# Passing Efficiency of a Low Turbulence Inlet (PELTI)

# Executive Summary and Report Summary
# of
# Final Report to NSF

Prepared by the LTI Assessment Working Group:
Barry J. Huebert[1], Chair
Steven G. Howell[1]
David Covert [2]
Antony Clarke[1]
James R. Anderson[3]

With Collaborating Authors
Bernard G. Lafleur[4]
Russ Seebaugh[4]
James Charles Wilson[4]
Dave Gesler[4]
Darrel Baumgardner[5]
Byron Blomquist[1]

[1] Department of Oceanography, University of Hawaii, Honolulu, HI 96822
[2] Atmospheric Science Dept, JISAO GJ-40, University of Washington, Seattle, WA 98195
[3] Mechanical and Aerospace Engineering, Arizona State University, Tempe, AZ 85287
[4] Department of Engineering, University of Denver, Denver, CO 80208
[5] Centro de Ciencias de la Atmósfera – UNAM, Universidad Nacional Autónoma de México,
Circuito Exterior s/n, Ciudad Universitaria, 04510 México City (D.F.)

Address inquiries to: huebert@soest.hawaii.edu

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*Disclaimer: The data on which this report is based was collected in July, 2000. This report is being submitted in early September, 2000. It commonly takes multiple years for investigators to process, quality-check, and publish data from flight programs of this complexity. In view of the extremely short time from data collection to report, perhaps it is reasonable for the authors to attach a "preliminary" label to the tables and plots herein. Errors will no doubt be discovered and corrected. However, we are confident that they would not change the fundamental conclusions about the functioning of the LTI.*

# Executive Summary

In July, 2000 we tested the new porous-diffuser low-turbulence inlet (LTI), developed at the University of Denver, by flying it and three other inlets on NCAR's C-130 in the Caribbean, using both dust and sea salt as test aerosols. Aerosols were analyzed using bulk chemical analysis of ions on filters, scanning electron microscopy (SEM) of filters, TSI aerodynamic particle sizers (APSs), and FSSP-300 (300) optical particle counters.

We found that the LTI consistently admitted more particles to the airplane than did either the NCAR Community Aerosol Inlet (CAI) or a shrouded solid-diffuser/curved-tube inlet (SD). APS size distributions behind the other inlets began to diverge from LTI values above 1-3 um, with mass concentrations of larger particles lower by as much as a factor of ten behind the CAI and a factor of 2 behind the SD. Modeling of particle trajectories in the LTI with Fluent predicts less than a factor of two enhancement of particles between a few and 7 microns. This was supported by the SEM analyses of particles behind the LTI and TAS.

Comparisons of bulk chemistry with an external reference total aerosol sampler (TAS) found no significant differences between the LTI and TAS, but both the SD and CAI passed lower values for most of the ions analyzed. Thus, the LTI filters can be used to determine the ambient mass mixing ratios of the analyzed ions. The inertial enhancements in the LTI diffuser and estimates of losses in transport to the LTI filter must be taken into account to accurately infer ambient concentrations based on LTI sampling. When this is done, the ambient mass mixing ratios estimated from the LTI filters agree within 20% with the mixing ratios determined from the TAS filters.

Relative to the LTI, the SD and CAI transmission efficiencies (the concentration in the sample flow divided by the ambient concentration) was lowest for "wet" aerosol (i.e., sea-salt), apparently because salt droplets are more likely than dry dust to stick when they impact on the walls of the other inlets.

We set out to test two hypotheses:

> A. *The LTI has a demonstrably higher aerosol sampling or transmission efficiency than both the CAI (the NCAR C-130 community aerosol inlet) and traditional solid diffusers for particles in the 1-7 um range.*

This hypothesis could not be falsified. All the chemical and physical evidence indicates that the LTI admits more particle mass in this range than the other inlets do.

However, we note that our real goal is to achieve efficiencies near unity. The ubiquity of losses in earlier inlets lead us initially to state this hypothesis in terms of "higher" efficiency, but enhancement by the LTI may cause efficiencies substantially above 1 for particles larger than 3-5 um. Since enhancements in laminar flow are calculable, most measurements can be corrected for them.

> B. *It is possible, using the LTI, to sample and characterize the number-size and surface area-size distributions of ambient dust and seasalt inside an aircraft with enough accuracy that uncertainties arising from inlet losses will contribute less than 20% to the assessment of radiative impacts*.

