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Sampling the vertical particle flux in the upper water column using a large diameter free-drifting NetTrap adapted to an Indented Rotating Sphere sediment trap

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ABSTRACT

Further development of the large, surface-tethered sediment trap (NetTrap) employed as part of the MedFlux program is described whereby the large collection capacity of the NetTrap is combined with an Indented Rotating Sphere/Sample Carousel (IRSC) sediment trap (IRSC–NT). This trap is capable of collecting particle flux either in a time series or settling velocity mode; settling velocity mode allows the collection of particles that fall within discrete settling velocity intervals. During short field deployments in the Mediterranean Sea the IRSC–NT configured in the settling velocity mode successfully collected unpoisoned samples for chemical and microbiological experiments. In addition to the development of the IRSC–NT, particle-settling behavior above and below the swimmer-excluding IRS valve was tested during on-deck experiments using a specially constructed water-tight trap. Chemical analyses of settling materials (published elsewhere) suggested that separation of particles by settling velocity was achieved. However, due to the motion of the ship, it was not possible to directly measure particle-settling velocities within the trap. Particle release from the IRS did not bias the apparent settling velocity spectrum. Rotation of the IRS did not engender turbulence at the surface of the sphere or within the skewed funnel below. Tests of different ball designs over the course of the MedFlux program showed that a "ridge and saddle" pattern was optimal for efficiently transferring particles under the IRS seal while still reducing swimmer entrance to the collection funnel. The large size of the IRSC–NT did not prevent it from drifting effectively with the current. Several modifications of the present design are proposed that should improve the accuracy of the settling velocity measurements.

1. Introduction

Using sediment traps to sample vertical particle flux in the upper water column of the ocean is a challenging task primarily due to high current velocities that can compromise trapping efficiencies, and high concentrations of macrofauna that can swim into the trap and contaminate the sample. Early sediment traps used in the ocean (Berger, 1971; Honjo, 1976; Wiebe et al., 1976; Soutar et al., 1977) showed that sinking particles could be collected efficiently, and it was learned that fluxes of material decreased with depth and were higher in areas of greater productivity (Suess, 1980; Martin et al., 1987; Pace et al., 1987). Since then, the use of sediment traps has increased markedly, particularly with the advent of the JGOFS studies. These early studies also showed the many biases possible when using traps (Knauer and Asper, 1989). Attempts to mitigate current effects have led to the development of neutrally buoyant traps (Buesseler et al., 2000; Stanley et al., 2004) that are designed to function as Lagrangian drifters, and surface-tethered traps (Staresinic et al., 1978; Peterson et al., 2005), that move with the current field, albeit with some resistance from the surface flotation. Researchers have tried to resolve the "swimmer" problem (Lee et al., 1988; Karl and Knauer, 1989; Michaels et al., 1990) by techniques such as post-collection removal by hand of large plankton from the trapped material ("picking swimmers"), or in-situ exclusion of swimmers through trap design innovations (Knauer and Asper, 1989) such as the "labyrinth of doom" (Coale, 1990), the

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Indented Rotating Sphere (IRS) trap (Peterson et al., 1993), and a modified PIT trap (Hansell and Newton, 1994).

Other major issues facing particle flux investigations include maintaining sample integrity during the collection process and collecting enough material for a wide range of chemical analyses. Typically, sample cups contain poisons (e.g., $HgCl_2$ or sodium azide) that prevent bacterial decomposition of the samples, or preservatives (e.g., formalin) that retain the physical morphology of the collected particulate matter, neither of which may be 100% effective at preventing alteration of the sample (Karl et al., 1984; Lee et al., 1992; Liu et al., 2006). Adding poisons or preservatives to trap samples also has the disadvantage that it precludes experiments that measure bacterial activity in the trapped material or it's use in subsequent experiments requiring active microbial communities. The addition of poisons or preservatives can be avoided by employing very short collection durations, but this necessarily reduces the amount of material collected. Sample size can be increased by either making the trap cross-section larger (Honjo and Doherty, 1988) or increasing the deployment duration. Increasing the trap cross-section may lead to greater hydrodynamic biases especially for conical-shaped collectors in relatively high current environments (Butman et al., 1986; Gardner, 2000). Increasing the deployment duration to increase sample size is not an option unless poisons or preservatives are used to minimize microbial degradation.

During the initial field expeditions of the MedFlux program in 2003, large amounts of unpreserved sinking particles were successfully collected by using a large ($3.14\,m^2$ cross-section), surface-tethered NetTrap (Peterson et al., 2005). The NetTrap required deployment durations of only 1–3 d to collect sufficient material (gram quantities) for combined bacterial, chemical, and radioisotope analyses (e.g., Goutx et al., 2007; Tamburini et al., 2009). The original NetTrap, however, was limited in its capabilities to collecting a single composite sample over the duration of the deployment. This article describes our current progress in expanding the collection capabilities of the NetTrap by adapting an IRS trap with sub-sampling Carousel (IRSC trap; Peterson et al., 1993) to the NetTrap, thereby replacing the single sample cod end with this valved, 11-cup collection mechanism. This modification allows the NetTrap to resolve particle flux on either a time series (TS) or settling velocity (SV) basis (Peterson et al., 2005) as well as isolate the sample cups during deployment and retrieval operations. The second-generation IRSC–NT was field tested at the MedFlux DYFAMED site in May 2006 in a series of short (~24 h) experiments. In addition subsequent lab studies augmented the field observations.

These experiments focused on four issues. First, while chemical analyses of settling materials suggest that in-situ separation of particles by SV was achieved (e.g., Lee et al., 2009; Wakeham et al., 2009; Szlosek et al., 2009), concerns remain as to the accuracy of this separation because the SV-IRSC trap temporarily retains the particles on top of the IRS. While sitting on top of the sphere, particles may aggregate or collapse, thereby changing their settling characteristics. Second, particles may not release completely and simultaneously from the sphere when it inverts, thus biasing the apparent SV spectrum. Third, rotation of the sphere might cause turbulence that could affect particle settling. Fourth, the large size of the IRSC–NT might cause it to not drift effectively with the current.

2. Materials and procedures

2.1. NetTrap modifications

Schematics for the redesigned IRSC–NT and the neutrally buoyant array are shown in Fig. 1; the original description of the trap, mooring and deployment method is in Peterson et al. (2005). The 1-m closing collar mechanism of the original NetTrap was retained even though the addition of the IRSC trap negates the need for the closing mechanism as far as sample integrity is concerned. However, releasing the closing collar before recovery collapses the net thereby reducing drag as the NetTrap is retrieved, a critical factor considering that the NetTrap contains 10^4 kg of water and the fine mesh (53 μm) net does not allow sufficient flow through the net to prevent tearing. The closing collar is held open at the top and bottom by two 2 m diameter rings that were strengthened in the redesigned trap and made of schedule 40 aluminum tubing. To adapt an IRSC trap to the bottom of the 3 m long nylon net, the IRS valve, skewed funnel (SF), and carousel modules were mounted in a stainless-steel frame (28 cm diameter $\times$ 2 m high) with attachment points at the top of the frame for a bottom bridle. This bottom bridle extends from the IRSC trap frame upwards to the bottom ring on the closing collar, effectively transferring all the weight of the trap to that bottom collar ring thus bypassing the delicate nylon net.

