Authors response concerning the Manuscript prepared for Atmos. Meas. Tech.

A tandem approach for collocated in-situ measurements of microphysical and radiative cirrus properties

The Authors would like to thank the anonymous reviewers for their time as well as their very good suggestions and remarks. We think it improves this publication a lot.
We would also like to thank Volker Ebert for his comment about the instrument, which we included in the trace gas instrument section.

In the following, we answer all comments. Additionally, a marked-up manuscript version is attached.

Questions and Answers regarding RC1:

Line 110-112: You mention that on the original AIRTOSS, the external body cover was used as a mounting point for additional payload. Please explain why this was modified.

That is correct. We wanted to use the external body just as a cover because it made it easier to open the AIRTOSS to check the instruments and to exchange the battery. Besides this fact, it was much easier to arrange the instruments on an internal frame during the construction process.
We made it more clear in the paper by writing:

> *For the modified version, the body cover is used only as a cover, which does not need a detailed strength calculation and certification. It also makes it more convenient to access the instruments and to recharge the replaceable battery after a measurement flight.*

Line 114: Air brakes are the red rectangles on the winglets in the back? This becomes clear only later on. – Describe the photo more clearly to a reader who might not know what air brakes are. Also, did you have several different flights during which you employed air brakes with different resistance coefficients to see which lead to the best performance in terms of horizontal flight positioning? Or did you construct the air brakes after flow simulations? ...ok, some of this is answered in Section 2.5 – you can also mention in line 114 that details are explained later. But if you don't, the reader is lost.

Thank you for this comment. Yes, the air brakes are the red rectangles on the winglets in the back. They were constructed after the flow simulations, and we used one test flight to check

the behavior of the whole AIRTOSS. It turned out that the simulations were correct, and the AIRTOSS stayed incredibly stable during the flights.
We explained it more accurately in the text and refer to Section 2.5.

> *Air brakes (red rectangles at the winglets) with different resistance coefficients were mounted onto the winglets to compensate for the shape of the asymmetric CCP and to keep the released AIRTOSS in a horizontal flight position. More details about the air brakes and the associated flow simulations are given in Section 2.6.*

Line 137: You mention that several heaters of the CCP were deactivated. – Mention if/how this measure affects the instrument performance?

You are completely right, that was a big issue before the campaign. We needed to save as much power as possible to get at least an operating time of around two hours for the AIRTOSS. The heaters, which were deactivated, are usually important for avoiding icing at the tips of the CCP by flying e.g. through mixed phase clouds. Another reason for the heaters is to avoid condensation on the optics of the CCP. We expected that the air masses in the vicinity of cirrus are so dry that icing or condensation wouldn't occur. In Figure 6, it is visible that the electronics/measurements were not affected by icing or condensation, because plausible 2D shadow images measured by the CCP-CIPg are shown.
We added this information to the paper.

> *To save power, several heaters of the CCP instrument were deactivated. This was possible, because the main purpose of the heaters is to avoid icing and condensation at the optics of the instrument, by flying through e.g. mixed phase clouds. Only those from the CCP - Cloud Droplet Probe (CCP-CDP) instrument (see Section 2.3) were running during the measurement flights to keep the electronics under stable temperature conditions.*

Line 335-353: This paragraph should be structured and phrased more clearly. For readability, it is better to introduce it like For flight X from Y to Y UTC, with the aircraft flying at XX m altitude and the AIRTOSS being at YYm altitude, cirrus filaments were detected during two sections (at X UTC and Y UTC). ...then go into detail. Instead of starting with details and then giving the big picture in the end. Also, in Fig.7a,b the quantity measured (downward irradiance needs to be added in the y-label). Axis labels and legend font is too small. Do the vertical bars indicate errors or standard deviations? What is the temporal resolution of the measurements?

Thank you for this comment. We introduced the flight and the associated atmospheric conditions already in Section 3. For this reason, we didn't want to repeat it. Nevertheless, we agree with your remark and changed the first sentence, which now includes the date, the time period of the flight leg and the altitude.

