NEW TECHNOLOGY FOR DREDGING MIXTURE VELOCITY MEASUREMENT

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ABSTRACT

Passive sonar based mixture velocity measurement was evaluated on a DEME trailing suction hopper dredger. A conventional electro-magnetic flow meter served as the velocity reference. Evaluation was carried out over a period of several months and included various operating conditions; i.e. trailing, turning and dumping of both sand and silt type mixtures. Velocity of the mixture ranged from 2 m/s to 10 m/s at densities varying from 1 t/m^3 to 1.8 t/m^3. Results show very good agreement between passive sonar based measured velocities and the reference.

Passive sonar based technology allows a velocity meter to be clamped around existing pipework without any modification. Existing liner material, paint or rust does not influence the measurement. Unlike clamp-on ultrasonic meters, either Doppler or transit-time based, sonar based metering is a passive technology which works equally well in pure fluids as in mixtures. The sonar based meter on this trailing suction hopper dredger was installed by a crew of two in less than six hours during a bunkering stop.

Flow metering technology based on passive sonar has been available for years in slurry plant and pipeline management in a variety of industries. Applications such as a velocity meter on cutter suction dredgers have shown that the technology is a viable, robust and low-cost alternative to conventional electro-magnetic flow meter technology. Without any wetted parts and with no moving parts the passive listening employed in a clamp-around embodiment has proven to withstand harsh, ambient and operating, conditions for periods in excess of 10 years without any maintenance or recalibration.

Over and above mixture velocity measurement, passive sonar based technology can also be used to derive the Gas Void Fraction (GVF) from a measurement of the speed of sound in the mixture. The speed of sound is measured using exactly the same hardware and can operate independently and in parallel to the velocity measurement providing two separate outputs. GVF in the discharge line of the main dredge pump may show high values of gas, over 5%. GVF could be used to control dredging operations to maintain low gas levels to decrease solids carry over, reduce pump wear and help increase efficient dredging operations.

Keywords: sonar, electro-magnetic, flow meter, density, gas void fraction.

INTRODUCTION

Dredging slurry mixture velocity is commonly measured by an electromagnetic or inductive flow meter for both cutter suction dredgers as well as trailing suction hopper dredger applications. Such flow meters require wetted electrodes and a non-conductive flow tube. Most commonly employed flow tube liner materials cannot withstand the abrasive conditions prevalent in dredging. Ceramic tiled liners will withstand the abrasive conditions but are sensitive to breakage due to impact which may result in disruptive failure. Wetted electrodes are prone to wear, breakage, and polarization requiring frequent re-adjustment of the meter factor. The wetted electrode seals may give rise to leak paths causing false readings and a variety of other issues.

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The advantage of a non-wetted velocity measurement principle has long been recognized as being highly advantageous in terms of operational reliability and maintenance burden. Clamp-on ultrasonic flow meters, both of the Doppler as well as of the transit time principle, have been evaluated for use in dredging applications. Whereas their use has found some acceptance on smaller bore pipe, virtually no big bore pipe applications exist. Transit time ultrasonic flow measurement is difficult if not impossible in mixture flow whereas Doppler based ultrasonic flow measurement suffers from a limited depth of investigation. Neither of the two is a full bore velocity measurement as the electro-magnetic flow meter is, transit time is a measurement along a line of sight only, Doppler is limited to a spot near the wall of the pipe.

Sonar based flow measurement (Boyes, 2003) offers both a non-wetted measurement principle as well as full bore sensitivity as the sensor is not a clamp-on but “clamp-around” the pipe (Kragas, 2002; Gysling, 2003, Gysling, 2004). Sonar based flow measurement is entirely passive “listening”, employs no moving parts and can be installed on existing pipe with minimal preparation whilst the process is running. Sonar based flow measurement has a long history in slurry plant and pipeline management (Maron, 2011; O’Keefe, 2008).

Some 12 years ago testing and development for the use of sonar based mixture velocity measurement in the dredging industry began with flow loop trials at the Delft University based dredging laboratory. The flow loop trials were necessarily done with a small diameter pipe. Static, dynamic and transient tests were carried out. The same year a test on a cutter suction dredger was successfully conducted.

Logistically the necessary support and development work in the technology introduction phase for marine applications is complicated and costly. Most of this occurred in land based applications in the Athabasca oil sands region and in various hard rock mining sites around the world. Such applications share a large number of characteristics, challenges and requirements with fewer logistical issues.

Since the acceptance and widespread use of sonar based flow meters in oil sands and hard rock mining applications a gradual introduction into dredging applications started with multiple, commercial installations on cutter suction dredgers. Last year the development and testing work for trailing suction hopper dredger type applications began on two vessels, one European based and one Asia based. Part of the testing on trailing suction hopper dredgers is communicated here.

