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DO NOT QUOTE OR CIRCULATE

A Miniature Optical Particle Counter
for
In-Situ Aircraft Aerosol Research

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Abstract

We describe modification of a commercial Met One 237A optical sensor to accept custom electronics consisting of a single logarithmic amplifier providing 256 size bins over the 0.3 to 14 μ m diameter range. Configuration of the device for airborne aerosol measurements is found to be effective for both miniature remote control aircraft and large research aircraft (NASA P3b). The instrument is rugged, low cost, low power and easily integrated into various platforms. The high size resolution and the high 1.6 lpm sample rate provides excellent count statistics and high sensitivity for ambient out of cloud aircraft measurements and for other diverse applications. It can be readily configured for isokinetic or subsokinetic aircraft sampling. Initial comparison with other optical particle counters over the Sea of Japan reveal it to be an effective instrument for in-situ aircraft measurements.

1. Introduction

Direct measurements of the size-distribution of atmospheric aerosol are an important component of many current airborne research activities. These include studies of atmospheric pollution, atmospheric chemistry, aerosol radiative effects on climate, visibility, electro-optic propagation, interpretation of satellite radiances, gas-particle interactions, emission studies, flux studies etc. A variety of techniques are presently employed using numerous instruments. However, airborne and other applications demand increasingly compact, rapid, robust, low-power capabilities without sacrificing size resolution. One such application is aboard light or unmanned airborne vehicles

(UAV) where payload limitations constrain the choice of tools available and where sampling at ambient conditions is desirable.

Recently, a number of small optical particle counters (OPC) have become available for clean room, personal or ambient sampling. However, these generally have coarse sizing capabilities and are often designed for routine use with unnecessary or undesirable functions and controls. One such instrument is the Met One Model 237A (Pacific Scientific Instruments, Grants Pass, OR) with six particle diameter size-bins between 0.5 and 10 μ m. While convenient for many purposes, this device has limited size resolution, poor calibration options, proprietary or non-existent computer interface options and lack other measurement features often required for aircraft use and/or related research objectives. In our work we find 6 size channels inadequate to resolve subtle changes in aerosol size that are of interest or to properly describe aerosol optical effects. Consequently, we sought to utilize the benefits of the small optical detector available in this instrument while changing the electronics, configuration, interfacing, software and inlet design to make it suitable for both regular aircraft research and use on our remote controlled UAV.

When aerosol samples are brought into an aircraft they can be significantly perturbed due to particle losses in inlets, transmission losses in sampling lines, size changes associated with humidity changes etc. Hence in-situ measurements in minimally disturbed air are desirable for many applications and external optical probes mounted on the aircraft fuselage or wings are frequently employed. Such “wing probes” are often in pods that weigh 20kg or more such as the Forward Scattering Spectrometer Probe (FSSP-300-300) (Fig. 1) manufactured by Particle Measurement Systems with a size resolution

of about 40 bins over the range 0.3-20 μ m (Fig. 1). The FSSP-300-300 range includes larger aerosol sizes and smaller cloud droplet sizes. Our miniature Optical Particle Counter (mini-OPC, Fig. 1) described here has 256 size bins and similar range as the FSSP-300-300 but is designed only for aerosol sampling and not cloud droplet measurements.

2. Instrument

The mini-OPC uses the laser and optical cavity (Fig .1) taken from a Met One 237A particle counter. The 780 nm wavelength laser diode (15mW) is collimated into a parallel 2.5 mm by 3.5 mm beam. The light enters the scattering chamber through a cylindrical 20 mm focal length lens that brings the 3.5 mm "thick" beam to a thin sheet crossing the aerosol flow that enters directly in one side of the optical block and out the other. The beam width is orthogonal to the aerosol flow and the beam continues into a light trap opposite the laser. The beam is nominally 0.1mm thick (maximum) at the laser-end edge of the inlet and is assumed diffraction limited, say 1000-1500nm at the thinnest point, which is somewhat offset about 1mm from the center of the inlet towards the light trap. This creates a tapered wedge for the effective scattering volume and gives a nominal transit time ("pulse width") at 10 m/s of 10 microseconds for a maximum beam thickness (0.1mm) down to possibly 100 nanoseconds. Measured typical pulse widths were typically 1-2 microseconds.

