NRC·CNRC

Documentation for aerosol dataset collected in the ESCAPE 2022 flight campaign

Prepared by: Dr. Keyvan Ranjbar, Dr. Leonid Nichman

Reviewed by: Dr. Leonid Nichman

Ver. 1.0

Acknowledgement:

We thank Environment and Climate Change Canada (ECCC) for allowing us to use their aerosol instrumentation and inlet for this campaign.

Description:

A suite of aerosol instruments were integrated on the NRC Convair-580 aircraft and operated in the ESCAPE flight campaign, between May and June, 2022. This documentation describes the operation of some of this equipment, namely the Condensation Particle Counter (CPC) and Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) which were installed in the aircraft cabin to sample via an isokinetic inlet installed on top of the fuselage. In addition, NRC wing tip mounted UHSAS was installed and sampled throughout the whole campaign.

Most of the flight time in the domain was spent in-cloud or in precipitation with the associated risk of flooding the cabin aerosol instruments, which led to the suspension of aerosol sampling. To address this issue, a Counter-flow Virtual Impactor (CVI) inlet system was integrated on the fuselage starboard side window. The CVI inlet allowed in-cloud sampling of the residual aerosol (remaining core after evaporation of the hydrometeors above a selected cut-off diameter). A cabin inlet-switching mechanism was developed to allow in flight switching between the sampling lines of an isokinetic inlet and a CVI inlet. The collected data includes information for in-cloud and clear-air aerosol particle size distributions and vertical profiles.

The quality of data form CVI inlet requires further review and validation and provided here for qualitative assessments only.

Contents

Instruments

The aerosol instruments used for sampling in this campaign are listed in Table 1 and described in detail below. The measurable quantities are summarized in Table 2.

Table 1. List of aerosol instruments.

Instrument	Model, S/N	Manufacturer	Owner	Reference
UHSAS-A	1710-011	DMT	NRC	UHSAS-A manual [1]
UHSAS-C	1210-039, AAA-0053	DMT	ECCC	UHSAS manual [2]
CPC	3775, 70902299	TSI	ECCC	CPC manual [3]
CVI inlet system	Model 1204, S/N 008	BMI	ECCC	CVI manual [4]
Isokinetic heated inlet	# AAA-0093	DMT	NRC	

Table 2. List of measurable quantities.

Instrument	Measurable quantities	operational range
CPC	• Total concentration	(~4 to ~3000 nm)
2 x UHSAS	• Total concentration "of CCN-like" • Particle size distribution	(60 to 1000 nm)
CVI inlet	• Allows advanced analysis of residual aerosol from the sampled hydrometeors	**hydrometeors** >8 µm

Wing UHSAS-A

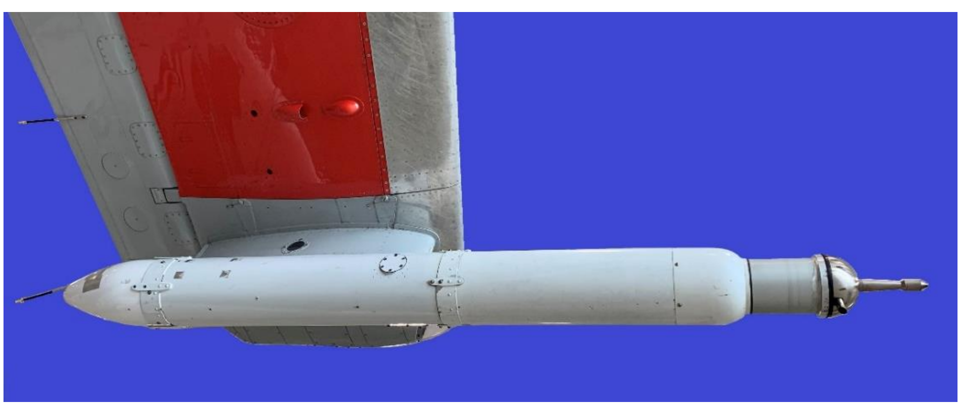

Figure 1. UHSAS-A (Port wing tip mounted UHSAS).

