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Interactive comment on "Incidence of rough and irregular atmospheric ice particles from Small Ice Detector 3 measurements" *by* Z. Ulanowski et al.

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Response to Anonymous Referee #1

We thank Referee 1 for extensive and insightful comments, and many suggestions on how to improve the article. Below we deal with individual numbered comments.

Main Comments

1.(a and b) A total of 23 test patterns from 16 particles were used in the comparison given here, as already shown in Fig. 4. Data from some of the particles was obtained for two orientations and up to three different image intensifier gain values. For example, for particle (b) and (f) there were two gains and two orientations, for particle (e) two orientations, and for particle (f) three gains and two orientations. The variability of roughness measures can be seen in Fig. 4 by looking at the spread of data points along the vertical axis. The Referee is correct in surmising that particle orientation can influence the roughness measures. We found that the speckle measures varied with the orientation of the particles. For the samples (b), (e) and (f) in the collection presented here the combined roughness varied with orientation between 0.32 and 0.38, 0.34 and 0.7, and 0.78 and 0.87, respectively. We interpret this variability as originating partly, or mostly, from the fact that the roughness measures depend on the presence or absence of features in the 2D scattering patterns: for smooth crystals bright spots and arcs appear (Ulanowski et al. 2006), and their presence leads to lowered roughness measures. However, the position of these features depends critically on crystal orientation, and in some orientations they may disappear entirely from the 6 to 25° scattering angle range encompassed by the SID-3 detector. See also the response to comment (7) below, where the spread in the halo ratio measured for single crystals is discussed, and similar considerations apply: the presence of the 22° "halo peak" (caused by refraction through the 60° prism angle of hexagonal crystals, and representing the minimum refraction angle) is equivalent to the presence of bright spots in the 2D pattern at scattering angles >22°. We have now extended the description of the test data in the Results section.

(c) we have not considered quantitatively the specific influence of crystal hollowness on pattern speckle or roughness measures, as at present we do not have sufficient numbers of realistic concave test particles for such study. However, in Discussion we

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already speculate that crystal complexity in general appears to influence scattering properties in a similar way to roughness. The same should apply to hollowness, so we have now inserted an additional sentence into the section discussing particle complexity.

(d) there is no precise "size range" for SID-3: since it is based on 2D scattering, unlike for other cloud probes, the instrument is not limited by the range of integrated scattered flux values or by the size and resolution of the detector array. Furthermore, as already stated in Methods, the intensifier gain can be varied to accommodate a wide range of scattered intensities, hence the size of particles that can be characterized.

(e) The test particles (we assume that this is what the Referee meant) were rough on all facets, although the roughness was "patchy" in some cases, as Fig. 7 clearly shows.

2. The cloud sampled was midlatitude stratiform cirrus associated with cyclonic systems. The aicraft sampling pattern consisted of a series of level runs each separated in altitude by 1000ft, and ranged from around cloud top to below cloud base. The cloud top temperatures were around -60 ℃ and the cloud base around -30 ℃. Observations near the cloud base included sublimating particles. The relative humidity with respect to ice, using the General Eastern chilled mirror hygrometer was mostly between 80 and 110% throughout the depth of the cloud. However, this hygrometer has slow response time and therefore will not see rapid changes in humidity, so when looking for possible relationships with roughness we used the fast FWVS hygrometer.

The maximum altitude of the FAAM aircraft is indeed less than 12km and the highest altitude reached during these flights were 10.9km.

We have inserted these comments, and additional details of the flights, into the Methods section.

3. Sizing by speckle is not the subject of this publication, and will be treated in detail in later work that is currently under preparation. We have used it only to check for

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possible correlation with the roughness measures, with negative outcome, as already stated in the main text.

4. The incidence of ice crystal shattering during CONSTRAIN was investigated by Cotton et al. (2013), and found not to be significant for SID-2. SID-3 has very similar geometry. We have added a comment emphasizing this point in the Methods section.

5. As stated in the main text, we found no correlation between particle size and roughness, so we have not included such a plot in the article. However, at the Referee's request we reproduce example results in Fig. 1 below.

6. Performance data on the FWVS are given in the publications already cited. Since relative humidity did not show clear relationship with the properties of interest, we have not gone into a detailed discussion of the FWVS. Moreover, the FWVS has since been superseded on FAAM. We show here an example comparison of relative humidity measurements during flight B504, including in addition to the FWVS, General Electric and Buck hygrometers – see Fig. 2 below. Agreement is good, in particular the General Eastern chilled mirror hygrometer typically agrees with the FWVS within 5-10% humidity. However, the FWVS has much faster response time.