A 15 mm dia. gold surface spherical mirror with a radius of 12.2 mm is mounted opposite the detector about 10 mm from the scattering volume and images a 100 degree

solid angle fraction of the scattered light to the detector, centered on 90 degrees. The detector is a 3.8 mm square silicon PIN diode mounted about 15 mm from the scattering volume. The detector also receives a rather insignificant direct 15 deg. solid angle fraction. We feed the detector output directly into a custom logarithmic pulse height analyzer (N. Ahlquist, Ms. Electron Inc., Seattle Wa.). The signal processor consists of a transresistance amplifier followed by a second-order Bessel response low-pass filter. The power density of the laser beam varies over the wedge-shaped scattering volume created by the cylindrical lens, but the total energy scattered for a given size and velocity particle is constant. For short duration input pulses the low-pass filter integrates them to a constant width pulse with amplitude proportional to their area. The cutoff frequency is selected to minimize the variation in peak height for monodisperse particles without greatly reducing the height of the longest pulses. This appears to give the best compromise of coincidence loss, flow rate sensitivity, size resolution and minimum detectable size.

The pulses feed a chain of 11 saturating amplifiers with a gain of about 2 each. The sum of the outputs from all stages form a piecewise linear approximation of log response over about 3 decades, down to the “thermal” random white noise from the detector load resistor. The transfer function can be described by a true log of the signal plus a small positive offset. The operating point of the idle amplifier chain is controlled by a gated baseline corrector to keep the output at this offset level between particles.

The log signal is digitized at 5Mhz by a 12 bit analog to digital converter and mapped into 256 voltage channels. Though stored as 256 discrete channels of data these are typically averaged over about 10 channels. A fast microcomputer extracts the peak

heights and discards overly-long pulses due to stray particles that escaped from the aerosol stream. The next pulse is not accepted until the signal is back down to the “thermal” noise baseline. The minimum time to resolve two particles is about 2 microseconds. The average busy time is measured and used to correct for coincidence losses up to about 10 percent. Particle concentrations of 1500-2000/cc can be counted before coincidence effects become significant. Other performance characteristics of a similar circuit adapted to lidar applications can be found in a paper by Lienert et al. (2001)

Additional modifications include reducing the original diameter of the MetOne 237A inlet from 2.4mm to 1.6mm and the inlet brought closer to the laser beam (about 1mm) in order to better define the particle pulses. This is done using a smaller diameter brass tube that also serves to extend the inlet for sampling in a straight axis parallel to the airflow for airborne applications. A target sample flow rate of 1.6 lpm results in speeds of about 13 ms^{-1} into the cavity and pulses of about $2 \mu\text{s}$ half width. Since sheath-air flow is not employed in our current system, some particles do leave the aerosol stream as it is drawn through the OPC cavity. These can drift around the cavity and through the laser beam to result in occasional detection of long stray pulses that can also raise the signal baseline. These particles can also deposit on the collecting mirror and reduce its reflectivity. We reduce these effects by feeding a filtered low flow (ca. 0.4 lpm to purge the cavity) through a 0.3 cm diameter fitting that replaces the manufacturers optical light trap that is normally present in the block opposite the laser. Hence both the lifetime of large particles drifting in the cavity is reduced and their trajectories are less likely to recirculate through the laser beam. This flow does not appear to influence particle passage through

the laser beam. We have operated with about 2.0 lpm total flow with about 0.4 of that as purge flow. At higher purge flow, some impact on concentration and resolution has been observed.

3. Airborne Application

The small size and weight (ca. 300g) of the mini-OPC makes it suitable for mounting in diverse applications including miniature airborne research platforms such as our remote controlled UAV (Fig 1e,f). This application will be discussed in a later paper. However, its convenience and capabilities are of interest for larger aircraft also. Because it can be easily mounted in a lightweight strut attached to a standard research aircraft window mounting-plate (Fig. 1d) the mini-OPC can be installed on most aircraft with little engineering or impact on payload. For pressurized aircraft, such as the NASA P3b discussed here, the electrical and airflow connections pass through bulkhead fittings at the base of the wing strut (Fig. 1 b,d) such that the strut is maintained at ambient temperature and pressure. A similar but smaller strut is employed on our 6 passenger Seneca aircraft.

For aircraft use, it is also important to deliver the flow to the inlet in a prescribed manner so that particle sampling and sizing characteristics can be controlled. Often it is desirable to keep the sample inlet flow close to aircraft speed so as to maintain isokinetic conditions and thereby obtain accurate measured particle concentrations for all sizes. At other times there are advantages to operating at non-isokinetic speeds. Ambient supermicrometer or “coarse” particle number concentrations are generally orders of magnitude lower than submicrometer or “fine” particle aerosol. Hence an inlet operated

at lower inlet velocity than the air passing it acts as “virtual impactor” thereby enhancing the concentrations of larger aerosol in a way that increases particle count statistics (Porter et al., 1992). This increase in coarse-particle concentration and count statistics can be beneficial if done in a predictable manner.

