5 Particle Flux in the Ocean: Oceanographic Tools

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5.1 INTRODUCTION

The flux of particles at any point in the ocean can be considered to be a product of their abundance and sinking speed. Therefore, to fully understand the dynamics of particle flux, it is important to also investigate these other parameters. In some cases where it is impractical to measure flux directly, it may be possible to estimate flux by determining size-specific abundances and sinking speeds and calculating flux as a product of these two parameters. In this chapter, the factors determining particle flux will be discussed, including technologies in use to measure each of the three parameters directly and the limitations associated with each.

5.2 DIRECT FLUX MEASUREMENTS

Conceptually, particle flux at a given point can be determined by simply placing a receptacle (sediment trap) in the water column to intercept the particles as they settle. Flux is then calculated by the mass collected divided by the collecting area and the time over which the collection was made. These devices have been in use for several decades and have provided valuable insight into the rates, timing and mechanisms of material and energy transfer in the oceans (Staresinic et al., 1978; 1982; Knauer et al., 1979; Reynolds et al., 1980; Bruland et al., 1981; Baker and Milburn, 1982; Simoneit et al., 1986; Deuser et al., 1988; Honjo and Doherty, 1988; Kempe and Jennerjahn, 1988; Wassmann and Heiskanen, 1988; Knauer and Asper, 1989; Ittekkot et al., 1991; Wefer and Fischer, 1991; Asper et al., 1992; Hargrave et al., 1994). Two of the most popular designs in common use today are the time-series trap designed by Honjo (Honjo and Doherty, 1988, Figure 5.1) and the MULTITRAP designed by Knauer and Martin (Knauer et al., 1979, Figure 5.2). These two designs illustrate the range of complexity in designs available to address a broad spectrum of research questions.

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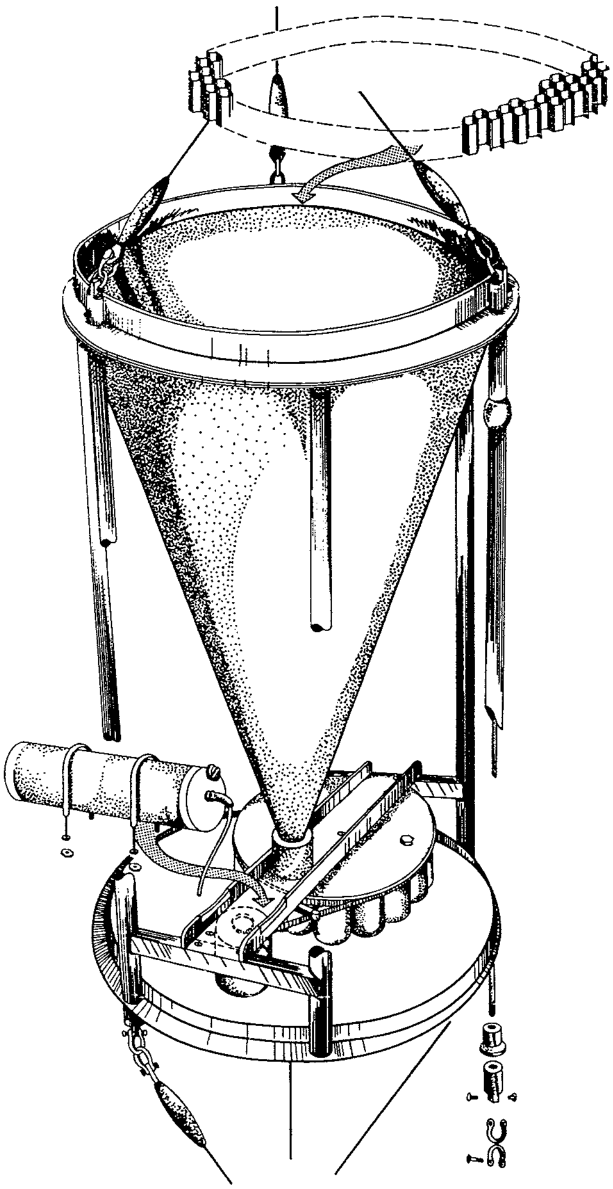

Figure 5.1 Drawing of the PARFLUX Mark V time-series sediment trap showing the collecting funnel, rotating sample collector, baffle and computerized controller. The trap opening of this model is 1.2 m^2, but more recent versions have been reduced to 0.5 m^2 (reproduced from Honjo and Doherty, 1988; reproduced by permission of the authors).