There remain two challenges that appear to be unique to the dredging applications particularly so on trailing suction hopper dredgers. The first one is the limited amount of free upstream free run pipe length; almost always the mixture velocity meter is installed close to the main dredge pump. The second one is the highly variable environment requiring short response times of the output signal with minimal delay with respect to changes in the actual velocity. This paper will address both in detail whilst leaving descriptions of the sonar measurement principle, the extensive field testing performed and the relative advantages of sonar based flow measurement to the reader. (Beranek, 1992, Nielsen, 2001, Schlichting, 1979, Landau, 1992 and references cited above)

INSTALLATION

Installation and configuration of the sonar based flow meter on board the trailing suction hopper dredger was accomplished in the spring of 2015 by a crew of two during a bunkering stop. Commissioning was completed the day thereafter during actual dredging operations consisting of trailing, turning and dumping of mostly silt based material from a narrow harbor basin which required many short radius turns of the vessel.

The chosen installation location was just downstream of the reference flow meter and as far up as was possible on the 44° inclined discharge pipe. A schematic of the pump room main components, i.e. pump, discharge piping and reference flow meter installation is given below in Figure 1. In variation of this schematic the spool piece downstream of the reference flow meter and the subsequent deck pass through were found to have been replaced by one spool piece. This replacement was not done to accommodate the sonar based flow meter. A sonar based flow meter, even fora big bore pipe work, has a small outer envelope and will fit between flanges no more than 881 mm (900 mm or smaller outside diameter) or 1300 mm (900 mm or larger outside diameter) apart. Each single piece is light enough to be easily handled by one man without any special tooling or heavy lifting equipment. A photograph of the actual installed meter is given in Figure 2. Note the tight spacing around the pipe work. On the one hand there is the 10 t lifting rail, on the other hand there is the water tight wall. The top of the pipe is encroaching the upper deck level to within a decimeter.

