Small Ice Detector (SID2H) Probe

UCAR Subcontract : S05-35616

OVERVIEW

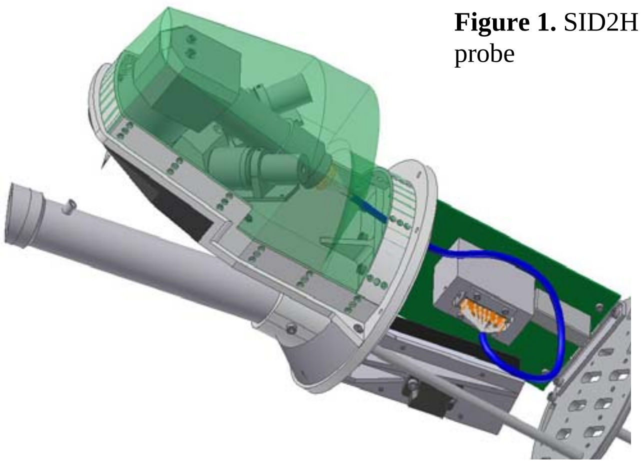


Figure 1. SID2H probe

The SID (Small Ice Detector) series of aircraft probes have been developed primarily to perform particle size and shape classification of water droplets and ice crystals in ice and mixed-phase clouds. The probes, designed for PMS canister mounting, achieve this particle classification at rates of several thousand particles per second by capture of the spatial pattern of light scattered by individual particles as they pass through a focused laser beam orthogonal to the flight direction. The first probe, SID1, used six discrete photomultiplier detectors to measure the spatial scattering from each particle. Its successor, SID2, used a dedicated hybrid photodiode (HPD) device, similar to a 1st generation intensifier, to capture the spatial pattern across 24 radial wedge pixels. The NCAR probe, SID2H, (the H designation from HIAPER), is essentially based on SID2 but has enhanced sensitivity though the use of a higher power laser, improved optical design, and a 32-anode photomultiplier and optical-fibre relay in place of the HPD detector.

1. Principle of Operation

Cloud microphysicists have at their disposal an impressive range of instrumentation for the in-situ study of cloud and aerosol particles. Instruments can count and size particles down to sub-micrometre sizes, whilst others, such as the CPI, can capture real images of individual particles in-situ. Such images are especially valuable to scientists as they allow the assessment of particle morphology and in some cases internal structure, thereby providing a means by which particle formation processes and particle history may be postulated. However, unavoidable optical aberrations and depth of field limitations result in image blurring and may restrict the usefulness of imaging techniques to particles greater than ~15-

20μm in size. Unfortunately, much of interest in cloud microphysics involves particles far smaller than this.

In contrast to imaging techniques, spatial light scattering patterns can provide information on particle morphologies for feature sizes down to the order of the wavelength of the illumination, typically a few tenths of micrometers, and do not suffer depth of field problems.

1.1 Spatial Light Scattering

Any discrete particle will scatter incident light spatially in a pattern which is dependent on the particle's size, shape, and internal structure (and on the wavelength and polarisation of the incident radiation). These *spatial light scattering patterns* can therefore facilitate investigations of small particles or particle features.

For example, Figure 2 illustrates the results of laboratory experiments in which forward scattered light patterns were acquired from a variety of particle types using a scattering geometry as shown in Fig. 3. These patterns were recorded using an intensified charge-couple device camera (ICCD) capable of single photon detection. The camera offers the advantage of capturing in detail even weak scattering features, although image read-out and acquisition restricts the rate of pattern capture to ~30 particles per second[a].