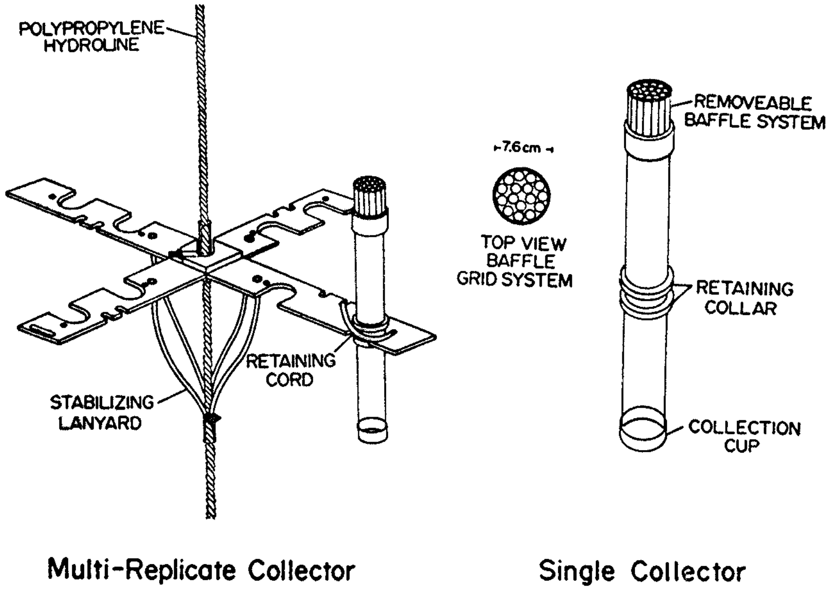

Figure 5.2 Drawing of the VERTEX MULTITRAP system showing an individual collector, support structure and baffle system. The simple design of this system assures high reliability and has gained it wide acceptance in a variety of applications (from Knauer et al., 1979; reproduced by permission of the authors).

In practice, expectations of accurate interception of the rain of particles are complicated by several factors which, in some cases, threaten to invalidate the results (Knauer and Asper, 1989). The three most important considerations are: 1) hydrodynamic bias in collection efficiency caused by the flow of water relative to the trap opening, 2) contamination of the sample by organisms which settle into the trap and die (referred to as swimmers), thus artificially enhancing the collection, and 3) remineralization or degradation of the particles during the interval of time between their arrival in the trap and retrieval of the sample. Investigators intent on collecting the most accurate samples possible must deal with each of these effects in turn and address them either in the design of the deployment or with specific technologies.

5.2.1 HYDRODYNAMIC BIAS

The most direct means of minimizing bias due to hydrodynamic effects are those which reduce the flow of water relative to the trap opening (Asper, 1988; Knauer and Asper, 1989). This can be accomplished by designing the deployment so that the trap is positioned in relatively tranquil water, in environments such as the deep-sea, trenches or restricted basins such as the Black Sea (Honjo et al., 1987).

In cases where this is possible, it represents the best solution to minimizing this effect. In other cases, the choice of either a surface- or seafloor-tethered array can be made so as to minimize current shear between the trap and the surrounding water (Staresinic et al., 1978; 1982). For example, if a sample from 40 meters' depth below the surface in a 500 meter water column is desired, it would generally be better to deploy the trap from a surface rather than a bottom array because the difference in flow vectors between the surface and 40m can be expected to be less than that between 40m and 500m.

