

Authors' response to the review of the manuscript titled "Modification, Calibration, and Performance of the Ultra-High Sensitivity Aerosol Spectrometer for Particle Size Distribution and Volatility Measurements During the Atmospheric Tomography (ATom) Airborne Campaign"; submitted to AMT on August, 9, 2017

The authors would like to thank the reviewers of the manuscript for their careful and positive evaluations. Our responses are listed below in blue, while reviewers' comments are in black.

Apart from the minor changes suggested by reviewers we have updated data presented in Fig. 11. We have noticed that an incorrect d_{log} values were used. The corresponding volatile and non-volatile fractions mentioned in Section 6.2 were also updated accordingly. These changed by ~1-2 % as compared to the initially reported values. This has not impacted integrated aerosol surface and volume concentration data reported here.

Reviewer #1 (received and published: 29 September 2017)

This is a very thorough and well-written manuscript describing the evaluation and performance of the UHSAS instruments deployed during the ATom field campaign. The authors have investigated every aspect of the instrument performance and carefully quantified uncertainties. They have provided detailed descriptions of their methods and experimental details. The instruments performed with close agreement under similar operating conditions. The initial results with one thermodenuded instrument suggested a large fraction of the aerosols were secondary in nature. As this field campaign continues, these results should be very enlightening and help to further our understanding and constrain uncertainties regarding the ability of aerosols to act as CCN. My main concern/question is regarding the sensitivity of the instruments to particle refractive index and instrument calibration while operating in the thermodenuded mode. With the exception of sea salt which has a refractive index similar to ammonium sulfate or organic carbon (more volatile fractions), other non-volatile species such as dust or soot have a higher refractive index than was tested as part of the calibration (not to mention effects of complex refractive index). Are the authors concerned about different uncertainties between the thermodenuded and non-thermodenuded instrument when comparing the two measurements? I recommend publication after addressing very minor comments below.

We thank reviewer #2 for positive evaluation.

Because the refractive index of the atmospheric particles is not known a priori, we decided to use ammonium sulfate-based UHSAS sizing calibration and evaluated uncertainties with a reasonable range of scattering aerosols. Ammonium sulfate has a refractive index ($m=1.527$) that is representative for the remote marine aerosol sampled during ATom. We emphasize in the Section 3.2 that soot is not sampled quantitatively because of incandescence and/or refractive index. For dust we are concerned about both shape and refractive index. Uncertainties in both instruments for such cases must be evaluated on a case-by-case basis using best estimates of the refractive index based on other measurements, coupled with optical simulations of instrument response. We have added a remark to this effect in Section 3.2.

The fact that the two UHSAS instruments are measuring aerosol with different refractive indices is something we haven't considered quantitatively. As the reviewer points out, this is a particular problem above the MBL, where dust is likely the dominant component. Frankly, the counting statistics are sufficiently poor that this error is likely to dominate any uncertainties during comparisons between the two instruments in the free troposphere except in specific dust and dust + biomass burning cases. We have added

a remark cautioning about this subtlety in Section 3.2, but believe this will have to be addressed on a case-by-case basis.

Figure 3: Do the solid lines represent fits to the data? Please note in caption.

Yes. Figure caption has been updated.

Page 18, line 25: I assume the “agreement” values correspond to slopes?

Yes. This sentence has been updated and now reads: “The corresponding slopes for aerosol surface and volume concentration varied between 0.97-1.02 and 0.95-1.08, respectively.”

Page 19, line 25: Add “number” before “concentration”

Corrected.

Page 20, line 2: I’m not sure “coarse-mode” is typically used for particles less than 1 μm ?

The sentence reads now: “In the FT, ~3 % of the particle volume was non-volatile, dominated by a few particles with with $D_p > 0.3 \mu\text{m}$ and uncertain due to poor counting statistics.”

Page 20, line 7, Figure 11 Caption: typo for “isn” before “the MBL case” and “UT” instead of “FT”.

Thanks for finding these subtle errors. We have fixed these two typos.

Reviewer #2 (received and published: 13 October 2017)

The manuscript presents a detailed description of modifications to and the subsequent evaluation of two optical particle counters (UHSAS) for use during a multi-year aircraft campaign. It also describes and characterizes a thermal denuder for measuring the non-volatile fraction of aerosol. The subject is appropriate for AMT and the manuscript is well written and clear. I recommend publication once the following minor points have been addressed.

We thank reviewer #2 for positive evaluation.

Section 3.1.1, line 10: Recommend changing "This bias" to be more specific, e.g., "The DMA sizing bias". Also, line 14 I believe the authors mean the biases are propagated to the aerosol and volume concentration uncertainties, correct? I assume no adjustment was made to the DMA diameters based on the PSL offset?

Line 10: The sentence reads now: “This DMA sizing bias is estimated to be about 7 % at sizes below 0.07 μm and decreases to 1% for sizes above 0.13 μm .”

Line 14: The sentence reads now: “Still, these potential biases are propagated through to the aerosol surface and volume concentration uncertainties discussed below.”

Concerning the latter comment above. That is correct. No adjustment has been made to the DMA diameters based on the PSL offset. The sentence reads now: “No adjustments were made to the DMA diameters, but

the potential biases when compared to the PSL sizes are propagated through to the aerosol surface and volume concentration uncertainties discussed below.”

Section 3., lines 3-9: The section should also mention that the complex RI of BC will also affect the sizing in addition to LII impacts. I think it is also helpful to the reader to clarify how the incandescence of BC would affect UHSAS sizing (e.g., BC cores heat up and vaporize coatings and affect scattered light signals as the particle moves across the beam, other effects?).

We agree. We have added the following text (page 8):

Line 3: “The refractive index of soil dust may exceed the range of real refractive indices considered here. In addition, dust can be both absorbing and aspherical. When dust is an important component of the atmospheric aerosol, uncertainties in both the denuded and thermodenuded UHSAS instruments should be evaluated on a case-by-case basis using best estimates of refractive index and shape based on other measurements, coupled with optical simulations of instrument response. Also, because the thermodenuded UHSAS instrument volatilizes non-refractory particles, the refractive indices in the aerosol measured by the two instruments will differ. This problem is probably minor in the MBL because sea-salt aerosol has a refractive index within the range of the calibrants. For the free troposphere, however, there may be substantial sizing biases between the two instruments that should be considered case by case using additional information on aerosol composition.”

Line 13: “Even without incandescing, the complex refractive index of BC particles ($n=2.26-1.26i$ at $\lambda=1064$ nm; Moteki et al. 2010) substantially alters UHSAS sizing compared with the calibration aerosol.”

Reference added:

Moteki, N., Y. Kondo, and S. Nakamura, Method to measure refractive indices of small nonspherical particles: Application to black carbon particles, *J. Aerosol Sci.*, 41, 513–521, 2010

Section 3.3: It appears the detection efficiency was only performed for UHSAS-2? Is there a reason for this? Even if results were similar it would be helpful to report diameters for 50% detection efficiency for both instruments for ammonium sulfate.

The detection efficiency was performed for both UHSAS-1 and -2 and results are reported in Table 1 (attached below for convenience). We did not include data for both instruments in Fig. 4 for clarity. We now refer specifically to Table 1 in Section 3.3 and comment that the detection efficiencies differ. The UHSAS-2 instrument is substantially older (serial #7) than the other, and has a lower laser power probably due to older, more contaminated optics.

We have added the following sentence: “Detection efficiencies for both UHSASs are provided in Table 1. The thermodenuded UHSAS begins detecting particles at a larger diameter than the other instrument.”

Table 1. Detection efficiency of UHSAS-1 and UHSAS-2

Particle	Real refractive index, n	Wavelength, λ (nm)	Reference	Dp50 (nm)	
				UHSAS-1	UHSAS-2
PSL	1.58	780	Yoo et al. (1996)	n/a	n/a
(NH ₄) ₂ SO ₄	1.527	1054	Hand and Kreidenweis (2002)	72.8 ^{+1.2} / _{-5.9}	62.8 ^{+1.0} / _{-5.9}
DOS	1.44	532	Pettersson et al. (2004)	75.9 ^{+1.2} / _{-6.0}	68.2 ^{+1.1} / _{-5.9}
Limonene oxidation products	unknown	n/a	n/a	78.9 ^{+1.3} / _{-6.0}	69.7 ^{+1.1} / _{-5.9}

Section 4.2, lines 2-4: The particle losses through the TD are only reported down to 150 nm, but the both UHSAS systems measure down to about 70 nm. More information regarding particle losses through the TD should be provided between 70-150 nm. Also, will pressure in the TD affect the losses? I assume this varied over a similar range as described for the UHSAS? I do not think more experiments are needed, but some brief discussion of potential impacts would be useful.

We do not currently understand the loss mechanism in the TD. The loss is larger than we expect for flow through the unheated TD. Based on the particle size and residence time in the TD, diffusion to the walls is one possible loss mechanism and may be larger than expected due to the activated-carbon fabric in the TD. Another possible loss mechanism would be if a portion of the flow in the TD occurred in activated-carbon fabric region and the fabric acted as a filter leading to losses in the unheated TD. Further laboratory measurements are planned to understand these losses.

However, for this manuscript, without a clear mechanism for the losses, we cannot extrapolate to smaller size and lower pressures and can only report our measurements at 150 nm and 835 hPa. We have added a sentence to manuscript stating that the particle loss mechanisms in the TD are not clear: “The mechanism and size-dependence of this particle loss is currently unclear and requires further investigation.”

Figure 6: What are the grey, circular "cloud" shapes on each side of the heated section at the top of the figure?

We are not sure what the reference is to. This is what we see on our screen and printouts.

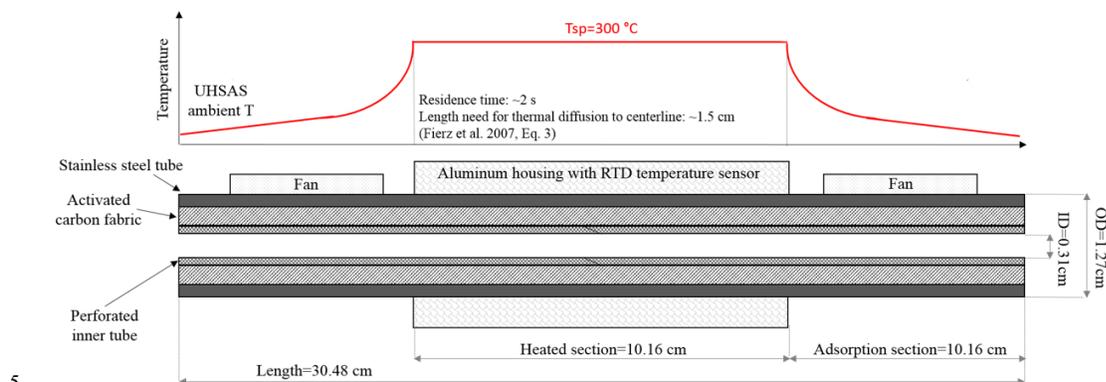


Fig.6. Schematic cross-section of the thermodenuder and conceptual temperature profile. Temperature is measured at a single point with a platinum RTD sensor inside the aluminium housing around the heated section. The thermal diffusion length estimate assumes standard pressure and temperature and typical flow in thermodenuder, small perturbations in temperature, and is use only for qualitative understanding of heat flow in the thermodenuder.

Section 5.3: Are sample flow rates changed during flights? A minor point, but it would be interesting to know if UHSAS response is affected by sample flow rate within a reasonable range. Assuming the residence time in the denuder could be maintained the count rate could be increased in the FT to improve the statistics and reduce uncertainties.

The sample flow rate changes in flight. As described in section 3.6, the sample flow rate drops when the UHSAS operates at lowest pressures. This effect does not affect UHSAS sizing characteristics (Fig.S1). We agree that maintaining the flow rate constant in the free troposphere would improve the counting statistics, and reduce uncertainties.

Section 6.1, line 17: I assume the reason to only compare 100-900 nm and not the full UHSAS size range is to avoid slight variations in detection efficiency and saturation? I am curious how well the instruments compare over the full range given by the manufacturer.

Yes, we wanted to compare over a range where both instruments measure with 100% efficiency. As indicated in Table 1, the UHSAS-1 (thermodenuded instrument) is not as sensitive as the newer unit, and 100 nm is safely above the roll-off in detection efficiency to ensure a fair comparison. The diameter of 900 nm has been chosen as the upper limit of the UHSAS sizing calibration curve based on measured ammonium sulfate particles (Fig.3). Above 900 nm the calibration is based on fitted parameters rather than the actual measured calibration particles.