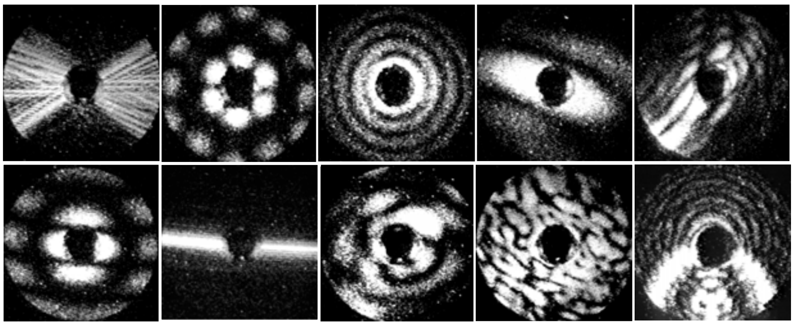


Figure 2: Spatial scattering patterns recorded from individual airborne particles. Top row L-R: curved fibre (~5μm length); salt crystal corner-on, (~3μm); water droplet (9μm); haematite ellipsoid (2μm); copper flake (~4μm across). Bottom row L-R: salt crystal edge-on (3μm); straight fibre (~0.4μm thickness); irregular particle with fine surface structure; irregular particle with coarse surface structure; binary droplet. Scattering angle ranges: 0-30°.

In each pattern, the beam direction is perpendicular to the page, the dark central circle being the shadow of the beam-stop. The extreme circumference of the patterns corresponds to 30° scattering from the beam direction. The wide variations in the patterns illustrates the information-rich nature of this form of classification data.

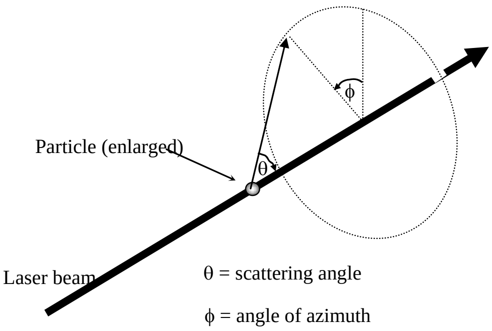


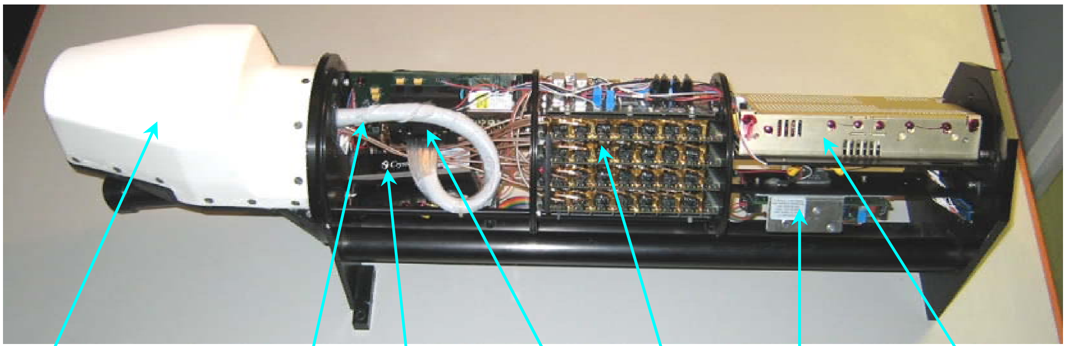
Figure 3. Schematic scattering geometry

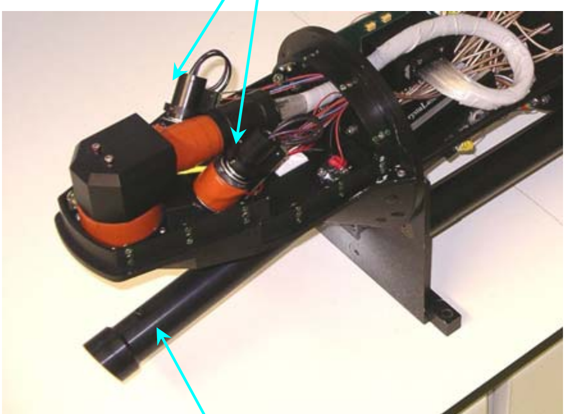
[a] A new aircraft probe, SID3, which uses an intensified camera to capture patterns such as those in Fig.2, is currently being built for the UK Met Office.