The airborne version of UHSAS is a modified PMS canister design that was fitted on the NRC Convair-580 research aircraft (Figure 1). This instrument was operated continuously between takeoff and landing. Inside the UHSAS-A, a laser beam illuminates particles, which scatter light that is collected by two pairs of Mangin optics. An amplification of the signal allows the system to detect particles as small as 65 nm.

The specifications for the instrument limit its operation to > - 40 °C and < 12 km altitude, however there have been some operational issues at lower altitude and warmer temperature, notably noise in the first channels or anomalously low measurements of concentration. These have been improved, but not eliminated, through modifications to the instrument. Small-diameter noise count in particular continues to be a problem. The probe covers the full size-range through the use of two different detectors, each having two gain circuits [1]. The instrument is designed to operate primarily in clear air, out of cloud, environment. A thorough review of the uncertainties of the instrument that need to be considered can be found in [6].

UHSAS-C cabin

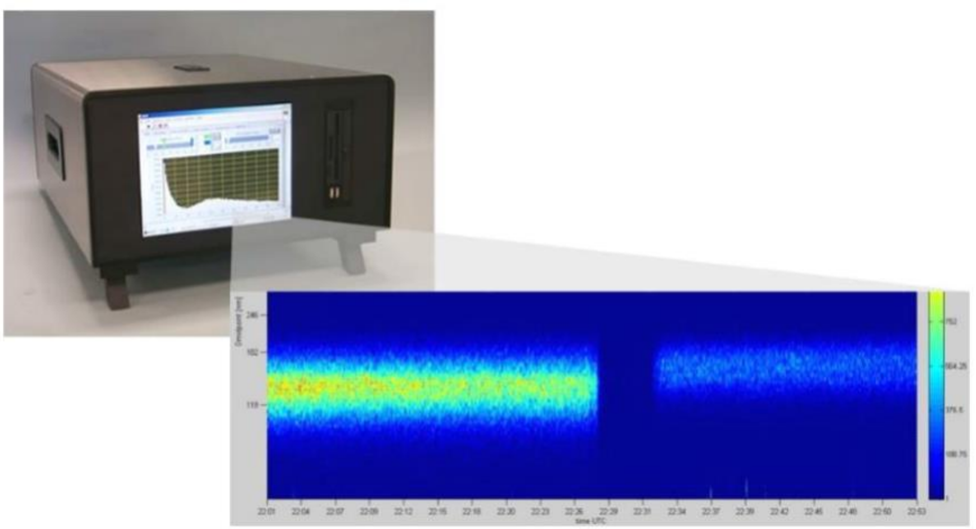

Figure 2. Cabin UHSAS with data visualization.

This commercial cabin instrument version (Figure 2) has similar specifications:

- Optically measures aerosols in the size range 60 nm < Dp< 1 µm
- Size resolution at 1 – 2 % of particle size
- Eliminates sizing uncertainty associated with scattering spectrometers that measure at sizes larger than the excitation wavelength.
- Particles size distributions collected in up to 100 size bins
- Can output size distributions at rates up to 10 Hz
- Able to count up to 3,000 # s^{-1}
- Uses two detection systems: a primary, highly sensitive Avalanche Photo-detector (APD)-based system to size smaller particles, and a secondary PIN photodiode system to size larger particles
- Compensates for small drifts in laser power via an automatic gain control.

The instrument was calibrated at NRC. For more details about the instrument see UHSAS-C manual [2].

CPC 3775

Condensation Particle Counter (CPC) model 3775 is a general-purpose counter that detects airborne particles down to ~4 nm (Figure 3). It provides highly accurate measurements over a wide concentration range from 0 to 10^7 particles cm^{-3}. The instrument condenses butanol on the aerosol and allow droplets growth followed by optical detector where they are counted. At low concentrations, the optical detector counts individual pulses produced as each particle (butanol droplet) passes through the sensing zone. For very high particle concentrations, the CPC model 3775 transitions from the single count mode to a photometric mode where the total light scattered from the particles is used to determine concentration based on calibration [3]. the constraints of the instrument are described in “Apendix A: Specifications” section of the CPC operational and service manual [3].

Figure 3. CPC 3775. Image by the manufacturer (TSI).