Numerous attempts have been made to calibrate or otherwise characterize the accuracy of trap collections, including studies performed in flumes (Gardner, 1980; Butman, 1986; Butman et al., 1986) and in the ocean (Bruland et al., 1981; Lorenzen et al., 1981; Jickells et al., 1987; Siegel et al., 1990; Buesseler, 1991; Asper et al., 1992; Gust et al., 1992; 1994). These studies show that traps appear to be collecting samples which are accurate to within a factor of two when deployed conservatively (Buesseler, 1991). Without some kind of absolute standard against which to compare trap results, however, most of these studies provide intercomparisons of the traps rather than actual calibrations (Knauer and Asper, 1989).

The only way to eliminate hydrodynamic bias is to remove any connection between the trap and any water stratum other than that which is to be sampled. Diercks and Asper (1993) describe a Neutrally Buoyant Sediment Trap (NBST) which consists of a platform with a buoyancy regulating system capable of maintaining the trap at a given depth and thus allowing it to drift freely with the current (Figure 5.3). This approach is similar to that of a hot-air balloon which is buoyed by the surrounding air, is not tethered to the ground, and which experiences no wind (Swallow, 1955; Davis, et al., 1992). Their approach to achieving neutral buoyancy is to use compressed air purge or flood a ballast tank in response to depth inputs from a pressure transducer. These inputs are processed by a microcomputer (Tattletale 5) which monitors the actual depth and the trend and compensates the trap's position accordingly.

While this solution addresses the hydrodynamic problem, it poses other problems including the need to track the platform continuously during its deployment and to recall it to the surface and locate it after the collection is complete. The Diercks and Asper (1993) solution to these problems was to install an acoustic release and ballast weight onto the platform to allow it to be tracked acoustically and to provide a backup recovery system in the event the on-board computer should fail. These requirements and the additional complexity of this system require an extra level of effort and cost which may not be warranted for routine use, but in cases where a calibration or uncompromised sample is required, the effort may be warranted (Knauer and Asper, 1989).

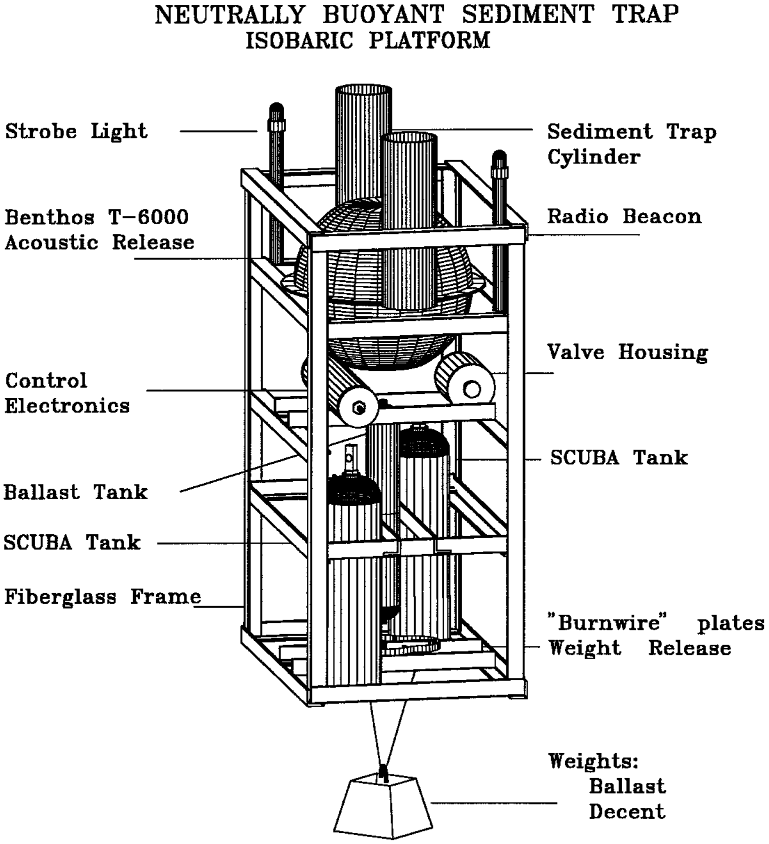

Figure 5.3 The neutrally buoyant sediment trap is intended to minimize hydrodynamic biases by reducing the flow of water relative to the trap opening. This is accomplished by having the trap float freely in the water with no attachments to either the sea surface or the sea floor. Neutral buoyancy is maintained by a microcomputer which varies the amount of water or air in a stainless steel ballast tank (Figure supplied by the authors, Diercks and Asper, 1993).