The optical geometry for acquiring such patterns may vary depending on the application and constraints imposed by the measurement situation. In some cases, patterns may be captured over wide ranges of angles θ and ϕ, through the use of ellipsoidal or parabolic reflectors surrounding the scattering point. In the case of the SID2H probe however, the need to avoid disturbing the particle and avoid possible shattering of particles on mechanical surfaces restricts measurement to the forward scattering zone, as indicated below.

2. The SID2H probe

The main components of SID2H are shown in Fig. 4 below:





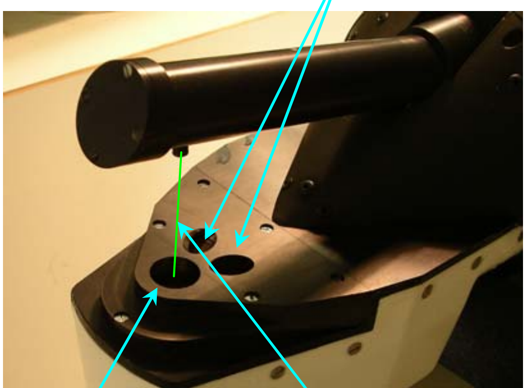


Figure 4: SID2H component parts.

2.1 Particle Detection

SID2H employs a continuous-wave 100mW Class 3b NdYAG laser (Crystalaser Inc.) operating at 532nm wavelength. The beam travels from within the PMS canister via beam-shaping and polarisation optics (contained within a hollow metal column) and is reflected by a front-silvered mirror across the sensing volume, as indicated in Fig.4. The beam power at the sensing volume is approximately 80mW.

At the point of particle detection, the beam cross-section is elliptical, approximately 3mm across by 140μm deep. For a valid scattering measurement, the particle must pass through the *sensing volume* that is optically defined by the two Particle Trigger Detectors as in Figure 5. The field-of-view of Trigger 1 is elliptical, approximately 400 x 200 μm, and is completely contained within the field-of-view of Trigger 2 (approximately 800 x 400 μm).

For a valid particle measurement, the particle must pass through the laser beam within the field of view of Trigger 1. In such an event, the signals from Triggers 1 and 2 will be coincident (in timing terms, Tr1 lies entirely within Tr2). When this happens, the spatial scattering pattern of the particle is recorded (see below).

Defining a sensing volume in this way is important since the multi-pixel detector that records the spatial scattering pattern has, unavoidably, a larger field-of-view than that of the Trigger detectors. This detector can therefore 'see' particles whose trajectories lie outside the sensing volume. The scattering patterns that result from these trajectories will be distorted by optical vignetting and aberration effects and must therefore be rejected.[b]

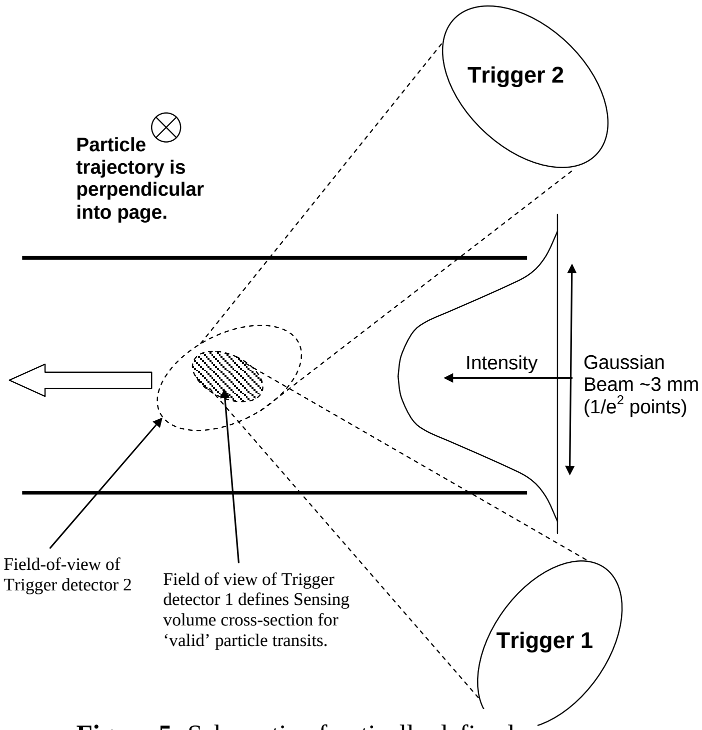


Figure 5: Schematic of optically defined Sensing Volume.

