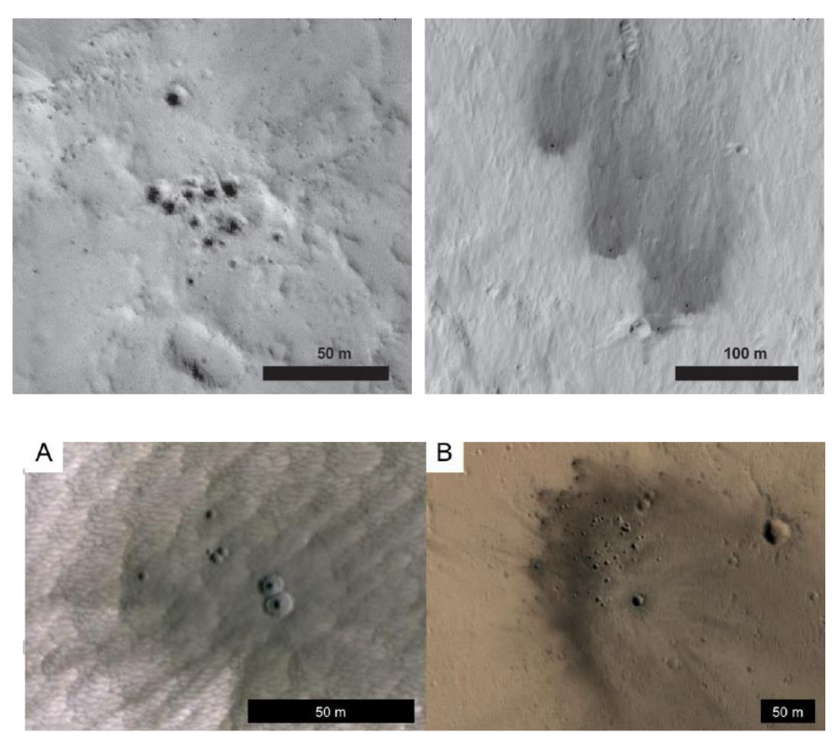
Introduction



In recent years, about 700 fresh dated meteoroid impact sites have been discovered on Mars (Malin et al., 2006; Daubar et al., 2013,2019), leading to the formation of single craters and crater fields, with crater sizes up to 50 m (1 m< due to resolution limit). 52% of known dated impacts occur as clusters. Examples of the fresh Martian clusters of craters are shown on Fig.1.

In the case of thick Earth atmosphere, meteoroids impacts rarely result in meteorites strewn fields and it is difficult to distinguish different material types. Meteoroid properties estimates depend on fragmentation, and its models (calibrated on relatively small number of events). Due to the more rarefied Mars atmosphere falling meteoroids are less destroyed and form fresh craters and crater clusters. Meteoroids on Mars give an unique possibility to see fragmentation results at similar to 30 km on Earth altitudes.

Fig.1. Examples of the fresh Martian impacts (from Hartmann et al. 2018;Daubar et al. 2019)

Impactors

Two types of meteoroids (asteroid and comet) were considered and corresponding impactor size were calculated based on scaling relations (Housen&Holsapple 2007) assuming rock target

$$D_{cr} = D_{imp}*0{,}93*\left(\frac{g*D_{imp}}{2*V^2}*\left(\frac{\delta}{\rho_{imp}}\right)^{\frac{2*\nu}{\mu}}+\left(\frac{Y}{\delta*V^2}\right)^{1+\frac{\mu}{2}}*\left(\frac{\delta}{\rho_{imp}}\right)^{\frac{\nu*(2+\mu)}{\mu}}\right)^{\frac{-\mu}{2+\mu}}$$

$$\mu = 0{,}55;\ \nu = 0{,}4;\ \delta\text{=2650 kg/m3}$$

$$V = V_0*\sin\frac{\pi}{4} = 10^4*\sin\frac{\pi}{4}$$

$$Y\text{=6.9 MPa}$$

here D_{cr} is crater diameter; D_{imp} means size of impactor with density ρimp; which enters the atmosphere at 45^0 with velocity V_0; g is gravity acceleration; δ is target density; ν and μ are constants defined by target; Y is effective strength of the target material.