> *Figure 8 shows a time series of downward spectral irradiance at 670 nm wavelength measured from the Learjet (Figure 8a) and AIRTOSS (Figure 8b) during a flight leg observed on 4 September 2013 between 09:35 UTC and 09:39 UTC, when the AIRTOSS was operated at an altitude of around 9900 m.*

We changed the legend in Figure 7 to make it obvious that downward irradiance measurements are shown. Axis labels and legend fonts are bigger too. The vertical bars indicate the error of the instruments and the running average uses the boxcar smoothing algorithm with 10 repetitions. We added this in the description of the figure. The temporal resolution is 1Hz for all measurements.

In Fig. 7c an increased NC (of CCP-CDP and CCP-CIPg) is obvious at 05:35:50UTC – why does the running average only increase a few seconds later. – How is the running average determined?

As already mentioned in the previous answer, we used the boxcar smoothing algorithm with 10 repetitions. This explains the behavior of the smoothing, because the running average increases a few seconds earlier as the peak.

Line 368-371: In this paragraph you mention that variation in the upward irradiance is mainly due to a lower level stratus cloud. You also state that the upward irradiance varies more strongly in the upper legs while it is less in the lower legs. – Shouldn't the influence of the underlying stratus be affecting the lower leg measurements more than the upper ones? – Please clarify. Also, an additional figure showing a satellite image with overlaid flight track would be good to illustrate the cirrus/stratus situation.

That's right, our wording is a little contradictory and the explanation is not complete. Two effects have to be considered here. First, the field of view of the irradiance optical inlet differs with distance to the cloud layer. A low stratus is more smoothed than a high cirrus, which is closer to the sensor. Therefore, the variability along a flight leg is mostly dominated by the cirrus inhomogeneities. Between the different legs, the stratus field might have changed and caused the differences of the mean values. Below the cirrus, these differences of the leg averages are in the range of the variability along a leg. In the third cirrus leg, the mean irradiance is increased due to the cirrus. This increase is a range similar to the standard deviation of the three upper legs. This indicates that the variability of the upper three legs is caused by the cirrus and not the stratus.
In the revised manuscript, we added following explanation:

Assuming that along the flight leg the low stratus is homogeneous with respect to the field of view of the irradiance optical inlet, these higher standard deviations are mainly caused by the spatial variability of the cirrus. The cirrus is located vertically closer to the irradiance sensor and, therefore, smaller horizontally inhomogeneities are resolved by the measurements.

We added a Satellite picture (Figure 5) where you can see the cirrus/stratus situation.

Lines 405-410: This is important! – It should be mentioned more clearly in the abstract. Please emphasize that only collocated irradiance measurements of the Learjet and the AIRTOSS give meaningful heating rates. Also, specify which heating rates are theoretically expected instead of only listing the corresponding references.

In the revised abstract we included this conclusion by:

"Due to unavoidable biases of the measurements between the individual flight legs, the single platform approach failed to provide a realistic solar heating rate profile while the uncertainties of the tandem approach are reduced. Here, the solar heating rates range up to 6 K day-1 at top of the cirrus layer."

Literature values of solar heating rates between 0.2-0.5 K/day were reported by Buchholtz et al. (2010) and Thorsen et al. (2013) for subvisible and optically thin cirrus. With an optical thickness of 0.6, the observed cirrus was optically thicker and higher heating rates can be expected. In the revised manuscript we added:

For subvisible and optically thin cirrus, they calculated heating rates in the range of 0.2-0.5 J day-1. These higher values might result from the higher optical thickness, τ=0.6, of the cirrus observed by AIRTOSS or be caused by horizontal inhomogeneities of the observed cirrus leading to horizontal photon transport as discussed by Finger et al. (2016).