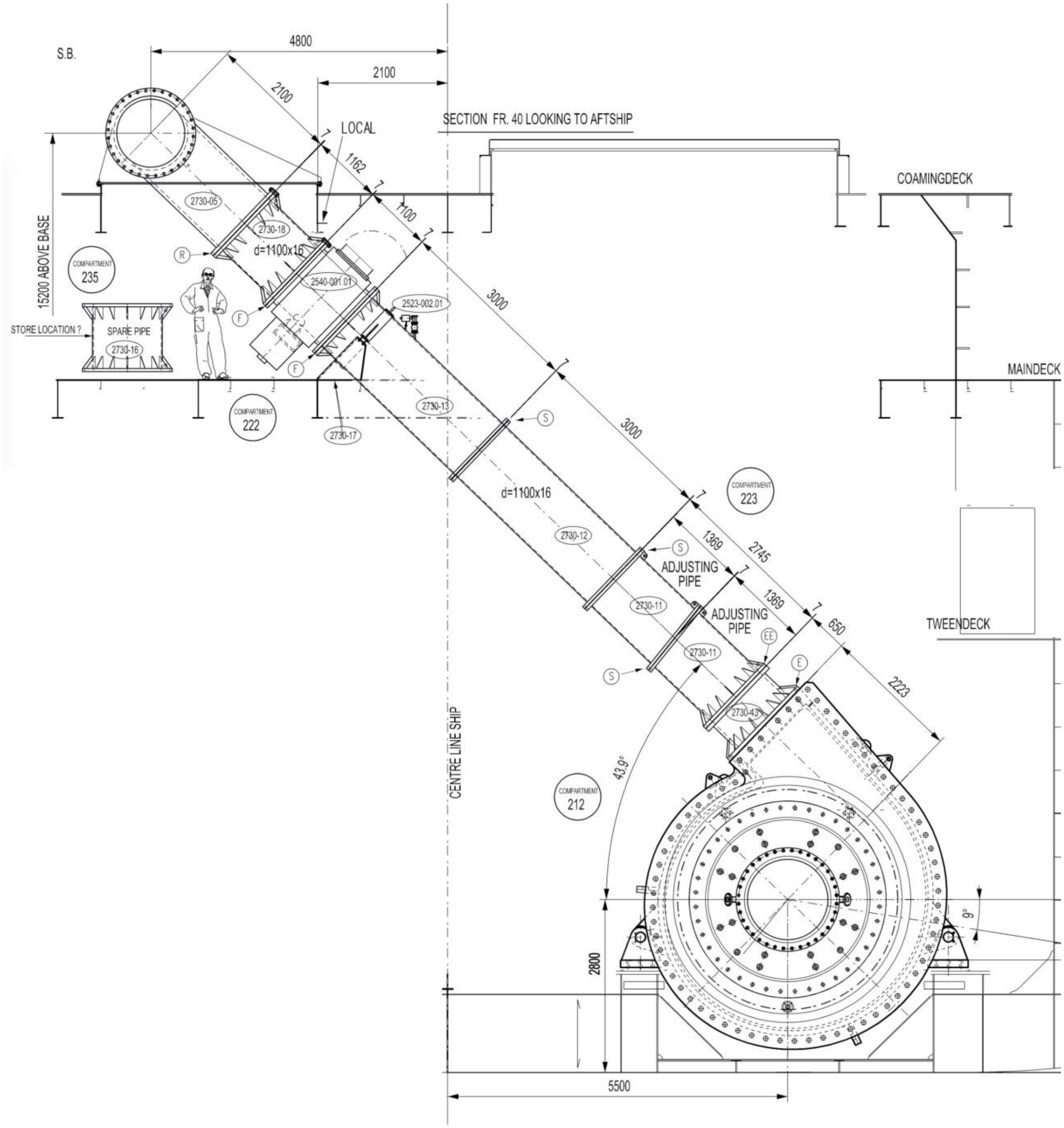

Figure 1. Sketch of dredge pump, piping and mixture velocity meter.

Installing the sonar based flow meter, which consists of a sensor band which wraps around existing pipe, required minimal pipe preparation. Loose paint and loose rust were removed, the pipe was cleaned using house hold detergent and any sharp spots were filed down. A weld seam, either axial or spiral, is not normally a problem unless unusually thick. The thick axial weld seam present on this composite Fedur pipe could be accommodated without grinding down by orienting the sensor band such that the seam is straddled by the rails at either end of the sensor band. The presence of a liner material, e.g. rubber, urethane or concrete either internal or external does not impair the measurement principle unless there is an airgap between the various materials of the pipe.

The sonar based flow meter transmitter box is a small, light-weight enclosure conforming to IP65. The connection between the sensor head clamped around the pipe and this transmitter is made by a, possibly armored, multicore cable of a maximum length of 91 m. The transmitter was clamped on two smaller pipes near the wall.

Figure 2. Photograph of the sonar based flow meter as installed.

Provision was made to log both measured velocity as well as measured speed of sound over 4-20 mA analog current loops to the ship's data acquisition system. Additionally, an Ethernet based service connection was catered for. The latter is not normally used.

The entire sonar based flow meter requires 25 W of electrical power. Power can be supplied by either AC (110 V or 220 V) or DC (24 V) sources.

CALIBRATION

Sonar based flow meters like other flow meters are calibrated in accredited flow laboratories using water as the working fluid. The conditions under which such calibration is carried out are ideal; the flow is stationary and fully developed turbulent flow exists giving a stable and well known shape of the velocity profile. In practice such conditions rarely exist. Particularly for big bore pipe installations it is often impossible to cater for sufficient upstream free run length of piping. In extreme cases this necessitates that the piping layout is copied in the flow laboratory and the calibration is performed on a rig which encompasses all the velocity profile disturbing elements present in practice.

In the case of sonar based flow metering of dredging mixtures of varying silt content it would not be possible to perform such a calibration in an accredited flow laboratory using the same pipe size, orientation and proximity to a large dredge pump. Experience has shown that sonar based flow meters perform well with default, water based calibration in slurry service, when installed between 20 and 30 diameters downstream of a slurry pump on either horizontal or vertical pipe. These conditions could not be met on the this trailing suction hopper dredger. It was therefore decided to determine the required calibration in situ using the existing electro-magnetic flow meter as a reference.

Calibration theory.

By experiment and theory alike the shape of the calibration curve for sonar based flow measurement is a linear function of the inverse square root of Reynolds number (Rothman, 2007). This function is given on the far right hand side in Equation 1, where a and b are arbitrary, dimensionless, calibration constants and Re is Reynolds number based on pipe inside diameter. The far left hand side is the relative offset between V the measured velocity and U the true volumetrically averaged velocity.

$$\frac{V-U}{U} = \Delta = a + \frac{b}{\sqrt{\mathrm{Re}}} \qquad (1)$$

Reynolds number Re is based on U, not V but by simple transformation the above equation can be cast in the form of a quadratic equation of the square root of the ratio V/U using Re*, the Reynolds number based on V not U.

$$\left(\sqrt{\frac{V}{U}}\right)^2 - \frac{b}{\sqrt{\mathrm{Re}^*}}\left(\sqrt{\frac{V}{U}}\right) - (1+a) = 0 \qquad (2)$$

It is easy to solve the quadratic in Equation 2 and derive an expression for the sought after value of U expressed entirely in terms of the measured velocity V, the calibration constants a and b, and the measured Reynolds number Re* which is dependent on the measured velocity V only. In practice, especially for big bore pipe the measured Reynolds number Re* is very large and the calibration coefficient b is small enough to neglect the term linear in the square root of the ratio of V and U. In such cases the required calibration is independent of the Reynolds number and is simply expressed by an offset correction as shown in Equation 3.

$$U = \frac{V}{1+a} \qquad (3)$$

For the size of the meter installed the value of the calibration constant "a" on water is -0.065. It was expected that this constant would not hold given the proximity of the dredge pump and the inclination of the discharge pipe. When pumping a dredging mixture there is a possibility of recirculation, especially at lower pump speed. When pure water is being pumped, e.g., when assisting the release of hopper contents during a dump, there is the possibility of pump jetting. Further complications arise because stable stationary flow rarely exists during actual dredging operations.

