Innovative Current Profiling Technology For Moored Applications

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Abstract- **Teledyne RD Instruments (RDI) has been awarded a contract from the National Oceanographic and Atmospheric Administration (NOAA) / Pacific Marine Environmental Laboratory (PMEL) [www.pmel.noaa.gov] to provide up to 140 acoustic Doppler current profiling instruments over a six-year period.**

This new current profiler will measure and communicate in real-time the highly accurate velocity and temperature measurements required for NOAA/PMEL's next generation mooring systems. These systems are intended for gathering climate information for improved detection, understanding and prediction of global climate events such as El Niño and La Niña.

Teledyne RDI's Doppler Volume Sampler (DVS) is a new product for this government application that will provide a greatly improved, cost effective alternative to traditional single point current measurement devices typically used for such deployments. The new low power DVS incorporates Teledyne RDI's 4-beam solution to detect mooring line interference, and can accurately measure velocity shear near the instrument. Other features include an internal high accuracy temperature probe and Sea-Bird's next generation underwater inductive modem technology for data monitoring.

I. Introduction

The Doppler Volume Sampler (DVS) was developed in direct response to a Request For Proposals (RFP) from the United States Department of Commerce, Western Administrative Support Center for the 3RD Generation Atlas Sensors [1]. The end user and evaluator of the proposals and of the delivered sensors is the Pacific Marine Environmental Laboratory (PMEL) of the National Oceanic and Atmospheric Administration (NOAA). NOAA PMEL has taken delivery of five first articles for testing and evaluation which is ongoing. This paper will explain the TRDI solutions to the unique engineering challenges presented by the RFP, but should not in any way be construed to imply NOAA PMEL endorsement of the DVS.

The RFP contained many sensors, one of which was termed the TVM (for Temperature, Velocity, Modem). The DVS was the Teledyne RD Instruments (TRDI) response to the TVM sensor requested in the RFP. The specifications for the TVM were such that special engineering effort was required to accommodate them, including:

1) *Multiple Sampling Modes:* To allow preprogrammed sampling, polled sampling, and averaged sampling under control of the end user.
2) *Data Storage and Battery Endurance:* sufficient for 95,000 samples with hourly inductive communications over a one year period (two years preferred).
3) *Temperature Sensor with 0.005 °C Accuracy:* preferably mounted integral to the instrument and with no solar bias.
4) *Clock Accuracy:* to 5 ppm.
5) *Inductive Modem Communications:* preferably mounted integral to the unit.
6) *Case Design/Materials:* To be corrosion resistant, with a minimum of Aluminum inside the instrument. Line shedding features should be considered. The possibility of severe strumming needed to be addressed.

In addition, TRDI had some additional requirements that we wanted to incorporate to bring additional value to the measurements:

1) *Compass Tilt Statistics:* for data quality assurance
2) *Error Velocity:* to indicate possible flow interference from the mooring line
3) *Velocity Profiling:* so that the presence or absence of velocity shear at the instrument depth can be determined.

Meeting each of these challenges provided some significant engineering challenges that will be detailed in this paper.

II. Engineering Solutions

A. Multiple Sampling Modes

The RFP defined four sampling modes that would be required: Polled, where the sensor takes samples on command for immediate transmission; Autonomous, where the sensor takes samples at pre-programmed intervals and stores the data on board; Combo, where the instrument can be queried for the last sample taken; and Averaging, where the sensor will report the average of all data acquired since the last request.

Implementing all of these modes as defined was relatively straightforward. However, TRDI decided to go a bit further and has implemented hardware and firmware that will allow a pre-programmed sampling strategy to work as a background process. That is, the DVS supports communication with the user without requiring interruption of the pre-programmed sampling strategy. In addition, the DVS can be commanded to gather additional samples without interrupting the pre-programmed sampling strategy. The end user has the option of either requesting the last ensemble stored in memory, or of commanding a new sample to be taken immediately and transmitted back. Collisions are avoided by checking if there is sufficient time to gather a new sample without interfering with the next pre-programmed sample – with the pre-programmed sample always having priority.

B. Data Storage and Battery Endurance

The RFP required this sensor to record up to 95,000 samples and support hourly communication via an inductive modem for one to two years. Battery packs were required to be internal to the instrument and be shippable without hazardous material restrictions. TRDI decided to build the DVS to support these requirements using alkaline batteries.