- ☐ Impactor size D_{imp} estimated on crater size D_{cr} is quit uncertain (2-3 times; Fig.3)
- ☐ Impactors are roughly 0.2-3 m in diameter. Impactors of these sizes are permanently observed on the Earth by bolide networks and satellites (UGS).
- ☐ The impactor (D,V,α) would create different size craters at different elevations above Martian surface.

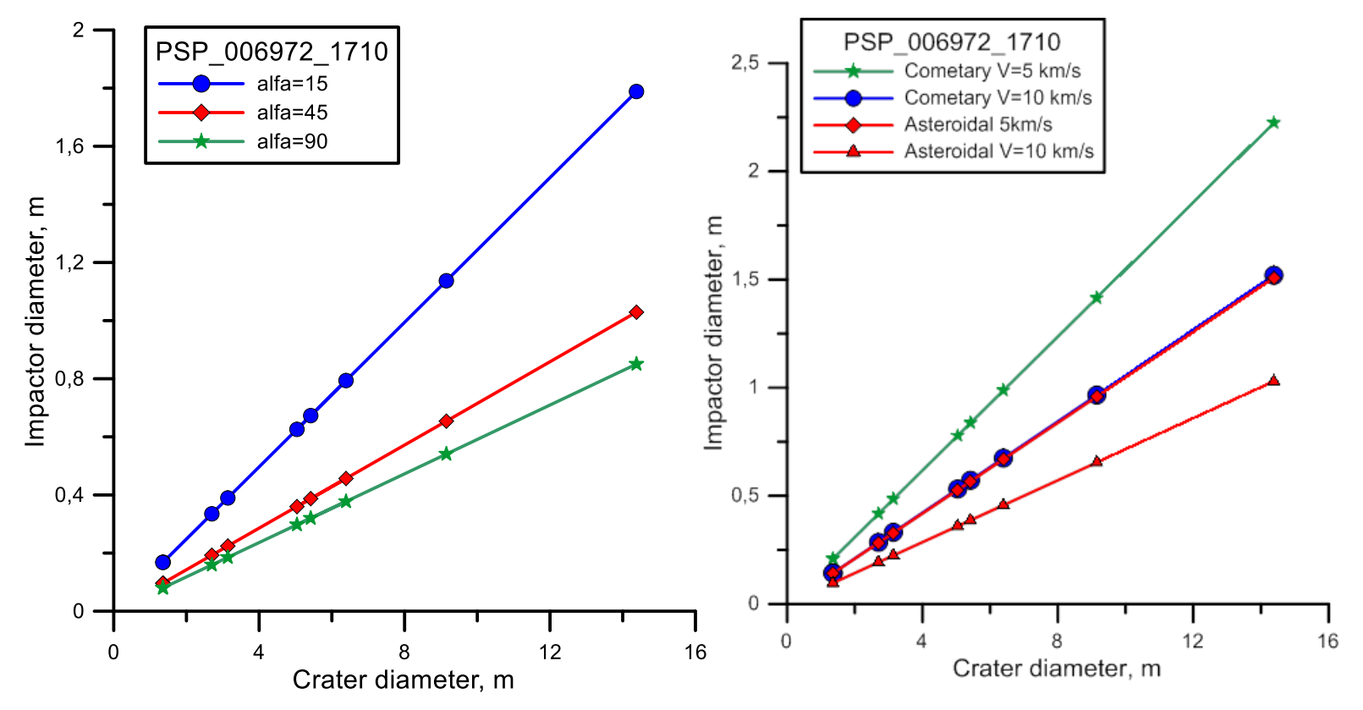


Fig.2. Uncertainty of impactor size calculation occurring due to uncertainty of

A. entry angle ;
B. impactor velocity and projectile density

Craters Strewn Fields Descrption

Scattering field depends on many factors, including impactor size, its strength and strength of its fragments, density, fragmentation pattern and others. The study of clusters can provide an opportunity to determine these characteristics. It was suggested (Daubar et al.,2019) that crater strewn field may be described by an ellipse, and the properties of the semi-axis allows to determine the impact angle and azimuth of the impactor trajectory. Daubar et al. (2019) used the Khachiyan algorithm (Oliker and Ostfeld,2014) to determine the ellipse. We decided to check how sensitive are the results to the used algorithm. Several approaches were considered. Two algorithms, which found best ellipses including 90% of craters in cluster, were selected (Podobnaya et al., 2020).