The NASA TRACE-P (Transport and Chemical Evolution over the Pacific) experiment provided us with an opportunity to test and compare our prototype instrument with other instruments was in an unknown and uncontrolled environment. We expected to encounter both clean and heavily polluted environments with variable amounts of dust. Hence, we designed an inlet that allowed us to operate from isokinetic to subisokinetic conditions (coarse particle enhancement) so that better statistics could be obtained at larger sizes. Since no time for testing was available this was based upon our experience with other diffuser inlets (Porter et al, 1992) and the physical constraints involved in incorporating it into our mini-OPC wing strut mount (Figure 1 b,c,d). Performance evaluations were not made until after the TRACE-P mission (see below).

The nominal inlet velocity into the mini-OPC sample tube (Fig. 2) is about 13m/s which is similar to moderate surface wind speeds but well below aircraft speeds. Our UAV airspeed is about 30m/s, our Seneca 1 airspeed is about 60 m/s and the NASA P3 airspeed is about 120 m/s. In order to accommodate high aircraft speeds we fabricated a diverging nozzle to slow down the airflow before it reaches the mini-OPC inlet. The nozzle used on the NASA P3 and Seneca, as indicated in Fig. 2, has a shallow (5 degree) half angle to reduce turbulence development at the inlet walls near the tip and a nozzle opening of about 4mm and about twice the diameter of the mini-OPC inlet tube. Four holes near the base of the nozzle act to exhaust the flow entering the nozzle. Flow

velocity is steadily reduced as the air moves to larger cross sections of the nozzle. The inlet tube length (shaded grey in Fig. 2) can be sized to position the inlet tube at a nozzle cross section where the decelerated airflow in the nozzle is appropriate for the desired performance. In this case we tried to achieve a modest subisokinetic mini-OPC inlet for the NASA P3b measurements discussed here, as described below. The UAV has a similar but smaller inlet arrangement in order to keep weight down.

Other features were added for the P3b installation. Because ambient aerosol size is a function of relative humidity (RH), we included a Humicap 50 (Viasala, Inc., NY) RH and temperature sensor at the exhaust of the mini-OPC to monitor it and compare to ambient values (Fig. 1b). While this is not likely to register the same conditions as that of the mini-OPC it can be used with ambient measurements to estimate OPC conditions. The mini-OPC collection mirror can be also be contaminated by very high aerosol concentrations that can change its reflectivity and the calibration. Hence, the mirror has been made easy to replace by sliding the assembly partially out of the strut (Fig. 1c) and removing the mirror through a hole in the support base. As a precaution against cloud droplets or raindrops entering the inlet we have also added solenoid valves (inside the aircraft - not shown) that reverse the flow and force purge air back through the unit and out the inlet. This arrangement did not prevent the largest cloud and raindrops from penetrating the instrument but dramatically reduced their presence and the contamination of the mirror. The solenoids are both manually activated and can be activated by computer control if RH values exceed some selectable threshold (eg. near clouds).

4. Calibration and Inlet Tests

Calibration was performed using polystyrene latex (PSL) calibration spheres and glass calibration spheres over the 0.3 to 12 μm range. An example of a calibration using 0.966 μm diameter PSL (S.D.=0.01 μm) is shown in Figure 3a. The peak is well resolved with the 256 channel sizing and reveals a halfwidth of about 10 voltage channels. Our resulting calibration curve linking measured output voltage to calibration sphere diameter is shown in Fig 3b along with a 'best fit' line describing our calibration relationship. At 0.966 μm the 10channel voltage halfwidth corresponds to a range of about 0.88 to 1.03 μm compared to about 0.955 to 0.975 (3 voltage channels) expected for the PSL particles. The larger observed halfwidth range shown here is due in part to the laser and optics configuration (ongoing refinements have already reduced this by almost a factor of two). Nevertheless, this performance is far superior to the 6 size bins used over the original full range of the MET1 instrument and provides very good resolution for most applications. The non-linear behavior in the calibration curve is primarily a result of the optical response to transitions from Rayleigh to Mie to geometric scattering (Bohren and Huffman, 1983). Some smaller fluctuations result from deviations from non-linearity in the logarithmic amplifier. Future versions of the electronics will reduce this effect. Actual sizing based upon this calibration suggests that sizes out to about 14 μm can be measured before saturation of the detector. The efficiency of particle detection at the nominal small particle limit near 0.30 μm is influenced by noise in this prototype version. New versions under development using a more sensitive detector and greater attention to internal scattering surfaces have improved sensitivity down to particle sizes below 0.23 μm .