CVI model 1204

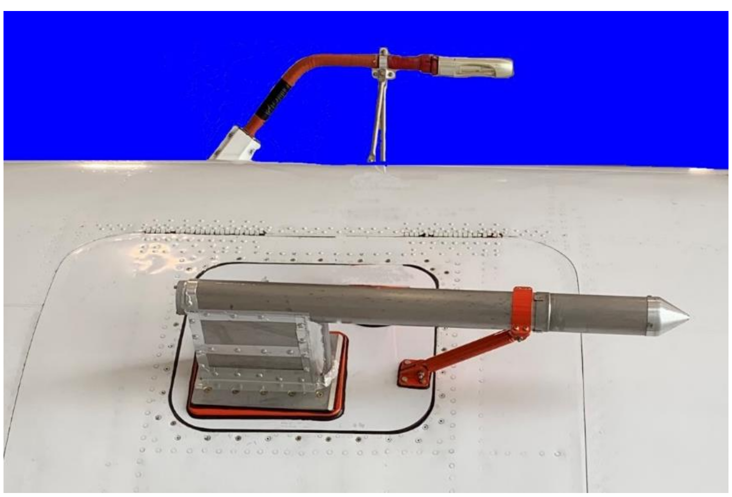

Figure 4. Aerosol Isokinetic inlet for clear-air sampling (interstitial aerosol) on top and a CVI inlet on the fuselage starboard window for in-cloud (residual aerosol) sampling.

The Model 1204 Counter flow Virtual Impactor (CVI) Inlet System [4,5] is designed for aircraft applications. It delivers variable counter flow rates between 1 and 10 lpm at a constant 15 LPM of sample flow to instruments for air speeds between about 50 and 150 m/s. The droplet diameter cut size of the CVI is user-adjustable between roughly 8 and 10 microns during operation. The panel maintains the desired counter flow rate in response to changes in air speed, temperature, and pressure.

The CVI was integrated on starboard side window of the fuselage, at the front, close to the cockpit (Figure 4). The CVI assembly was installed on the aircraft using an adaptor plates with a specified tilt in the angle of attack (~2 deg), similar to the angle of adapter plates of underwing pylons, designed to account for aircraft pitch during sampling. The CVI housekeeping data was recorded at 1 Hz resolution and aligned on to the core DAS time grid.

Sample droplets have a minimum Stokes number or inertia to pass through the counter flow and into the sample air flow. The droplet Stokes number is generally controlled by the velocity of the droplets and their diameter. The diameter corresponding to the minimum Stokes number for sampled droplets is referred to as the 'cut size' diameter of the inlet. It is defined as the size at which 50% of the ambient droplets penetrate the counter flow and enter the sample flow. Droplets smaller than the cut size are rejected (blown away from the tip) by the counter flow, while droplets larger than the cut size penetrate the counter flow and enter the sample flow (Figure 5). For a given counter flow, droplet velocity, temperature, and pressure, the cut size of droplet that penetrates into the inlet is fixed [4].