2.2 Spatial Scattering Pattern Capture

The sensing volume is 26 mm from the front surface of the detection optics assembly as indicated in Figure 6. The optics are designed to ensure that the recorded scattering patterns are insensitive to lateral variations in the trajectories of particles within the cross-section boundaries of the sensing volume. As with the Trigger Optics, they incorporate a narrow-band interference filter (532nm) to minimise the influence of ambient daylight.

[b] As in other instruments that use similar optical methods to define a measurement space, the space itself does not have sharply defined boundaries. Optical aberrations and vignetting cause a finite roll-off at the edges of the measurement space and this results in its extent being particle-size dependent (larger particles having a slightly larger measurement space).

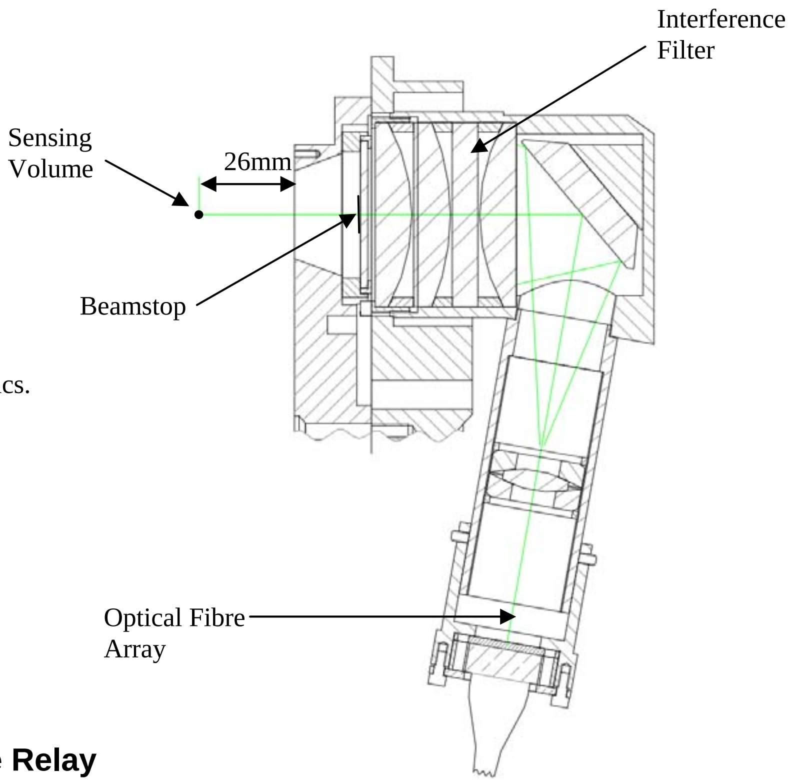


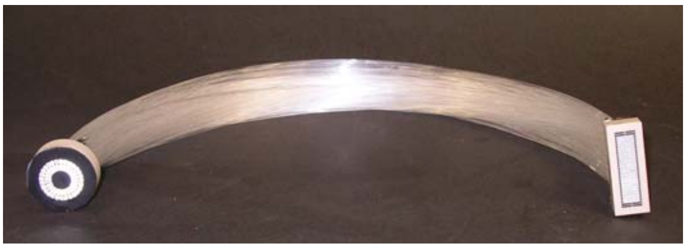
Figure 6: Scattering pattern collection optics.