This hypothesis also could not be falsified. It essentially asks how well aerosol size distributions behind the LTI represent ambient particle distributions and light scattering. The LTI bulk chemical concentrations were statistically identical to the TAS bulk concentrations of $Na^+$, $Cl^-$, $SO_4^=$, $Mg^{++}$, and $Ca^{++}$, which represent the ambient mixing ratios of those species. The SEM analyses showed that the LTI and TAS number concentrations were statistically identical up to 2 μm; above 2 μm the LTI showed enhancement within model-predicted limits. When Fluent model-derived inertial enhancements associated with the LTI diffuser and losses associated with transport to the LTI filter are taken into consideration, they explain the observed 20% agreement between LTI and TAS.

Corrections for modest but predictable LTI enhancements also provide light scattering assessments that are representative of ambient size distributions up to 7um. Additional contributions to scattering from yet larger aerosol are unlikely to approach 20% for realistic aerosol cases. The error in radiative forcing due to positive and negative sampling biases depends both on the transmission efficiency and the fraction of the mass and total optical depth in each size interval. For those sizes that contribute little to the optical depth, a poor transmission efficiency will cause little error in radiative forcing calcualtions. It is worth noting, however, that over- or under-sampled sizes could still cause significant errors for other issues, such as the computation of deposition fluxes and heterogeneous reaction rates.

**CONCLUSION:** Our conclusion, therefore, is that the LTI represents a significant advance in our ability to sample populations of large particles from aircraft. Its efficiency is near enough to unity to enable defendable studies of the distributions and impacts of both mineral dust and sea salt. Corrections will need to be applied for enhancement of particles in the 3-7 um range. We recommend that the ACE-Asia program use LTIs to provide samples to the various aerosol instruments on board the NCAR C-130.

# Report Summary

## A. Introduction

It has long been known that typical diffuser-and-curved-tube airborne inlet systems remove particles from sampled airstream, so that instruments downstream receive air that has been depleted of supermicron particles. Since most instruments require that air be decelerated from aircraft velocities to a few m/s prior to its analysis, decelerating diffusers have been widely used in airborne sampling. Apparently the highly-turbulent flow just inside the tip of these conical diffusers causes the largest particles to be impacted on the walls of the diffuser. With the possible exception of mineral particles that may bounce off the walls, this has the effect of removing large particles and distorting the particle-size spectrum behind diffusers.

A workshop was convened at NCAR in 1991 to assess the state of knowledge about inlet systems. Attendees concluded that it was not possible at that time to sample supermicron particles from aircraft without substantial and unquantifiable size-dependent negative biases, and made several recommendations for ways to study and improve airborne aerosol inlets (Baumgardner et al., 1991). The notion of a shallow angle diffuser with a shrouded inlet prompted the design of the NASA SD employed in this study. Similarly the NCAR Community Aerosol Inlet (CAI) incorporated several features intended to minimize artifacts. One of the most promising suggestions from the 19901 workshop was that of Denver University researcher Russell Seebaugh, who noted that aerodynamic engineers have for years suppressed turbulence in diffusers by using boundary layer suction to prevent the separation of the boundary layer from the diffuser walls. Since that time, Seebaugh and his colleagues Bernard LaFleur and James C. Wilson have developed that concept in the laboratory. This led to the fabrication of the LTI that is the focus of this report (Figure S1).

## B. Approach

**Hypothesis A** can be tested relatively simply, since it only requires measurements inside the aircraft, on air streams that have already been decelerated. We used three matched aerodynamic particle sizers (TSI Model 3320 APS's) to measure the physical size distribution behind our three test inlets: the LTI, CAI, and SD. The difference between the APS distributions provides a direct test of Hypothesis A. Nephelometers behind each inlet provided a real-time signal in flight to guide the test and a relevant integral measure of light scattering that is appropriate to the tests and one of the goals of ACE-Asia, radiative transfer. We also collected filter samples for chemical analysis behind each of these inlets. That included both Teflon filters for ion-chromatographic analysis of major anions and cations (Barry Huebert's group) and streakers with Nuclepore filters (SEM analyses by Jim Anderson). In dust, Anderson counted and sized the particles behind each inlet with automated SEM (without chemical analysis) that could amass statistics on thousands of particles.