Practical calibration.

The goal of practical "calibration" is to establish if there is a single dimensionless calibration constant "a" that can be used in Equation 3 over a wide range of operating conditions in terms of mixture velocity, mixture density, possible mixture gas content and vessel dredging operations. If such a single constant "a" were to exist it would make the sonar based flow meter a universal instrument for dredging mixture velocity measurement. By itself it is already a good sign that theory predicts no influence on the offset due to variations in Reynolds number. In order to establish whether such a constant "a" exists the available electro-magnetic flow meter, installed at a required distance from the pump will be used as a velocity reference. The flowing conditions and the expected response of the two meters, reference and sonar, must however be taken into account. (Laukkanen, 2012)

- Proximity to the main dredge pump.
  Centrifugal dredge pumps are hydrokinetic machines generating momentum in the fluid mixture being pumped. Normally a pump's snail house or a diffusor is used to convert momentum into pressure to drive the flow in the discharge line. On dredge pumps there is virtually no such effect as there is not a real snail house nor is there a diverging section. Any other form of flow conditioner, e.g. a vortex breaker, a converging section of pipe is not normally present either. As a result the velocity profile in the discharge line can be expected to be sharply peaked ("jetting") and differing widely from a fully developed turbulent flow profile. Electro-magnetic flow meters are known to be quite robust to such symmetric velocity profile distortions. The validity of a sonar based flow meter's calibration is critically dependent on the presence of fully developed turbulent flow profiles.
- Incline at 44° of the discharge pipe.
  Whereas for horizontal flow as well as for vertical upward flow of settling slurries there exists a considerable body of both empirical and theoretical insight into the distribution of the solid phase over the pipe's cross section (Shook, 2002, Matousek, 1997), there is virtually nothing known of the latter in inclined pipe at angles of 44°. It would seem reasonable to anticipate stratification over the pipe's cross section and the possibility of back flow at the pipe's bottom cannot be ruled out. Sonar flow meters for slurry applications have been designed to properly handle stratified flows. Electro-magnetic flow meters on the other hand are sensitive to asymmetric velocity profile distortions particularly when such occur in the neighborhood of the electrodes.
- Fast flow and density variations.
  During trailing, the drag head will experience differences in sediment hardness, density and particle size distribution. The sea bottom may not be perfectly flat causing the drag head to "dig in" or "float" at times. Both result in abrupt variations in mixture density resulting in fast flow variations. For drag head control an adequately short response time of the mixture velocity meter is required. Electro-magnetic flow meters react almost instantaneously to flow rate variations as the induced voltage measured is proportional to the average velocity and the measurement principle is analog. Sonar based flow meters heavily depend on advanced processing algorithms to extract an average fluid flow velocity from pipe vibration and noise. Whereas the sonar based flow meter can easily keep up in response rate with a radiometric density meter an instantaneous response is not possible.
- Low discharge pressure and the presence of gas.
  Because of biological activity some types of sediment may contain high amounts of gas. Whereas vacuum based degassing systems are being used to prevent the entrance of gas into the pump, such a system may not be able to cope with the combination of high density, fast flow variation and large amounts of gas. The relatively low discharge pressure and the close proximity to the pump will then result in the presence of free gas, as opposed to dissolved gas, in the discharge line. A sonar based meter, because of the capability to measure speed of sound in parallel to fluid flow velocity can easily compensate for the presence of gas bubbles which are homogenously distributed. An electromagnetic flow meter, however will over report the average velocity in the same situation.

It should be noted that the orientation of the electro-magnetic flow meter used as a reference here (Figure 2) is not optimal for either density measurement or velocity measurement. Rotating the meter so as to establish a horizontal line of sight between the electrodes would be best. Such an orientation would keep the electrodes away from the most severe asymmetric velocity profile distortions and at the same time it would result in a more representative density measurement in heavily stratified flows.

RESULTS

Results are presented for dredging in two main sediment mixtures. The first is common sea bottom sand as encountered in deltaic estuary. The second is mostly silt as found in open harbor basins. The results are presented in a common format for both. As the evaluation period spanned many months there is a wide choice of data days available. The days chosen are thought to be representative of the prevailing conditions of dredging in each type of sediment.

Sand

The major characteristics of dredging in mainly sandy sea bottom sediment are shown in Figure 3 below. This multi pane plot depicts a 24 hour period, midnight to midnight in the autumn of 2015 when the vessel was dredging in a deltaic estuary. Log data from the vessel itself was used and processed. Each day consists of 43200 records as the data is recorded at 2 second intervals.