5.2.2 SWIMMERS

Because of the scarcity of solid surfaces in the ocean and because of the presence of the collected particles, plankton and nekton are often attracted to sediment traps. Once inside they may be killed through contact with the poison and thus contribute their remains to the sediment sample and artificially enhance its contents (Lee et al., 1988; Karl and Knauer, 1989; Michaels et al., 1990). Most investigators deal with this problem by simply picking the remains of these organisms out of the sample (Karl and Knauer, 1989). This straightforward approach is complicated by the somewhat subjective judgement of which remains are those of swimmers and which are those of organisms which died a natural death and should be included in a sample of downward flux of particulate matter (Michaels et al., 1990). Most visible particles in these samples are the remains of organisms, many of which are known to naturally associate with settling particles, so these evaluations are not clearcut (Michaels et al., 1990). Another approach is to use a screen over the trap mouth to prevent swimmers from entering the trap interior (Karl and Knauer, 1989). These screens, however, are thought to provide an artificial "bottom" to the trap and thus reduce its aspect ratio (ratio of height to diameter) and therefore alter its hydrodynamic response to flow and allow particles to be scoured from sample by even weak currents. They may also break up large, settling aggregates and alter their sinking characteristics to the extent that they fail to contribute to the sample. For these reasons, screens have not seen widespread use although some investigators continue to use them in parallel with non-screened traps.

An elegant solution to the swimmer problem has been suggested by Peterson et al. (1993) who built a mechanical device to exclude swimmers from the sample without affecting the sample (Figure 5.4). This device consists of a dimpled sphere located at the base of the trap and just above the sample receptacle. Particles entering the trap accumulate on the upper surface of this sphere and are periodically transferred to the underlying sample cup by rotating the sphere. This device has been shown to be very effective in eliminating most large swimmers from the samples, but smaller organisms, whose abundance can be substantial, continue to be included. Also, portions of the sample are often retained by the sphere and returned to the upper, non-preserved portion of the trap as the sphere rotates, presenting them to the organisms residing there.

5.2.3 REMINERALIZATION/DECOMPOSITION OF THE SAMPLE

Many attempts have been made to find the ideal preservative to prevent microbial decomposition while not interfering with the analyses of interest (Manganini and Honjo, 1985; Lee et al., 1988). The most popular are mercuric chloride (Manganini and Honjo, 1985) and formalin, but others have been used with some success as well. In addition to reducing microbial activity, formalin has the advantage of preserving and hardening the chitinous portions of crustacean carapaces, which facilitates their removal. Regardless of the preservative, most investigators recover the supernatant fluid and analyze it for additions of substances from the particles.