Line 407: Here you mention that a cirrus geometrical thickness of more than 200m is too large to allow for positioning of the Learjet above and the AIRTOSS below the cloud layer. Earlier you stated a longer steel wire length – please clarify why the AIRTOSS cannot be positioned below thicker clouds?

We used a maximum length for the steel wire of 3000 ft (914 m). With this length and a speed of 165 m s^{-1}, the AIRTOSS was positioned 180 m below and 896 m behind the aircraft. This caused a temporal misalignment of 5 s. During this campaign, we didn't extend the length of the steel wire rope, because the restricted measurement area would have been to small to keep the AIRTOSS under control. In addition, we didn't want to increase the temporal misalignment. We added this information to the manuscript.

> *During the AIRTOSS-ICE cam- paign the steel wire was only released to a length of up to 914m (3000 ft) to keep AIRTOSS under manageable conditions within the borders of the the relatively small restricted military areas. Under these conditions and with an airspeed of 165 m s^{-1} , AIRTOSS stayed approximately 180 m below and 900 m behind the Learjet. This horizontal displacement introduces a delay of about 5 s between Learjet and AIRTOSS instantaneous location.*

Line 427-428: What exactly can you derive by combining microphysical and radiative measurements. You did show several graphs of collocated measurements but it become not quite clear how this knowledge can be used. – Is it possible to validate radiative transfer retrievals of particle size (based on measured radiative properties) with the simultaneously measured particle size distributions? Or how else can the measurements be used for more in-depth cirrus studies?

Yes, this was one of the main motivations for why the AIRTOSS was developed. Such a closure study was already published by Finger et al. (2016). In situ cloud microphysics of another cirrus case were used in radiative transfer simulations to calculate the cirrus optical layer properties. At the same time, the collocated irradiance measurements on AIRTOSS were used to derive the optical layer properties and were compared to the model results. This comparison helped to quantify the impact of ice crystal shape, effective radius, and optical thickness on the cirrus radiative forcing. We added the reference to Finger et al. (2016) in the conclusion of the revised manuscript.

> *Further results are presented by Finger et al. (2016) in a closure study, which combines in situ cloud and radiative measurements to quantify the impact of ice crystal shape, effective radius, and optical thickness on cirrus radiative forcing.*

Line 443-448: Only here you mention that the shown results are taken from a proof-of-concept campaign and that thus the AIRTOSS steel-wire was not extend further. – Please mention that in the very beginning of the manuscript.

We didn't extend the steel-wire further, because we needed to keep the AIRTOSS at a manageable distance in the relatively small restricted areas. This information is added in the manuscript.

Section 2.6: The trace gas measurements seem totally unrelated to the paper in which you are focusing on collocated measurements microphysical and radiative properties. Unless you convince me how they add to the entire story, I would suggest to remove the parts referring to the trace gas measurements. You only briefly refer to the trace gas measurements again in lines 455-457. – This is not sufficient to justify the inclusion of the trace gas measurement description.

As pointed out in your comment, we do not show a case where trace gas data do play a central role since we observed the particles in the upper troposphere. However, specifically at the tropopause the additional information on the tracers (specifically N2O) provides some unique information on the tropopause location to the tandem observations and thus the full setup. Mueller et al. (2015) used these measurements during AIRTOSS-ICE on the Learjet to identify the occurrence of cirrus particles in stratospheric air masses by the amount of N2O, which demonstrate the importance of the full payload for the measurement concept. The N2O instrument was further flown for the first time during AIRTOSS-ICE. We therefore see the trace gases as part of the full technical tandem setup and thus would like to keep this section. Since we would like to publish the manuscript in the AM*Techniques* journal, which is dedicated to publishing advances in remote sensing and in-situ measurement techniques. In our understanding, this also includes the documentation and information about the complete payload of the tandem platform including the trace gas instruments as part of the full measurement concept.

Minor Comments:

Sometimes you refer to the towing sensor shuttle as AIRTOSS, sometimes as the AIRTOSS. Be consistent and choose if you want to call it a noun or if you want to refer to it as proper name.