Reviewer #3 (received and published: 13 November 2017)

GENERAL COMMENT

The manuscript describes the results of a well-conducted study on the characteristics of two modified aerosol spectrometers (UHSAS) operated on the NASA DC-8 during the ATom airborne campaign. The implemented modifications concern mainly the stabilization of the sample flow at reduced and variable pressure levels which usually occur during airborne operation, and the introduction of a thermal denuder. The studies have been carefully designed and conducted, and the paper is clearly structured and well written. The topic fits well into the scope of AMT and the manuscript deserves publication after few minor revisions have been considered.

We thank reviewer #3 for positive evaluation.

Minor revision are requested for these topics:

1. In Section 5, potential uncertainties in particle sizing from the unknown refractive index and the unknown impact of particle non-sphericity are not discussed in detail. For comparison, a detailed study on the impact of refractive index and shape uncertainties on particle size distributions determined by an optical particle spectrometer is reported by Fiebig et al. (2002) for the PCASP which uses almost similar collection optics as the UHSAS. The authors may link their findings to these results to get an estimate of the expected range of uncertainties.

We are not entirely sure we have fully understood reviewer's comment.

In Section 5.1 we stated that we did not investigate the effect of particle shape on UHSAS sizing accuracy. The ATom project focuses on the remote atmosphere where well-aged particles (assumed to be spherical) are expected to dominate the submicron aerosol (outside of sea-salt and dust cases). Examples of uncertainties representative of conditions encountered during ATom flights are summarized in Table S3.

The paper by Fiebig et al. (2002) focuses on biomass-burning aerosol properties and associated uncertainties. We feel that linking these two studies is not straight forward, therefore we decided not to include a reference to this paper here.

In section 3.2 we have added few sentences that might be relevant to the reviewer's comment above: "The refractive index of soil dust may exceed the range of real refractive indices considered here. In addition, dust can be both absorbing and aspherical. When dust is an important component of the atmospheric aerosol, uncertainties in both the denuded and thermodenuded UHSAS instruments should be evaluated on a case-by-case basis using best estimates of refractive index and shape based on other measurements, coupled with optical simulations of instrument response."

2. Sections 3.5 and 3.6 may be combined since the only effect of pressure on particle sizing will arise from flow variations. A good example for the effect of an instable flow on the calibration of an optical particle counter is given by Bundke et al. (2015). The authors may refer to this instrument characterization study to compare their results.

We agree and we have combined these two subsections and modified section 3.5 header to: "The effect of pressure on sample flow and particle sizing"

We mention in Section 3.5 that this reduction in sample flow at low pressure sampling conditions is caused by a small leak in the optics block downstream of the detection region. Therefore, we directly measure the sample flow to account for this effect on concentration. Further, we have shown that the leak does not affect UHSAS sizing characteristics (Fig.S1). This is a unique situation to our instrument therefore we feel the suggested citation is not needed here.

3. In Section 3.1 the authors may add information n the size range of the produced aerosols. This would complete the information to the reader about the experiments performed in this study.

Thank you for noticing. We have added a size range and the sentence reads now:

Page 5 line 27: "Particles with a range of diameters between 0.05 and 1 μm were generated in two ways: 1) by using an atomizer to produce ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$), polystyrene latex (PSL) spheres, or di-2-ethylhexyl (dioctyl) sebacate (DOS) particles (Table 1); or 2) from new particle formation and condensational growth from limonene ozonolysis products in a flow tube reactor."

MINOR COMMENTS

Abstract: The abstract may be shortened to 250 – 300 words, e.g., the first sentence can be skipped and some details can be shifted to the text body.

Thank you for this suggestion, however we would like to keep the current version of the abstract.

Page 2, line 17: you may write: “to a size-proportional voltage pulse”.

Corrected.

Page 2, line 25: I suggest rephrasing: “wished to dry the air sample and to install a thermodenuder used to distinguish non-volatile particles. These sample : : :”

Corrected.

Page 3, line 24: please modify "between 0.06 – 1 μm in diameter".

Corrected.

Page 10, line 6: It should read: “life time”.

We think “live-time” is used there correctly.

REFERENCES

Bundke, U., Berg, M., Ibrahim, A., Tettich, F., Klaus, C., Franke, H., Fiebig, M., and Petzold, A.: The IAGOS-CORE aerosol package: Instrument design, operation and performance for continuous measurement aboard in-service aircraft, *Tellus B*, 67, 28339, doi: 10.3402/tellusb.v67.28339, 2015.

Fiebig, M., Petzold, A., Wandinger, U., Wendisch, M., Kiemle, C., Stifter, A., Ebert, M., Rother, T., and Leiterer, U.: Optical closure for an aerosol column: Method, accuracy, and inferable properties applied to a biomass-burning aerosol and its radiative forcing, 107, doi:10.1029/2000JD000192, doi: doi:10.1029/2000JD000192, 2002.

Modification, Calibration, and Performance of the Ultra-High Sensitivity Aerosol Spectrometer for Particle Size Distribution and Volatility Measurements During the Atmospheric Tomography (ATom) Airborne Campaign

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Abstract. Atmospheric aerosol is a key component of the chemistry and climate of the Earth's atmosphere. Accurate measurement of the concentration of atmospheric particles as a function of their size is fundamental to investigations of particle
15 microphysics, optical characteristics, and chemical processes. We describe the modification, calibration, and performance of two commercially available, ultra-high sensitivity aerosol spectrometers (UHSASs) as used on the NASA DC-8 aircraft during the Atmospheric Tomography Mission (ATom). To avoid sample flow issues related to pressure variations during aircraft altitude changes, we installed a laminar flow meter on each instrument to measure sample flow directly at the inlet as well as flow controllers to maintain constant volumetric sheath flows. In addition, we added a compact thermodenuder operating at
20 300°C to the inlet line of one of the instruments. With these modifications, the instruments are capable of making accurate (ranging from 7 % for $D_p < 0.07 \mu\text{m}$ to 1 % for $D_p > 0.13 \mu\text{m}$), precise ($< \pm 1.2$ %) and continuous (1 Hz) measurements of size-resolved particle number concentration over the diameter range of 0.063-1.0 μm at ambient pressures of >1000 to 225 hPa, while simultaneously providing information on particle volatility.

We assessed the effect of uncertainty in the refractive index (n) of ambient particles that are sized by the UHSAS assuming
25 the refractive index of ammonium sulfate ($n=1.52$). For calibration particles with n between 1.44 and 1.58, the UHSAS diameter varies by +4/-10 % relative to ammonium sulfate. This diameter uncertainty associated with the range of refractive indices (i.e. particle composition) translates to aerosol surface area and volume uncertainties of +8.4/-17.8 % and +12.4/-27.5 % respectively. Additional to sizing uncertainty, low counting statistics can lead to uncertainties of <20 % for aerosol surface area and <30 % for volume with 10 s time resolution. The UHSAS reduction in counting efficiency was corrected for
30 concentrations >1000 cm^{-3} .

Examples of thermodenuded and non-thermodenuded aerosol number and volume size distributions as well as propagated uncertainties are shown for several cases encountered during the ATom project. Uncertainties in particle number concentration

were limited by counting statistics, especially in the tropical upper troposphere where accumulation mode concentrations were sometimes $<20 \text{ cm}^{-3}$ (counting rates $\sim 5 \text{ Hz}$) at standard temperature and pressure.

1. Introduction

The concentration of particles as a function of size is fundamentally related to both direct (aerosol-radiation) and indirect (aerosol-cloud) effects of aerosol on climate. Particles with diameters (D_p) $> 0.1 \mu\text{m}$ efficiently scatter and absorb solar radiation (e.g., Charlson et al., 1992). Particles with $D_p > 0.05 \mu\text{m}$ serve as cloud condensation nuclei (CCN; Clarke and Kapustin, 2002; Dusek et al., 2006; Köhler 1936). CCN play a role in cloud formation and in altering radiative properties and lifetime of existing clouds (Albrecht, 1989; Twomey, 1974, 1977). Measurement of aerosol size-resolved number concentration is crucial to understand aerosol sources and sinks, optical properties, cloud nucleation potential and chemical transformations, and consequently to constrain models of aerosol-cloud-climate interactions.

There is currently a variety of techniques available for measuring aerosol size distributions (McMurry, 2000) but only some of these are fast enough to sample aboard aircraft. The ultra-high sensitivity aerosol spectrometer (UHSAS; Droplet Measurement Techniques (DMT) Inc., Longmont, CO, USA) is one such instrument. The UHSAS is an optical particle counter for measuring particles from $0.06\text{-}1 \mu\text{m}$, which is often used for laboratory, ground-based and airborne measurements. It counts and sizes particles by measuring the amount of light scattered by individual particles as they traverse a focused laser beam. A fraction of the side-scattered light is then collected by the optical system and focused onto two photodetectors where it is converted to a size-proportional voltage pulse. The size of particle is determined from the height of the voltage pulse by using a calibration curve obtained from measurements of spherical particles with known size and composition. Size distributions are obtained by accumulating the individual pulse magnitudes of a population of particles into a histogram.

Two versions of UHSAS are currently commercially available. One, designed for airborne measurements, is enclosed in an underwing canister for in-situ sampling, while the other one is intended for ground-based aerosol sampling. Here we focus on the modification, accuracy and operation of two UHSAS instruments (hereafter referred to as UHSAS-1 and UHSAS-2) during the first and second ATmospheric Tomography Mission (ATom) field campaigns in summer 2016 and winter 2017, respectively. The ground-type UHSAS instruments were chosen for this study over the wing-mounted version because we wished to dry the air sample and to install a thermodenuder used to distinguish non-volatile particles. ~~T~~hese sample treatments are not possible with the compact, wing-mounted instrument. The ground-type UHSAS has been deployed in various airborne-based campaigns (Brock et al., 2011, 2016; Kassianov et al., 2015; Yokelson et al., 2011). However, as reported by Brock et al. (2011), modifications to the flow system are required to make them suitable for airborne sampling.

Cai et al. (2008) reported a laboratory evaluation of the UHSAS and Brock et al. (2011) report modifications to the flow system; however, a complete evaluation of the accuracy and precision of the UHSAS instrument for airborne operation is lacking. Here we describe modifications to the ground-based UHSAS for airborne operation, detail the installation of a compact

thermodenuder in a second UHSAS for aerosol volatility studies, and evaluate the accuracy, precision and in-flight performance of both UHSAS instruments during the first two of four ATom airborne campaigns.

1.1 The ATom mission

The ATom mission uses a DC-8 aircraft to survey the remote atmosphere over the Pacific and Atlantic Oceans from $\sim 80^\circ$ N to $\sim 65^\circ$ S while making repeated vertical profiles from 0.15-12 km to provide information on greenhouse gases, reactive and tracer species, and aerosol composition and size distribution. At the conclusion of the ATom project in spring 2018, the DC-8 will have made four global circuits, one circuit for each season. The UHSAS instruments are a part of a suite of fast-response aerosol size distribution instruments focusing in particular on the spatial variation in the abundance of 0.003-4.8 μm sized particles (Brock et al., in preparation; Williamson et al., in preparation). Scientific goals for these instruments include identifying the spatial extent of new particle formation in the remote troposphere and the associated mechanisms and controlling parameters, quantifying the growth of newly formed particles to cloud-active sizes, and determining the importance of aerosols from continental sources to the remote troposphere.

By operating two well-calibrated UHSAS instruments, one with a thermodenuder (UHSAS-1), and one without (UHSAS-2), the size-dependent particle volatility can be determined continuously, which is particularly useful for airborne sampling where fast time response is needed. Volatility is an important physical property defined by the chemical composition of the condensed species and may reflect the origin of the particle (Huffman et al., 2008; Jonsson et al., 2007). Most secondary compounds (such as sulfates, nitrates or organics) are expected to volatilize below 300°C while primary particles such as soot, sea salt and soil dust survive heating (e.g., Clarke, 1991; Clarke and Kapustin, 2002; DeCarlo et al., 2008). Measurements of particle volatility help identify the contribution of secondary particles formed in the free troposphere (FT) to the budget of CCN-sized particles in the marine boundary layer (MBL), and how this contribution varies with altitude and location in the remote atmosphere.