The addition of the IRSC trap to the NetTrap adds approximately 2 m to the overall length of the instrument making a total length of ~11 m (Fig. 1). Deployment of the trap required a second block be attached to the "A" frame to hoist the IRSC collector over the side simultaneously with the net. The weight of IRSC collector requires an additional 30 kg of flotation be added to the "string of pearls" at the surface. To reduce weight and size, a single PVC pressure case was used containing both the electronics and battery pack. The pressure case was mounted on the stainless-steel frame, below and in line with the trap. The instrument package was launched IRSC–NT first followed by the wire rope, flotation string and telemetry buoy.

2.2. NetTrap drift measurement

The relatively large size and weight of the NetTrap and the associated flotation package created some concern that the entire package might not drift effectively with the current thereby causing large in-situ current velocities across the opening of the net. Therefore on one deployment an Aanderaa RCM9 Mark-II current meter was hung 2 m below the bottom of the IRSC trap frame. The surface buoy of the array was then tracked by ship's navigation, and the velocity-over-ground determined, which was then compared with the current velocities measured at the depth relative to the NetTrap.

2.3. On-deck SV trap performance observations

Shipboard observations were performed using a specially modified, water-tight IRSC trap with a controller program that allowed manual starting of the valve–carousel program sequence. Possible turbulence generated by the rotation of the IRS was tested by filling the trap beneath the sphere with seawater and adding 1 L of dyed (Coomassie blue) seawater above the sphere. Dye dispersion was recorded with a video camera during the IRS and carousel rotation sequences.

Particle behavior within the SV-IRSC trap was investigated in a series of qualitative shipboard experiments in which fresh particulate matter was introduced into an IRSC trap and the particle behavior observed by videography as the sphere rotated and the particles released and settled into the SF below. For the particle behavior experiments the trap was completely filled with filtered (5 μm) seawater and particles were introduced at the top, 0.76 m above the IRS. The particles were collected at night using a 480 μm plankton net towed at a depth of 30 m (chlorophyll maximum). The plankton concentrate was diluted 2:1 with

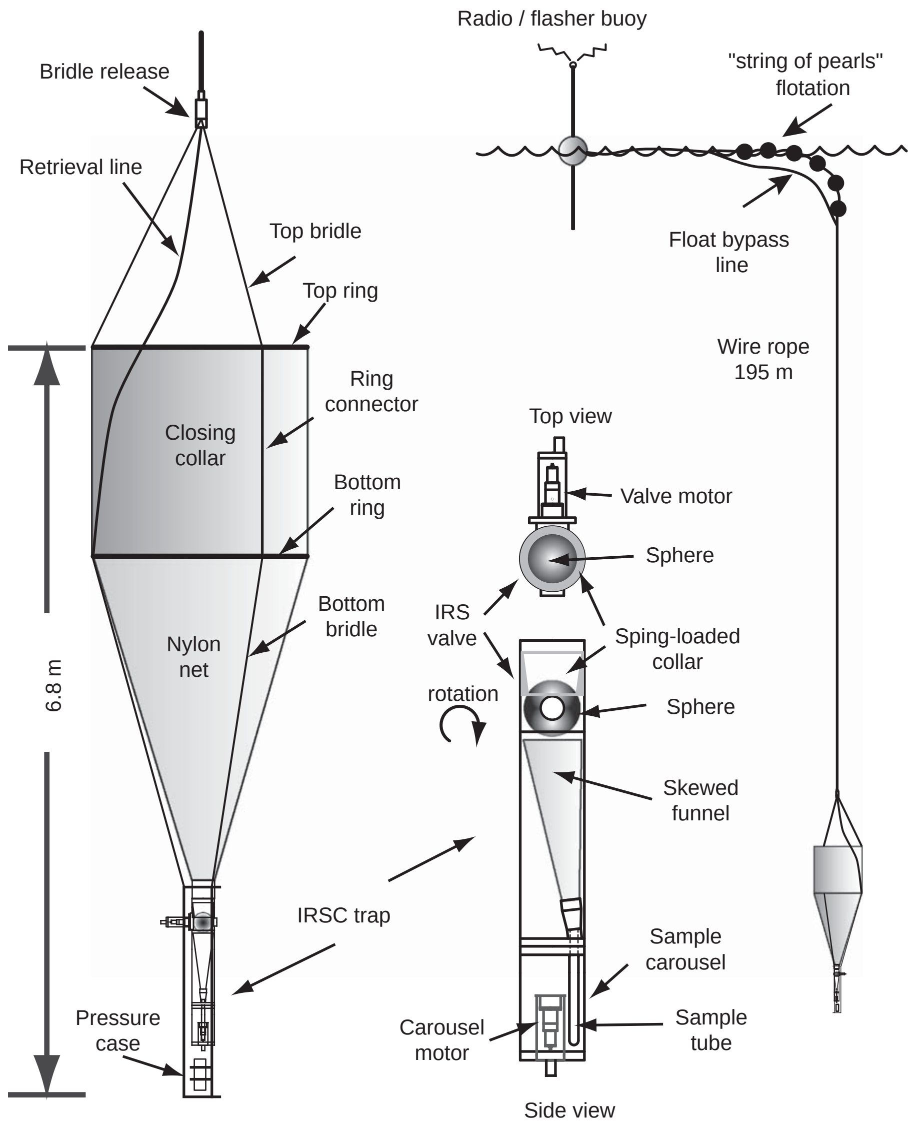

Fig. 1. Schematic of the free-drifting IRSC–NetTrap array. The blow-up of the IRSC trap shows the skewed funnel's relationship to the IRS valve rotation direction that results in particles being deposited into the nearly vertical side of the skewed funnel and away from its more sloping wall.

seawater and transferred to 4.2 L rotating tanks (2.4 rpm for 16 h) to aggregate the particles (Shanks and Edmondson, 1989). Aggregates form in a size range relative to their rotational velocity (Engel et al., 2009a, b) and were concentrated by siphoning off the supernatant seawater, and split into fifths using a McLane WSD-10 sample splitter. The SV trap was programmed (Table 1) to rotate the valve every 90 or 180 min, and to move the carousel at variable time intervals that partitioned the 'flux' into sinking velocities ranging from >979 to 11 or 5.4 m d^{-1}. Particles were added at the start of the program sequence (i.e., 90 or 180 min before the first valve rotation) and videotaped as they sank to the top of the IRS, as they were released from the IRS, and as they settled within the SF.

Table 1
Carousel rotation scheme for on-deck settling velocity trap.

Sample tube	Time open (min)	Cumulative time (min)	Minimum settling velocity (m d^{-1})
2	1	1	979
3	1	2	490
4	1	3	326
5	2	5	196
6	2	7	140
7	3	10	97.9
8	4	14	69.9
9	6	20	49.0
10	10	30	32.6
11	15	45	21.8
12a	45	90	10.9
12b	135	180	5.4

The collection period for the last tube was either 45 or 135 min (see text). The fall distance between the IRS and the sample tube is 0.68 m.