The TRACE-P experiment [http://www.gte.larc.nasa.gov/gte_fld.htm#TRACE] in March 2001 allowed us to evaluate the mini-OPC on the P3b aircraft under research conditions. Because we had no time to characterize our new inlet configuration prior to the TRACE-P experiment, post experiment flow evaluations were necessary. These were carried out in our wind tunnel that provides air velocities up to about 35 m s^{-1} over about a 160 cm^2 cross sectional area. During these tests the inlet and mount were located in the center flow out of the tunnel where velocities were near 32 ms^{-1} . Air speeds were determined in front of and around the inlet using a velocity transducer (TSI Inc., Mod. 8455) and the associated pressure fields near and in the inlet were determined using a pitot tube. This wind tunnel velocity is only about 30% of aircraft velocities employed during TRACE-P but for the purposes of this assessment the results are assumed to scale accordingly. This assumption is consistent with the less than 3% difference between incompressible and adiabatic determinations of “ram” pressures at TRACE-P aircraft speeds (Zham, 1927).

The deceleration of air as it enters the diverging nozzle produces a “ram” air pressure that is directly related to the velocity of the air relative to the OPC inlet velocity. The apparent ram pressure was measured along the center axis of our inlet using a pitot tube calibrated against measured velocities in the tunnel. This pressure was also corrected for the small pressure perturbation induced by the inlet in the tunnel flow. Our test configuration allowed direct measurements past the mini-OPC inlet tube position as used on TRACE-P (vertical arrow). The indicated air speed at the mini-OPC sample tip (Figure 4) is proportional to the square root of the pressure (Zham, 1927) and corresponds to about 19 ms^{-1} at the TRACE-P position for the wind tunnel speed of 32

ms^{-1} . This scales to about 63ms^{-1} at this location under nominal TRACE-P P3b flight speeds (120ms^{-1}). Hence, the 13.8ms^{-1} mini-OPC sample tube flow used during most of TRACE-P meant the mini-OPC sample tube was typically subisokinetic by a factor of about 4.5.

This subisokinetic sampling is a result of two factors. First, our mini-OPC sample inlet opening was 32mm back from the tip while it should have been 45mm behind the tip if flow at the tip scaled only with nozzle cross section. This is calculated to have contributed a factor of 2.6 to the subisokinetic ratio. A similar factor of about 1.7 was found to be due to velocities in the nozzle being significantly enhanced along the axis compared to near the walls. This latter behavior is also suggested by the lack of a pressure change (no velocity change) in the first 6mm behind the inlet tip (Fig. 4) in spite of the increasing cross sectional area of the nozzle (Fig. 2). Hence, the size distributions measured by the mini-OPC on TRACE-P have been corrected for this subisokinetic sampling. As determined above, these yield enhancements of the largest sizes by about a factor of 4.5 for 10 μm particles but have little effect on particles with diameters below about 1 μm (eg. Porter et al., 1992). The data shown below indicate the effect of this size dependent correction.

5. Instrument Performance

TRACE-P took place over the Pacific Ocean between Hong Kong and Japan and included deliberate efforts to study both pollution and dust aerosol such that particles of all sizes detectable by the mini-OPC were represented. The TRACE-P experiment aboard the P3 aircraft included exposure to natural, pollution and dust aerosol conditions.

Installation on the P3b aircraft also made our custom LAS-X OPC (Clarke, 1991) and wing probe (FSSP-300) (both Particle Measurement Systems, Boulder, CO) available for extended comparison under a wide range of aerosol environments. The mini-OPC support wing and nozzle (Fig. 1) had to be fabricated for immediate installation on TRACE-P and no wind tunnel or performance tests were possible. Hence, engineering considerations were recognized but not optimized. The mini-OPC was mounted on the right side of the aircraft [as was the FSSP-300] on the first window-plate behind the cockpit area (Fig. 1d) and about 6m behind the nose of the aircraft. The inlet was about 30cm away from the fuselage that had a surface boundary layer estimated at about 10cm at this location (determined from prior aircraft tests). The window plate also included the shrouded inlet to the laser optical particle counter (LAS-X) and both inlets were angled upward about 1.5 degrees to match the nominal angle of attack of the aircraft. Deviations of ± 1 degree can be expected depending upon fuel load and altitude etc. This shrouded inlet has been evaluated during inlet tests as part of the PELTI (Preliminary Evaluation of the Low Turbulence Inlet, 2000) experiment where it was found to have good transmission performance for dry particles (eg. within 15% actual for 4 μ m) and somewhat worse for wet particles (eg. within 30% of actual for 4 μ m), presumably due to “wet” particles colliding with and sticking to the wall (Huebert et al., 2000).