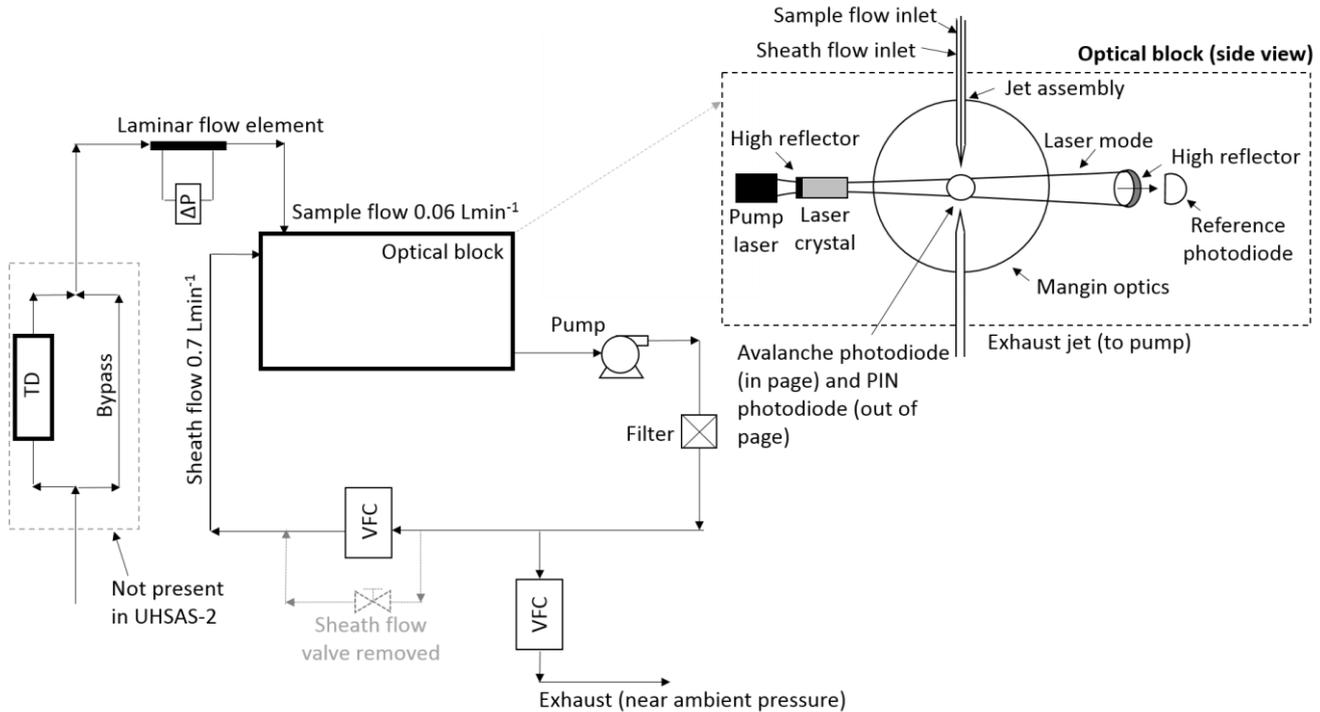
2. The ultra-high sensitivity aerosol spectrometer (UHSAS)

2.1 Operating principles

The UHSAS (Cai et al., 2008) measures aerosol size-resolved number concentration between 0.06-1 μm in diameter in 99 logarithmically spaced bins with user-selected time resolution. The UHSAS uses a high-intensity infrared laser (a semiconductor-diode-pumped solid-state neodymium-doped yttrium lithium fluoride ($\text{Nd}^{3+}:\text{Y LiF}_4$), operating at 1054 nm with intra-cavity circulating power of $\sim 1 \text{ kW cm}^{-2}$), an inlet jet assembly and two detection systems: a highly sensitive avalanche photodiode (APD) to detect and size the smallest particles, and a less sensitive secondary PIN photodiode to size larger particles (Fig.1). These detectors are located at 90° on either side of laser beam, aligned with the intersection of the aerosol stream and the laser beam.

When particles exit the inlet jet assembly in the optical block they traverse the center of the focused laser beam and scatter light into the detection system. Scattered light collected by two pairs of Mangin optics (over solid angle of $33\text{-}147^\circ$) is imaged onto the APD and PIN photodetectors. The center region of the solid angle ($72.5\text{-}104.8^\circ$) is not sampled due to the hole cut out in the outer of the mirrors, with the detector size being a negligible fraction of this hole area (Brock et al., 2016). This geometry contrasts with that reported by Cai et al. (2008), who used scattering angles from $22\text{-}158^\circ$ to simulate UHSAS response. The geometry we report was determined in consultation with the manufacturer and agrees with values given by Petzold et al. (2013). The amount of scattered light reaching the detectors is a function of not only particle size, but also refractive index (n) and shape.

Each photodiode produces a photocurrent pulse, which is converted to a voltage pulse through analog amplifiers. The signal from each detector is amplified by two different gain circuits (high and low), providing a total of four independent gain stages with some overlap (one particle may be separately sized by each of two adjacent gain stages). The outputs from these gain stages are combined by linear regression in the overlap regions to provide a single scale for accurate sizing across the full range of the UHSAS response.



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Fig.1: UHSAS with its modified flow system including schematic of the UHSAS-1 and UHSAS-2 inlets. The sample air at a flow rate of $60\text{ cm}^3\text{min}^{-1}$ enters the inlet and in UHSAS-2 goes directly through the laminar flow element, while in UHSAS-1 additionally a thermodenuder (TD, $T=300^\circ\text{C}$) was installed so the flow first enters the switching (Hanbay) valve and either bypasses or passes through the TD before it enters the laminar flow element. Optical block schematic adopted from UHSAS User Manual.

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2.2 Modified flow system

Because the ground-based version of the UHSAS was not designed for operation on aircraft where pressure changes, flow system modifications are essential for airborne use. In the standard UHSAS configuration the aerosol sample flow is controlled and measured by a mass flow controller mounted on the exhaust side of the pump (Fig.1). If mass flow were maintained in flight, the volumetric flow rate would change inversely with air density, leading to changes in particle velocity through the laser beam and thus pulse width. A further issue is associated with transient sample flow response to pressure changes during aircraft altitude changes. Because the inlet nozzle restricts the sample flow entering the optical block, there is a time lag between any external pressure change and the pressure within the UHSAS optics block. This pressure disequilibrium changes the inlet flow to the optics block in a way that is dependent on the rate of pressure change and the fluid dynamics of the nozzle flow, which may vary with altitude because it depends upon Reynolds number (R_e). Because the particle number concentration is calculated from the measured count rate and sample flow rate, it is essential to account for these transient effects and directly measure the flow rate at the inlet. Finally, using a needle valve to control the split between the aerosol and sheath flows results in the sheath-aerosol flow ratio varying with changing pressure because pressure drop through the valve is also Reynolds-number-dependent and will vary with pressure, even at a constant volumetric flow rate.

Because of the above issues, the flow system of both UHSAS instruments was modified (Fig.1; Table S1). The modifications include installation of a laminar flow element with a differential pressure transducer to directly and precisely measure the time-varying sample volumetric flow rate at the optics block inlet, and replacement of the sheath flow valve with a volumetric flow controller (VFC) to directly monitor and control sheath flow. The Alicat mass flow controller on the exhaust side of the instrument, which is connected to an exhaust line near inlet pressure to control the exhaust flow, was switched to operate in volume flow control mode. The inlet laminar flow meter and differential pressure transducer were calibrated together over a flow range of 0-0.1 Lmin⁻¹ using a volumetric flow calibration standard (DryCal DC-Lite, Bios, Inc., Butler, NJ, USA). The modified UHSAS is operated at ~0.06 Lmin⁻¹ total inlet flow and 0.7 Lmin⁻¹ sheath flow. The original UHSAS LabView software was modified to accommodate these changes.

3. Laboratory performance

3.1 Aerosol generation method

The sizing performance of the UHSAS and the effects of particle composition and concentration were investigated in the laboratory (Fig.2Fig-2). Particles with diameters between 0.05 and 1 μ m were generated in two ways: 1) by using an atomizer to produce ammonium sulfate ((NH₄)₂SO₄), polystyrene latex (PSL) spheres, or di-2ethylhexyl (dioctyl) sebacate (DOS) particles (Table 1Table 4); or 2) from new particle formation and condensational growth from limonene ozonolysis products in a flow tube reactor.

3.1.1 Atomized aerosol and DMA

Particles were generated using an HPLC-grade water (or HPLC-grade isopropanol in the case of DOS) solution and a custom-built Collison-type atomizer (May, 1973). Atomized droplets were dried in a silica gel diffusion drier, charged by a Po^{210} radioactive source and (except for the PSL) size-selected in a custom-built differential mobility analyzer (DMA) with a recirculating sheath flow. The sizing uncertainty (σ_S) of the DMA was $\pm 1.6\%$ estimated from the sum in quadrature (square root of the sum of squares) of the sheath flow (σ_Q), pressure (σ_P), temperature (σ_T) and voltage (σ_V) uncertainties as described in Eq.1.

$$\sigma_S = \sqrt{\sigma_Q^2 + \sigma_P^2 + \sigma_T^2 + \sigma_V^2} \quad (1)$$

A sizing bias to smaller diameters was identified when using NIST-traceable polystyrene latex (PSL) microspheres with diameters between 0.07-0.4 μm (Thermo Scientific, Inc. Waltham, MA, US). This DMA sizing bias is estimated to be about 7% at sizes below 0.07 μm and decreases to 1% for sizes above 0.13 μm . However, we believe that the actual bias is $< 7\%$ as these PSLs were checked against an independent DMA by P. Campuzano-Jost of the University of Colorado, and the results were similar, suggesting a surfactant coating on the smaller PSL sizes rather than a DMA sizing error. ~~Still~~ No adjustments were made to the DMA diameters, but these potential biases when compared to the PSL sizes are propagated through to the aerosol surface and volume concentration uncertainties discussed below.

The calibration DMA operated at a 1:10 aerosol to sheath flow ratio and sheath flow rates of 3 to 5 L min^{-1} . The monodisperse aerosol flow exiting the DMA was diluted using particle-free air to match the flow rate of the instruments located downstream. The incoming particle free air was homogeneously mixed with calibration particles in a short section of turbulent ($Re > 4000$) flow and sampled by the two UHSAS instruments and a CPC (Model 3022A; TSI Inc., St. Paul, Minnesota, USA). The relative humidity (RH) of the aerosol flow was monitored by two RH sensors (Vaisala HMP60) installed in the DMA, one on the sample flow exiting the DMA and the other on the sheath flow exiting the DMA column, and was typically $< 10\%$. It was important to dry the atomized $(\text{NH}_4)_2\text{SO}_4$ aerosol prior to size classification to avoid sizing biases due to the uncontrolled evaporation of water in the DMA and UHSAS and refractive index effects in the UHSAS.

3.1.2 Flow tube reactor and DMA

A secondary organic aerosol (SOA) from limonene ozonolysis was generated in a borosilicate glass (Pyrex) flow tube reactor as described in Williamson et al. (in preparation). Particles formed from limonene oxidation were size selected in a DMA as described above.