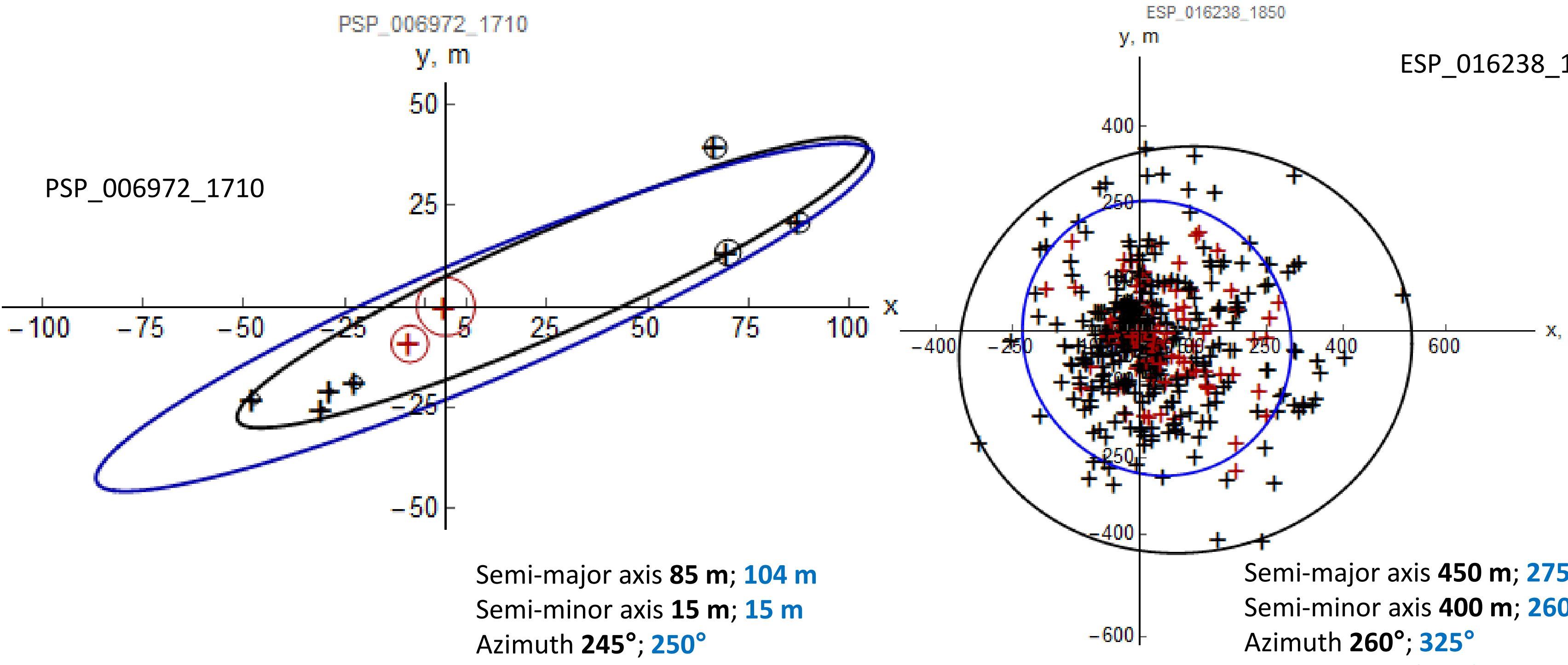
First algorithm, called next **MVE**, was used by Daubar et al (2019). Bootstrap procedure (Efron and Tibshirani, 1986) was used for more reliable results and possible incomplete data compensation. Minimal square ellipses which cover 300 random craters sets were built for each cluster. Averaged ellipse is used as the result. Next algorithm, called below **Stat**, is a statistical ellipse, integrated to Wolfram Mathematica software.

Orientation of the projectile trajectory is defined by two angles – entry angle and azimuth. Ellipse major axis inclination determines the trajectory azimuth, flight direction was chosen from the ellipse center to the direction, where total diameter of the fragments is larger. Clusters under consideration contain from 2 to 465 craters. Minimal crater size in clusters is about 1 m, due to the resolution of used cameras.

55 clusters include more than 5 craters, and for them we found scattering ellipses, covering 90% of craters in cluster. Size of the scattering ellipse contains information about fragmentation. Besides, parameters of the meteoroid trajectory can be estimated (for example entry angle and azimuth).