Thanks for the comment, we want to use a name for it and changed it in the manuscript.

Line 4: "detached from" should be extended by "detached from the aircraft via a cable" to illustrate the setup more clearly

We changed it.

Line 6: replace "layer clouds" by the more scientific term "stratiform clouds"

Changed.

Line 6: motivate why you need "sophisticated numerical flow simulations" - to quantify shattering effects on the CCP?

Changed it to: Sophisticated numerical flow simulations were conducted in order to optimally integrate an axially asymmetric Cloud Combination Probe (CCP) inside AIRTOSS.

Line 9-10: move this sentence about the steel cable to line 4 for clarity
Already changed.

Line 13 (and 287): The sentence seems backwards: ice crystals grow from small to large sizes (via diffusional growth/aggregation), thus the sentence should be phrased: ...maximum size in the observed...increases from 30mum to 300mum with decreasing altitude.
We changed it.

Also, shouldn't the change in maximum size of the PNSD rather refer to geometrical cloud depth than merely altitude? Please clarify.
We used this explanation to describe the figure. A few sentence later we explain why the cloud particles are distributed like that.

Line 16: Remove "consequently" or replace it by "thus"
It is just a synonym. We prefer "consequently".

Line 16: Add "growth" between microphysical and process
Changed!

Line 17: is the solar downward irradiance on the Learjet measured above/in/below the cirrus?
Line 18: Clarify where the cloud is positioned with respect to the tandem platform to determine heating rates
The tandem platform did sample the cirrus at different altitudes. During the profile both platforms had been below, in, and above the cirrus. From the measurements at different altitudes, profiles of heating rates are derived. To clarify this approach in the abstract, we changed this part to:

> *Measurements of solar downward and upward irradi- ances at 670 nm wavelength were conducted above, below, and in the cirrus on both, the Learjet and AIRTOSS. The observed variability of the downward irradiance below the cirrus reflects the horizontal heterogeneity of the observed thin cirrus.*

Line 25: THEIR microphys. Prop. ; warm or cool (plural!)
Thank you. We changed it.

Line 26-28: rearrange sentence structure to proper English. "Especially the ice particle shape was found to determine ... (e.g., Wendisch ...)"

Changed.

Line 29: You cannot talk about "such effects" of surface roughness when you haven't previously talked about surface-roughness. – Modify the sentence accordingly.
Changed.

Line 47: Clarify if the "two helicopter borne platforms" refer to two helicopters flown simultaneously or if not, what kind of platforms you refer to.
Changed.

Line 54: Replace "speed" by "aircraft velocity"
We changed it.

Line 55: released by means of a steel wire
Changed.

Line 56: In "the study of" Frey et al....
We changed it.

Line 58: "this" not "his"
Thank you.

Line 60: If the Frey et al. 2009 study is based on the proof-of-concept campaign, it should be mentioned clearly. Also, the proof-of-concept sentence should be moved before line 56. Try to ease the reader into the subject, go from larger picture to more detailed description.
Changed.

Line 94: What is the limited distance? Give a value.
Unfortunately, we are not able to give a precise number for the distance.

Line 103: Title of this subsection should be "Specifications of the AIRTOSS"
We changed it.

Line 113: remove comma
Thanks.

Line 121: "of up to 914m"
Changed.

Line 128: "less than the maximum ..."
Changed.

Line 137: to save energy
Thanks.

Line 138: explain abbreviation CCP-CDP
Okay.

Line 139: a voltage
Changed.

Line 141: no commas
Changed.

Line 153: mounted on
Changed.

Line 154: Seems like a word is missing after particle-by-particle data analysis/algorithm/technique?
We made it more clear.

Line 158: Specify what you mean by size: maximum dimension?
It is the maximum dimension diameter. We corrected it.

Line 163: citations should be given in chronological order
Changed.