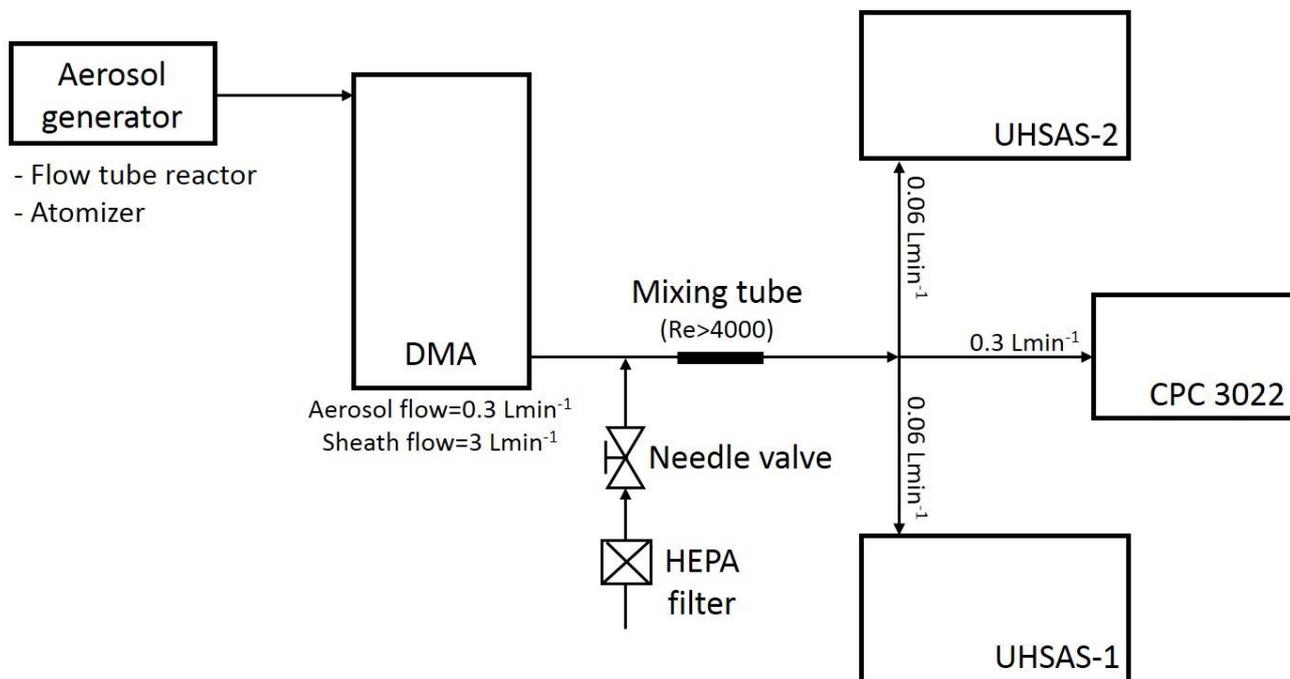


Fig.2. A schematic diagram of the aerosol generation and measurement set-up at atmospheric pressure conditions. The calibration aerosol was generated either in a flow tube reactor or the atomizer. Apart from PSL, all atomized particles were sent through a diffusion drier to DMA for size selection, while PSL particles were delivered from the atomizer directly to both UHSAS instruments following dilution with dry air.

3.2 The effect of composition on particle sizing

Particle sizing in the UHSAS is a function of the amount of light scattered onto the instrument's photodetectors. The quantity of scattered light however, is a function not only of size, but also of the composition-dependent aerosol refractive index (Bohren and Huffman, 1983). Particles of $(\text{NH}_4)_2\text{SO}_4$ were used to relate scattered light intensity to particle size, since their refractive index at 1054 nm ($n=1.527$; Hand and Kreidenweis, 2002) lies in the middle of the typical range of refractive indices for atmospheric particles composed of mixed sulfate salts and organic compounds. However, the composition of the atmospheric particles is not known *a priori*. The refractive index of organic aerosol in particular is not well constrained (Dick, 2007; Kanakidou et al., 2005). Kim and Paulson (2013) suggest values for refractive index (at $\lambda=532$ nm) for biogenic and anthropogenic secondary organic aerosol (SOA) of 1.44 and 1.55, respectively. To constrain the effects of particle refractive index on UHSAS sizing we investigated a range of nearly monodisperse calibration particles having different known refractive indices (Table 1, Fig.3), including $(\text{NH}_4)_2\text{SO}_4$, PSL microspheres, and DOS, as well as limonene oxidation products (with an unknown refractive index). For particles of $D_p < 0.6 \mu\text{m}$ and a real refractive index (n) of 1.44-1.58, the diameter

measured by the UHSAS may vary by between +4/-10 % relative to the one based on $(\text{NH}_4)_2\text{SO}_4$. The propagation of this potential bias to reported aerosol surface and volume concentrations uncertainties is discussed in Sect. 5.1.

The refractive index of soil dust may exceed the range of real refractive indices considered here. In addition, dust can be both absorbing and aspherical. When dust is an important component of the atmospheric aerosol, uncertainties in both the denuded and thermodenuded UHSAS instruments should be evaluated on a case-by-case basis using best estimates of refractive index and shape based on other measurements, coupled with optical simulations of instrument response. Also, because the thermodenuded UHSAS instrument volatilizes non-refractory particles, the refractive indices in the aerosol measured by the two instruments will differ. This problem is probably minor in the MBL because sea-salt aerosol has a refractive index within the range of the calibrants. For the free troposphere, however, there may be substantial sizing biases between the two instruments that should be considered case by case using additional information on aerosol composition.

Finally, we note that light-absorbing black carbon (BC) particles are mis-sized in the UHSAS. The optical cavity laser power is $\sim 1 \text{ kW cm}^{-2}$; at 1054 nm, similar to that in the single particle soot photometer (SP2; Schwarz et al., 2010), and some limited laboratory studies we performed suggest that BC incandesces and vaporizes in the UHSAS. Even without incandescing, the complex refractive index of BC particles ($n=2.26-1.26i$ at $\lambda=1064 \text{ nm}$; Moteki et al. 2010) substantially alters UHSAS sizing compared with the calibration aerosol. Because the number concentration of BC cores with volume-equivalent diameter (assuming void-free density of 1.8 g cm^{-3}) in the range 90-550 nm accounted for less than 5 % of the particle concentration in the same size range during the ATom-1 mission (except for the case of biomass burning plumes off the coast of Africa), mis-sizing due to BC is a minor effect in general in ATom. For cases of specific plumes from combustion sources in which BC is an abundant aerosol component this assumption should be re-evaluated.

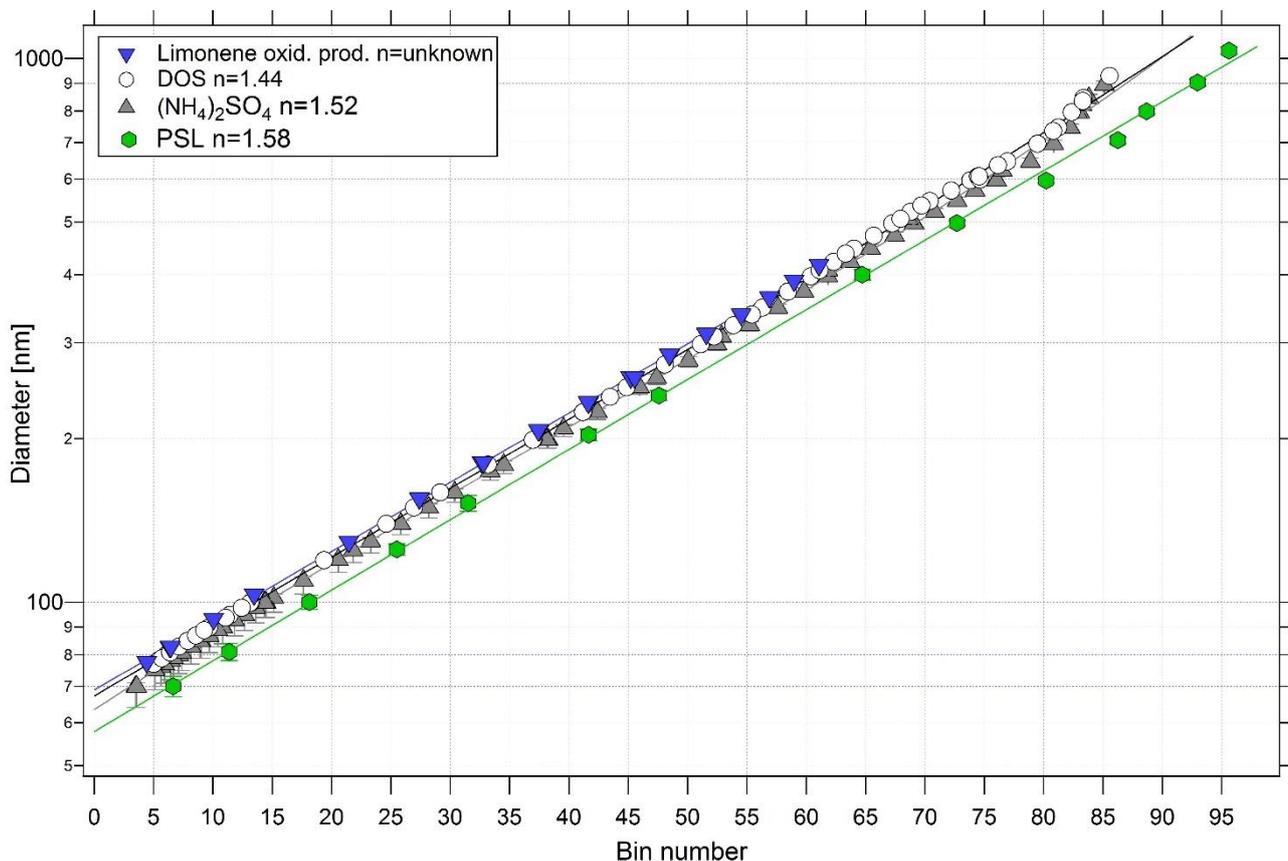


Fig.3. Calibration particle diameter as a function of UHSAS-2 (not thermodenuded) bin number for particles composed of PSL, (NH₄)₂SO₄, DOS and limonene ozonolysis products. Solid lines represent fits to the data. Uncertainties are shown for (NH₄)₂SO₄ and PSL but are often obscured by the symbols.

5

3.3 Particle detection efficiency

The detection efficiency, the ratio of concentration of particles of a given size measured by the sum of all bins of the non-thermodenuded UHSAS-2 to that measured by a TSI 3022A CPC, depends on the refractive index of the calibration particles used. Fig.4 presents the detection efficiency for the non-thermodenuded UHSAS as a function of mobility equivalent diameter for (NH₄)₂SO₄ and DOS particles, which varies due to the differing refractive indices of these compounds. The diameter uncertainties were calculated as described in Eq.1, and were corrected for the possible sizing bias observed using PSL standards. In a similar manner the uncertainties in the efficiency were calculated using the UHSAS and CPC uncertainties from the flow and pressure measurements and counting statistics. Detection efficiencies for both UHSASs are provided in Table 1. The thermodenuded UHSAS begins detecting particles at larger diameters than the other instrument.

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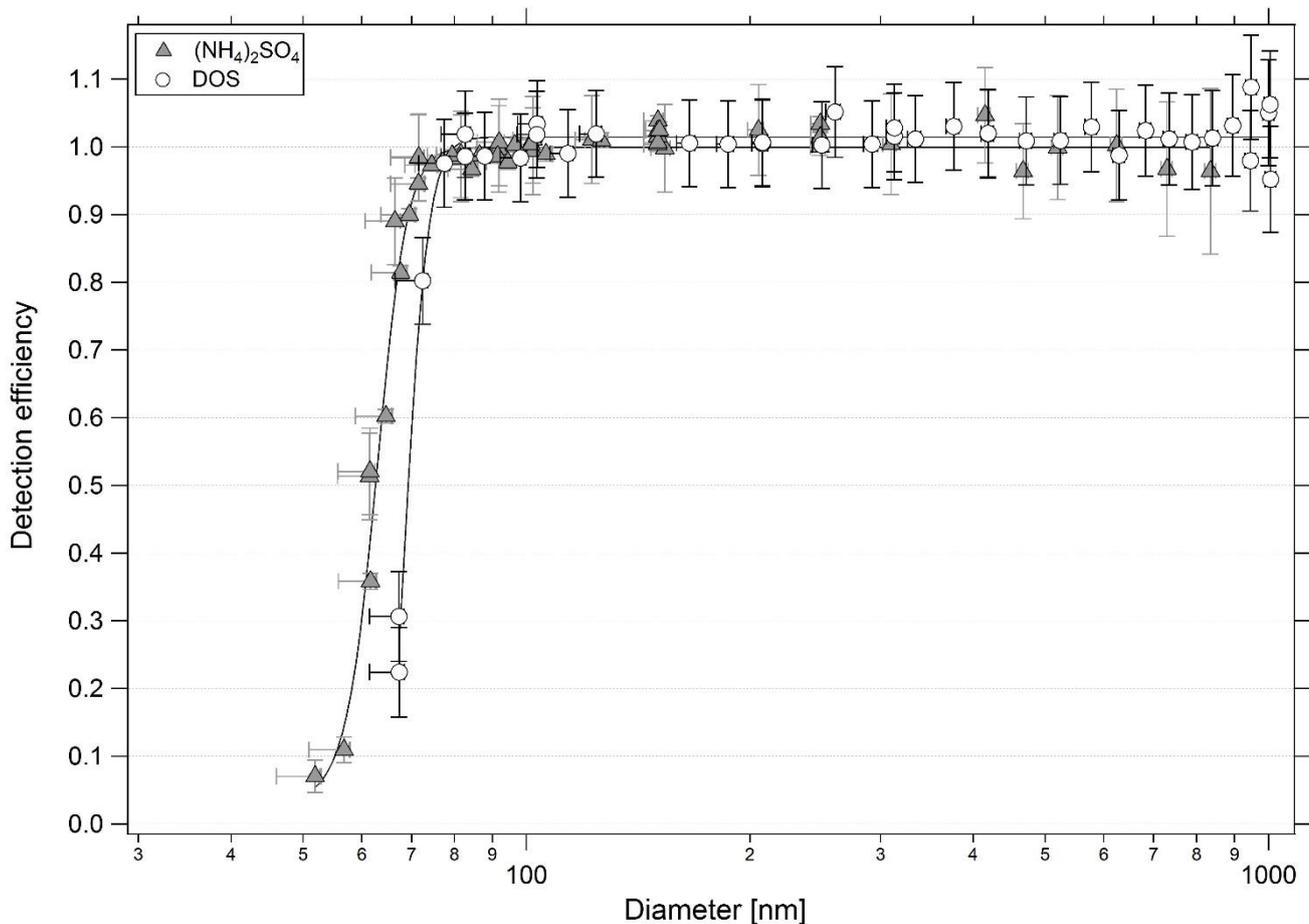