2.4. Lab-based SV trap experiments

A second set of dye experiments was performed in the laboratory to investigate possible turbulence produced by rotation of the sphere. The water-tight trap was completely filled with filtered (5 μm) seawater ($S = 33$) from Stony Brook Harbor. Several drops of dyed (bromothymol blue) seawater were carefully placed on the surface of the sphere (in the grooves), which was then rotated and the dispersion of the dye captured in a sequence of photos. The dyed seawater solution in this experiment was slightly more dense than the Comassie blue solution used in the on-deck experiments.

Laboratory observations of particle behavior within SV-IRSC trap were also conducted using seawater collected from Stony Brook Harbor. The seawater was transferred to rotating tanks (5 rpm for 24 h) to aggregate the particles (Shanks and Edmondson, 1989). Samples were not poisoned, and all experiments were conducted at room temperature. Two types of experiments were performed: (1) aggregates were added on both the nearly vertical and sloping sides of the skewed funnel and the particle interactions with the wall observed; (2) aggregates of different sizes were carefully released at the top of the SV trap and their sinking velocities measured across three 15 cm intervals above, and three 15 cm intervals below the IRS valve. In this second type of experiment, particles were also retained on top of the sphere for four different time periods (0.01, 1.15, 3.5 and 5.25 h) to investigate any changes in particle-settling characteristics (e.g., collapse, etc.) while sitting on the sphere.

3. Results

3.1. NetTrap drift observations

One of the main concerns with shallow, surface-tethered sediment traps is that there may be a large difference between the ambient current and the speed of the trap itself, thereby causing hydrodynamic biases in particle trapping. Fig. 2A shows the track of two NetTrap deployments at the DYFAMED site during April 2006. Two NetTraps were deployed at ~200 m depth 5.4 h apart, each remaining in the water for approximately 26 h (Table 2). The first trap deployed was an IRSC–NT equipped with a current meter below the IRSC (Fig. 1), and the second (5.4 h later) was a single NetTrap with a simple cod end rather than an IRSC module. The average depth recorded by the current meter was remarkably steady at 230 ± 0.4 m (data not shown), which places the mouth of the NetTrap at 221 m below the surface. The remarkably constant depth reflects the large drag of the net coupled with the “string of pearls” flotation package, which acts as a shock absorber for wave motion.

The data in Table 2 indicate that over the entire deployment period the IRSC–NT had an average speed-over-ground of ~1.0 km h^{-1} (~28 cm s^{-1}), and the standard NetTrap was about 0.1 km h^{-1} slower than the IRSC–NT. However, when the average speeds between way-points are compared (Fig. 2B) it can be seen that both traps traveled at the same speed over ground (~30 cm s^{-1}) during the first half of the deployment (0–~17 h), then as the speed of the traps declined, the IRSC–NT actually experienced slightly slower speed-over-ground than the standard NetTrap. The traps begin to slow as the current direction shifts in a complete counter clockwise circle (Fig. 2C). The current meter data (Fig. 2C) show that the average trap speed through the water was much slower than its speed over ground (approximately equal to the current speed at 221 m), averaging 4.9 ± 2.0 cm s^{-1}. Interestingly the IRSC–NT current meter recorded slower flow rates during the period when the speed-over-ground was highest. The similarity of the two drift tracks (Fig. 2A) suggests that the NetTraps were reliably following the in-situ current at depth at this location while the low trap speed relative to the flow at 221 m suggests the traps were not experiencing significant hydrodynamic biases (Butman et al., 1986).

3.2. Ball indentation patterns

The initial testing of the IRS concept in the early 1990s included evaluation of several indentation patterns, with the dimpled pattern shown in Fig. 3A proving best at reducing zooplankton “swimmer” contamination while maintaining a complete transfer of particles into the SF. During these early

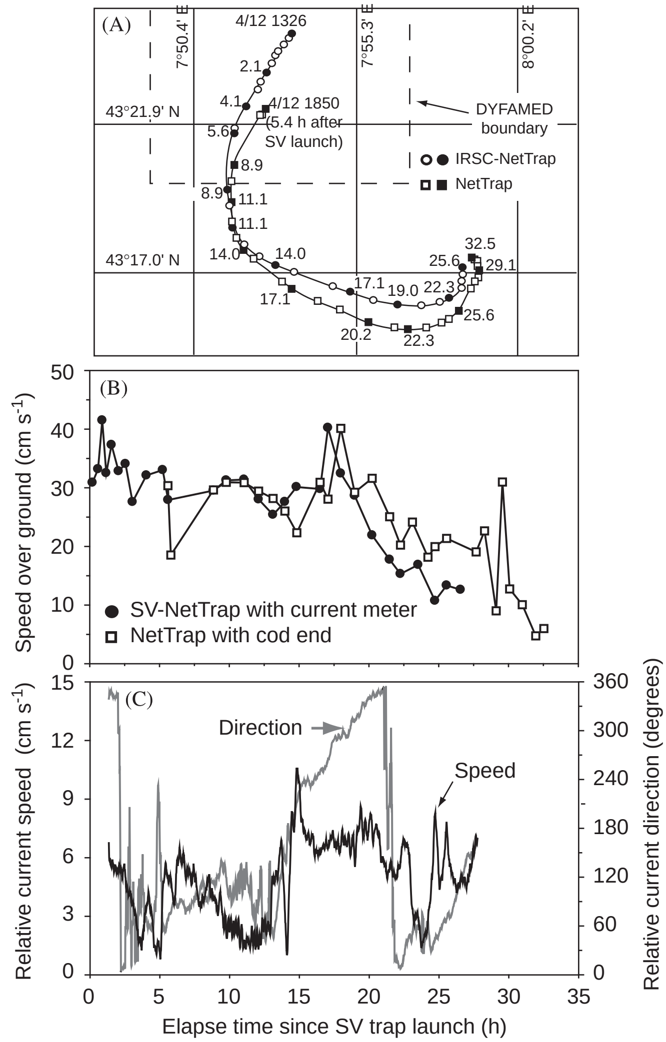

Fig. 2. (A) Drift tracks of two NetTraps, one a IRSC–NetTrap with a current meter attached below the trap and the other a single cod end NetTrap (Peterson et al., 1993, Fig. 3). The symbols represent way-points from ship's navigation. The IRSC–NetTrap trap was launched first, 5.4 h before the second trap. The numbers beside the filled symbols are elapsed time since the launch of the IRSC–NetTrap. (B) Speed over ground of the two traps computed between way-points shown in A. (C) Current speed and direction recorded by the current meter attached to the NetTrap.

Table 2
NetTrap drift data.

Parameter	SV-NetTrap with current meter	NetTrap
Deployment time	12 Apr. 2006, 13:26	12 Apr. 2006, 18:50
Deployment location	43 25.019°N 7 53.374°E	43 22.543°N 7 52.537°E
Retrieval time	13 Apr. 2006, 15:00	13 Apr. 2006, 21:23
Retrieval location	43 16.992°N 7 58.568°E	43 17.498°N 7 58.935°E
Duration (h)	25.6	26.6
Distance over ground (km)	25.2	23.7
Average speed over ground (km h^{-1})	1.02	0.89

experiments in Dabob Bay, WA, fluxes of material $>850\,\mu m$ in size (almost exclusively large zooplankton, Fig. 4A) were reduced by an average of 88% relative to preserved (formalin), non-valved control traps (Fig. 4B). Analysis of primarily autochthonous biochemicals (pigments, amino acids, and lipids) indicated significant exclusion ($>80\%$) of zooplankton $<850\,\mu m$ in size (Peterson et al., 1993; Hedges et al., 1993; Wakeham et al., 1993). Comparisons were also made between unpreserved valved (Fig. 4C) and non-valved (Fig. 4D) traps both of which had very few swimmers. The results of the two non-valved traps suggests that swimmers were entering and leaving the unpreserved trap while in the two-valved traps there was little swimmer activity beneath the IRS valve whether or not the preservative was present in the trap.