Craters Strewn Fields

- Data for 77 crater fields (clusters) is considering. They contain from 2 to 465 craters. For 55 clusters with more than 5 craters scattering ellipses were constructed.
- Both MVE and Stat cover 88% from all cluster craters in general.
- MVE and Stat poorly describe clusters with less than 10 craters.
- MVE describes clusters with minimal square ellipses in comparison with Stat. For biggest clusters MVE covers larger than 90% craters.



PSP_006972_1710

Semi-major axis **85 m**; **104 m**
Semi-minor axis **15 m**; **15 m**
Azimuth **245°**; **250°**
Entry angle **80°**; **80°**
Covering **26**; **27** of 28 craters

ESP_016238_1850

Semi-major axis **450 m**; **275 m**
Semi-minor axis **400 m**; **260 m**
Azimuth **260°**; **325°**
Entry angle **30°**; **20°**
Covering **462**; **417** of 465 craters

Fig. 3. Examples of crater locations inside clusters. Red points - largest quartile of craters. Ellipses refer to considered methods: **Stat** and **MVE**. Axes origin is at the largest crater in cluster.

Comparison with previous results

Obtained scattering ellipses were compared with results from Daubar et al. (2019):

- **MVE** and Stat provide an agreement in the results of entry angles with precision about 10°, the difference with **Daubar et al. (2019)** doesn't exceed 15° in general.
- Obtained trajectory projection angle demonstrates not more than 20° difference between **MVE**, **Stat** and **Daubar et al. (2019)** in most cases.
- Average difference from ellipses in **Daubar et al. (2019)** : **MVE** – 1.65; **Stat** – 1.43 times larger.
- For 40% of clusters difference in azimuth estimations isn't more than 30° and for 50% of clusters the direction of flight differs (180°±30°).