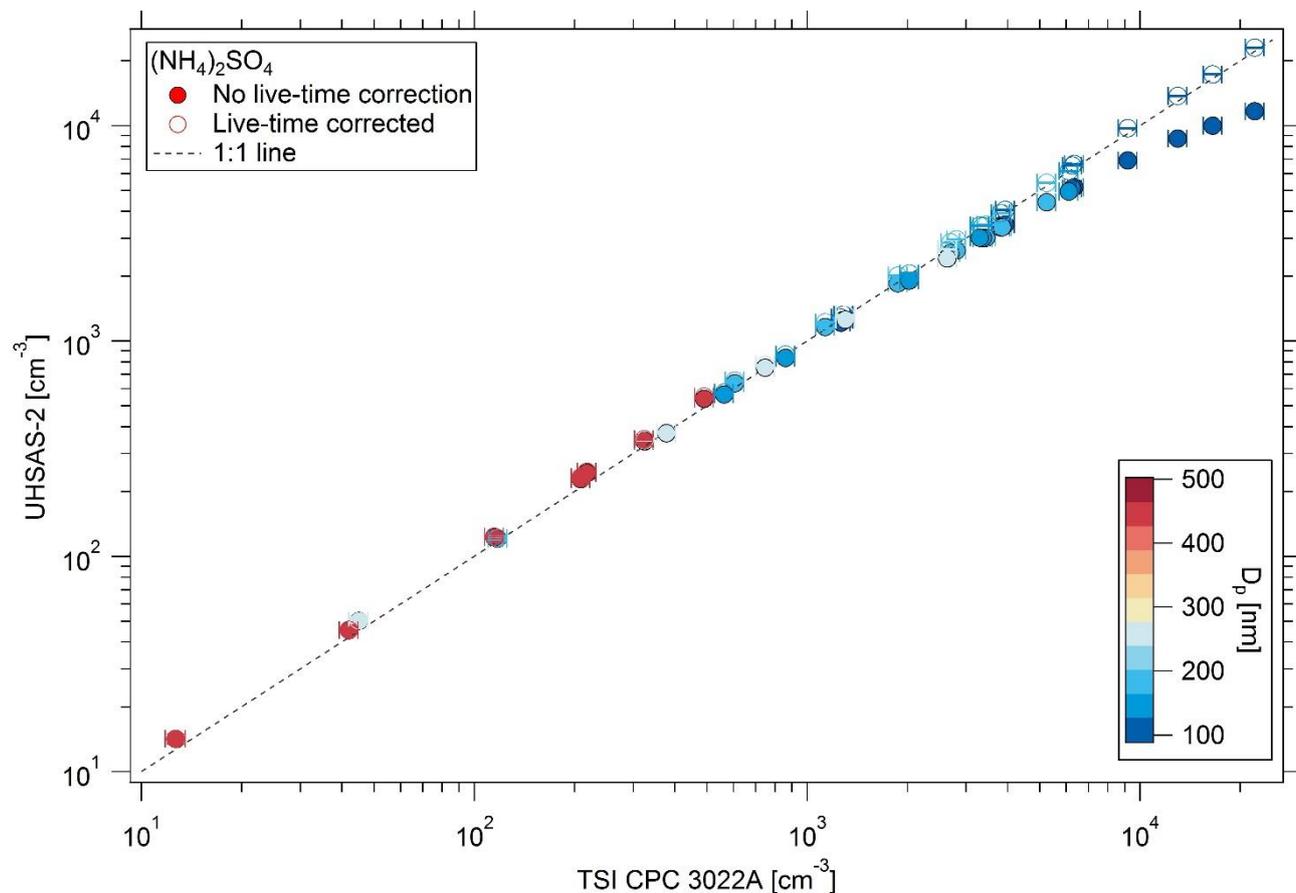
Fig.4. Detection efficiency of the non-thermodenuded UHSAS-2 instrument as a function of mobility equivalent diameter for (NH₄)₂SO₄ and DOS aerosol. Data are corrected for coincidence. Solid lines are fits presented to guide the eye.

5 3.4 The effect of concentration on particle counting

The UHSAS sensitivity to particle concentration was quantified using atomized (NH₄)₂SO₄ particles with diameters >0.1 μm and concentrations between 1 and 10⁴ cm⁻³. All concentrations and flow rates presented in this paper are at STP conditions. The UHSAS exhibited a non-linear reduction in counting efficiency relative to the reference CPC at concentrations >1000 cm⁻³ due to particle coincidence in the optical sensing volume (Fig.5). Since the UHSAS software does not monitor and correct for coincidence effect, or live-time, while the CPC software does, we determined a phenomenological correction based on the observed counting efficiency as a function of count rate (Eq. 2):

$$N_{true} = \frac{N_{meas}}{1 - \tau * N_{meas} Q_{samp}}, \quad (2)$$

where N_{true} is the corrected number concentration (equal to the CPC concentration), N_{meas} the measured number concentration, and Q_{samp} is the measured volumetric sample flow rate. Based on fitting the data in Fig.5 to Eq. 2, for the UHSAS-1, $\tau=7.81 \times 10^{-5}$ s while for the UHSAS-2, $\tau=5.36 \times 10^{-5}$ s. These values represent the average particle pulse width for each instrument.



5 **Fig.5. Relationship between the UHSAS-2 and the CPC particle number concentration (cm^{-3}) for nearly monodisperse $(\text{NH}_4)_2\text{SO}_4$ aerosol of various sizes ($> 0.1 \mu\text{m}$) at ambient pressure. Dashed line represents 1:1 correspondence line.**

3.5 The effect of pressure on sample flow and particle sizing

Laboratory evaluation of the UHSAS operation at reduced pressure conditions is important for the interpretation and validation of the airborne data during the ATom flights. To investigate possible pressure dependencies, a needle valve and an external pump were used to reduce the instrument pressure. The flow passing through a needle valve downstream of the atomizer was split into sample and bypass flows, the latter of which was connected to the pump. The exhausts of the UHSAS instruments were also connected to the bypass flow line to keep them at near-inlet pressure. A mixture of four PSL sizes was atomized and measured as instrument pressure was adjusted to as low as 250 hPa. The sizing of the UHSAS instruments showed no statistically significant pressure dependence (Fig.S1). The mean bin number and replicate standard deviation associated with each of the four PSL sizes at various pressure settings is 10.5 ± 0.19 , 24.5 ± 0.24 , 47.6 ± 0.2 and 64.5 ± 0.2 for the 81, 125, 240

and 400 nm PSL particles, respectively. Using the standard $(\text{NH}_4)_2\text{SO}_4$ calibration curve (Fig.3), which relates bin number to particle diameter, the equivalent relative standard deviations in diameter were ± 0.6 , 0.7, 0.5, and 0.7 % for the four diameters, respectively.

5 **3.6 The effect of pressure on sample flow**

Using the same set-up ~~as described in the paragraph above~~, we investigated the effect of changing pressure on the sample flow. The aerosol volumetric flow rate showed a pressure dependence, decreasing from $60 \text{ cm}^3 \text{ min}^{-1}$ at around 850 hPa to about $35 \text{ cm}^3 \text{ min}^{-1}$ at 250 hPa (near the minimum pressure encountered during ATom). This flow reduction is caused by a small leak in the optics block downstream of the detection region. It was impractical to disassemble the complex optics assembly to find the source of this leak. Therefore, we directly measure the sample flow to account for this effect on concentration, and the leak does not affect UHSAS sizing characteristics (Fig.S1).

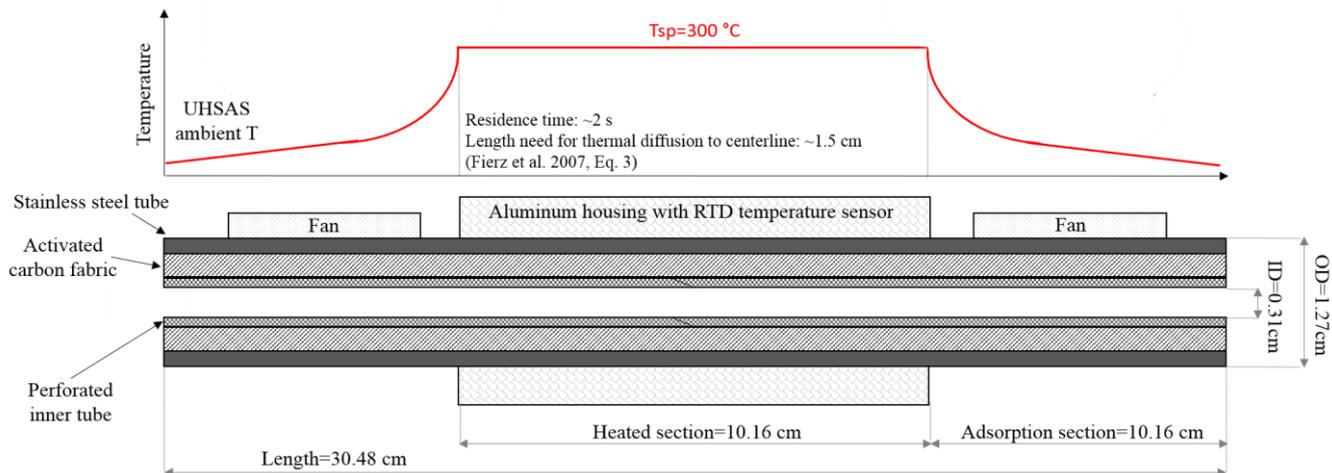
4.0 Thermodenuder

A compact thermodenuder was designed and installed in UHSAS-1 to determine the number and volume fraction of volatile particles (Fig.6; Table S2). This measurement is used to identify particles that are formed from secondary products (e.g., sulfates, nitrates, and organics) from primary particles (e.g., soil dust and sea-salt; Clarke, 1991; Huffman et al., 2008). Quantifying the volatile to non-volatile aerosol fraction during ATom may help improve understanding of the importance of secondary particles relative to sea-salt as CCN in the MBL, an area of active scientific inquiry (e.g., Bates et al., 2016; Quinn et al, in press).

4.1 Design

20 We constructed a custom thermodenuder based on the design principles outlined by Fierz et al. (2007), who improved denuder performance by providing a heated adsorption section. This thermodenuder operates at a lower flow rate and is of a smaller size compared to previous designs. An electric actuator (MDM-060DT, Hanbay Inc., Pointe-Claire, Quebec, Canada), driving a Swagelok valve (SS-43YF2) is used to automatically switch between sampling through the thermodenuder or bypassing it. The thermodenuder consists of a heated section (length, $L=10.16 \text{ cm}$, inner diameter (ID)= 0.48 cm) held at a fixed temperature
25 ($T=300^\circ\text{C}$) followed by an adsorption section of same dimensions (Fig.6; Table S2). Both sections are housed in a stainless steel tubing ($L=30.48 \text{ cm}$, $OD=1.27 \text{ cm}$) which contains an inner porous, perforated tube of the same length constructed from two pieces and manufactured using a metallic 3D printing technique, direct metal laser sintering (Xometry, Gaithersburg, MD, USA). This perforated tubing is wrapped with activated carbon fabric (Zorflex; 4.066 g). The outer tube passes through an aluminium housing which holds the tube and temperature sensor in place and is wrapped with a heating tape and fiberglass
30 insulation material. Two fans installed in the outer casing of the heating section the entrance and exit sections of the

thermodenuder cool these sections of the outer tube. A thermal process controller monitors a resistance thermal detector (RTD) and controls the temperature of the aluminium bloc housing using a cylindrical cartridge heater. The temperature of the housing is maintained in flight at 300 ± 0.5 °C. The residence time of the aerosol in the thermodenuder as well as the temperature profile in part determine thermodenuder performance. Fierz et al. (2007) developed simple guidelines for selecting an appropriate thermodenuder heated section length for a particular sample flow rate. Our thermodenuder meets these recommendations and provides a residence time in the heated section between 1.59-3.7 seconds. We do not directly measure the thermal profile within the compact thermodenuder.