Line 172: Again, this last sentence seems like it was added as an afterthought. Consider moving it after the reference to Knollenberg, maybe by combining those two sentences.
Changed.

Line 178: at the bottom
Thank you.

Line 180: wavelengths
Changed.

Line 180: irradiance sensor; give reference for horizontal alignment requirement
Changed.

Line 191: ...symmetric, ... (comma)
Changed.

Line 194-197: this sentence needs to be simplified or devided into two for clarity. What do you mean by "aiming at their compensation"?
We meant: "with the goal to compensate these effects". We changed the sentence though.

Line 219: As a result, ...
Changed.

Line 235: Accordingly, ...
Thank you.

Line 272: of less than...
Thanks.

Line 293: growth process
Changed.

Line 294: water vapor diffusion; the particles don't descent, they sediment
Changed.

Line 300: explain the term area ratio
Regarding to Frey (2011), it is just the area of the shadowed pixels (measured by e.g. the CCP-CIPg instrument) divided by the calculated particle area using the maximum dimension diameter. We added this information in the manuscript.

Line 304: what orientation was assumed for the falling columnar ice crystal?
As you can see from the area ratio, the ice crystal is horizontally orientated. To make this more clear, we mentioned it in the manuscript.

Line 304: replace numbers with "estimated terminal fall velocities"
Thanks.

Line 307: Why does aggregation only occur several hours after particle formation at such ice particle number concentration? – Try to present the reader with a good story, instead of with many questions.
Because the probability for collision is low. We added it.

Line 326: What do you mean by "undisturbed"? constant?
Thank you for this comment. We changed the sentence to:

> *Above the cirrus, the downward irradiance is almost constant over the entire legs indicating clear sky for both platforms.*

Line 349: add citation

Inserted.

Line 350: is affected by what? Do you mean "shows variation"?

Exactly, thank you.

Line 359: the "in-cloud" inhomogeneities

Already changed.

Line 363: Start the sentence with "to make measurements comparable, ..."

Changed.

Line 367: Sentence is unclear. Please clarify what the horizontal bars indicate: the standard deviation along individual flight legs or the variability of the radiation along the flight legs?

Changed.

Line 406: why radiance? I suppose you mean "irradiance"?

Correct.

Line 420: Is SMART really a sensor?

Changed.

Line 426: Remove comma

Thanks.

Line 454: Again, the reader wonders: What is the higher sampling rate? – Please mention it and relate to the sampling rate and the sample area of the CCP.

To explain it better we used the sample volume and changed the manuscript.

> *To perform microphysical measurements with a higher temporal resolution, the implementation of holographic instruments is also an attractive alternative. These instruments have a larger sample volume of up to 305cm^3, which is much higher than the sample volume of the CCP-CDP instrument (45 cm^3 for an aircraft velocity of 165 m s^{-1}).*

Questions and Answers regarding RC2:

On reading the abstract I was not convinced why I needed to use this system. I think the paper needs to do a bit more to convince the reader that this is a useful technique.
We made it more clear in the abstract why this system is a useful technique.

> *Vertically resolved solar heating rates were derived by either using single platform measurements in different altitudes or by making use of the collocated irradiance measurements in different altitudes of the tandem platform. Due to unavoidable biases of the measurements between the individual flight legs, the single platform approach failed to provide a realistic solar heating rate profile while the uncertainties of the tandem approach are reduced. Here, the solar heating rates range up to 6 K day−1 at top of the cirrus layer.*

line115. Does this mean that certification is limited to one payload and any changes require another certification?
Yes, this is typical for airborne research platforms. The certification process is linked to a specific configuration. Nevertheless, it is possible to certify multiple configurations from the beginning for one platform. Then you are allowed e.g. to change instruments during a campaign.

section 2.6. It would seem more natural to move this section to just after section 2.3 or 2.4. Or move the flow simulation earlier. At the moment the flow simulation section sits in the middle of sections describing instrumentation.
Yes, you are right. Thank you for the comment. We moved the flow simulation section to the end of Section 2.