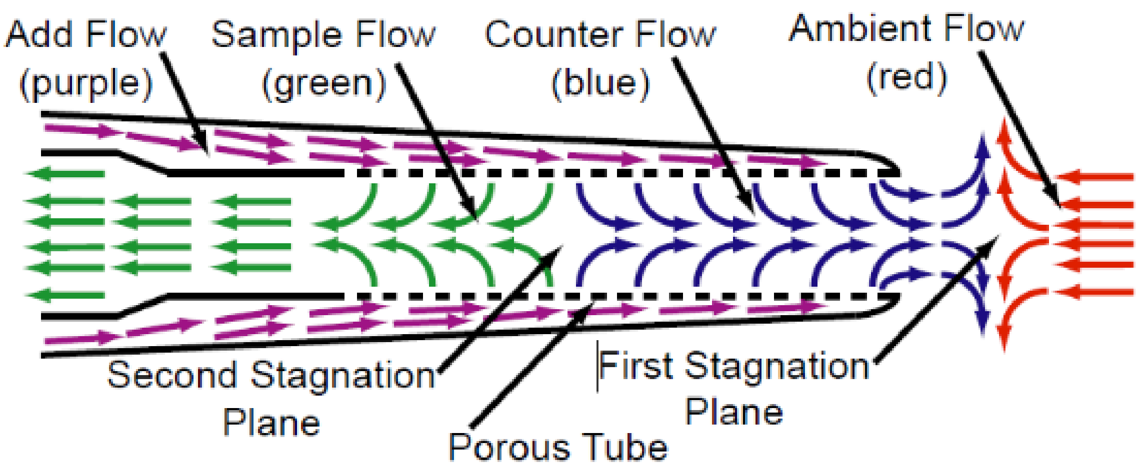

Figure 5. CVI inlet tip and the different flows illustration reproduced from the CVI manual [4].

Particles with sufficient momentum (Stokes number) can travel through the counter flow and into the sample flow. Water droplets large enough to penetrate into the inlet system are decelerated and exposed to warm temperatures in order to evaporate their water and reduce their size. The size reduction is important to ensure efficient sampling of the droplets, which are too large to be drawn effectively into the sampling system. The dry, heated (to counter flow temperature) sample flow denudes (evaporates the water from) these particles. These dried residual particles sampled are typically considered to be cloud condensation nuclei (CCN), as they originally likely participated in the activation of cloud droplets within cloud. However, it is possible that the size, composition, and morphology of the dried residual particles have been altered by the coalescence process of cloud droplets with non-activated particles or by other processes like compaction during the denuding step. The smaller, residue particles are drawn into the inlet sampling manifold where the aforementioned instruments can be used to measure aerosol size, concentration, chemical composition and other properties. The calculated transmission efficiencies through the external probe body for residue particles between 0.01 and 6 microns in diameter are greater than 95% [4]. The “enhancement factor” (EF) of the CVI inlet can be calculated for each second of the flight using the quality controlled input variables of the True Air Speed and CVI sample flow.

$$\text{EF} = \frac{Area_{tip} * TAS}{Sampleflow} \sim 5.3$$

For validation purposes, EF was also calculated empirically within a selected flight segment in SLD environment (MVD ~10mm). The FCDP Median Volume Diameter (MVD) was ~10 µm with ~60% of droplets sized between 2 to 8 µm and therefore are sampled with lower transmission efficiency 20-40% via the CVI, respectively (according to the transmission curve provided by the manufacturer). The calculated Enhancement Factor (glass beads) is higher than the empirical factor observed (~4.5) in the comparison of the sampled small SLD vs. residual aerosol (droplets smaller than 8 µm were not accounted due to their low transmission efficiency).

Isokinetic inlet

In clear air, measurements of the total dry aerosol particle population was done behind a heated isokinetic inlet installed on top of the fuselage (Figures 4, 6). Two thermocouples on the inlet itself were used to control the 4 inlet heaters. Three additional thermocouples measured the inlet tubing extension inside the cabin, cabin temperature downstream (near ceiling), and temperature near the aerosol rack. All thermocouples were connected to an ADAM (8-channel thermocouple input module). Using a high-volume blower, the main flow through the inlet was kept isokinetic and laminar, near the true air speed of the aircraft (~100 m s^{-1}) while excess flow was ejected through the starboard window exhaust hole. When the sampling was switched to the CVI inlet, a back-flush pump would turn on to blow backflow of filtered air through the isokinetic inlet to prevent water accumulation or snow clogging in the isokinetic inlet during CVI sampling.