10 **Fig.6. Schematic cross-section of the thermodenuder and conceptual temperature profile. Temperature is measured at a single point with a platinum RTD sensor inside the aluminium housing around the heated section. The thermal diffusion length estimate assumes standard pressure and temperature and typical flow in thermodenuder, small perturbations in temperature, and is use only for qualitative understanding of heat flow in the thermodenuder.**

4.2 Thermodenuder performance

- 15 Particle losses through the thermodenuder were determined relative to either a TSI 3022A CPC or the second UHSAS instrument. With the thermodenuder operating at room temperature, losses through the sample selection valve and heater plumbing were < 13 % for particles with $D_p > 0.15$ μm . The mechanism and size-dependence of this particle loss is currently unclear and requires further investigation. With the heater on and the thermodenuder operating at 300 °C, losses of non-volatile NaCl particles did not change significantly.
- 20 The efficiency of volatilizing particles in the thermodenuder was tested using DMA-size-selected particles from the generation of NaCl, $(\text{NH}_4)_2\text{SO}_4$, and limonene oxidation products at concentrations < 1000 cm^{-3} . The UHSAS-1 alternated sampling between the thermodenuded and unheated sample lines every 2-3 minutes. The temperature of the thermodenuder was

increased in steps from room temperature up to 310°C and the fraction of particles exiting the thermodenuder (relative to the unheated sample) at three different particle sizes was determined (Fig.7Fig-7). Particles composed of $(\text{NH}_4)_2\text{SO}_4$ were most volatile, limonene oxidation products were less volatile, while NaCl was not volatile at the temperatures investigated. Smaller particles of $(\text{NH}_4)_2\text{SO}_4$ and limonene oxidation products volatilized at lower temperatures than larger particles of the same material, suggesting the particles were highly viscous, glassy, or solid. The effect of particle concentration on the performance was checked with particles generated from limonene oxidation products at 0.15 μm in diameter and concentrations of up to 11000 cm^{-3} . All particles at these concentrations were effectively volatilized, with no "break-through" effects observed. In no cases was there any evidence of recondensation of volatilized material to form new particles or to add material onto partially volatilized or non-volatile particles.

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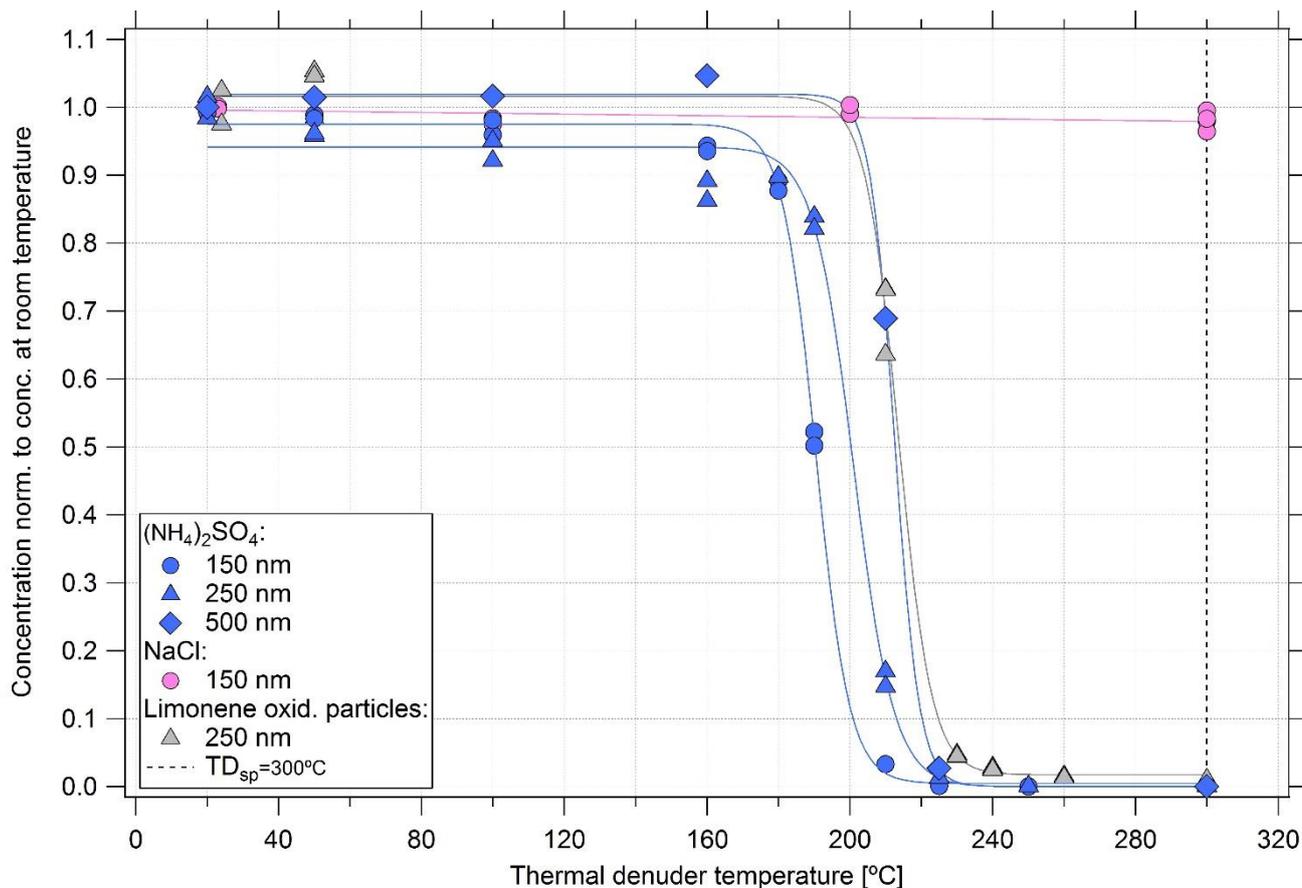


Fig.7. Particle response to heating as a function of temperature of the thermodenuder, particle size and composition. Data normalized to the number measured at ambient temperature. Solid lines are used to guide the eye. The stability of the set temperature (dashed line) was within $\pm 0.5^\circ\text{C}$.

5. Uncertainties

5.1 Uncertainties due to refractive index

Uncertainties in the aerosol volume and surface calculated from atmospheric dry size distributions depend on possible biases associated with the actual refractive index and shape of the particles vs. the calibration aerosol, as well as on random uncertainties associated with counting statistics, flow rate, pressure, and sizing precision and calibration accuracy. Since the ATom project focuses on the remote atmosphere where well-aged particles are expected to dominate the submicron aerosol (outside of sea-salt and dust cases), we did not investigate the effect of particle shape on sizing accuracy. Since the refractive index of organic compounds in the atmosphere is unknown but is likely bounded by our different calibration materials (e.g., (Kim and Paulson, 2013) we use the range of instrument response to the different calibration aerosols to estimate the likely effect of potential refractive index biases on aerosol volume and surface area derived from the UHSAS measurements.

As an example of the effect of these potential sizing biases on measured size distributions, we have selected a period of time from one of the ATom-2 flights (2017/02/10, Christchurch-Punta Arenas) when in the free troposphere (P~200-400 hPa). Using the range of instrument response curves for $(\text{NH}_4)_2\text{SO}_4$ ($n=1.52$), DOS ($n=1.44$) or PSL ($n=1.58$), the reasonable range of possible particle diameters associated with each UHSAS channel (bin) could vary by as much as +4/-10 % (as described in Sect. 3.2). These diameter uncertainties propagate into aerosol volume and surface uncertainties +12.4/-27.5% and +8.4/-17.8 %, respectively as calculated from each 1s size distributions (Fig.8). Examples from this and other cases representative of conditions encountered during ATom flights are summarized in Table S3.

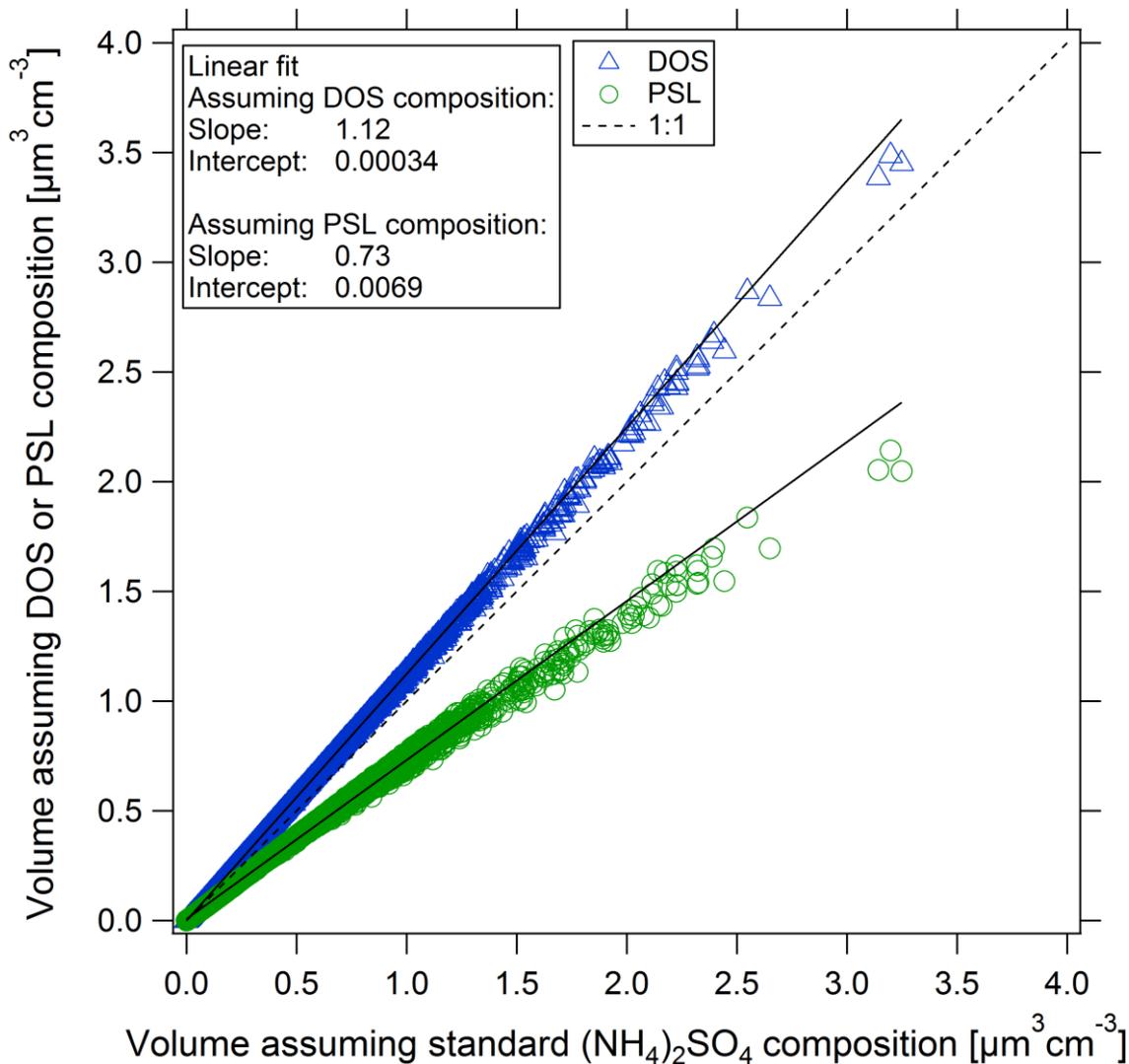


Fig.8. Comparison of the calculated aerosol volume from the UHSAS-2 measured dry size distributions based on calibration particles with refractive indices between 1.44 and 1.58: $(\text{NH}_4)_2\text{SO}_4$ ($n=1.52$), DOS ($n=1.44$) and PSL ($n=1.58$). Flight data shown (2017/02/10) are from 1 s measurements. Solid lines represent a double-sided orthogonal distance regression linear fits.