line 260 0ppb - is it really that sensitive?
We got that information from the manual. A more detailed look in Köllner (2013) showed that the lower threshold is at 0.9 ppb for 700hPa. We changed it.

line 295 - do you mean smaller ice crystals nearer the top (lower fallspeeds and hence longer residence times at that altitude) ?
Yes, exactly. To make it more clear, we changed a few words.

line 307. What was the relative humidity with respect to ice? Can you reconcile the 2D imagery in figure 6 with the diffusion grown images in Bailey and Hallett 2009 JAS fig5 for your temperature and humidity range?
We looked into Baily and Hallett, but also into Heymsfield and Miloshevich, JAS, (2005). The particle shape and size look similar. That is the case, because we were under similar conditions (RH ~ 102%, Temp: -35 to -45°C). Unfortunately, the CCP-CIPg instrument does not deliver as good of a resolution like the instruments in the other publications. For that reason, we mentioned in the conclusions that a holographic instrument would be a good

option for future campaigns.

line 358-360. This is the heart of the reason for flying a tandem formation. If you have one platform within cloud measuring the downwelling radiation and another platform slightly below measuring the same radiation then the difference between those two signals is going to provide information about the intervening cloud. It should not matter that one platform is not at cloud top. Perhaps the errors in the radiation measurements are too large to do this with the separation that was being used? Could a calculation be done to estimate what thickness is required?

Yes, this is correct. In general, having both platforms in the cloud still provides the cloud properties in the intervening layer. We actually analyzed this when calculating the profile of heating rates in Section 4.2. For the tandem approach, heating rates between both platforms are derived. The results of this exemplary case showed that, in general, the separation was still sufficient to derive cloud optical properties between the two platforms with reasonable uncertainty. However, the current distance used for the measurement setup is at the limit for resolving differences in the irradiance profiles in case of thin cirrus. This is obvious by the large uncertainties estimated for the heating rates in Fig. 8. Similar conclusions had been made for a second case analyzed by Finger et al. (2016).
In the revised manuscript we removed the original statement and added the following discussion:

> *However, the approach by Werner et al. (2014) for analyzing the collocated number concentration and cloud remote sensing works only if the radiation measurements are performed well above the cloud. In the case of the AIRTOSS-Learjet tandem this would limit the analysis to the uppermost cirrus layer. However, operating radiation measurements on both platforms, the cloud optical layer properties can be derived as presented by Finger et al. (2016). Using the collocation for cloud layers well inside the cloud can also be analyzed.*

It should now be possible to do a closure study where the microphysical information from AIRTOSS is assumed to represent a column of cloud between AIRTOSS and the Lear. An average along the leg could be used. This column can then be modelled with a radiation code to estimate the effect on the radiation. The radiative response of this column of cloud can then be compared with the measured radiative difference. To me this would be the unique selling point of this system- the ability to carry out this type of analysis. This sort of closure study could be used to try and constrain unobserved quantities such as crystal roughness.

Yes, this was one of the main motivations for why the AIRTOSS was developed. Such a closure study was already published by Finger et al. (2016). In situ cloud microphysics of another cirrus case were used in radiative transfer simulations to calculate the cirrus optical layer properties. At the same time the collocated irradiance measurements on AIRTOSS were used to derive the optical layer properties and were compared to the model results. This comparison helped to quantify the impact of ice crystal shape, effective radius, and optical thickness on the cirrus radiative forcing. We added the reference to Finger et al. (2016) in the conclusion of the revised manuscript.

> *Further results are presented by Finger et al. (2016) in a closure study, which combines in situ cloud and radiative measurements to quantify the impact of ice crystal shape, effective radius, and optical thickness on cirrus radiative forcing.*

Fig8. Yes, this plot is good. The advantage of using the tandem platform for heating rates over single platforms should be emphasized more in the abstract.

Thank you! We mentioned it in the abstract.