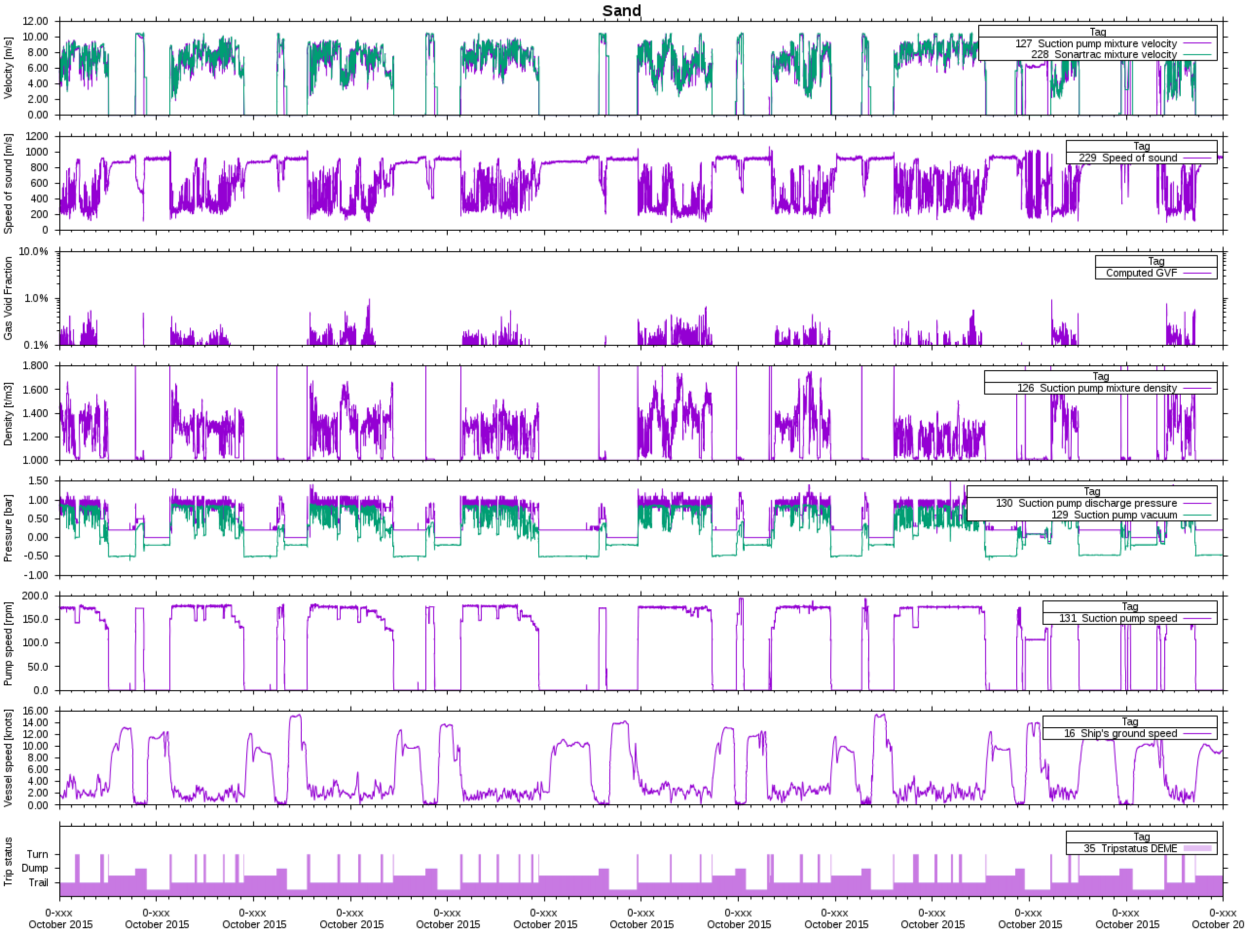

Figure 3. Operational record for one day sand dredging.

The eight characteristics given are, from top to bottom pane, mixture velocity (sonar and reference), speed of sound in the discharge line, computed Gas Void Fraction (GVF) of the mixture, mixture density, suction and discharge pressure of the pump, pump speed, vessel's ground speed and trip status.

As can be seen long trails with few turns were made at mostly constant pump speed. Nevertheless the mixture velocity, density, speed of sound and suction pressure show high variability. The computed GVF never increases above 1% by volume in this type of sediment.

Three major vessel operational status marks prevail; trailing, dumping and turning. The other marks indicate plain sailing with an in-operational dredge pump. The vessel operational status has a marked influence on the characteristics as shown; therefore, a comparison of measured mixture velocity is provided conditional on the same status. In the cross plot trellis display given below as Figure 4, all nine cross plots share a common horizontal axis which represents the independent variable measured reference velocity. The first column of three pertains only to the vessel in trailing action, the second shows the comparisons when the vessel is turning and the last column of three cross plots shows the results for the hopper dumps. All data shown is for the same day as given in Figure 3.