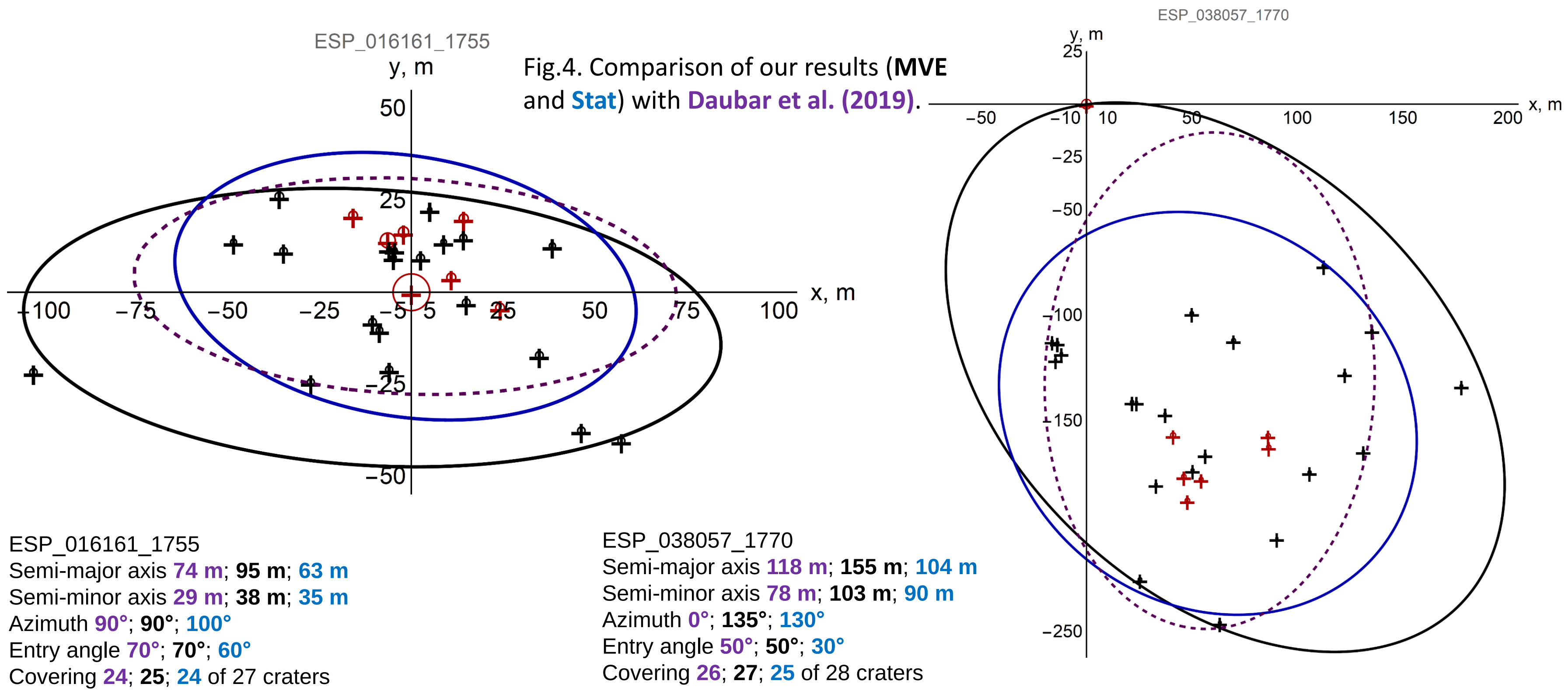


Fig.4. Comparison of our results (**MVE** and **Stat**) with **Daubar et al. (2019)**.

ESP_016161_1755
Semi-major axis **74 m**; **95 m**; **63 m**
Semi-minor axis **29 m**; **38 m**; **35 m**
Azimuth **90°**; **90°**; **100°**
Entry angle **70°**; **70°**; **60°**
Covering **24**; **25**; **24** of 27 craters

ESP_038057_1770
Semi-major axis **118 m**; **155 m**; **104 m**
Semi-minor axis **78 m**; **103 m**; **90 m**
Azimuth **0°**; **135°**; **130°**
Entry angle **50°**; **50°**; **30°**
Covering **26**; **27**; **25** of 28 craters

Earth scattering ellipses

As an independent testing, the considered methods of constructing a scattering ellipse were applied to two recent terrestrial meteorite strewn fields - Ozerki and Chelyabinsk meteorites, for which all trajectory parameters are known. Entry angle into the atmosphere and azimuth were found from the obtained scattering ellipses.

Ozerki meteoroid:

- June 21, 2018
- Lipetsk region, Russia
- Maximum brightness height 27.2±0.9 km
- Meteoroid parameters: diameter 4 m, velocity 15 km/s, density 3240 kg/m^3
- Observed flight azimuth was 58°±3°, it is very different from our estimates (307°-320°)
- Entry angle was 78° from horizontal (based on videos) with our estimates of 33-35°