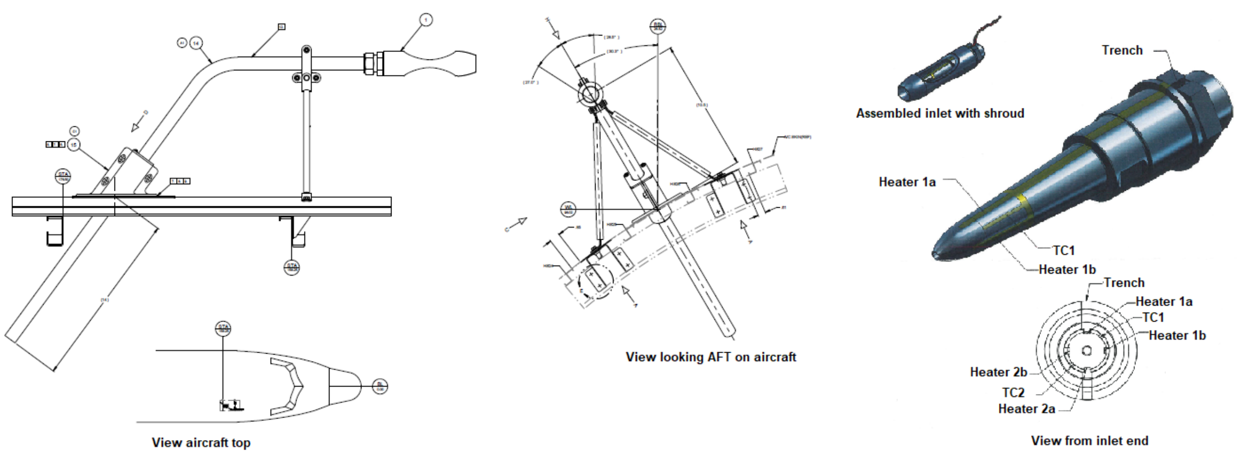

Figure 6. Left: Drawings of the heated isokinetic inlet assembly. Right: Drawings with indication of heaters location, reproduced from DMT manual.

Operation in flight

There was limited flexibility to accommodate aerosol sampling strategies in ESCAPE. However, a flight C-RF09 and C-RF10 were designated as aerosol sampling flight.

The CPC is capable of operating at altitude up to 2 km or inlet pressures of up to 750 hPa, while during the campaign, the aircraft occasionally climbed up to 7 km (410 hPa). The reduced pressure has a direct impact on the flow through the internal critical orifice and reduce the 1-butanol saturation ratio in the internal condenser. Therefore, altitude dependent bias in counting efficiency is inevitable [7]. Moreover, the Instrument operates with a liquid Butanol reservoir, tilting angle of the reservoir may impact the operation of the instrument by variation of the available vapors for condensation. In clouds, liquid water accidentally ingested through the isokinetic inlet may flood and remain in the instrument until it is opened and the water is actively evaporated.

Sampling

The sampling periods and data availability are summarized in Table 3. For the sampling the switching mechanism had been used to shift between the isokinetic inlet and the CVI inlet when needed by the operator. The isokinetic sampling of un-activated, out-of-cloud, interstitial particles was used in the clear air atmospheric conditions, while wing UHSAS-A sampled throughout the whole campaign with an inherent bias during in-cloud sampling.

Table 3. Aerosol sampling details during ESCAPE (instrument operation times do not necessarily fully overlap with flight time).

Flight	***Date***	***Start***	***End***	***Duration***	***UHSAS wing***	***UHSAS cabin***	***CCN***	***CPC***
C-RF01	31 May, 2022	14:09	18:36	4h27				
C-RF02	02 June, 2022	15:05	19:22	4h17				
C-RF03	02 June, 2022	21:15	01:18	4h03				
C-RF04	04 June, 2022	18:55	23:00	4h05				
C-RF05	08 June, 2022	14:55	19:05	4h10				
C-RF06	09 June, 2022	19:55	00:08	4h13				
C-RF07	10 June, 2022	20:12	00:50	4h38				
C-RF08	11 June, 2022	19:40	00:22	4h44				
C-RF09	12 June, 2022	17:10	21:46	4h36				
C-RF10	14 June, 2022	17:10	21:38	4h28				
C-RF11	16 June, 2022	15:03	19:19	4h16				
C-RF12	16 June, 2022	20:43	01:08	4h25				
C-RF13	17 June, 2022	15:00	19:38	4h38				

75 - 100%	50 -74%	20 - 50%	< 20%

Data adjustments applied to the current datasets are summarized in the table below (Table 4).

Table 4. Corrections and flagging for nanoparticle sampling in ESCAPE archive.