**Hypothesis B** is considerably more difficult to test, since it involves comparing aerosol distributions behind the LTI to those in ambient air. The crux of the problem is to measure the ambient (reference) distribution with a system that does not itself suffer from inlet or other artifacts. One of the most defendable external references is the bulk concentration of particles, as measured by the TAS designed and built in the NCAR shop. This external sampler permits an analysis of every particle that enters the inlet tip, whether it has been deposited on the inside of the diffuser or collected on its filter. The diffuser is lined by removable cones, which are replaced with each filter sample and extracted after the flights. As long as one samples isokinetically, we can be assured that the sum of the cone extract and its filter contains every particle that entered the TAS tip and is representative of the ambient aerosol concentration. TAS was used to measure reference ambient concentrations of both seasalt and dust. When sampling dust, the size of mineral aerosol was preserved in the TAS extracts (except for aggregates), so that the ambient (TAS) and LTI size distributions could both be measured directly by SEM. Only comparisons utilizing a single physical principal (either SEM or IC analyses) were considered to be valid tests of the LTI.

The FSSP-300 is another external device that seemed to offer the best hope for characterizing the ambient size distribution that could then be compared to a similar probe mounted internally behind the LTI. However, inconsistencies in the internal FSSP data and uncertainties concerning the nature of the flow in its sample volume led to comparisons that we are unable to reconcile with the other aerosol measurements. It is worth noting that the counting efficiency of 300s in these different configurations has never been calibrated, in contrast to their sizing ability. Hence, we have focussed on the TAS data as our external reference.

## C. LTI Modeled Performance

The design of the LTI was expected to lead to some enhancement in larger particles. This occurs when particles with sufficient inertia deviate from the curving streamlines caused by aspirating most of the flow through the sides of the LTI porous diffuser. However, losses of some larger particles in this prototype are caused by the 90 deg bend in the tube behind the inlet (Fig. S1). Fluent calculations that account for these enhancements and losses (Fig S2) indicate that a net enhancement should become evident around 3μm and approach about 40% by 6μm. In the final Figure of this Summary (Fig. S6) we correct for this enhancement

## D. Observations

### D.1. Aerodynamic Particle Sizers

Aerodynamic Particle Sizers (APS, Model 3320, TSI Inc, St. Paul MN) (Wilson and Liu, 1980) were used to count and size particles according to their aerodynamic diameter, $D_{ae}$, in the range from 0.8 to 13 µm downstream of each of the three inlets, the LTI, CAI, and SD. Each APS unit drew its 5 l/min from an identical distribution plenum one of the inlets as described above. The APS measurements were overseen by Steve Howell of UH and Dave Covert, of the University of Washington.

Figure S3 contains two examples of APS volume distribution data from Flight 8 collected concurrently from the LTI, CAI and SD for so called “dry” and “wet” conditions in the presence of coarse aerosol. Note that we plot volume distributions (rather than number) to make factors of two or less differences in the largest sizes evident. “Dry” refers to low relative humidity (RH) conditions common above the marine inversion and in the presence of dry dust aerosol. “Wet” refers to higher RH conditions common to the marine boundary layer where coarse sea-salt is deliquesced into a “wet” saline droplet (although at this low wind speed much of the small mode may be dust). In the “dry” case (Fig S3, Left) at 2100 m altitude the LTI and SD concentrations are similar up to 1.5μm, after which SD concentrations are about 20% lower than the LTI. However, CAI concentrations are less than 50% of corresponding LTI values. In the “wet” case (Fig. S3, right) at 30 m discrepancies are much greater: SD concentrations are about 60% of LTI values between 2 and 7 μm while CAI values are far less: about 10-20% of the LTI values over this range.

### D.2. Bulk Analysis of Anions and Cations

Filter samplers behind each inlet were compared with data from the Total Aerosol Sampler, TAS. Since TAS enables an analysis of every particle that enters its tip (whether on the Teflon filter or extracted from the interior walls of the inlet cone), it serves as an ambient reference for other filter samplers. Because analyzing TAS samples involves handling and extracting a cone as well as s filter, the precision of TAS will never be as good as that of a single filter analysis, but its lack of sampling bias means that it has a definable accuracy. Ion chromatography was used to analyze all filters and TAS samples for $Cl^-$, $SO_4^=$, $Na^+$, $Ca^{++}$, and $Mg^{++}$. The major source of uncertainty was the variability of blank concentrations.