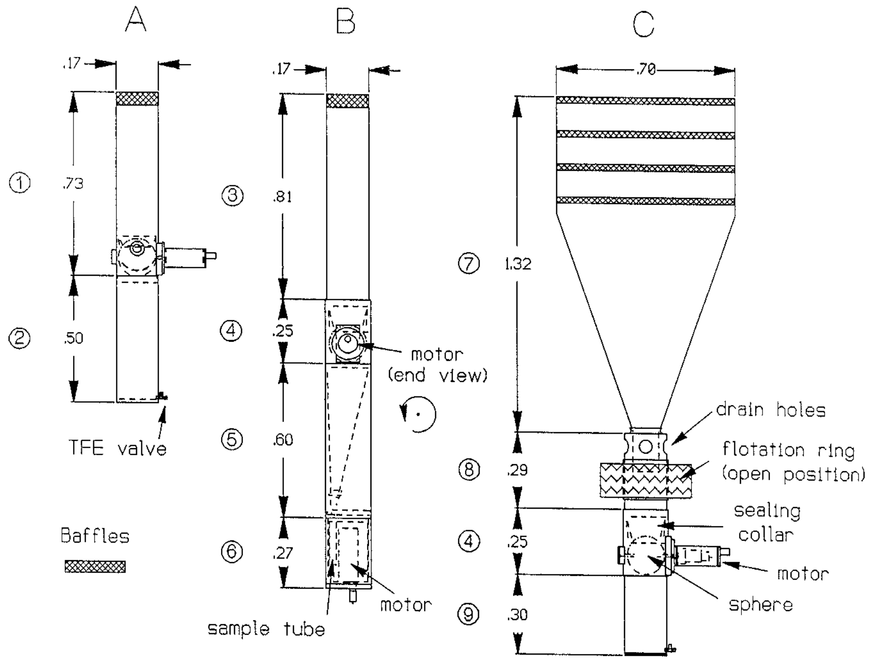

Figure 5.4 Schematic of indented rotating sphere (IRS) sediment traps. A. Prototype IRS valved trap. B. Narrowmouth valved trap with carousel subsampler. C. Widemouth valved trap which collects a single composite sample. Component key: 1 - combination baffled narrowmouth collector/IRS valve; 2 - single-sample accumulator; 3 - baffled, narrowmouth interceptor; 4 - IRS valve and motor; 5 - skewed funnel; 6 – 12 - sample carousel; 7 - baffled, widemouth collector; 8 - flush valve/adapter; 9 - short, single-sample accumulator (from Peterson et al., 1993; reproduced by permission of the authors).

5.3 PARTICLE ABUNDANCES

Determinations of total suspended mass can be made by filtration of large volumes of water, but when size-specific particle abundances are required, optical methods are generally employed (Costin, 1970; Sternberg et al., 1974; Bartz et al., 1978; Spinrad, 1986; Eisma et al., 1990; Agrawal and Pottsmith, 1994). Even the relatively straightforward task of water filtration requires attention to detail because of the possible artifacts. The most accurate determinations are those performed at low vacuum pressures, with the final rinsing and filter recovery operations performed on a laminar flow bench to minimize airborne contamination. Accurate recovery of particulate organic carbon (POC) remains elusive because the accepted practice of rinsing the filters with distilled water to remove sea salts has been shown to result in the lysis of cells and the loss of intracellular components. Transmissometers are useful in determining relative abundances of particles in a given water column, but must be carefully calibrated against known particle concentrations to give quantitative but not size-specific results.

Optical methods for size-specific determinations are characterized by the size range of interest and are capable of ranges from microns to centimeters. On the low end of this range, traditional techniques have employed ship or laboratory-based instruments such as the Coulter counter, but new technology has recently been introduced which will allow *in situ* determinations of particle sizes (Agrawal and Pottsmith, 1993; 1994). These instruments use the near-forward scattering of laser light and are applicable to sizes from 5 to 500 microns.

In natural seawater, many particles exist as aggregates of smaller constituents in a loose and highly porous organic matrix (Suzuki and Kato, 1953; Shanks and Trent, 1980; Alldredge and Cox, 1982; Asper, 1986; Alldredge and Gottschalk, 1988; Alldredge et al., 1990). The challenge of determining the abundance of these large aggregates (often referred to as "marine snow") lies in their fragile construction. Attempts to sample aggregates using water bottles or nets usually result in their dis-aggregation, and intact aggregates have been observed to settle quickly inside the bottle and escape recovery by falling below the level of the spigot (Gardner, 1977).