7. While the coefficient of determination may appear low, it is statistically highly significant, given the large size of the sample – 239 data points, a note was added in Fig. 9 caption. Furthermore, we now emphasise in the revised Discussion that the halo ratio determined from SID-3 data is for single particles, each in its own orientation: as such, the ratio is subject to wide variation due to the orientation, which is likely to be contributing most of the observed variability. Had the halo ratio been determined for an ensemble of particles (as is the case for the Polar Nephelometer) the variability is likely to have been much lower and the (negative) correlation even stronger.

However, to reassure the Referee, we have added to Fig. 9 a plot of the mean halo ratio calculated for discrete roughness intervals. It can be seen that the halo ratio decreases almost monotonically with roughness, except at the very ends of the data range where

Table 1. Mean values and standard deviations (in brackets) of roughness measures of ice crystals in the three cloud cases shown in Fig. 6, obtained from 2D SID-3 scattering patterns.

Case	Energy	log K	RMS/SD	Combined roughness
marine cirrus	0.239 (0.084)	1.38 (0.39)	1100 (336)	0.586 (0.175)
continental	0.218 (0.062)	1.33 (0.25)	605 (139)	0.485 (0.103)
mixed phase	0.224 (0.0714)	1.20 (0.26)	936 (228)	0.586 (0.123)

data points are scarce and variability is greater – see Fig. 3 below. The correlation coefficient was -0.22 (coefficient of determination 4.7%), significant at the 0.1% level, based on 239 data points.

8. We have added descriptive statistics and statistical tests for differences between the roughness measures in the three cloud cases to the revised Results. The tables given here, also included in the revised text, show means and standard deviations of roughness measures and the outcomes of the significance tests. The differences significant at the 5% probability level are shown in bold in Table 2. Note in particular that for the continental airmass cirrus case, as compared to the marine cirrus one, there is significantly lower roughness for all measures apart from kurtosis. We stress the significance of this difference in the revised Discussion. We have also inserted the numbers of data points (2D patterns) analysed for each cloud case in the Results section: "marine cirrus (239 patterns) and mixed phase (199 patterns) flights, as well as one cirrus flight in a continental airmass (59 patterns)".

Other Points

1. This is a partial misunderstanding: the instrument used by Field et al. (2003) was SID (SID-1) not SID-2. However, we have added a citation to the reference.

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Table 2. Significance tests for differencees between the roughness measures of ice crystals in the three cloud cases shown in Fig. 6 (marine cirrus, continental cirrus, mixed phase), obtained using the t-test method. Shown are the probabilities that the null hypothesis of no difference between the measures is true (low probabilities correspond to more significant differences). Values <5% are given in bold to highlight significant differences.

Case A	Case B	Energy (%)	log K (%)	RMS/SD (%)	Combined roughness (%)
marine	continental	**3.9**	18	$\mathbf{4.3 \times 10^{-42}}$	$\mathbf{5.0 \times 10^{-6}}$
marine	mixed phase	**4.2**	$\mathbf{4.7 \times 10^{-7}}$	$\mathbf{3.0 \times 10^{-7}}$	99
continental	mixed phase	59	$\mathbf{6.3 \times 10^{-2}}$	$\mathbf{1.4 \times 10^{-37}}$	$\mathbf{6.5 \times 10^{-7}}$

2. We refer to the work by Shcherbakov (2013) in the revised text.

3. Done.

4. We have altered the text to read "In a study by Baum et al. (2011) some space-borne depolarization lidar measurements could be explained by modeling ice crystals with rough surfaces".

5. The text now reads "Gayet et al. (2011) found prevalent particles with imperfect or complex shapes at the trailing edge of mid-latitude frontal cirrus, while the leading edge was dominated by more regular plates that produced a 22° halo signature." We are not certain if firm conclusions can be drawn from the absolute values of the asymmetry parameter as measured using the Polar Nephelometer, mainly because of uncertainty due to the missing low scattering angles.

6. As discussed in the paper, the roughness measures are at this stage semi-quantitative. Therefore, they cannot yet be associated with specific features of ice crystal geometry, and it is also too early to put meaningful uncertainties on their values. Further work is required before this can be achieved.