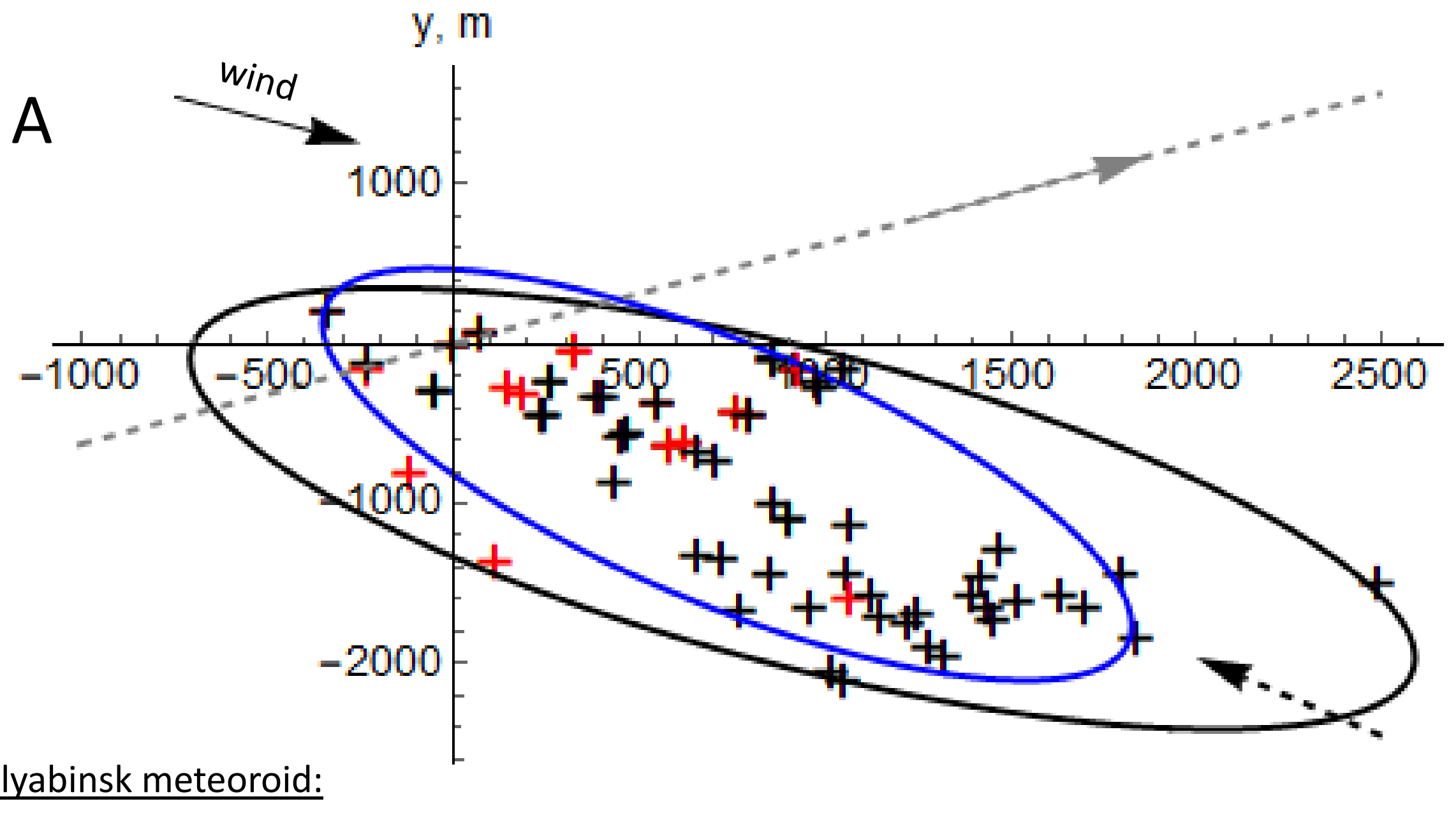


Fig.5A. Scattering ellipses, covering found fragments (**MVE** and **Stat**). Pluses – fragments location (maximal quantile marked red). Black dashed arrow - mean azimuth. Gray arrow - flight direction from Kartashova et al. (2020).

Chelyabinsk meteoroid:

- February 15, 2013
- Chelyabinsk, Russia
- Meteoroid parameters: diameter 19 m, velocity 19 km/s, density 3300 kg/m^3
- Calculated azimuths are 284-285°, which is very close to independent sources (Popova et al., 2013; Borovička et al., 2013)
- Entry angle estimation was 18° from horizontal with our estimates of 7-8°