In converting the TS-IRSC trap to a SV-IRSC trap it was thought that the small dimples (Fig. 3A) might not provide enough clearance for the particles to pass under the spring-loaded sealing collar (Fig. 1), and so different grooved patterns were developed as shown in Figs. 3B–D). The grooves become progressively wider and deeper going from Fig. 3B–D, and the shallowest grooves in Fig. 3B were machined into an original dimpled ball creating a "ridge and saddle" pattern. The trade-off is that while a wider or deeper groove allows particles to pass through the IRS valve with less damage, it also makes it easier for swimmers to pass beneath the sphere. While no quantitative measurements were made, it was apparent from visual inspection of the trapped material that the amount of zooplankton material present in the samples increased from patterns B to D. Indeed, pattern D allowed even small fish to pass beneath the seal of the IRS. Patterns A and B both had the least zooplankton material and appeared to be equally as efficient at excluding the swimmer flux. Since pattern B has more seal clearance for the particles it is now considered the preferred pattern for SV traps.

3.3. *Particle behavior within the IRSC trap*

3.3.1. *On-deck experiments*

Understanding the particle behavior within the SV-IRSC sediment trap is essential to engender confidence in the in-situ separation of the particle flux on the basis of SV. Particles that enter the trap do not fall directly into a sample cup, but rather land on the IRS and accumulate in the depressions of the IRS for typically 12–24 h. The sphere then rotates 180° at constant speed (duration 30–40 s) transferring the particles under the sealing collar and into the SF. The reason for the long delay time is so that slowest sinking particles from the previous valve rotation have enough time to traverse the 0.68-m long SF into the sample cup. Faster rotation frequencies (shorter collection times) are possible only if the minimum sinking velocity is increased. For example a 3 h IRS rotation frequency would mean that only particles settling faster than $5.4\,m\,d^{-1}$ could enter the last sample tube before the carousel returns to the first tube ready for the next valve rotation. High rotation frequencies are desirable because particles would

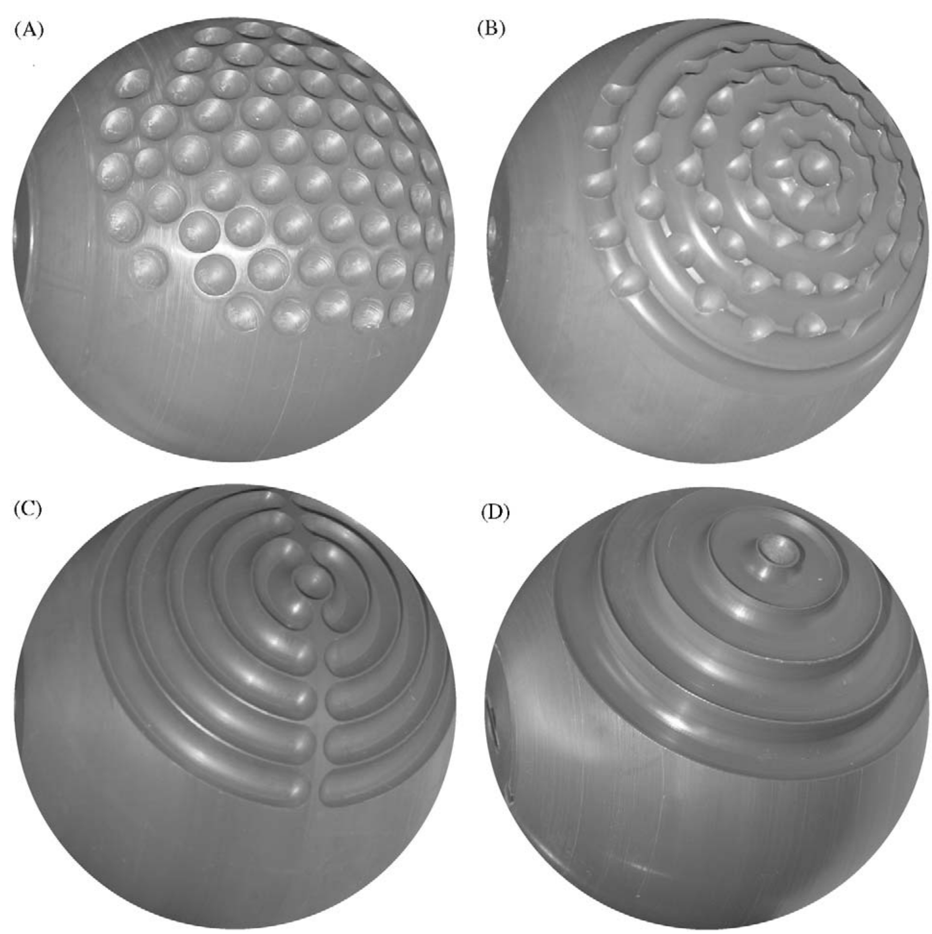

Fig. 3. Four types of spheres that were tested in the IRS trap during MedFlux. (A) Standard time series dimpled sphere (71 dimples, 10 mm in diameter, 3 mm deep). (B) Modified dimple ball (ridge and saddle) in which five circular grooves (9 mm wide, 3 mm deep) were machined over the dimples. (C) Five sets of semi-circular grooves (1 mm wide, 4 mm deep. The ridge formed by the semi-circular pattern is perpendicular to the axis of rotation and provides a surface for the spring-loaded sealing collar to ride upon during rotation. (D) Four extremely wide (15 mm) and deep (6 mm) grooves.

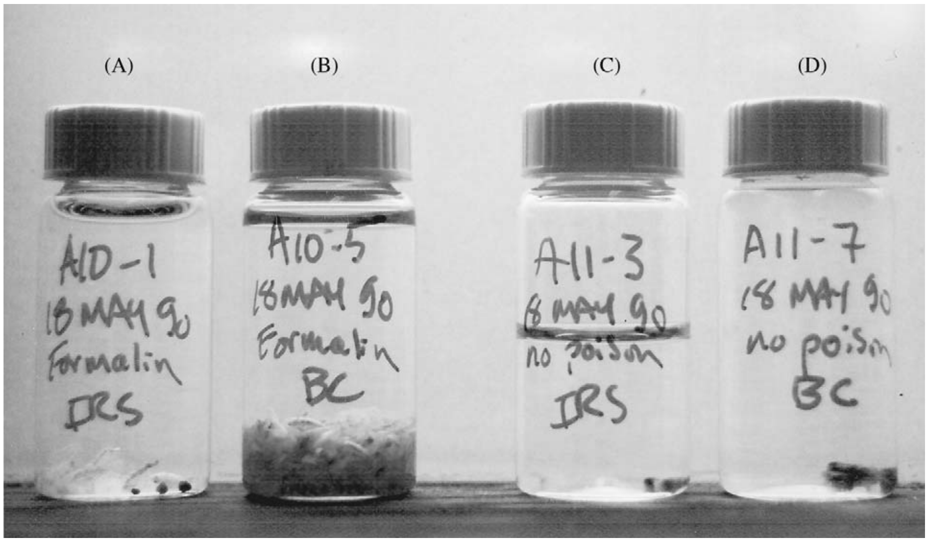

Fig. 4. Photograph of >850 μm samples from 1990 Dabob Bay, WA USA trap testing. (A) Formalin treated IRS trap; (B) formalin-treated IRS trap with ball and collar removed (no valve control); (C) IRS trap with no poison or preservative; and (D) no valve control without poison or preservative. Samples contain mostly euphausiid and copepod zooplankters. All traps were deployed at the same time on two multi trap arrays less than 0.5 km apart.