	Applied
Time synch correction	✓
In-cloud flagging	✓
Inlet sampling efficiency correction	×
Wind direction and inlet shadowing by the fuselage correction	×

Dataset structure

Here we summarize the aerosol dataset variables uploaded to the archive. For thorough analysis these aerosol datasets should be used in conjunction with atmospheric state (e.g., Temperatures, Pressure, RH, horizontal wind direction), aircraft state (e.g. altitude, geo-position), and cloud microphysics (e.g. cloud/clear-air classification) data in the EOL archive.

UHSAS-A

Variable name	Description	Units	Notes
bin_lower_uhsas_w	UHSAS-A bin lower edges	µm	
bin_upper_uhsas_w	UHSAS-A bin upper edges	µm	
Nuhsas_w	UHSAS-A Number Particle Size Distribution	#	
scatter_uhsas_w	UHSAS-A housekeeping parameter: background DC molecular scatter level from the APD	volts	housekeeping
current_uhsas_w	UHSAS-A housekeeping parameter: current being supplied to the instrument'	volts	housekeeping
sampleflow_uhsas_w	UHSAS-A housekeeping parameter: flow of the sample air	sccm	Use for concentration calculations
sheathflow_uhsas_w	UHSAS-A housekeeping parameter: flow of the sheath air	sccm	housekeeping
ref_uhsas_w	UHSAS-A housekeeping parameter: laser reference voltage	volts	housekeeping
temp_uhsas_w	UHSAS-A housekeeping parameter: voltage from the temperature sensor	volts	housekeeping
pres_uhsas_w	UHSAS-A housekeeping parameter: ambient pressure	kPa	housekeeping
time	seconds since 1970-01-01T00:00:00+0000	s	

UHSAS-C

Variable name	Description	Units	Notes
bin_lower_uhsas_c	UHSAS-C bin lower edges	µm	
bin_upper_uhsas_c	UHSAS-C bin upper edges	µm	
Nuhsas_c	UHSAS-C Number Particle Size Distribution	#	
scatter_uhsas_c	UHSAS-C housekeeping parameter: background DC molecular scatter level from the APD	volts	housekeeping
current_uhsas_c	UHSAS-C housekeeping parameter: current being supplied to the instrument'	volts	housekeeping
sampleflow_uhsas_c	UHSAS-C housekeeping parameter: flow of the sample air	sccm	
sheathflow_uhsas_c	UHSAS-C housekeeping parameter: flow of the sheath air	sccm	housekeeping
ref_uhsas_c	UHSAS-C housekeeping parameter: laser reference voltage	volts	housekeeping
temp_uhsas_c	UHSAS-C housekeeping parameter: voltage from the temperature sensor	volts	housekeeping
pres_uhsas_c	UHSAS-C housekeeping parameter: ambient pressure	kPa	housekeeping
time	seconds since 1970-01-01T00:00:00+0000	s	

CPC:

Variable name	Description	Units	Notes
cpctconc	CPC total number concentration	$\#/cm^3$	
time	seconds since 1970-01-01T00:00:00+0000	s	

Flow (CVI and Isokinetic inlet):

Variable name	Description	Units	Notes
vol_flow	Aerosol isokinetic inlet Volume Flow	LPM	
mass_flow	Aerosol isokinetic inlet Mass Flow	LPM	
flow_sp	Aerosol isokinetic inlet Flow Set Point	LPM	
Samp_inlet	Boolean indicator for the selected sampling inlet: 1 for CVI, 0 for Aerosol isokinetic inlet		
time	seconds since 1970-01-01T00:00:00+0000	s	

Quicklooks

In this section we present some quicklooks generated using the datasets in the archive (Figures 7-10).