2.3 Optical Fibre Relay

As mentioned, unlike its predecessor, SID2H uses a 32-anode photomultiplier detector (Hamamatsu H7260) rather than a hybrid photodiode to record the scattering data. This results in a significant improvement in sensitivity (between two and three orders of magnitude) and therefore higher signal quality for signals from the smallest particles around 1 μm in size.

However, the 32 channels of the PMT are arranged in a linear array, and therefore a fibre-optic relay is used to convert the radial spatial scattering pattern to this linear format.

The relay incorporates 252 step-index PMMA optical fibres, each 750 μm diameter and 45cm length. The fibres are potted into machined formers, as shown in Figure 6a below. At the input face of the relay, the optical fibres are arranged into 28 radial wedges, each comprising 9 fibres. These are transposed at the output face into 28 parallel rows of 9 fibres (Figure 7 right-hand side). Two anodes at either end of the 32 anode PMT array are unused.



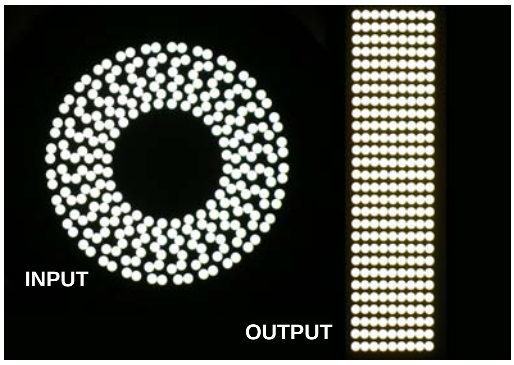


Figure 7: Optical fibre relay (above), and input and output fibre arrangements (opposite)

The radial configuration of the fibres in the input face of the relay is a compromise between achieving high packing density (ie: low interstitial optical losses), and mechanical integrity of the machined former used to hold the fibres in position whilst potting. At the output face, the rows of fibres are on a 1mm period to match the anode spacing of the multi-anode PMT. Optical cross-talk between adjacent anodes is estimated to be approximately 6%. Overall losses in the fibre relay through absorption and packing efficiency are estimated to be 50%. However, these losses are far outweighed by the 2-3 order of magnitude gains achieved through the use of the PMT rather than hybrid-photodiode device in the original SID2

The 28 outputs of the PMT are each connected to a DC Restoration Circuit that ensures measurements are relative to a fixed ground level regardless of changes that may occur in ambient light levels (eg: from sunlight to cloud). When a particle passes through the sensing volume, the Trigger Detector signals are used to verify a ‘valid’ event and the 28 outputs of the PMT are integrated over the duration of the signal pulse. (For flight speeds of 180m/s, this will be ~0.75 μs). Each signal is then multiplexed to an A/D converter and the digitised outputs sent inboard together with other timing and diagnostic information. More details of this process can be found in the detailed Probe Documentation.

3. Data Display

Data relating to particle scattering, particle arrival time at the sensing volume, and other diagnostic readings such as laser temperature, are transmitted down the aircraft wing to an inboard host computer. This provides some real-time information relating to particle scattering and throughput, and stores all data for post-flight analysis. The data display screen is shown in Figure 8 below:

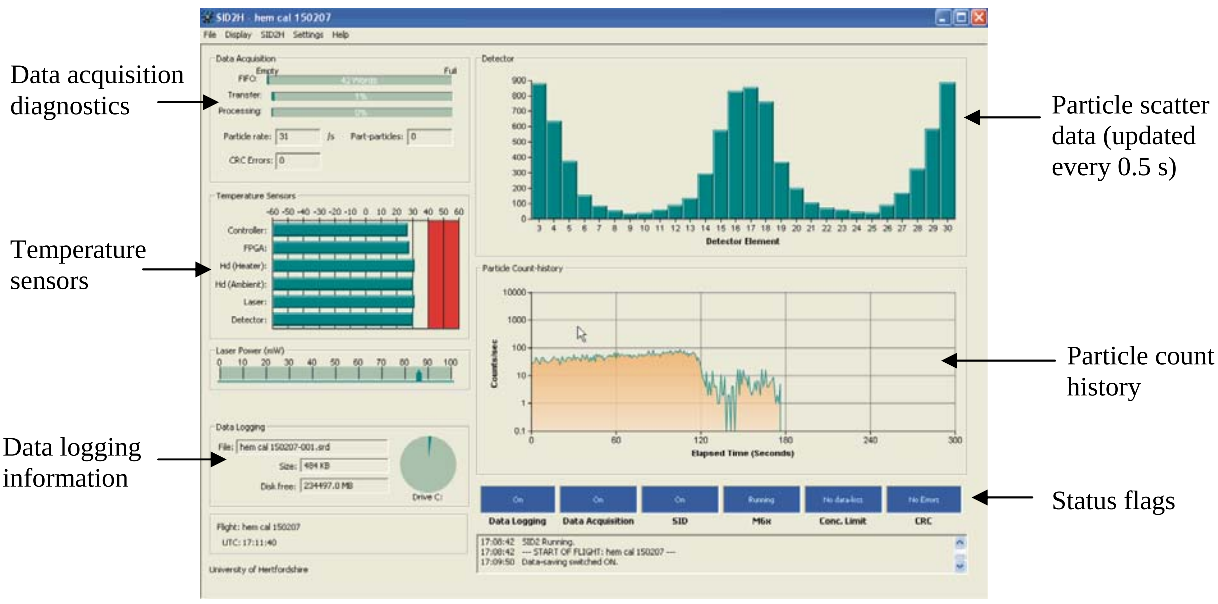


Figure 8: In-flight SID2H control and data display.

The main elements of the display are the two graphical plots. The top-most histogram showing exemplar scattering data from particles is updated approximately twice per second.

This allows the user to visually determine the approximate morphology (spherical, near spherical, highly asymmetric etc.) for the particles being encountered by the probe at that time. The lower plot shows a rolling history of the particle count rate per second. This may be converted to a particle concentration history if the flight speed is known.

Further details of the display functions are contained within the SID2H delivery documentation.

Post-flight, the recorded data may be replayed and examined in detail using, for example, user selectable time slicing of data. Figure 9 shows a typical post-flight screen-dump. The raw data is saved and may be converted into a format suitable for output to MatLab™ or other mathematical processing software package.