5

5.2 Uncertainties due to flow and pressure

Random uncertainties may arise from uncertainty in sample flow rates and uncertainty in the pressure measurement used to convert instrument concentrations to standard temperature and pressure (STP; 0°C and 1013 hPa). Uncertainty in the sample flow rate is $\pm 0.86\%$ based on repeated calibrations of the sample flow meter over a range of $0\text{--}0.1 \text{ Lmin}^{-1}$ using a reference calibration device (DryCal DC-Lite, Bios, Inc., Butler, NJ, USA). The uncertainty in the STP flow rate is the sum in quadrature of the flow calibration variation, the uncertainty of the DryCal flow calibration device ($\pm 0.25\%$), the uncertainty in the

10

differential pressure transducer reading ($\pm 0.25\%$), and the uncertainty in the sample pressure (Eq. 1). The uncertainty of the measurement of the UHSAS-2 sample pressure at sea-level pressure is better than 0.38% when comparing to a reference pressure gauge. At <300 hPa, this pressure uncertainty was 3.8 % due to the lower accuracy of the pressure reference standard used for lower pressures. The total propagated random uncertainty for the STP sample flow is $<3.9\%$.

5 5.3 Uncertainties due to counting statistics

Very low concentrations of accumulation-mode particles were often encountered in the free troposphere during the ATom mission. Uncertainties associated with resulting poor counting statistics at 1s resolution are reduced by averaging over longer time intervals. The uncertainty caused by the counting statistics was estimated for 1, 10 and 60s data averaging times using various STP concentrations ($20\text{--}440\text{ cm}^{-3}$) representative of typical MBL and the upper FT conditions encountered (Table S3).

- 10 As an example, uncertainties for STP concentrations of $\sim 150\text{ cm}^{-3}$ and $\sim 30\text{ cm}^{-3}$ as measured in the MBL for 1s acquisition intervals were ± 8.7 and $\pm 18\%$, respectively. In the FT the uncertainties were much greater: ± 14 and $\pm 41\%$ for STP concentrations of $\sim 440\text{ cm}^{-3}$ and $\sim 25\text{ cm}^{-3}$, respectively. Actual instrument counting rates in the FT were much lower than for equivalent STP concentrations measured in the MBL because of lower air density.

5.4 Uncertainties due to instrument stability and calibration repeatability

- 15 Although careful calibrations undertaken using a DMA in the laboratory provide a precise assessment of UHSAS sizing characteristics, a method to validate the calibration stability of the UHSAS instruments in the field, where the DMA could not be carried, is critical. A solution of four PSL sizes (81, 125, 240 and 400 nm) in HPLC-grade water was atomized producing an aerosol with four distinct concentration peaks that could be measured by the UHSAS (Fig.9Fig-9). The sizing channel associated with each PSL diameter was determined by fitting a Gaussian curve to each peak in the size distribution histogram.
- 20 The standard deviation of the identified peak bin was determined for a total of 84 calibrations taken before and after each flight, and at high altitude in-flight during test flights. The mean bin number and replicate standard deviation associated with each of the four PSL sizes is 10.8 ± 0.4 , 25.2 ± 0.3 , 47.4 ± 0.2 and 64.6 ± 0.2 for the 81, 125, 240 and 400 nm PSL particles, respectively. Using the standard $(\text{NH}_4)_2\text{SO}_4$ calibration curve (Fig.3), which relates bin number to particle diameter, for the UHSAS-2 instrument the equivalent precisions in diameter were ± 1.2 , 0.8, 0.7, and 0.7% for the four PSL sizes, respectively
- 25 (Fig.9Fig-9). Because the power in the optical cavity is sensitive to contamination of the optics, the UHSAS sizing calibration may shift over time. This was observed during the middle of the Atom-1 mission in the UHSAS-1 when optical power dropped by 27 %. Because of the repeated calibration checks with the PSL particles, we were able to correct the observed size distribution with minimal errors despite the shift in calibration. Upon return to the laboratory, the instrument was recalibrated, then cleaned until laser power was restored and then calibrated again.

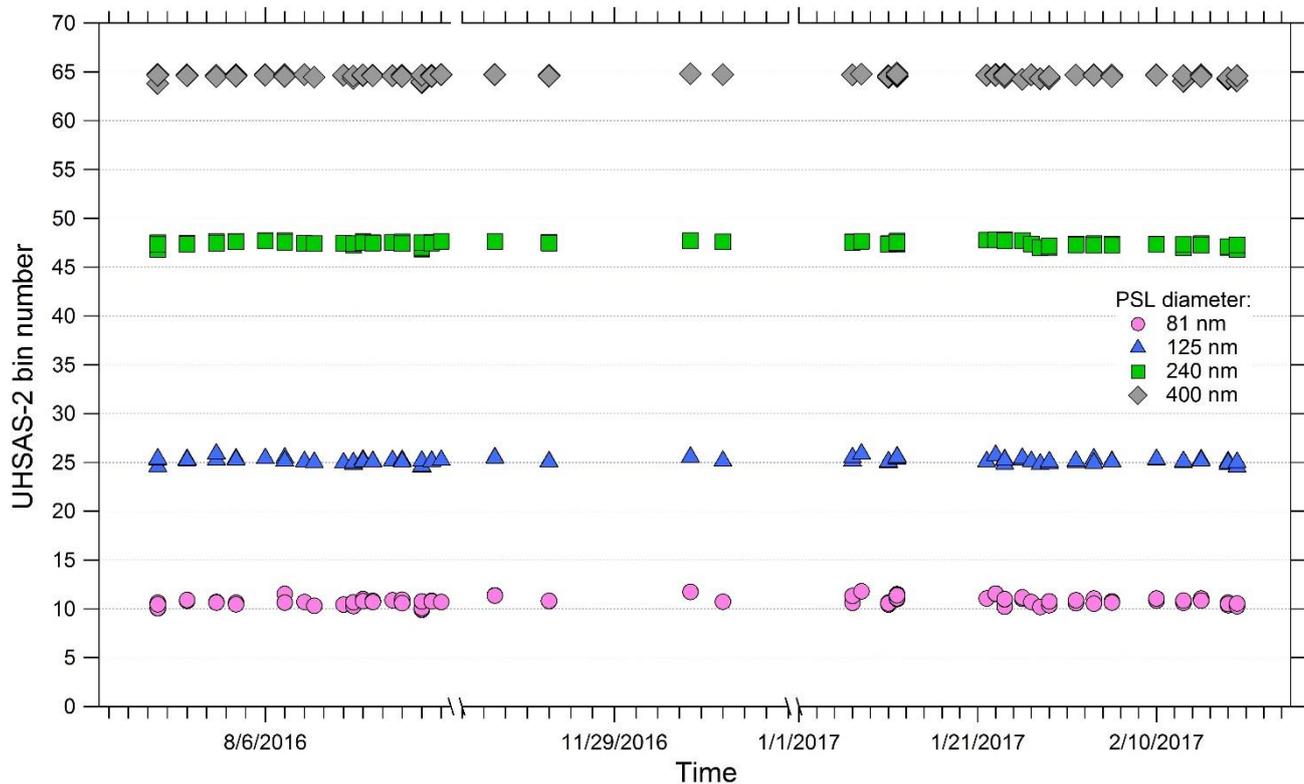


Fig.9. Fitted peak bin number for four PSL size standards and as a function of time from July 2016-February 2017, showing calibration precision and the stability of the UHSAS-2 sizing during ATom-1 and -2.

5 5.5 Total uncertainties

The total relative uncertainties for aerosol number concentration, surface and volume for cases of low and high particle number concentration measured in MBL and FT during ATom-2 mission are summarized in Table S3. The total uncertainty consists of random uncertainties due to the counting statistics, sample flow and pressure measurements, and possible systematic uncertainties due to sizing biases from the unknown refractive index of the atmospheric aerosol. The total uncertainty for aerosol number, surface and volume represents the sum in quadrature (Eq.1) of the random uncertainties plus the linear addition of possible systematic sizing biases propagated through the surface and volume calculation.

We have not considered particle shape and homogeneity as a potential source of uncertainty. Given the laser wavelength of ~~1053-1054~~ 1053-1054 nm, and because most particles encountered in ATom were aged and likely only modestly aspherical, we do not expect shape sizing biases to be significant except for some larger sea salt and fresh dust particles.

6. In-flight performance

In this section, we describe the performance of the modified UHSAS instruments measuring dry aerosol size distributions, both directly sampled and thermodenuded, on the DC-8 aircraft during the ATom-1 (July-August 2016) and ATom-2 (January-February 2017) missions. Brock et al. (in preparation) more thoroughly describe the inlet and sampling configuration and provide comparisons between several aerosol instruments on the ATom payload. The measured internal UHSAS instrument pressures varied between ~1100 (due to ram pressure) and 225 hPa, which corresponded 0.15-13 km in altitude. The two UHSAS instruments sampled in parallel at 1 Hz downstream of a Nafion dryer that reduced sample RH to < 20 %. Periods of in-cloud measurement were excluded from the reported data due to aerosol sampling artefacts caused by droplet or ice crystal impacting the inlet, which produced spurious counts in the UHSAS instruments.

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6.1 Consistency of aerosol number concentration, surface and volume measured by UHSAS-1 and UHSAS-2

During the ATom-1 deployment the thermodenuder on the UHSAS-1 instrument was not operated, allowing for direct comparison between the two UHSAS instruments. We compare number, surface, and volume concentrations over the diameter range from 0.1-0.9 μm to see if the measurements agree within the estimated uncertainties. We focus on the first five flights of ATom-1, between 2016 July 29-2016 August 8, before the laser power on the UHSAS-1 instrument shifted. The number, surface and volume concentrations were highly correlated between the two instruments ($r^2 > 0.98$), with slopes within 5 % of 1 (Fig.10). This agreement is well within the propagated uncertainties over the full dynamic range of 0-3000 cm^{-3} , 0-380 $\mu\text{m}^2\text{cm}^{-3}$, and 0-16 $\mu\text{m}^3\text{cm}^{-3}$ for number, surface area, and volume concentrations, respectively.

During ATom-2, when the UHSAS-1 was operated with the thermodenuder, the two UHSAS instruments could be compared by periodically switching the UHSAS-1 flow to bypass the thermodenuder when in MBL. During the non-thermodenuded sampling intervals, the agreement in concentration measured during first three flights (01/29-02/03/2017) over the Pacific was found to be between 0.97 ± 0.011 and 1.04 ± 0.01 (for 1 s data). The corresponding agreement slopes for aerosol surface and volume concentration varied between 0.97-1.02 and 0.95-1.08, respectively.

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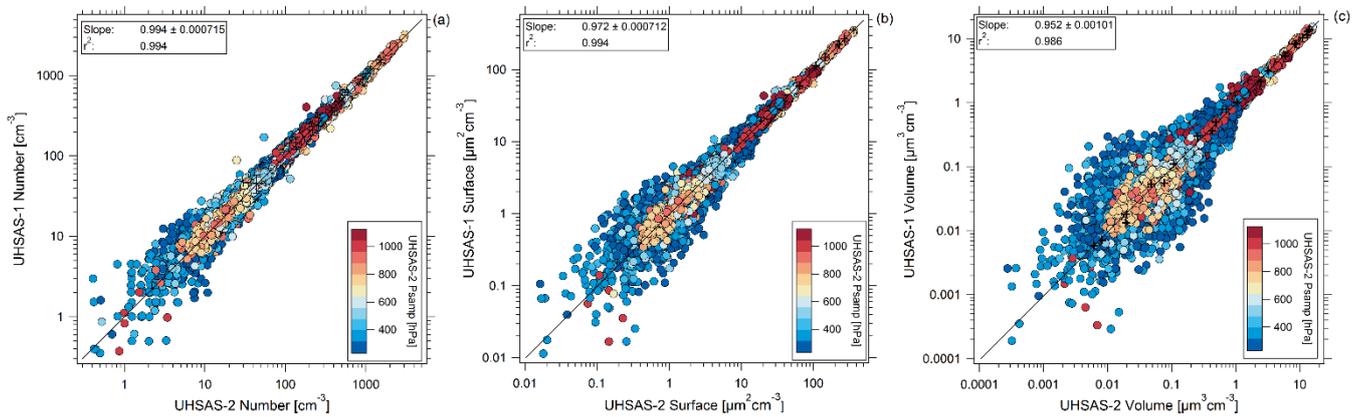


Fig.10. Comparison between the UHSAS-1 and UHSAS-2 instruments on ATom-1 from 2016 July 29-2016 August 8 for (a) dry particle number, (b) surface area, and (c) and volume concentrations for diameters from 0.1-0.9 μm . Each point is a 10s average. The r^2 values indicated here refer to one-sided linear fit, while the solid lines represent double-sided orthogonal distance regression linear fits to non-transformed data. Estimated uncertainty is shown on a subset of points.