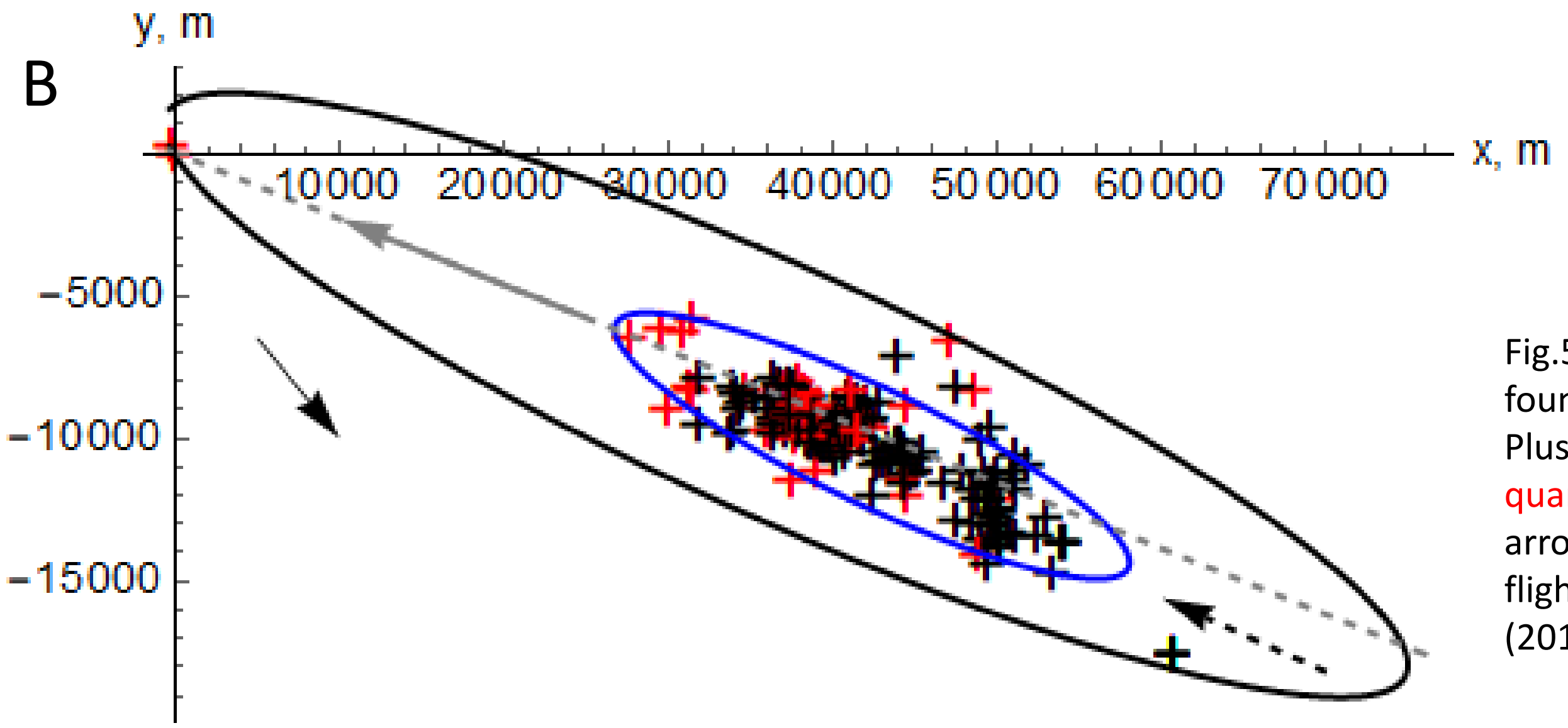


Fig.5B. Scattering ellipse, covering found fragments (**MVE** and **Stat**). Pluses - location of fragments (maximal quantile marked red). Black dashed arrow - mean azimuth. Gray arrow - flight direction from Popova et al. (2013).

Crater ejecta

- ○ HiRISE (High Resolution Imaging Science Experiment) is a camera which made high resolution images of Mars. Due to it we can look to the images of craters arrangement in considering clusters and their ejecta.
- ○ For oblique impacts crater ejecta is asymmetrical and is more pronounced in the direction of flight (Shuvalov,2011).
- ○ For some clusters tracks of the shock wave can show the direction of meteoroid flight (Burleigh et al., 2012; Ivanov et al., 2010).
- ○ The images allow us to consider craters ejecta in detail for a number of clusters.
- ○ For 40 from 55 clusters, we could define the direction of meteoroid flight based on ejecta pattern.
- ○ Comparison of meteoroids flight direction, received from craters ejecta, with azimuths from scattering ellipses, showed a discrepancy: for 12 clusters difference is not more than 45° and for 19 clusters results differ on direction (180°±45°). Other results do not correlate.
- ○ Bad correlation of results implies the need of considering other ways of finding the meteoroid flight direction. Strewn field modeling is planned.