Figure S4 compares $Cl^-$ behind all the inlets with TAS $Cl^-$ in the left panel and with LTI $Cl^-$ in the right panel. The LTI concentration is indistinguishable from that of TAS, while the SD and CAI brought considerably less $Cl^-$ into the cabin. We conclude that the LTI reproduces ambient Cl- concentrations to within at least 20%, in spite of enhancements and losses that may affect the larger end of the sea salt size distribution. The relative behavior of the inlets is clearer when SD and CAI samples are plotted against the LTI in the lower panel. Similar differences were noted for the other ions:

**Average Ratios of Species Concentrations Behind Various Inlets to TAS Concentrations**

| **Ratio** | **Cl** | **SO4** | **Na** | **Mg** | **Ca** | **NSS(Mg)** |
|---|---|---|---|---|---|---|
| LTI/TAS | 1.15 | 1.03 | 0.94 | 0.86 | 1.03 | 1.23 |
| Solid/TAS | 0.58 | 0.84 | 0.54 | 0.51 | 0.74 | 1.32 |
| CFilt/TAS | 0.17 | 0.52 | 0.20 | 0.19 | 0.25 | 0.86 |
| CImp/TAS | 0.16 | 0.50 | 0.18 | 0.19 | 0.24 | 0.79 |

This chemical data suggests that the sea salt and dust modes are sampled with nearly-unit efficiency by the LTI. It also shows a demonstrable lowering of efficiency when the LTI flow was made turbulent rather than laminar. In these cases the majority of the mass distribution was smaller than 4 um so that LTI enhancement biases were not large.

### D.3. Scanning Electron Microscopy

Streaker samplers enabled the collection of Nuclepore filter samples behind each inlet on every flight leg. In addition, on high altitude legs we exposed Nuclepore filters in TAS, so that we had an ambient SEM reference for mineral dust particles. Only about 10% of the dust particles adhered to the TAS cone (dry particles tend to bounce off), so most of the particles did not need to be extracted for analysis. Thus, the SEM enabled comparisons of particle size distributions behind each inlet for comparison with the ambient distribution from TAS.

It should be noted that these size distributions differ from those measured by the APSs. A significant fraction of the large particles were tabular clays, whose complex shapes defy simple descriptions such as diameter. Furthermore, the extra drag of these complex particles would cause them to appear small for their mass in the APS, where the smallest particles tend not to deviate from the path of the air. Ironically, because of their large surface to mass ratio, they would size large for their mass in instruments that measure light scattering. Reconciling these various measurements has given us many insights about ways to study dust particles in ACE-Asia.

Two dust samples from Flight 8 have been extensively analyzed by SEM. As Fig. S5 demonstrates, there is good agreement (<20% in the number distribution) between TAS and the LTI below 2 um, which suggests that the sampled volumes have been correctly accounted for. Above 2 um the TAS and LTI distributions in this sample diverge to suggest an enhancement by the LTI of a factor of 2 in the 3-8 um range. The other sample shows overlap up to about 6 um and then enhancement by only about 20% up to 8 um (see full report). This data, which is our most reliable comparison of ambient and internal particle sizes, is in general agreement with the modeling (suggesting a small enhancement) and the ion chemistry (suggesting that the bulk of the sea salt mode is sampled with no more than modest enhancement).

### D.4. Nephelometer

The Radiance Research nephelometers (530nm) behind each inlet characterized the integral light scattering of the aerosol from 8 to 168 deg. Larger particles concentrate a greater proportion of their scattered light in the forward direction such that this angular truncation underestimates the scattering contribution of the largest particles. However, we also used a second nephelometer behind the LTI inlet with an aerodynamic size cut near 1μm to characterize the submicrometer scattering and subtract it from the total to identify coarse scattering only. For the PELTI data discussed here, submicrometer scattering was about 1/3 of the total such that total scatter was dominated by coarse particle scattering in spite of possible truncation losses due to forward scatter from the largest particles. Although the LTI consistently saw higher mass concentrations, light scattering values behind the LTI and SD inlets were virtually the same when compared over the experiment, with leg average differences generally much less 10% (see full report for Figure). On the other hand, scattering data behind the CAI was consistently about 40% less than LTI or SD values. The relationship between size and scattering is explored in Section D.6.