Because of these characteristics, marine snow aggregate concentrations are usually monitored using photographic techniques which image a large volume of water, but make no physical contact with the particles (Eisma et al., 1983; 1990; Honjo et al., 1984; Lampitt, 1985; Asper, 1987; Davis and Pilskaln, 1993). This technique was pioneered by Honjo et al (1984), but has been adapted and improved by many investigators since its inception, including incorporation of multiple cameras, video imaging and deployment on a remotely operated vehicle (ROV) (Davis and Pilskaln, 1993). While this technique produces excellent results, time-consuming analyses of many images are required to produce the data.

5.3 SINKING SPEEDS

By far the most difficult characteristic to assess is the rate at which particles settle through the water column. This measurement is complicated by ambient turbulence, shear and advection in the water as well as the difficulty inherent in establishing a stable frame of reference (Kajihara, 1971; McCave, 1975; Shanks and Trent, 1980; Alldredge and Gotschalk, 1988; Kineke and Sternberg, 1989). Sinking speed measurements made from free vehicles are likely to result in determinations of the relative motions of the particle and vehicle rather than an absolute sinking speed. Determinations made from a mooring or floating array are complicated by the motion of the water relative to the instrument. Asper (1987) and Asper et al. (1992) used a semi-enclosed volume of water in a sediment trap to photographically time aggregates falling through a known distance. This technique produced excellent results, but is capable of detecting only those particles which are within the resolution limits of the cameras, and is only able to assess those particles which actually settled into the trap. Particles or aggregates settling at very slow speeds (less than ca. 1 m d^{-1}) do not enter the trap in significant quantities and are therefore not incorporated into the measurements.

New techniques on the horizon which promise to enhance our ability to monitor particle dynamics include a multi-aperture detector and a dual-purpose imaging and sending device known as MOPAR (Moored Optical PARticle). The multiple aperture device uses several photodiodes in an array to follow the trajectories of particles in a manner patterned after an insect's compound eye (Figure 5.5), and has the advantage of simplicity of components. This system is in the final test and software development stage at this time, and its inventors are optimistic that it will ultimately be capable of providing three-dimensional trajectories of multiple particles simultaneously. The MOPAR (Figure 5.6) is designed to be installed on a mooring and will enclose a volume of water in a delicate manner chosen to minimize aggregate breakup. Once the volume is sealed, it will be imaged by both a shadowgraph technique and a laser diffraction instrument. Together, these will provide the means to determine size-specific particle abundances and sinking speeds.

5.4 SUMMARY

Determination of the vertical flux of mass and energy through the water column continues to be a major goal of oceanographic research. As such, attempts will continue to be made to improve the technology with which we approach this problem so that the most accurate assessments possible are obtained in a cost effective manner. Along with the sophisticated equipment which has recently been introduced, the simple sediment traps and optical devices which have been used for decades will continue to provide the basic flux measurements scientists depend on. The potential for biases with all such samplers is great, however, and scientists should be aware of the potential impacts of these effects on their samples and should continue to interpret their results cautiously. Minimal environmental data should be acquired in all cases, including flow and sea state if surface-tethered, so that the samples can be qualitatively assessed and results discarded if the potential for bias is too great. This conservative approach to the application of the data, along with new technologies and approaches to looking at the phenomenon of particle flux, will allow us to monitor these processes to the level of accuracy which we desire.