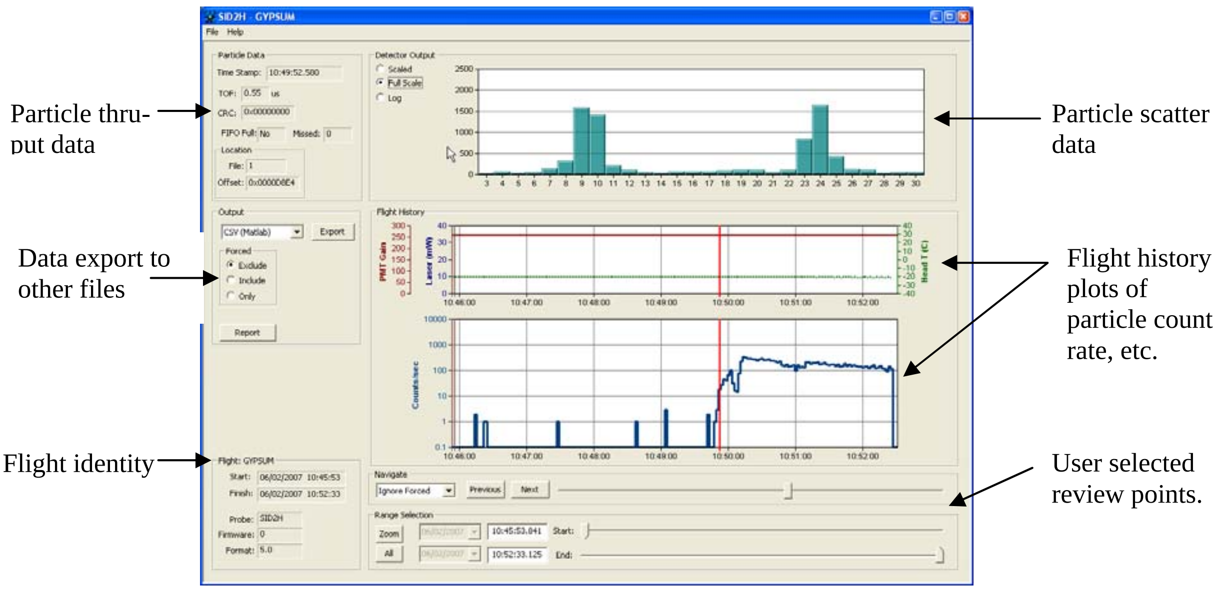


Figure 9: Post-flight SID2H data review and analysis screen

Again, further details of the display functions are contained within the SID2H delivery documentation.

4. Routine Functional Testing

With the probe and host computer connected and powered up, the simplest way to test system functionality is to rapidly move an object (eg: pencil) through the laser beam approximately 26mm (1") from the outer surface of the collection optics assembly. The object movement should be detected by the system and should result in some bars in the 'scatter' histogram rising to positive levels.

A more sophisticated approach is to use a compressed air canister (ie: often used to remove dust from optical surfaces). Place a loose fitting hollow tube around the spout of the air supply as shown in Figure 10, and aim the airflow at a point approximately 26mm (1") from the outer surface of the collection optics assembly. Ambient airborne particles will be accelerated into the airflow by the Venturi effect and should achieve velocities high enough to avoid signal pulse removal by the DC restoration circuitry. Particles greater than ~1µm in size should be detected and the 'scatter' histogram on the display screen should show scattering patterns.

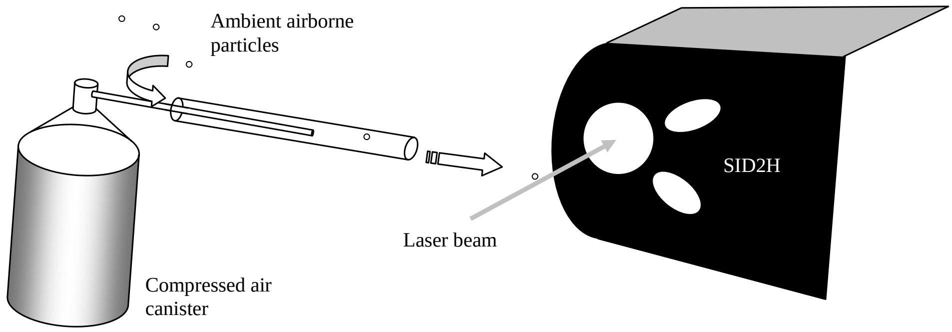


Figure 10: Routine functional SID2H test.

It is possible to 'seed' the airflow by first spraying some water droplets into the ambient atmosphere to be then drawn through the airflow tube. Spraying water droplets directly towards the sensing volume from an aerosol spray atomiser or similar may trigger the electronics, but the droplet concentrations may be so high as to result in excessive particle coincidence in the collection optics field-of-view and therefore unpredictable scatter histogram patterns.

4.1 Calibration testing

Calibration testing requires the delivery of particles of known size and shape through the sensing volume at a known velocity. This may be achieved in the laboratory using an apparatus as shown in Fig.11 below.