### D.5. FSSP-300 Wing/Cabin Comparison

Two FSSP-300s were provided by the NCAR Research Aviation Facility and NASA Ames Research Center. Darrel Baumgardner and Jeff Stith oversaw these measurements. The gains of the amplification sections of both probes were adjusted to insure that each probe showed peaks in identical channels for the same calibration aerosol sizes. Small differences in collection angles will make a small contribution to sizing differences and the Gaussian intensity distributions of the two laser beams may cause differences, although the average uncertainty should be similar for the two instruments. There is approximately a 20% uncertainty in determining the size of particles from the FSSP scattered light measurements.

When mounted upon opposite wings both probes generally performed similarly, with flight-leg average concentrations in identical size bins differing by between zero and 300% (Figure 3.6.1 in full report). However, when either probe was mounted inside the C-130 with a sample cavity arrangement designed to maximize sensitivity by focusing the particles into the center of the beam, unexplainable sizing was evident in the cabin probe (see full report Figures 3.6.2 and 3.6.3). Since we are aware of no tests of FSSP counting efficiency in this altered flow configuration and since no consistency was found between the FSSP and any of the other observations reported above, we cannot defend the internal FSSP distributions as realistic representations of the aerosol from the LTI.

### D.6. Impact of Inlets on Optical Properties

The above data (chemistry, SEM, APS, light scattering) clearly show that the LTI passes more aerosol mass than the SD and far more than the CAI. Model results indicate that some of this may arise from enhancements in the transmission of larger aerosol. The light scattering data indicate that for these test aerosols differences between LTI and SD transmission of the optically significant sizes seen by the nephelometers are often similar (<10%) while the CAI transmits only about 60% of optically significant sizes for PELTI conditions. In order to bring these various observations into focus we have taken the “wet” and “dry” cases illustrated above in the APS data for flight 8 and presented them in Figure S6. In view of the large deficiencies of the CAI we will focus on differences between the LTI and shrouded SD inlets. We would prefer to compare with ambient optical properties, but without a measure of optical depth through a layer we have no such reference.

Is the more expensive and complex LTI a significant improvement over a shrouded SD for measuring aerosol optical properties? To answer that we apply the corrections to LTI data for model enhancements shown in Fig. S2 that reduce the original LTI concentrations. (This is now our best guess at ambient properties.) Small corrections are also applied to the SD for large-particle transmission losses. Original and corrected data are shown for both LTI and SD data in Figure S6. Our best estimate of the performance differences are seen in the differences between the bold green (corrected LTI) and bold red (corrected SD) lines. These are plotted as volume distribution, scattering distribution and cumulative scattering for the “dry” and “wet” cases.
For the “dry” case the differences in the dry volume distributions are small but do approach about 20% in the 3.5 to 5μm range where volume is largest for this case. This also shows up as a similar 20% difference in scattering extinction over this size range but because these particle sizes are less efficient at scattering light than smaller particles this is not a region that dominates the scattering distribution. Consequently, the effect on modeled cumulative scattering as size increases only shows about a 6% lower value for the SD when compared to the LTI.

For the “wet” case, differences in corrected SD and LTI aerosol volume is significant between about 1.5 and 6 μm with SD values about 35% lower than LTI values. The associated scattering distributions for this case are similarly lower over the same size range. In this case the LTI effect on cumulative scattering is about 17%, indicating a significant improvement in optical characterization with the LTI. This is somewhat larger than the difference measured by the nephelometers behind the two inlets, but it is dominated by particles larger than 3um where nephelometer truncation (9-168deg) error leads to underestimates in scattering compared to modeled results (0-180deg).

## E. Conclusions

- The chemical and SEM data that show the LTI is admitting essentially all of the TAS mass.

- The SEM data indicates an enhancement of particles in the 2-8 um range of a factor of two or less.

- The FLUENT modeling of particle trajectories in the LTI predicts a slight enhancement, reaching 44% in the vicinity of 6 um.

- In view of these observations, we feel that the LTI is a clear improvement over other inlets and provides a means to characterize ambient optical properties well within the 20% uncertainty that was our goal. Because of the rapid fall-off in scattering efficiency with size, only very large increases in large particle mass with diameters above 7µm could introduce uncertainties in scattering due to losses through the LTI that might approach 20%.

Details of the methods, figures showing much of the data, and a critique of each method are all contained in the full Report.