Table 3
Observations from the on deck SV-IRS trap particle settling experiments.

	Experiment #1	Experiment #2	Experiment #3	Experiment #4
Date	10 Apr. 2006	11 Apr. 2006	12 Apr. 2006	13 Apr. 2006
Program start	16:00	17:00	22:00	19:00
Valve rotation	90 min; /constant speed	90 min; constant speed	180 min; constant speed	180; stop/start every 5 s
Plankton sample	8 Apr., 02:00, two 480 μm; 30 m dilution 1:2	8 Apr., 02:00, two 480 μm; 30 m dilution 1:2	8 Apr., 02:00, two 480 μm; 30 m dilution 1:2	11 Apr., 22:00, two 480 μm; 30 m dilution 1:2
Aggregation	2.4 rpm; 16.3 h no split	2.4 rpm; 16.3 h split into fifths	2.4 rpm; 16.3 h split into fifths	2.1 rpm; 20 h split into fifths
Material added time: amount	16:00–16:30 low, slowly 19:00 high	17:00–19:15; two 1/5 splits added	22:00–22:15; two 1/5 splits added	19:00; one 1/5 split added
Observations	• At minimal particle additions only zooplankton-related particles sink at a constant rate (speeds ~150 m d^{-1}), while aggregates sink at different speeds. • When highly concentrated particles are added fluffy aggregates started sinking continuously (speeds around 30 m d^{-1}). • After the 20:30 and 22:00 rotations some fluffy aggregates were observed on the lower side of the valve and lying on the skewed side of the funnel. • Slow settling or suspended particles are still in the collecting tube and in the SF at 13:00 on 11 April.	• Rotation at 20:00 released mostly large aggregates some of which remained attached to the sphere or funnel walls. • The ball flip at 21:30 released mostly large and some mid-size aggregates. The number of aggregates stuck to the valve has not increased significantly, but the amount of aggregates resting on the low slope wall of the funnel has. • When aggregates detach from the ball they have an oblique trajectory related to the inertia transferred from the ball. • Detach mostly when the ball stops.	• SF rotated 180° to test wall accumulation. • The massive addition of particles added at the beginning of the experiments leaded to a high concentration of particles that sunk towards the ball efficiently before the first ball flip. • High particles coverage on the ball before the first flip lead to aggregation between particles. • Ball flip at 1:00 dumped a lot less particles and less remained stuck to the ball after the turn. • On 13 April, 13:30, particles were still stuck to the funnel wall and the face of the valve that received the massive particle rain; the opposite ball face was clean.	• Ball flip at 22:00 showed that repeated stops/starts helped the particles become detached from the ball and descend with trajectories on the desired side of the funnel. • Ball flip at 2:30 released some large size aggregates that traveled down the funnel in less than 7 min; much faster than any of the particles added to the collecting tube before the rotation at 0:15. • Funnel washing prior to the experiment may have helped the particles slide down the funnel. Particles colliding with the wall maintained descending trajectories with less deceleration. • On 14 April, 12:00, some particles were still attached to the wall of the funnel, but clearly far less than during former experiments.

spend less time atop the sphere where they may interact (aggregate or collapse) or be degraded by swimmers.

Four qualitative experiments designed to observe particle-settling behavior within the SV trap were performed on the ship's deck, each lasting about a day. The particle additions, valve and carousel parameters, and observations for each experiment are given in Table 3. Testing the SV-IRSC trap on deck is not an ideal situation because the motion of the ship and thermal gradients (especially during the day) can lead to eddy and convection currents within the trap. Such currents were noticed in 3 of the 4 experiments. Eddy effects were greatest in the interceptor module above the IRS valve and greatly attenuated below the valve because the seawater is completely isolated within the trap. Thermal convection should not be a concern in situ where the temperature is uniform. Once particles are transferred beneath the IRS, current-induced eddy effects that can occur in the upper regions of an in-situ trap (Butman et al., 1986) are also no longer a concern. Unfortunately the ship's motion affected particle settling above the IRS to such an extent that it was not possible to determine accurate settling velocities from the video footage preventing any compare of settling velocities above and below the IRS valve.

It is important that, as the IRS rotates, particles do not leave the indented surface of the sphere and float above the rotating ball. If this were to happen, particles would not be transferred beneath the sealing collar and be deposited in the SF. Fig. 5A shows a snapshot from a video of the IRS rotating with concentrated Coomassie blue dye filling the depressions in the IRS. As the IRS rotates there is very little turbulence as was evidenced by the fact that the dye does not flow out of the depressions until rotation is essentially complete at which time the slightly denser (than seawater) dye solution flows out of the IRS depressions. The ridges between the grooves are clearly visible indicating that only the dye in the grooves passed beneath the sealing collar and that the solution in the grooves is experiencing little turbulence. Hence turbulence due to valve rotation does not seem to be a concern when transferring particles to the SF.

During the four particle-settling experiments, valve rotation appeared to efficiently transfer all the particles from the top to the bottom of the IRS. Observations of particle release from the IRS as it rotated past 90° revealed that some of the larger aggregate particles adhered to the groove ridges and were released only after being carried further toward the sloping side of the SF (Fig. 6). The fact that some particles are not released onto the nearly vertical side of the SF leads to particles colliding with and adhering to the sloped wall (Fig. 7). Any interaction with the walls of the SF will slow the settling particles, leading to erroneously slow settling velocities. In the last experiment the IRS was programmed to start and stop every 5 s during its rotation. While this jerky motion was not 100% successful in causing particles to release from the sphere, it did improve particle release significantly without creating any significant turbulence.

3.3.2. Lab-based experiments

Results for the dye tests performed in the lab are shown in a sequence of photos in Fig. 5B–J. Dye first appears below the IRS at around 60° rotation (Fig. 5C) and remains on the nearly vertical side of the SF as it sinks. Results for lab-based particle-settling experiments in which one or two particles were added at the top of the trap and passed through the IRS valve with minimal contact time are given in Table 4 and Fig. 8A. The experiment was repeated five times, and in each case particles decelerated slightly as they approached the surface of the ball and as they entered the narrow part of the skewed funnel. The SV ratio for the upper two intervals (1 and 2 above: 4 and 5 below, Table 4) relative to the third interval (3 above and 6 below) was 1.29 ± 0.27 above the valve and 1.27 ± 0.25 below. Over all particles also settled more slowly beneath the valve than above it with an average above/below ratio of 1.27 ± 0.07. Overall particle-settling velocities were ~25% less beneath the IRS valve than above it, with an average above:below ratio of 1.26 ± 0.07. Experiments where particles had different contact times with the IRS (Fig. 8B–D) showed no major effect on SV by contact time.