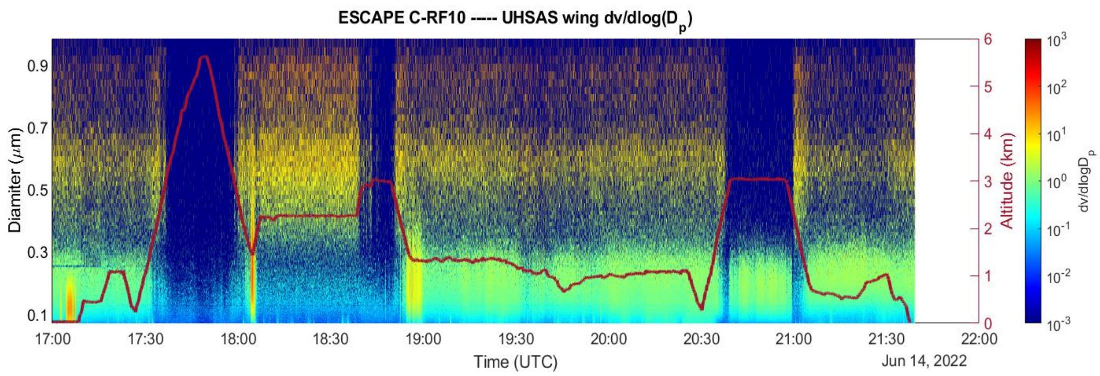

Figure 7. UHSAS-A wing volume size distribution (PSD) time series for C-RF10. Brown line shows the aircraft altitude during this flight

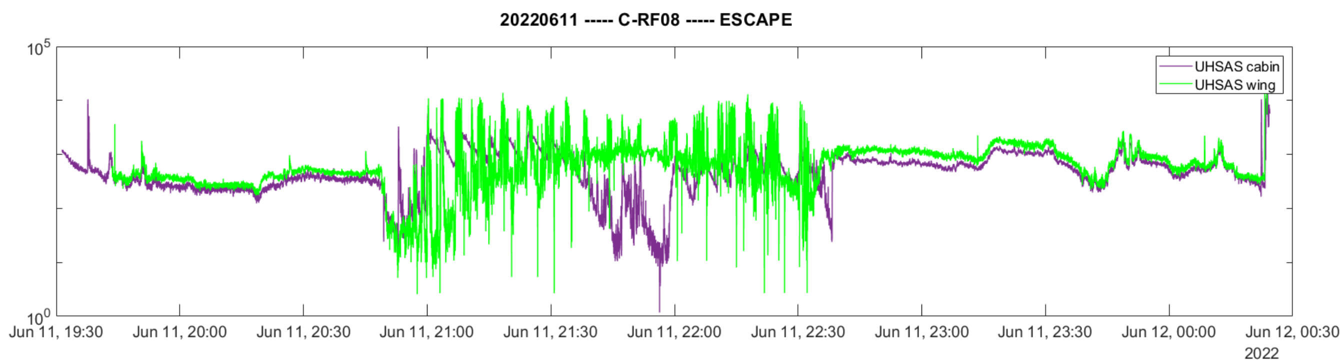

Figure 8. UHSAS-A wing and UHSAS cabin total concentration for flight C-RF08

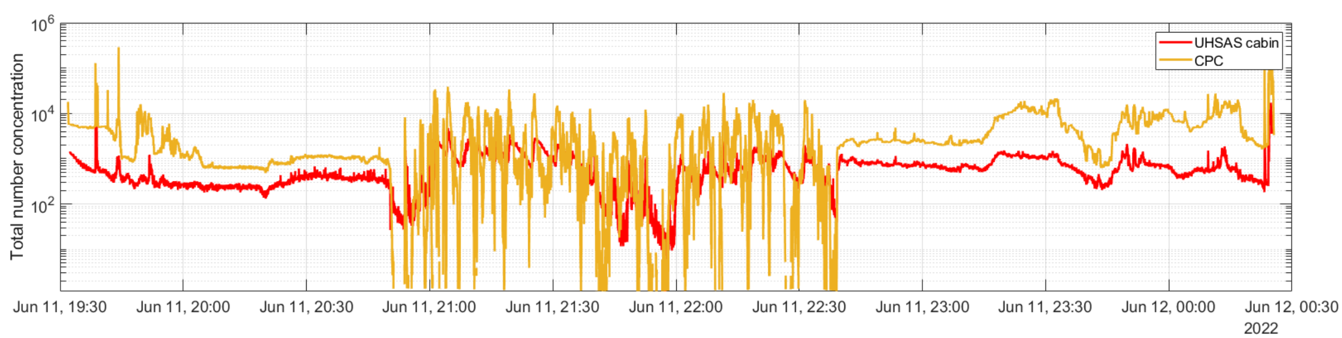

Figure 9. C-RF08 CPC total concentration overlapped with UHSAS-C total concentration.