A new velocity sampling strategy was devised to accomplish better than 1 cm/s accuracy within one second, allowing the DVS to spend much of its time in sleep mode consuming minimal power. TRDI is departing a bit from some of our previous formalisms with this strategy in that a "sample" is here defined as acquiring as many measurements of velocity, temperature, heading, pitch and roll as can be accomplished within one second (including wake-up, processing and recording). The number of velocity measurements that can be made in one second depends on the number and size of the bins in the profile, and typically ranges from ~20-100 measurements in the one second sample. The compass/tilt sensor incorporated has a wakeup time of less than 50 ms, with 10 measurements gathered during the one second sample time. The temperature sensor is sampled 1-2 times during the one second sample time. Heading, pitch and roll (HPR) are used to transform the data, with the values used for the transformation updated with each new measurement during the one second sample in order to accomplish a better vector average.

Though the DVS is capable of better than 1 cm/s accuracy in one second of measurement, there are environments where a longer measurement time is desired (*e.g.* near the surface in a wave environment). The DVS allows the user to program multiple samples into an ensemble average for these environments.

The Next Generation Inductive Modem Module (IMM) from Sea-Bird Electronics (SBE) is incorporated into the DVS because it features a significant reduction in power requirements over earlier versions.

The DVS recorder consists of two 8 MB flash chips, and a new data format was developed to accommodate 95,000 samples within the available memory. Software to download the data from the recorder can convert it to TRDI standard formats compatible with existing software for viewing and analysis.

C. Temperature Sensor with 0.005 °C Accuracy

Doppler velocity measurements require that the temperature be known to some precision as changes in temperature will affect the speed of sound which in turn will affect the velocity measurements. However, changes of several degrees are required to affect a 1% error in velocity, so most Doppler sensors incorporate thermistors of substantially lower accuracy than the 0.005 °C accuracy requirement of the RFP. TRDI decided to team with SBE to incorporate an OEM version of their SBE 38 temperature sensor.

Thermistor assemblies and electronic boards are delivered from SBE as matched and calibrated sets. The handling associated with integrating these components within the DVS induces uncertainly in SBE's initial 0.001°C calibration accuracy. With decades of manufacturing and calibration history on many thousands of the same thermistor, Sea-Bird estimates that its initial calibration could be degraded approximately 0.002°C as a result of dismantling after calibration and later assembly. Their voluminous history of long-term drift easily supports the prediction that these sensors will remain stable within an additional 0.002°C for ten years. The resulting 0.005°C specification may be conservative. Post-assembly calibration verifications will soon be conducted to assess the actual effects on initial accuracy.

The user's need to verify continued proper function and the validity of the long-term drift prediction is legitimate. Fortunately, both malfunction and drift assessment can be suitably performed with a competent single-point check. Sensors with gross errors or malfunction would simply be replaced. Since healthy thermistors drift by offset. A single-point comparison to high accuracy reference is all that is needed to make a simple correction and restore accuracy. TRDI intends to provide this service.

On the issue of solar bias, researchers at NOAA PMEL have determined that thermistors mounted internal to an instrument deployed near the surface can be biased by as much as 0.13 °C (at 20 m depth) due to the solar heating of the material within which the thermistor is mounted [2]. For that reason TRDI has opted for a large probe extending away from the instrument and mounted in a protective cage, shown below in Fig. 1. This cage has protected the thermistor through direct impact during a drop test from one meter.

D. Clock Accuracy of 5 ppm

This is a very tight specification that is not possible to meet with currently available real time clocks (RTC) because the oscillators used in any RTC will vary somewhat with temperature. The DVS incorporates a special firmware loop to periodically read the temperature sensor and automatically update the offset applied to the RTC results. If the DVS is configured for later deployment this circuit will periodically

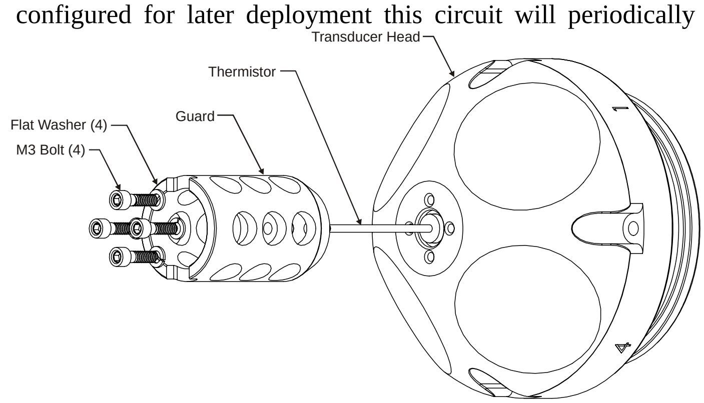

Figure 1. Assembly drawing showing thermistor probe and shield arrangement incorporated into the DVS.

wake up the DVS to apply this correction even while waiting for the intended deployment time.

E. Inductive Modem Communications

The RFP required inductive modem capability compatible with SBE protocols, and preferably mounted internal to the instrument (no cables). TRDI opted for the next generation SBE IMM which was being developed concurrently because of its much lower power requirements.