Figure 5 shows an example of the size distributions measured by the mini-OPC and the onboard LAS-X for a period of elevated dust concentrations in low humidity air during TRACE that allow us to characterize the coarse particle sizing characteristics. Both instruments employ integral side scattering optics. The LAS-X includes a HeNe laser (632nm), custom electronics and a dryer dilution flow that has been employed for

our aerosol measurements for a number of years (Clarke et al., 1996) and allows for sizing between 0.1 and 12 μm . All sizes are based upon calibration of dry latex spheres with refractive index of about 1.5. Because concentrations of larger aerosol (say 3 μm) are about three orders of magnitude lower than 0.3 μm particles, ambient data are averaged over about 50 minutes so that statistically significant counts (eg. greater than 50 particles per size bin) are present for both fine and coarse particle dust aerosol in both instruments. This data period was selected since it was aloft under relatively dry (30%RH) conditions such that correction for possible differences in particle size due to different instrument RH is minimal. We note that the LAS-X data represents distributions averaged over one minute and taken every three minutes (18 one min averages) since this system was cycled to look at other thermally heated aerosol for 2 min out of each 3 min period. Also, the higher sample flow rate (1.6 vs. 0.3 lpm) and subisokinetic sampling (up to a factor of 4.5 enhancement) increase relative mini-OPC sampling statistics by a factor of 5 to 24 depending upon particle size.

The mini-OPC data is shown (Fig. 5) both before and after correction for the size dependent effect of subisokinetic sampling. The volume distribution (area under curve is proportional to aerosol volume) best reveals sizing performance at larger sizes due to the cubic dependence of volume on particle diameter. Little subisokinetic correction is evident below 1 μm but before reaching 8 μm the correction approaches an asymptote near a factor of 4.5. Note that below about 5 μm the mini-OPC data after correction for subisokinetic flow is within about 15% of the LAS-X OPC data and within the combined flow uncertainties expected here. At larger sizes the corrected mini-OPC shows significantly higher ambient concentrations. This is because both the sample inlet and

tubing to the LAS-X OPC have particle losses that have not been accounted for and because the LAS-X inlet itself is known to have particle losses for sizes above about $7\mu\text{m}$. Hence we contend that the mini-OPC has equivalent performance to the LAS-X particle counter between 0.4 and $5\mu\text{m}$ and probably superior performance above that size.

The high flowrate of the mini-OPC (1.6 lpm) relative to the LAS-X (0.3 lpm) and FSSP-300 (0.25 lpm) means the mini-OPC also has an intrinsic factor of 5 or better count statistics than the other instruments. This is particularly valuable, over its size range, for measurement of the coarse particles (eg. dust) generally present at low number concentrations and makes it effective at measuring representative size distributions in rapidly changing environments such as those encountered during vertical descents. This is demonstrated over a range of conditions (Fig. 6) for a descent profile over the Sea of Japan during TRACE-P where highly structured pollution and dust plumes were encountered.

The detailed vertical structure in aerosol optical properties for these continental aerosol plumes is illustrated here in the concurrently measured profiles of aerosol light scattering (nephelometer Model 3071, TSI Inc.) and light absorption coefficients (Partical Soot Absorption Photometer, Radiance Research) during the descent (Fig. 6a). These data (15 s average) provide a context for the size distributions measurements. The integrated aerosol volume from the LAS-X, mini-OPC and FSSP-300 are included in Figure 6b. Small altitude offsets evident here are due to one minute average values recorded for the mini-OPC and LAS-X while 15 s data was stored for the FSSP-300. These integral volume measurements are clearly correlated. Differences are consistent with the recognition that coarse particles dominate the volume so that the FSSP-300 with

greatest sensitivity to largest aerosol is highest, followed by the mini-OPC and then the LAS-X having the most limited upper size range and showing the lower volume. Note that at the near surface altitudes the FSSP-300 shows relatively higher concentrations where ambient RH (measured on aircraft system) is highest. Again this is as expected in view of the dilution drying used in the onboard LAS-X measurements and for the partially dried mini-OPC aerosol (due to ram heating and warmer purge flow) in conjunction with a near surface source of larger “wet” sea-salt aerosol present at higher RH and detected by the FSSP-300. Note that under more polluted settings where the smaller accumulation mode aerosol dominates the mass, the LAS-X (with its superior sensitivity below $0.3\mu\text{m}$) will best resolve the actual aerosol volume.