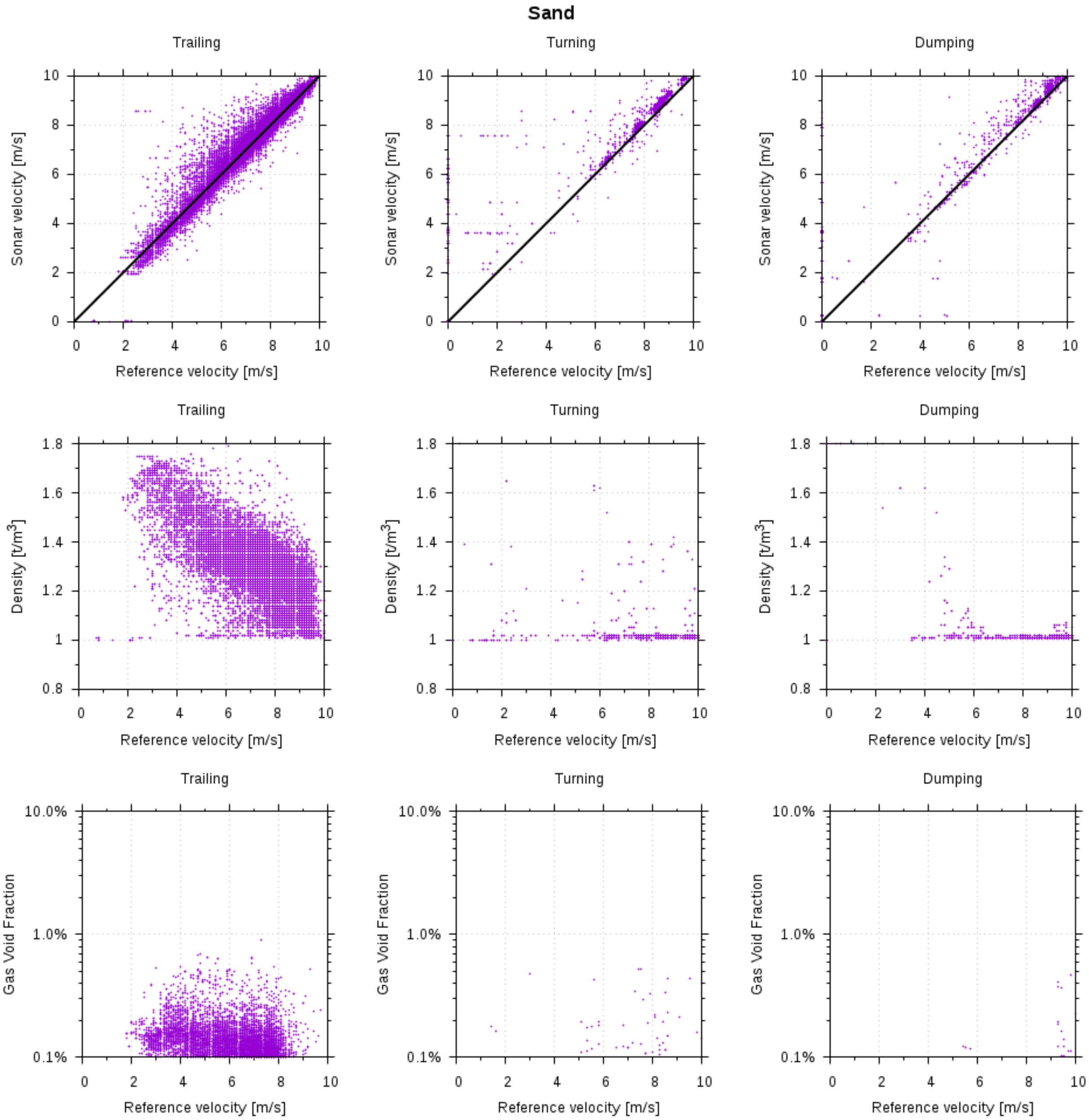

Figure 4. Comparison of velocity, density and GVF for sand.

The top row of three cross plots share the same dependent variable; the sonar measured mixture velocity. The middle row gives density and the bottom row GVF.

Apart from conditioning upon the trip status no single data point was left out, discarded or thought to be "un-representative". The entire data set is plotted across each row of trellis plots. The day chosen is representative of other days when dredging in the same type of environment. Details may be slightly different but the same overall behavior is found throughout, day after day.

By counting the number of occurrences falling in bins of a certain width we may show the distribution in a statistical sense by histograms. The trellis display below in Figure 5 does just this, following the same general layout as the cross plot trellis of Figure 4. The top row represents the relative deviation of the sonar measured mixture velocity from the reference. The middle row gives the distribution of reference velocity, whereas the bottom row gives the distribution of density.