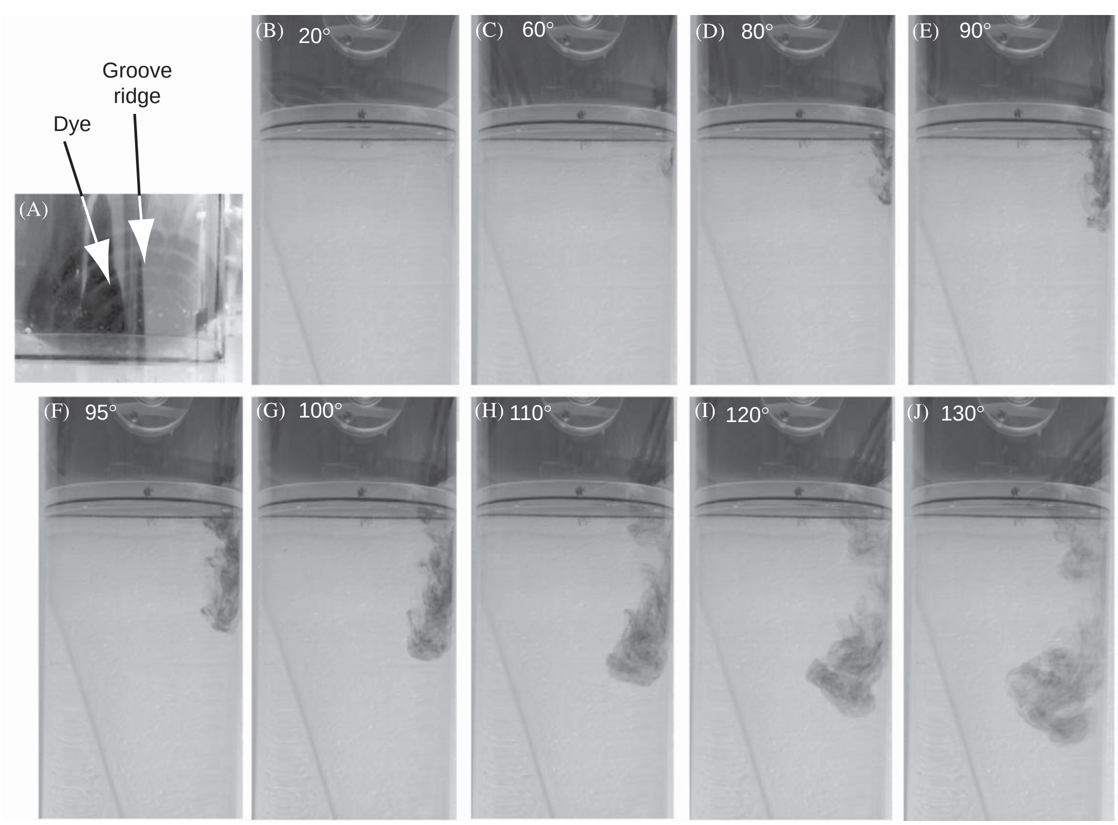

Fig. 5. Dye experiments: (A) on-deck snapshot taken from video footage of sphere at ~130° (rotation ~2/3 complete) showing no movement of nearly neutrally buoyant dye within the grooves. Vertically trending light and dark areas are caused by reflections on the surface of the clear acrylic trap shell. (B–J) Sequence of photos taken in the laboratory showing the flow of the slightly more dense dye down the nearly vertical side of the skewed funnel as the sphere rotates from 0° to 130°.

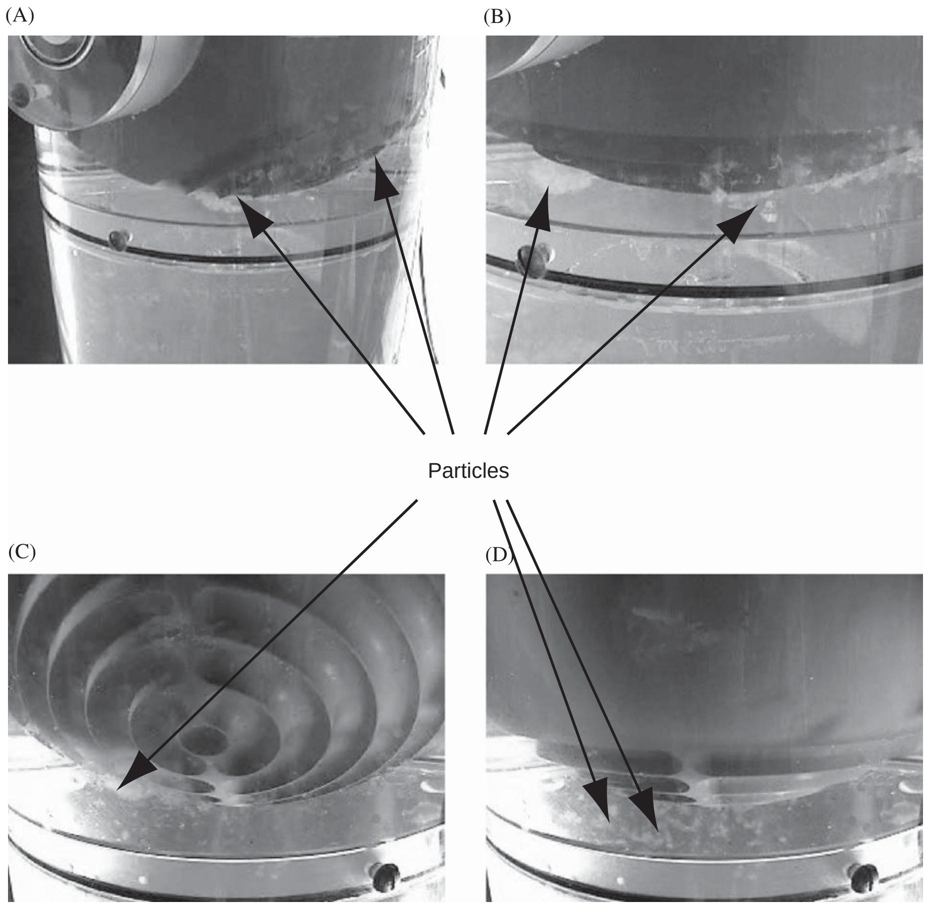

Fig. 6. Snapshots taken from video footage of particle release from IRS. (A) Snapshots from experiment #3 (Table 3) with steady ball rotation speed and (B) particle release during experiment #4 with 5 s start/stop rotation scheme.