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7. Unfortunately, in the work of van Diedenhoven et al. (2013) the geometric optics model was used, which puts into question the values of the asymmetry parameter that were computed – see e.g. the anonymous interactive comment in Atmos. Chem. Phys. Discuss., 12, C11998–C12002, 2013, www.atmos-chem-phys-discuss.net/12/C11998/2013/.

8. The main difficulty with the "tilted facet" method, in addition to any inaccuracy, is that it does maintain an association between the scattering properties and surface geometry, and such does not permit one to solve either the direct or the inverse scattering problem. It is merely a computational "ersatz", and so has somewhat limited predictive value – it is more akin to a parameterization. In terms of 2D patterns and speckle, we have seen no results from this method that we can evaluate, so it is difficult to comment on the suitability. However, the condition that must be met by any method to reproduce speckle patterns is that (a) the phase of the scattered waves and (b) diffraction are accounted for. This is not the case for most implementations of geometric optics using the Monte Carlo approach.

9. We have inserted the words "up to the homogeneous freezing threshold and sometimes slightly above".

10. We do not agree that the humidity and halo ratio scatter plots are similar: we have dealt with the issue of correlation between the halo ratio and roughness in point (7) of the "Main Comments".

11. We did not suggest that including ice roughness would result in agreement between observations and models, merely that it would "improve the agreement", in other words shift modelling results in the right direction. We have now added the text "However, other factors may also contribute to the discrepancy" to emphasize this point.

References

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Interactive comment on Atmos. Chem. Phys. Discuss., 13, 24975, 2013.

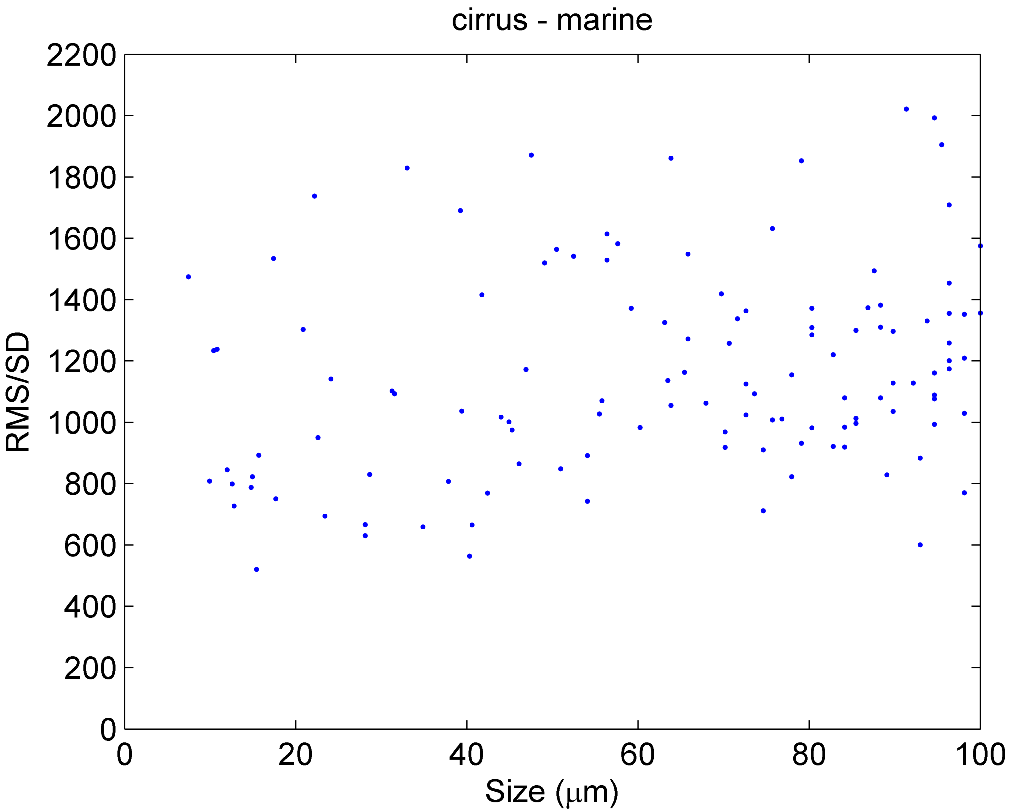

Fig. 1. ce crystal size derived from SID-3 plotted with the RMS/SD particle roughness measure.