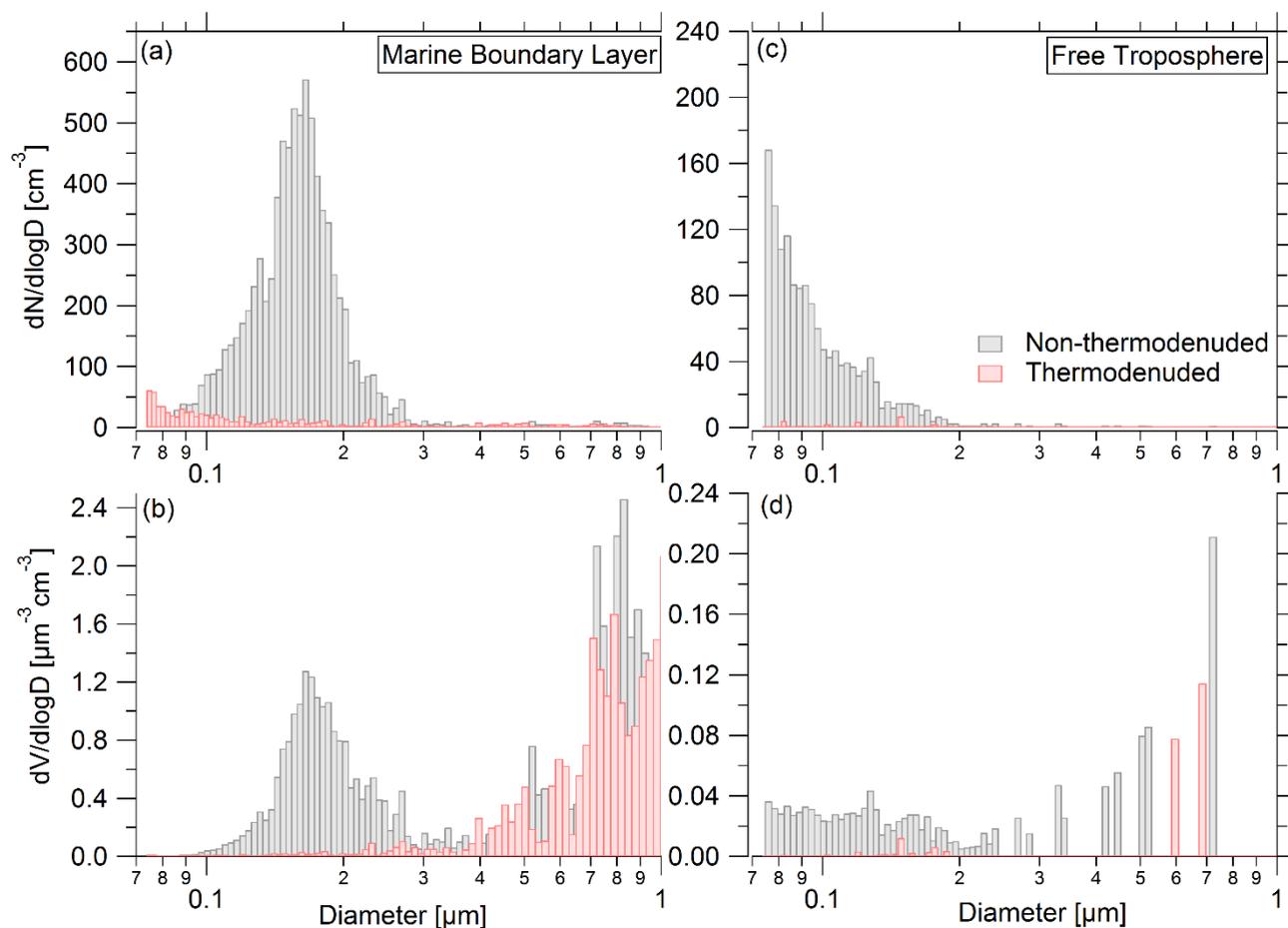
6.2 Measurements of non-volatile aerosol fraction

The thermodenuded UHSAS was developed to help identify the fraction of particle number and volume (roughly proportional to mass) associated with primary particles such as sea-salt and dust as opposed to those that are produced by secondary processes (most particles composed of organic, nitrate, and sulfate species). Several measurements and modeling studies (Clarke and Kapustin, 2002; Korhonen et al., 2008; Mericanto et al., 2010; Quinn et al., 2017; Raes, 1995) suggest that secondary particles formed in the FT play an important role in governing CCN abundance in the MBL, despite the presence of sea-salt. It is possible that sea-salt may dominate aerosol mass in the MBL, but that CCN concentrations may be controlled by secondary processes, even those occurring in the FT above (Clarke et al. 2013; Raes, 1995; Twomey, 1977; Quinn and Bates, 2011).

To demonstrate the utility of the ATom UHSAS measurements for such investigations, we present examples of thermodenuded and non-thermodenuded aerosol number and volume size distributions for a single MBL case (measured for 50 s at 22°N latitude over the central Pacific) and a single FT case (measured for 360 s at 3° N over the central Pacific) during ATom-2 on 2017 January 26 -(Fig.11). In the MBL (Fig.11(a),(b)) volatile aerosol species dominate number concentrations, while non-volatile particles (presumably sea-salt) comprise ~5254% of aerosol volume (or mass) for D_p between 0.1 and 0.9 μm . The non-volatile (sea-salt) mode was largely $>0.3 \mu\text{m}$ in diameter, clearly distinct from the smaller mode of volatile particles centered at $\sim 0.15 \mu\text{m}$ volume mean diameter. Small amounts of non-volatile (sea-salt) mass extended down to diameters $<0.1 \mu\text{m}$, consistent with prior studies (Bates et al. 1998; Clarke et al., 1997; Mericanto et al., 2010; Middlebrook et al., 1998; Murphy et al. 1998; Quinn et al., 2017 in press).

The number concentration of accumulation mode particles with D_p between 0.1-0.9 μm in the clean air of the FT (Fig.11(c),(d)) was $\sim 7 \text{ cm}^{-3}$ and 9694% of these were volatile. The peak modal diameter was smaller than could be detected by the UHSAS,

implying the dominance of the Aitken mode aerosol (0.012-0.06 μm). These particles were recently formed from gas phase precursors (Williamson et al., in preparation). In the FT, ~~~24-26~~ % of the particle volume was non-volatile, dominated by a few ~~coarse mode~~ particles with $D_p > 0.5 \mu\text{m}$ and uncertain due to poor counting statistics.



5 Fig.11. Example of an averaged dry aerosol size distribution from UHSAS-1-TD and UHSAS-2 as sampled in the MBL (21.74° N, 1080 hPa; 2017/01/27, 01:15:26-01:16:16) showing (a) number and (b) volume; and for a separate size distribution sampled in the FT (3.4° N, 293 hPa; 2017/01/26, 21:32:47-21:38:47) showing (c) number and (d) volume. For particles with D_p between 0.1 and 0.9 μm , ~~isn~~in the MBL case ((a), (b)) 94 % of the total number and ~~54-52~~ % of the total volume volatilized in the thermodenuder, while in the ~~FT-FT~~ case ((c), (d)) 94-96 % of the number and 76-74 % of the volume volatilized.

10 7. Summary and context

Two UHSAS instruments were modified, calibrated, tested in the laboratory, and operated during the first and second deployments of the ATom mission. The instruments are capable of continuous 1 s measurements of size-resolved particle number concentration with high accuracy and precision over a diameter range of 0.063-1.0 μm from >1100 to 225 hPa, while simultaneously measuring particle volatility. Precision is limited by counting statistics, especially in the remote FT. The

modified flow system of the UHSAS allowed direct monitoring of the sample flow rate and eliminated flow measurement issues associated with the pressure variations during aircraft altitude changes. The sizing of the UHSAS instruments showed no statistically significant pressure dependence, crucial for consistent airborne sampling. Detailed calibrations with laboratory aerosols spanning a range of refractive indices (1.44-1.58) representative of the atmosphere allowed us to constrain the uncertainty associated with the unknown composition of the atmospheric aerosol. An equation to correct for particle coincidence was derived to improve the quantification of the counting accuracy at concentrations from ~1000 to >20,000 cm⁻³. Two UHSAS instruments agreed in flight to within 5 % for integrated number, surface, and volume concentrations from sea level to ~13 km altitude. We developed a compact thermodenuder for one of the UHSAS instruments, characterized its performance, and demonstrated its utility for quantifying size distribution of the nonvolatile fraction of the aerosol. Both modified UHSAS instruments worked well with no significant failures while flying on a DC-8 aircraft during the ATom missions.

The ATom observations taken with these instruments provided representative (non-targeted) measurements, across an unprecedented latitude range over both ocean basins, of vertically resolved, size dependent aerosol properties that are related to radiative effects, to the ability of aerosols to act as CCN, and to the sources and abundance of primary vs. secondary particles in the MBL and FT. Hence, the size distribution data gathered by the UHSAS instruments over altitudes between ~0.2 and ~13 km will improve our understanding of global aerosol characteristics in the under-sampled regions of the atmosphere that closely resemble natural conditions minimally perturbed by pollution. These new measurements may be placed in the context of similar data gathered over more than two decades by Clarke et al. (Clarke, 1991; Clarke et al., 2013; Clarke and Kapustin, 2002, 2010; Clarke et al., 1997; 1998), and others (e.g., Anderson et al., 1996) to help fill gaps in knowledge of aerosol properties, processes, sources, sinks, and aerosol-cloud-climate interactions.

The ATom measurements will continue in 2017 and 2018 with continued global measurements during the Northern Hemisphere fall and spring seasons. The past and future ATom measurements, placed in the context of chemical and meteorological conditions and combined with size distribution measurements from 0.003-4.8 μm (Brock et al, in preparation; Williamson et al., in preparation), will help constrain model simulations of the processes that govern particle formation and their evolution in remote regions (Lee et al., 2013; Hamilton et al., 2014). Only if aerosol production mechanisms, sinks and transformations are understood can models accurately simulate global CCN distributions in the pre-industrial, modern, and future atmosphere, and the resulting effects on climate through aerosol-cloud interactions.

Data availability

Calibration and laboratory testing data are available upon request to the corresponding author. In-flight data are available at the ATom data archive: https://dx.doi.org/10.5067/Aircraft/ATom/TraceGas_Aerosol_Global_Distribution.

Author contributions

All authors contributed substantially to the work presented in this paper. A. Kupc and C.A. Brock modified the instruments. N. L. Wagner and C. A. Brock developed the thermodenuder. M. Richardson developed the software. A. Kupc designed, carried out experiments and analysed data. A. Kupc and C. Williamson calibrated instruments and collected data during ATom-1 and
5 -2 missions. A. Kupc prepared the manuscript with contributions from all co-authors.

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15 Disclaimer

This publication's contents do not necessarily represent the official views of the respective granting agencies. The use or mention of commercial products or services does not represent an endorsement by the authors or by any agency.

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Table 1. Detection efficiency of UHSAS-1 and UHSAS-2

Particle	Real refractive index, n	Wavelength, λ (nm)	Reference	Dp ₅₀ (nm)	
				UHSAS-1	UHSAS-2
PSL	1.58	780	Yoo et al. (1996)	n/a	n/a
(NH ₄) ₂ SO ₄	1.527	1054	Hand and Kreidenweis (2002)	72.8 ^{+1.2} / _{-5.9}	62.8 ^{+1.0} / _{-5.9}
DOS	1.44	532	Pettersson et al. (2004)	75.9 ^{+1.2} / _{-6.0}	68.2 ^{+1.1} / _{-5.9}
Limonene oxidation products	unknown	n/a	n/a	78.9 ^{+1.3} / _{-6.0}	69.7 ^{+1.1} / _{-5.9}

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