4. Discussion

4.1. *NetTrap drift*

The average flow relative to the SV NetTrap was $4.9 \pm 2.0\,\mathrm{cm\,s^{-1}}$ (Fig. 2C), which is considered acceptable for large conical-shaped traps (Butman et al., 1986; Honjo and Doherty, 1988). The average speed of $\sim 5\,\mathrm{cm\,s^{-1}}$ is at the low end of surface-tethered traps deployed at the Bermuda Atlantic Time Series of $5–20\,\mathrm{cm\,s^{-1}}$ (Johnson et al., 1991, as referenced in Valdes and Price, 2000), and $4–11\,\mathrm{cm\,s^{-1}}$ and $8–15\,\mathrm{cm\,s^{-1}}$ by Stanley et al. (2004). These velocity and current meter data suggest that there was little shear across the mouth of both the IRSC and standard NetTraps, and thus hydrodynamic bias was minimal.

4.2. *Settling velocity trap*

From the qualitative observations of the on-deck SV-IRSC trap experiments there appear to be four major issues that might hinder accurate particle SV separation. First, build up of high particle concentrations on top of the IRS may lead to particle aggregation, which would alter the SV of the particles deposited into the SF. This is probably not as serious an issue in situ as it was for the on-deck experiments because unnaturally high “fluxes” were introduced into the on-deck traps. An in-situ flux of $500\,\mathrm{mg\,m^{-2}\,d^{-1}}$ entering an IRSC trap would yield a maximum particle coverage on the sphere of only about $50\,\mu\mathrm{g\,cm^{-2}}$ in a 24 h period. For TS traps particle density on the sphere would be even less of a concern because typically the IRS is rotated 4–6 times a day to isolate the particles as quickly as possible. For a large NetTrap the coverage would be $8.6\,\mathrm{mg\,cm^{-2}}$ in a 24 h period. Strategies to reduce particle coverage of the IRSC–NetTrap sphere would include shorter deployments than a day and rotating the valve more frequently. It may be possible to diminish trapped particles from interacting with each other while on the surface of the sphere by employing different indentation patterns. For example a much smaller diameter dimple pattern made of hundreds of depressions may keep particles better isolated from one another.

Even if particles do not aggregate while accumulating on the IRS, they may still collapse thereby changing their SV (Alldredge and Gotschalk, 1988). We suggested earlier that a calibration might be necessary for an accurate SV calculation (Peterson et al., 2005, and see below). However, no discernible changes were observed in the sinking rate of large particles above and below the ball in our on-deck experiments, although they were not highly quantitative. In addition, most of the particles collected in sediment traps in the Mediterranean appeared visually to be much denser than the aggregates made in the rolling tanks for use in these experiments. The trap material included opaque fecal pellets while the aggregates were loose and fluffy. Later laboratory experiments showed that the SV of particles were an average of 26% slower below the ball. This is the opposite of what we expected if particle collapse occurred. Since particles slowed as they approached both the IRS valve and the narrow portion of the skewed funnel, we assume that boundary or wall effects as the funnel narrows led to the slower settling.

A second concern with the IRS is failure of particles to release from the ball as each indentation passes over the nearly vertical

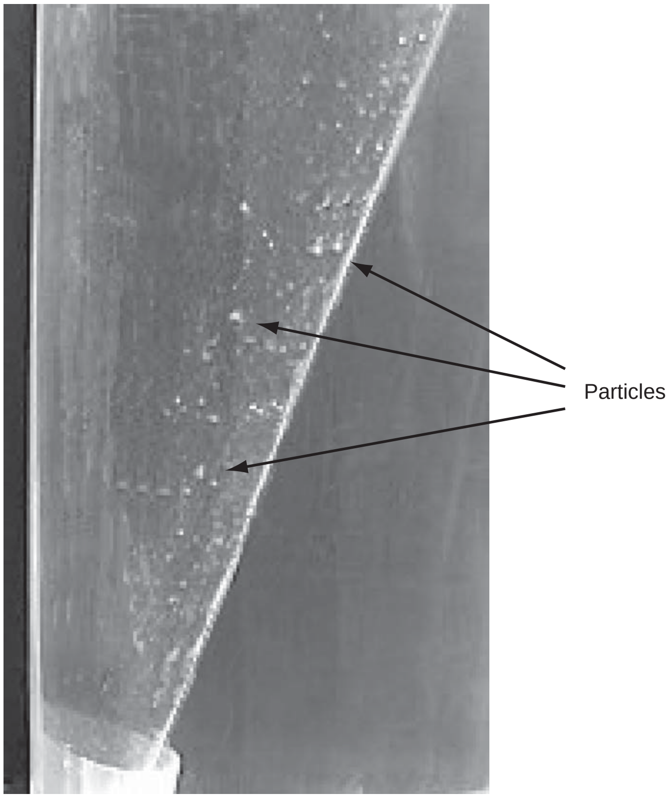

Fig. 7. Snapshot from video of experiment #2 (Table 3) showing typical hang-up of particles on the shallow sloped side of the skewed funnel.

Table 4
Particle settling velocities (m d^{-1}) within the IRSC sediment trap at various intervals above and below the IRS valve.

Interval data	Run #				
	1	2	3	4	5
Above IRS valve					
1: 0–15 cm SV	627	425	454	387	263
2: 15–30 cm SV	470	314	347	338	235
3: 30–45 cm SV	366	329	248	338	216
0–45 cm SV	465	350	329	353	237
SV ratio 1/2	1.33	1.35	1.31	1.15	1.12
SV ratio 2/3	1.29	0.95	1.39	1.00	1.09
SV ratio (avg. 1&2)/3	1.50	1.12	1.61	1.07	1.15
Average (1&2)/3 SV ratio	1.29 ± 0.27 ($n = 5$)				
Beneath IRS valve					
4: 0–15 cm SV	399	321	286	356	219
5: 15–30 cm SV	439	274	286	244	188
6: 30–45 cm SV	263	269	244	216	191
0–45 cm SV	350	286	271	260	199
SV ratio 4/5	0.91	1.17	1.00	1.46	1.17
SV ratio 5/6	1.67	1.02	1.17	1.13	0.99
SV ratio (avg. 4&5)/6	1.59	1.11	1.17	1.39	1.07
Average (avg. 4&5)/6 SV ratio	1.27 ± 0.25 ($n = 5$)				
Overall SV above:below ratio (0–45 cm above SV/0–45 cm below SV)					
Ratio	1.33	1.22	1.22	1.36	1.19
Average ratio	1.26 ± 0.07 ($n = 5$)				

The IRS valve was rotated as soon as the particles touched the surface of the sphere (<0.1 h) to minimize any effect of particle contact with the sphere.

side of the SF (Fig. 7). Particles that stick to the IRS and release toward the sloped side of the funnel will have a greater tendency to adhere to the wall of the SF and thus settle through the SF more slowly or be removed from the sinking flux altogether. In experiment #4 (Table 3) particle release was significantly enhanced simply by re-programming the rotation subroutine to pause every 5 s throughout the 30–40 s rotation period. This would imply that particle adherence to the PVC is weak and it should be possible to prevent particles from sticking to the IRS.

If particles can be efficiently delivered to the nearly vertical side of the SF, this should alleviate a third concern, which is that particles might be slowed as they collide with the walls of the funnel. This phenomenon may be responsible for the "tail" in the particle size distribution seen in mass data (Lee et al., 2009) and discussed by Armstrong et al. (2009). In experiment #4, (Table 3) simply cleaning the SF thoroughly before the experiment seemed to reduce the tendency of particles to adhere to the walls of the SF. Some of the observed particle retention on the wall may have been due to bacterial growth on the walls of the funnel, since there was ample time for this to occur as the experiments were carried out under the Mediterranean Sun.