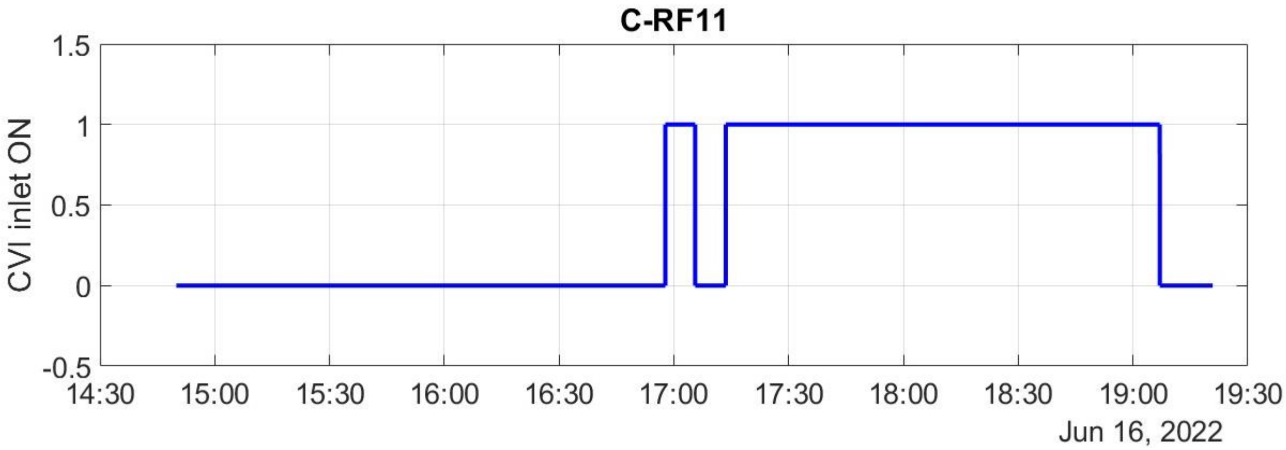

Figure 3. C-RF11 CVI operation period step function (on=1, off=0).

References

1. Ultra High Sensitivity Aerosol Spectrometer Airborne (UHSAS-A), Operator manual, DOC-0211, Rev D-3, Software Version 4.1.0, Droplet Measurement Technologies, 2013.
2. Ultra High Sensitivity Aerosol Spectrometer (UHSAS), Operator manual, DOC-0210, Rev E-4, Software Version 4.1.0, Droplet Measurement Technologies, 2013.
3. CPC manual: TSI Condensation Particle Counter Model 3775, Operation and Service Manual, Revision K. April 2014.
4. CVI Manual: Counter flow Virtual Impactor Inlet System Model 1204, Brechtel Manufacturing Incorporated, Manual Version 2.0, 2014.
5. Shingler, T., Dey, S., Sorooshian, A., Brechtel, F. J., Wang, Z., Metcalf, A., Coggon, M., Mülmenstädt, J., Russell, L. M., Jonsson, H. H., and Seinfeld, J. H.: Characterisation and airborne deployment of a new counterflow virtual impactor inlet, Atmos. Meas. Tech., 5, 1259–1269, https://doi.org/10.5194/amt-5-1259-2012, 2012.
6. Kupc, A., Williamson, C., Wagner, N. L., Richardson, M., and Brock, C. A.: Modification, calibration, and performance of the Ultra-High Sensitivity Aerosol Spectrometer for particle size distribution and volatility measurements during the Atmospheric Tomography Mission (ATom) airborne campaign, Atmos. Meas. Tech., 11, 369–383, https://doi.org/10.5194/amt-11-369-2018, 2018.
7. Nobuyuki Takegawa & Hiromu Sakurai (2011) Laboratory Evaluation of a TSI Condensation Particle Counter (Model 3771) Under Airborne Measurement Conditions, Aerosol Science and Technology, 45:2, 272-283, DOI: 10.1080/02786826.2010.532839.