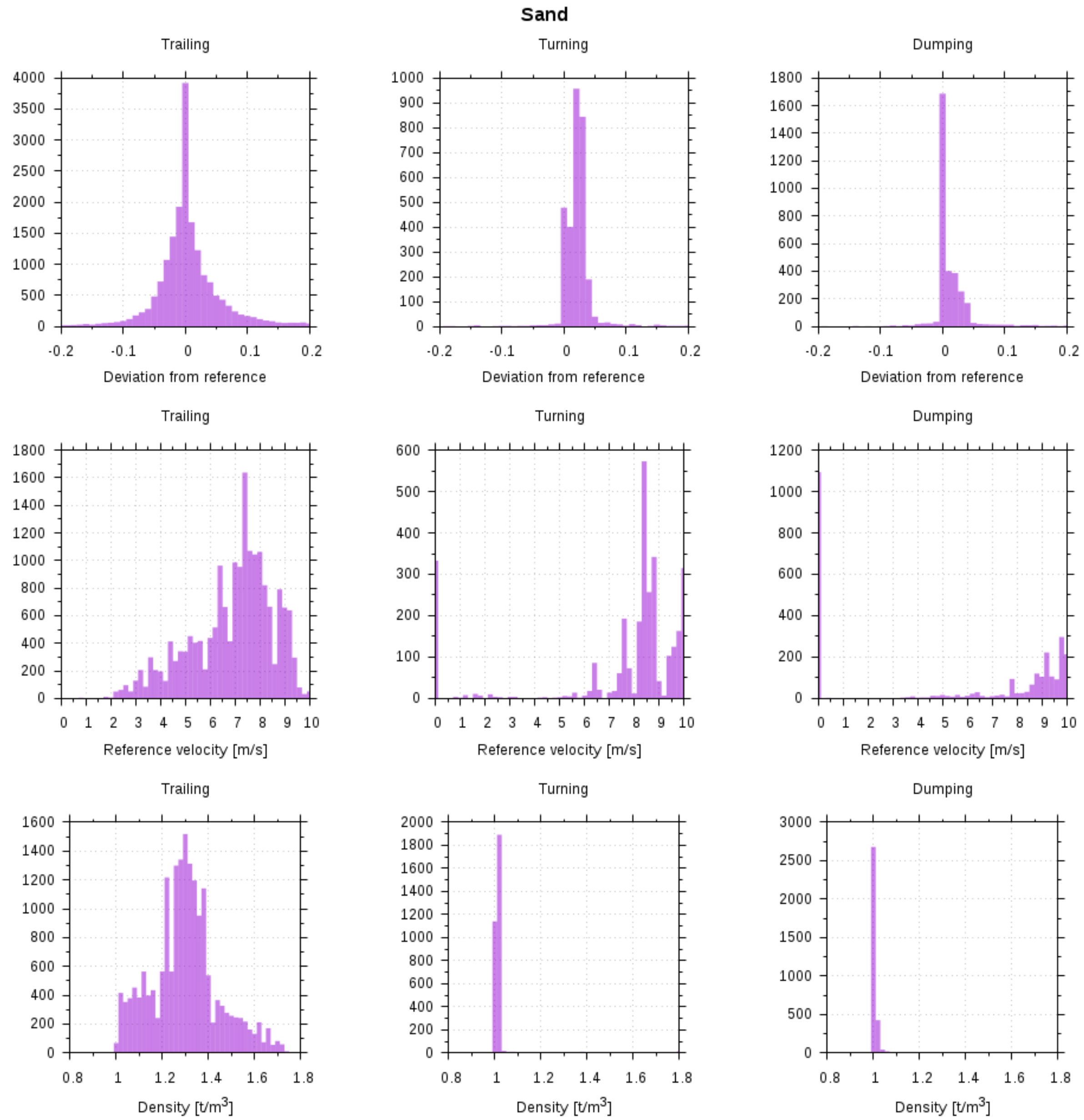

Figure 5. Histogram of deviation, velocity and density for sand.

For the purpose of this evaluation, the top row is evidently the most important one. In trailing, a very strongly peaked unimodal distribution of small skew is observed. The peak is located at 0.0 indicating no bias of the sonar mixture velocity with respect to the reference. During turning a bias of about 2% is observed, whereas during dumping, which also is essentially just water being discharged, no bias exists. Observe however how in both turning and dumping a fair number of very low reference velocity points occur. This casts some doubt on the conditioning flag used, i.e. the status may change in the log before this actual condition is met in practice.

Silt

The major characteristics of dredging in mainly silty, harbor bottom, sediment are shown in Figure 6 below. This multi pane plot depicts a 24 hour period, midnight to midnight in the spring of 2015 when the vessel was dredging in a narrow harbor basin. Log data from the vessel itself was used and processed. Each day consists of 43200 records as the data is recorded at 2 second intervals.