Finally, there is the problem of slowly settling particles that may not sink out of the SF in the allotted time between valve rotations. These very slowly setting particles will be deposited in an unknown distribution among the 11 SV classes. Ideally these particles should be flushed out of the SF before the next valve rotation (see Section 5).

5. Future development and testing: improving the SV-IRSC trap design

A proposed modified IRSC trap is shown in Fig. 9 in which two cameras and a SF pumping system have been added to the trap. All necessary camera and pump technologies for such a system currently exist. The electronics of the IRSC trap are capable of controlling the pump, video and lighting, and only an additional power source for the lighting and pump would be required. Cameras could be placed above and below the IRS valve to measure incoming and outgoing particle behavior and settling velocities, as well as to observe particle release from the sphere. Similar camera systems have been developed for use on bottom landers in conjunction with sediment transport studies (Sternberg and Nowell, 1999). The camera would be a self-contained unit in underwater housings with sea cables to a separate underwater light.

The current IRS is made of PVC with no polishing or special coatings that might reduce the tendency of particles to stick to the sphere. Spheres made from other materials such as Teflon® or with better indentation designs may well enhance particle release from the sphere. The SF is made of acrylic plastic, which may not be the ideal material for resisting adherence of settling particles. Again Teflon® or other "non-stick" coatings may be a better choice.

The pumping system would fill the SF with filtered seawater before every valve rotation that starts a new SV separation. The purpose of the pumping system would be to collect any remaining suspended particles in the trap (the very slowest sinking material) that did not have enough time to enter a sample cup. In Armstrong et al. (2009), we observed a secondary peak in SV that may be a trap artifact if there are unknown interactions due to carry-over of the slowest-settling particles in the trap. This pumping mechanism would allow us to address that question. The pump would draw out the seawater in the SF at the bottom through a filter, while replacement seawater would enter the SF at the top through a filter as well. Filtering the water within the SF would require making the SF water tight by simply adding seals at the top and bottom.

Placing cameras above and below the IRS would allow estimates of the settling velocities of particles before and after

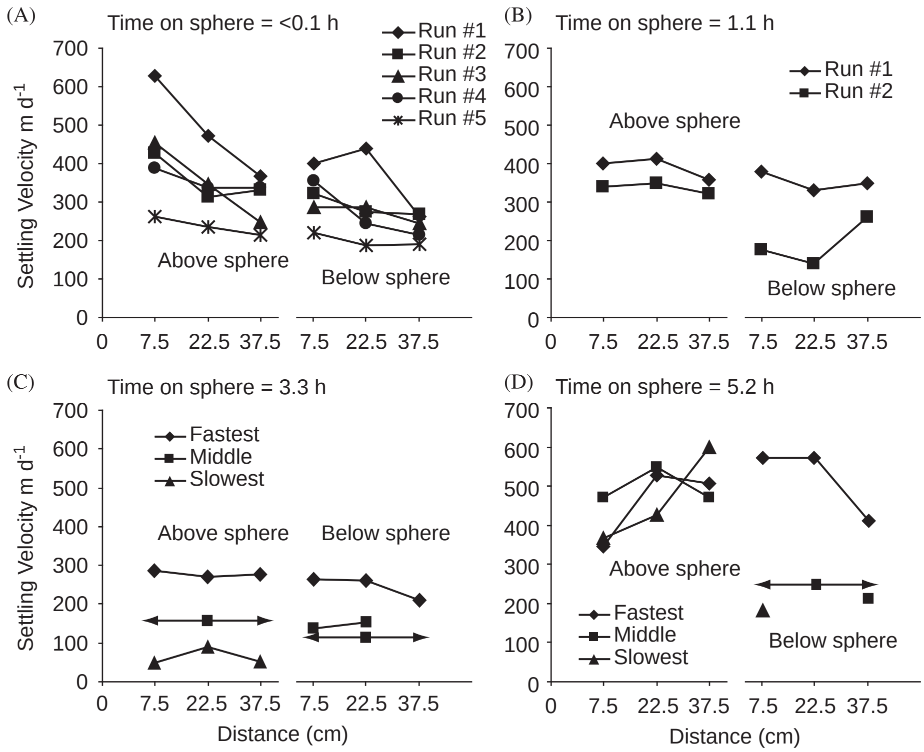

Fig. 8. Settling velocities of particles measures within the IRSC trap at three intervals above and three intervals below the IRS valve. Four panels show settling experiments with increasing contact times with the IRS: (A) <0.01 h, (B) 1.1 h, (C) 3.3 h and (D) 5.2 h. In experiments A and B, only one or two particles were added to the trap. In experiments C and D, a wider range of particle sizes was added to the trap and the fastest, middle and slowest particle SVs recorded.

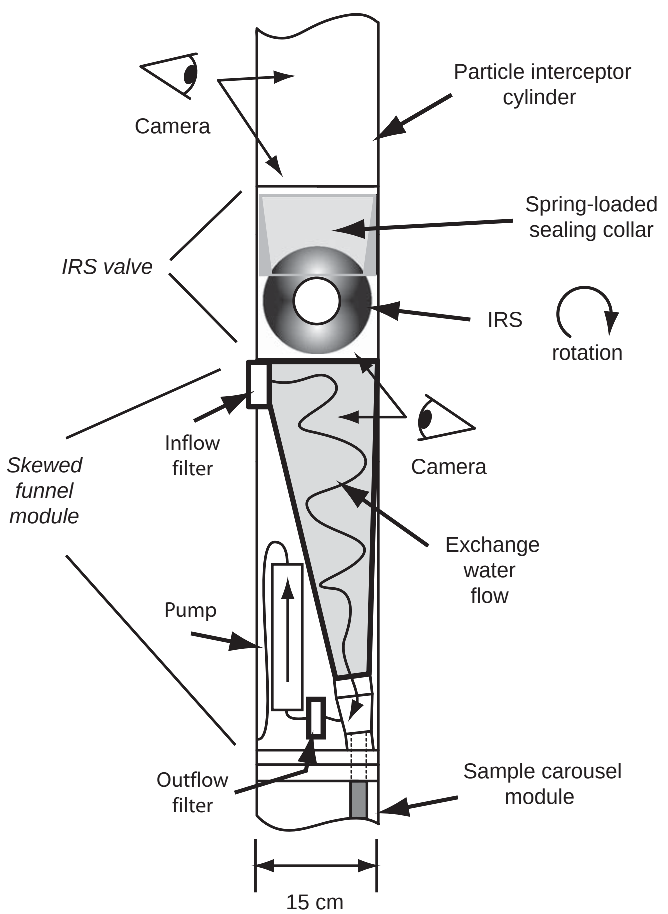

Fig. 9. Proposed new SV-IRSC trap schematic showing locations of cameras (eyes) and the SF pumping system.

contacting the sphere. These data could then be used to make corrections for changes in settling velocities due to processes like aggregation or physical collapse while on the sphere. The cameras would also be used to observe the distribution of particles on the top of the sphere, any swimmer feeding activity, and to watch particle release from the indentations as the sphere rotates. New materials to reduce particle interactions with the trap can also be tested under in-situ conditions by observation with the remote cameras.

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