The IMM itself is mounted to the end-cap of the DVS, which also mounts the inductive coupler. In this manner, we are able to make the IMM an option on the DVS that only affects the end-cap assembly. The mounting arrangement is shown in Fig. 2.

F. Case Design/Materials

Initially TRDI planned to use a Delrin housing with an Aluminum strengthening sleeve to best reconcile our inner diameter requirements with the outer diameter requirement of the RFP while also meeting the 750 m depth rating and corrosion resistant material requirements of the RFP. However, during the bid evaluation process we were informed that NOAA PMEL would prefer to avoid using exposed Aluminum inside the pressure housing because of the potential for leaks from defective alkaline battery packs. Potassium Hydroxide could leak from a damaged alkaline battery, and it will react with Aluminum to form copious quantities of Hydrogen gas. The DVS housing was then changed to a filament wound material with a Delrin end-cap and transducer head.

An additional concern was the possibility of lines from passing vessels stripping the DVS from the mooring line. The IMM coupler serves to shed lines sliding up the mooring line, and a special insert was created to shed lines sliding down the mooring line (assuming an up-looking deployment as shown in Fig.3).

Researchers at NOAA PMEL have determined that energetic mooring line strumming can introduce substantial bias in the velocity measurements [3], and conclude that a large vane to dampen out instrument motion as a result of strumming substantially reduced the bias. TRDI developed a vane that can be mounted directly to the mounting clamps. If the vane is not deployed, then two inserts are provided to help shed lines that may be sliding over the instrument as shown in Fig. 3.

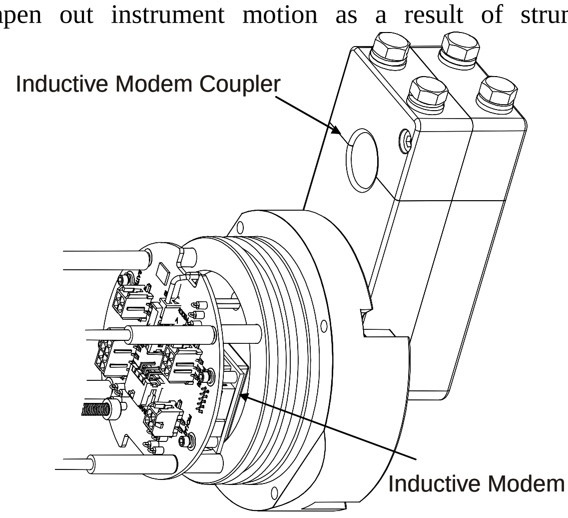

Figure 2. IMM and coupler mounting on DVS end-cap

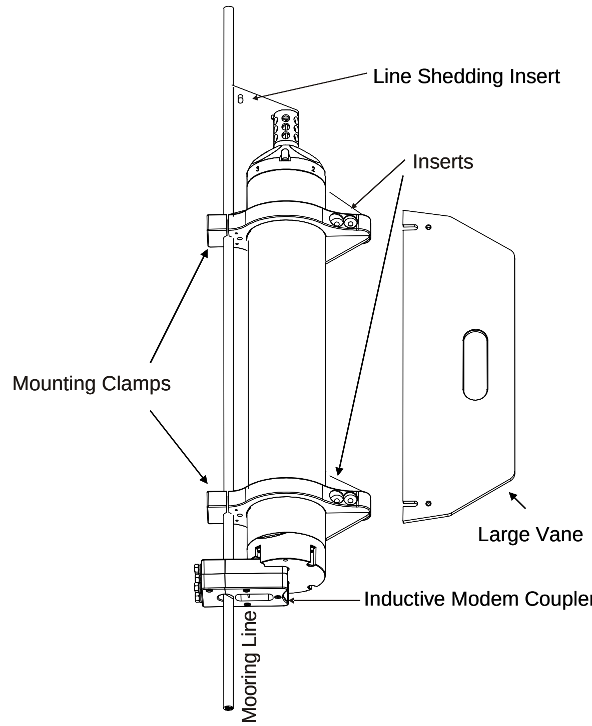

Figure 3. Mounting hardware for the DVS including the line shedding insert over the thermistor probe, the clamps, the large vane and the line shedding inserts for when the large vane is not used.

G. Compass Tilt Statistics

As mentioned previously, mooring line strumming has been shown to introduce bias in moored velocity measurements [3]. In addition to adopting the large vane approach recommended in the reference to help dampen out strumming of the instrument itself, TRDI measures and records the standard deviation of the heading, pitch and roll measurements from the compass tilt sensor during the measurement interval. High standard deviations of these measurements would indicate strumming motion, and should serve as a good quality flag on when strumming is suspected that may have affected the measured velocities.