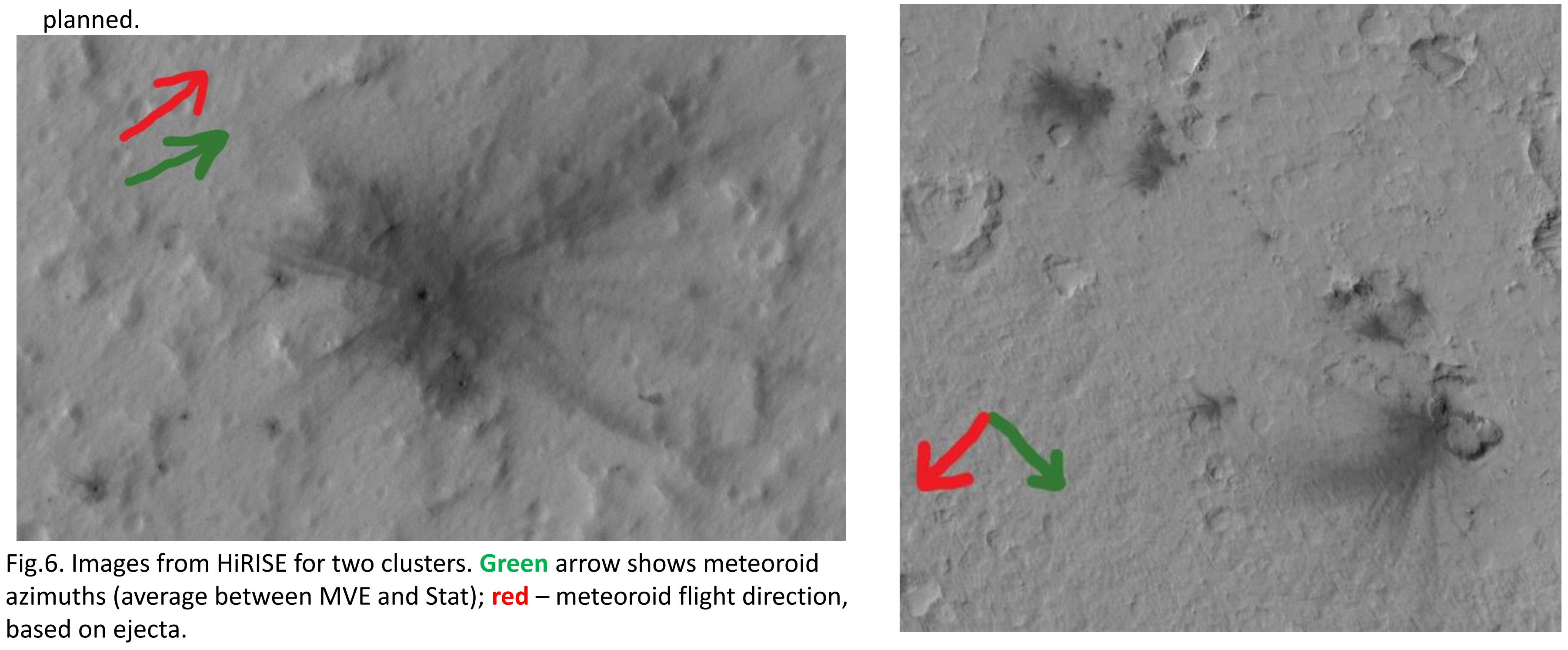


Fig.6. Images from HiRISE for two clusters. **Green** arrow shows meteoroid azimuths (average between MVE and Stat); **red** – meteoroid flight direction, based on ejecta.

Summary

- ✓ Crater strewn fields were described by an ellipse. It is suggested that it allows to estimate trajectory azimuth and entry angle. Several methods of ellipse construction were applied to fresh Martian crater clusters. Best ones were chosen.
- ✓ Meteoroid flight direction was calculated to the side from the ellipse center, where the total size of craters (fragments) is larger.
- ✓ All results shows no more than 20° difference in most cases for the angle of meteoroid trajectory projection. Meteoroids flight directions were compared with Daubar et al. (2019): for 40% of clusters difference is less than 30°, for 50% - the direction of flight differs (180°±30°).
- ✓ Meteoroid entry angle depends on the ratio of scattering ellipse semi axes, its estimations in most cases do not differ more than on 15°.
- ✓ Comparison of scattering ellipses with results from Daubar et al. (2019) demonstrated difference in area of ellipses about 1.5 times. Considering scattering ellipses in average cover 88% of craters in cluster.
- ✓ Scattering ellipses were constructed for two Earth meteoroids – Ozerki and Chelyabinsk. It was shown that it is possible to estimate the azimuth and the entry angle for large fragments with a flat entry trajectory, whose fall is little affected by wind. The scattering field of small fragments of a meteoroid with an almost vertical trajectory of entry is determined only by wind drift.
- ✓ For some clusters meteoroid flight direction was found by crater ejecta. It was compared with azimuths, calculated from scattering ellipses: for 12 from 40 clusters directions fit with accuracy of 45° and for almost 20 clusters directions are opposite (180°±45°). Bad correlation of results implies the need of considering other ways of finding the meteoroid flight direction. Scattering fields simulation is in plans.

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