In order to examine smaller particle characterization with the mini-OPC we have plotted the same data for the profile in Fig.7 as a continuous surface area size distribution (shaded by concentration contours). Since surface area depends on the square of the diameter instead of the cube (volume) both submicrometer and supermicrometer particles contributions are better revealed. A typical representative size distribution from 1.5km is also included below each contour plot for clarity. The mini-OPC and FSSP-300 data are also truncated at $0.3\mu\text{m}$ where their signal to noise limits are reached while the LAS-X provides well resolved sizes down to about $0.1\mu\text{m}$. The more variable contours in the distributions for the FSSP-300 data reflect a combination of coarse size bins and limited sample volume compared to the LAS-X and mini-OPC. Clearly, the mini-OPC exhibits excellent qualitative and quantitative characterization of aerosol size. The high flow rate clearly provides improved count statistics over those of the LAS-X and FSSP-300.

6. Conclusions

We have developed, tested and deployed a prototype custom mini-OPC and inlet system for in-situ aircraft studies of non-cloud aerosol. The unit employs a solid-state laser and optical block from a MET1 237A optical particle counter coupled to a custom designed logarithmic amplifier, electronics, and sample inlet configuration. The device has been found to work successfully for applications on small remote-controlled aircraft as well as full size research aircraft.

Comparison with size distributions obtained concurrently using a LAS-X (inside aircraft) and FSSP-300 (mounted on wing) optical particle counter were undertaken as part of the TRACE-P experiment sampling both pollution and dust aerosol near Japan. Though not optimized for this application, the prototype mini-OPC was found to work dependably and with quantitative performance under a range of conditions and provides reliable size distributions from about 0.3 to 14 μ m. Low particle losses for larger aerosol resulted in improved characterization of large aerosol than was possible with the LAS-X. The simpler optical system and high flow rate provided superior performance compared to the FSSP-300 up to about 14 μ m particle sizes. The small size, low power, low cost, versatility, wide size range and high resolution of the device makes it ideal for a large number of airborne and surface applications.

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Figure 1. a) Side by side comparison of the mini-OPC (circled) and standard FSSP-300 compared here; b) Exploded view of P3b wing strut with mini-OPC, electronics, inlet cone, RH sensor; c) mini-OPC with inlet removed and partially extracted for mirror change; d) mini-OPC strut (middle) as mounted with other inlets on P3b during TRACE-P; e) UH UAV; f) mini-OPC mounted in nose of UAV (circled) and interfaced with onboard computer (middle) and other instruments.

Figure 2. Cross section through wing strut, mini-OPC and diffuser nozzle inlet showing principal design elements as used aboard the NASA P3b during TRACE-P.

Figure 3a. Mini-OPC voltage response to indicated PSL calibration aerosol. Upper channel tail includes doublets and triplets of primary size (see text).

Figure 3b. PSL and glass bead calibration curve that establishes mini-OPC output voltage vs. size.

Figure 4. Air speed at tip along center of diffusing nozzle in wind tunnel operating at 35 m/s and tip speed scaled up to expected TRACE-P conditions. Subisokinetic ratio is calculated based upon the scaled TRACE tip speed. The vertical arrow indicates position of mini-OPC sample tube inlet in nozzle during TRACE-P associated with 4.5 subisokinetic ratio.

Figure 5. Comparison of mini-OPC volume distributions before and after subisokinetic correction (see text) with onboard LAS-X OPC distribution.

Figure 6. a) Vertical profiles of aerosol light scattering, light absorption and ambient humidity revealing aerosol column optical structure.

b) Corresponding profile of integral volume concentration from the mini-OPC LAS-X and FSSP-300 size distributions. Relative concentrations are consistent with size ranges of instruments and operating humidity(see text).

Figure 7. Concentration contours of surface area as measured by the LAS-X, the mini-OPC and FSSP-300 for a vertical profile near Japan on TRACE-P. The lower sensitivity limits of 0.3 μ m have been masked off on the latter two instruments. An example of a distribution from each instrument as measured at 1.2km is also included below each panel for clarity.