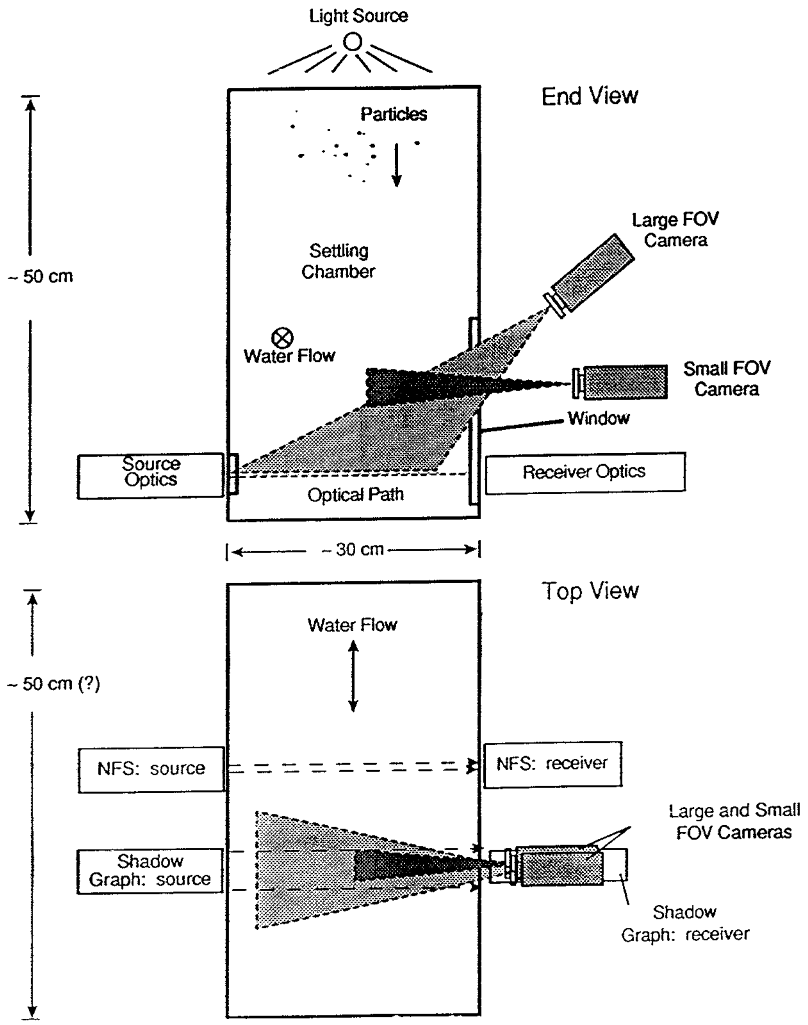

Figure 5.5 Schematic of the MOPAR instrument which is under development at Dynamics Technology in California. The sizes and sinking speeds of particles entering the system will be determined by both shadograph (cameras) and laser diffraction techniques (Near Forward Scattering, NFS; from Patton and Chang, 1992; reproduced by permission of the authors).

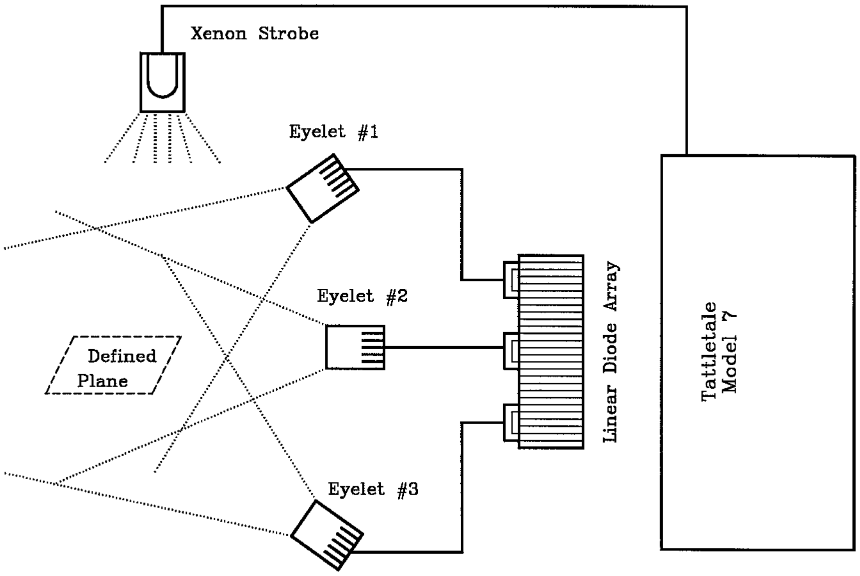

Figure 5.6 Drawing of Multi-Aperture Sensor System (MASS) showing the principal components. Signals from each of the 7 eyelets are processed to provide particle motion information in a manner analogous to an insect's compound eye (Figure provided by Ocean Optics).

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