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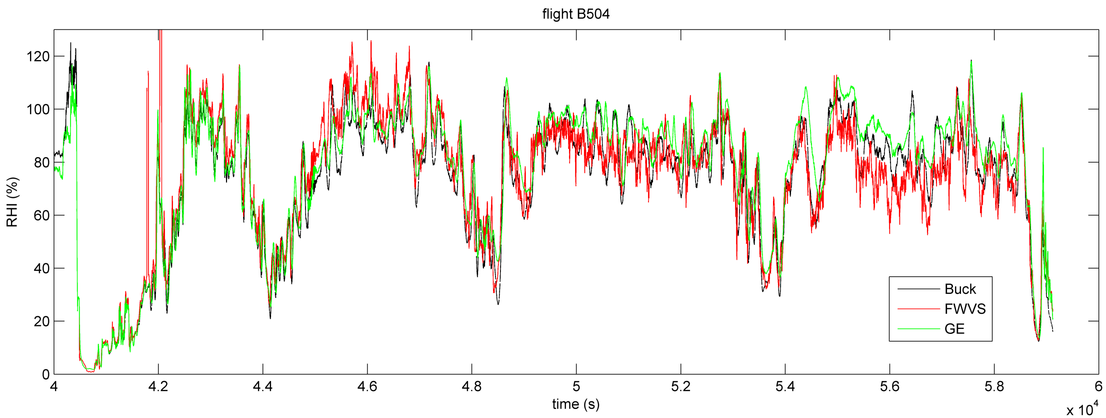

Fig. 2. Timeseries of relative humidity with respect to ice for cirrus flight B504. FWVS, General Eastern and Buck hygrometer data is shown.

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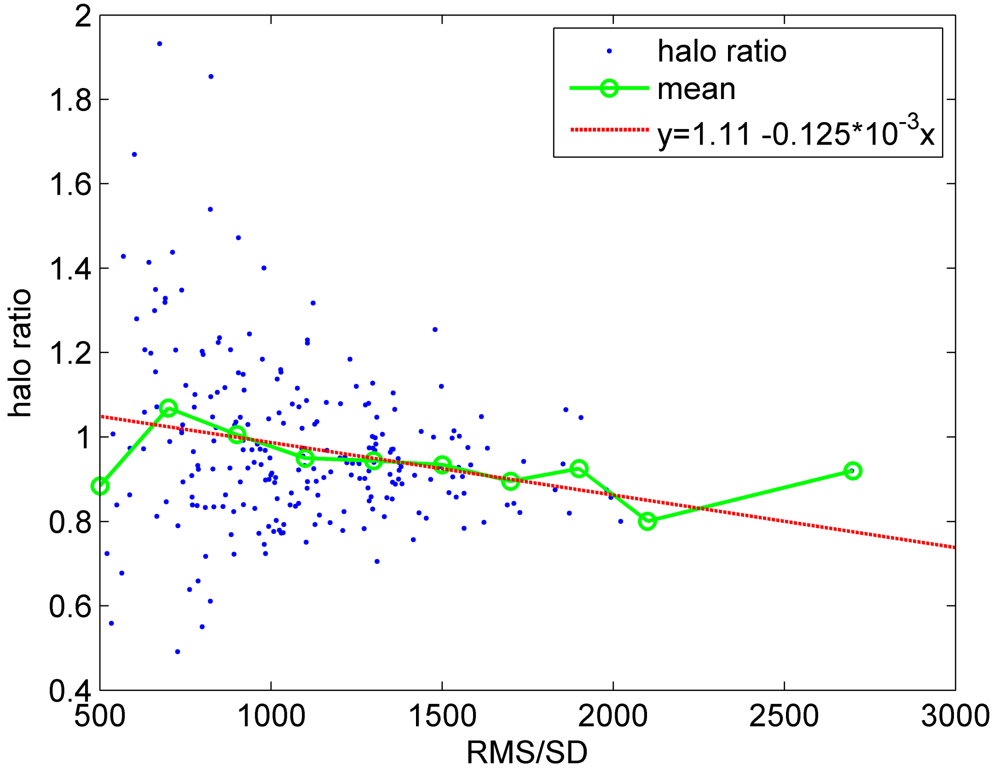

Fig. 3. Halo ratio plotted vs. roughness measure RMD/SD in marine airmass cirrus. Also shown is mean halo ratio for fixed roughness intervals, and a regression line (coefficients in the legend).

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