H. Error Velocity

Error Velocity is a measurement common to all nearly all TRDI Acoustic Doppler Current Profilers (ADCPs) and serves as one of our first line indicators of data quality. It is probably worth explaining it a bit further. A single transducer is capable of measuring the velocity profile in a straight line between the transducer and the object(s) being measured. A two dimensional velocity field can be calculated within the plane defined by combining the measurements from two transducers. Likewise, a third transducer would be required to calculate a three dimensional velocity field. However, since the beams are pointing in different directions, the extent to which the velocity field deduced from combining the measurements from these three beams matches reality relies critically on how homogeneous is the flow field within the area encompassed by the three beams.

TRDI generally employs a redundant transducer as this can provide a measurement of how homogeneous is the actual flow. Like most ADCPs, the DVS has a four beam, Janus configured transducer head with beams located at 90° azimuth resulting in two pairs of opposing beams. One pair of opposing beams provides measurement of the horizontal velocity within the plane they inscribe along with a measurement of the vertical velocity. The second pair of beams provides a measurement of the horizontal velocity in the direction orthogonal to the first pair, and a second, independent measurement of the vertical velocity. The extent to which the two independent vertical velocity measurements agree gives a solid indication of whether the measured volume is homogeneous.

The Error Velocity reported is the difference between the two independent vertical velocity measurements, which has then been scaled to have magnitude equivalent to the expected variance in the horizontal measurements.

TRDI particularly wanted to include this measurement in the DVS because it is intended to be mounted directly to a mooring line which could generate a flow disturbance. This idea is illustrated in Fig. 4.

I. Velocity Profiling

It was always our desire to provide an instrument capable of measuring a profile of the velocity field near the instrument.

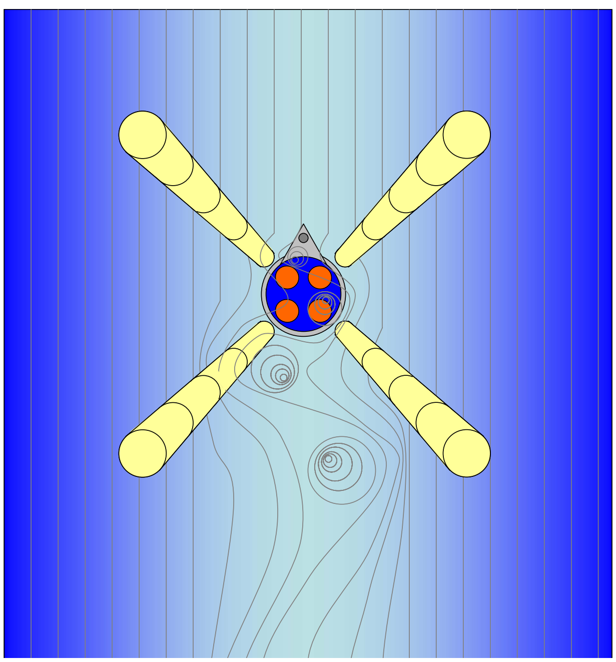

Figure 4. An illustration from above a DVS where the flow lines are disturbed by the mooring line in the near bins.

The underlying assumption behind every current meter deployment is that the measurement at the single depth is representative of a much larger depth. In many parts of the world ocean this may be true; however there is no way to know for certain without deploying multiple current meters or an ADCP.

Since the DVS is capable of profiling to short ranges, the user has the opportunity to investigate shear. Significant velocity changes from bin to bin would call into question just how representative is the measurement of a larger depth range. The absence of such significant changes would tend to confirm that the measurements are indeed representative of a larger depth range.

CONCLUSIONS

The DVS was developed in response to an RFP from NOAA, and the requirements of that RFP combined with additional requirements from TRDI has resulted in an instrument that is a substantial improvement over existing current meters in many ways. The DVS has been designed for year long deployments on a single alkaline battery pack. Additional samples can be commanded without interrupting pre-programmed data acquisition. Temperature compensation has been incorporated to meet a 5 ppm accuracy specification on the real time clock. Sea-Bird's next generation inductive modem module (IMM) and OEM version of the high accuracy SBE 38 temperature sensor, offering decade-long stability without periodic recalibration, are incorporated directly into the instrument. It is a four beam ADCP, so it provides profiles of velocity to investigate flow homogeneity and shear as possible quality assurance indicators.

Most exciting is that the DVS is capable of measuring profiles of velocity with better than 1 cm/s accuracy in one second. This opens up a wealth of possibilities for future research.

ACKNOWLEDGMENTS

I would like to acknowledge the researchers at NOAA PMEL who have proven invaluable in helping to make the DVS into what it is and will be becoming. In addition, I would like to acknowledge the folks at Sea-Bird Electronics who have helped us tremendously with support of the next generation IMM and for the reasoning presented here on how we expect to maintain a 0.005 °C accuracy without periodic recalibration.

REFERENCES

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