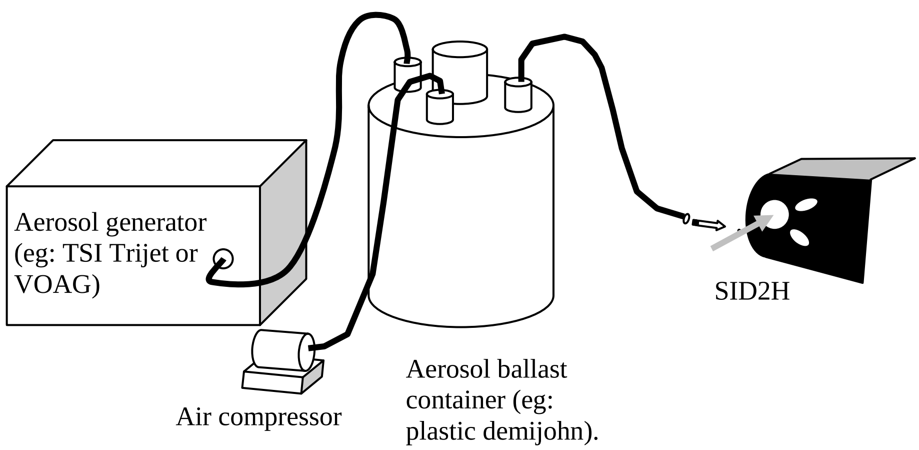


Figure 11: typical apparatus for SID2H calibration testing.

Spherical Particles

An aerosol generator such as a TSI TriJet (TSI Inc., St Paul, MN) is used to generate an aerosol of monodisperse latex microspheres of known size; typically ~3μm to 5μm diameter suspensions are best. The aerosol is delivered into a ballast container (~2-3 cu.ft capacity) which is then pressurised further using a small air pump. The outflow from the ballast chamber is delivered to the SID2H sensing volume through a plastic tube terminating in a narrow-bore exit tube (to accelerate the particles). The original aerosol concentration should be such as to minimise particle coincidence in the probe sensing volume.

Since SID2H integrates the signal pulses produced by particle transit through the sensing volume, correct size calibration requires a knowledge of the velocity of the particles since this obviously governs pulse duration and therefore integrated value. Ideally, the particles should have a velocity equal to that normally achieved by the aircraft during field measurements. However, such high velocities may be difficult to achieve in the laboratory and lower velocities, 50-100m/s, could be used with the results scaled to allow for the artificially long pulse durations.

Unless there is a means at hand to measure the air velocity directly (eg: via laser Doppler velocimetry), the simplest means of assessing particle velocity is to examine the particle light-scatter signal pulse duration using an oscilloscope.

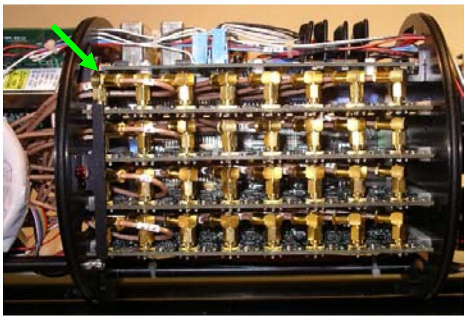


Figure 12: Scatter signal access point

This requires removal of the Trigger SMA connector (arrowed in Figure 12) and inserting between the connector and its socket a length of coax cable comprising :

(Female SMA to BNC) – (BNC T-piece) – (BNC to SMA male).

By connecting this cabling into the Trigger signal path, the probe can remain operational while the trigger pulses are observed on the scope via connection to the BNC T-piece. Once the signal pulse duration is known for a given experimental set-up, the velocity can be computed from a knowledge of the beam-depth (140μm). The integrated scatter signal values may then be scaled linearly to establish what particles of equal size would produce at a specified aircraft speed.

For example, if 4μm diameter latex sphere particles produce average pulse durations of 3.0μs and the mean integrated scatter signal value (ie: average histogram column height for the given particle) is 500 (arbitrary units); then, given a beam-depth of 140μm, the particle velocity will be approximately 46m/s. A similar 4 μm droplet measured during flight at an aircraft speed of 180m/s would then result in a mean scatter value of ~125.

Note that this does not take into account secondary factors, such as particle refractive index, that will affect scattered light intensity and therefore signal integration values. Comparison of SID2H data with particle size data from other field instruments such as FSSP probes is therefore advisable to achieve additional confidence in size data integrity.

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