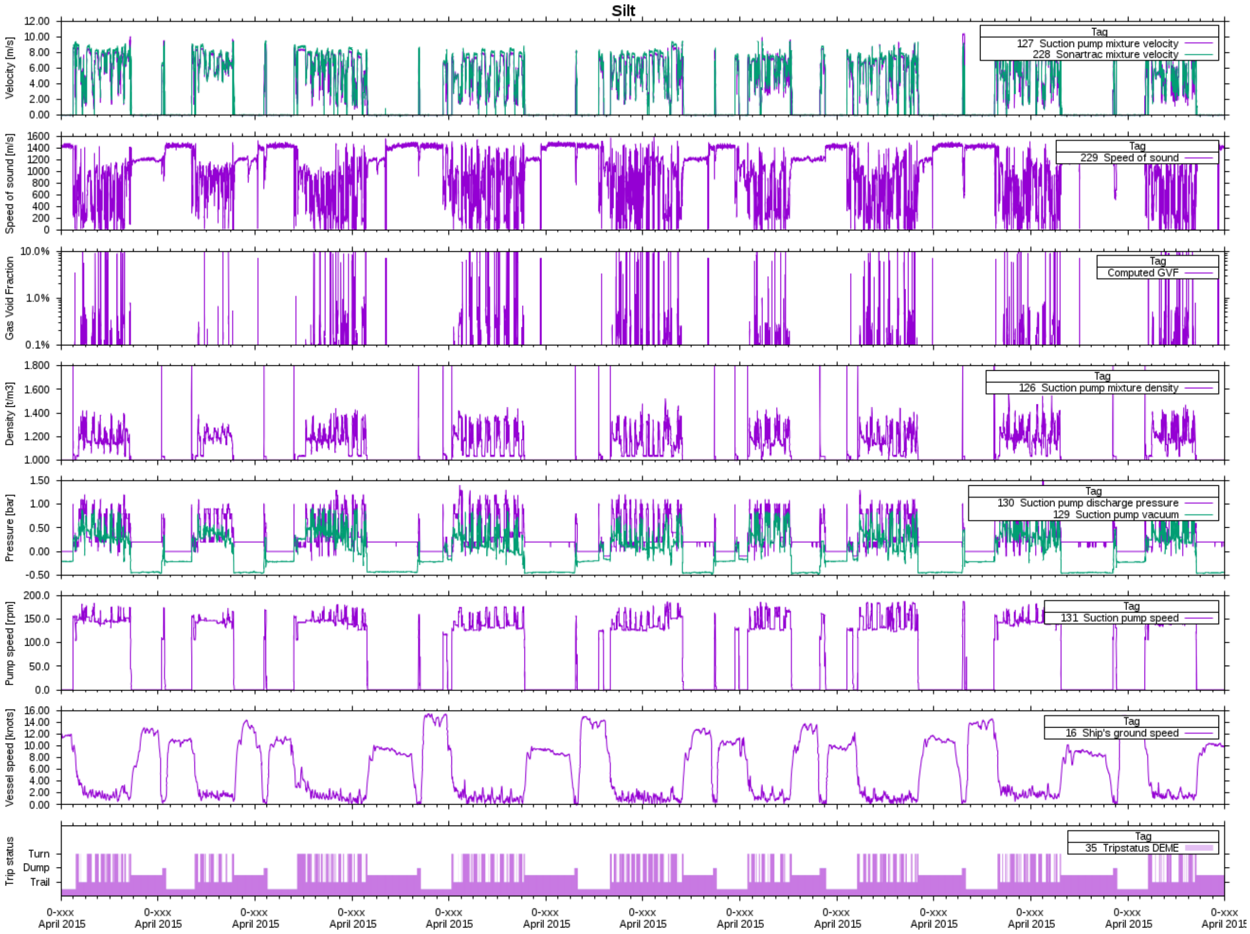

Figure 6. Operational record for one day in silt.

The eight characteristics given are, from top to bottom pane, mixture velocity (sonar and reference), speed of sound in the discharge line, computed Gas Void Fraction (GVF) of the mixture, mixture density, suction and discharge pressure of the pump, pump speed, vessel's ground speed and trip status.

As can be seen long trails with many, sometimes long, turns were made at highly variable pump speed and a large difference between suction and discharge pressure. The mixture velocity, density, speed of sound show an equally high level of variability. The computed GVF increases to above 10% by volume in this type of sediment.

As before three major vessel operational status marks prevail; trailing, dumping and turning. The other marks indicate plain sailing with an in-operational dredge pump. The vessel operational status has an even stronger influence on the characteristics as shown. As before therefore a comparison of measured mixture velocity is provided conditional on the same status. In the cross plot trellis display given below as Figure 7, all nine cross plots share a common horizontal axis which represents the independent variable, the measured reference velocity. The first column of three pertains only to the vessel in trailing action, the second shows the comparisons when the vessel is turning and the last column of three cross plots shows the results for the hopper dumps. All data shown is for the same day as given in Figure 6.

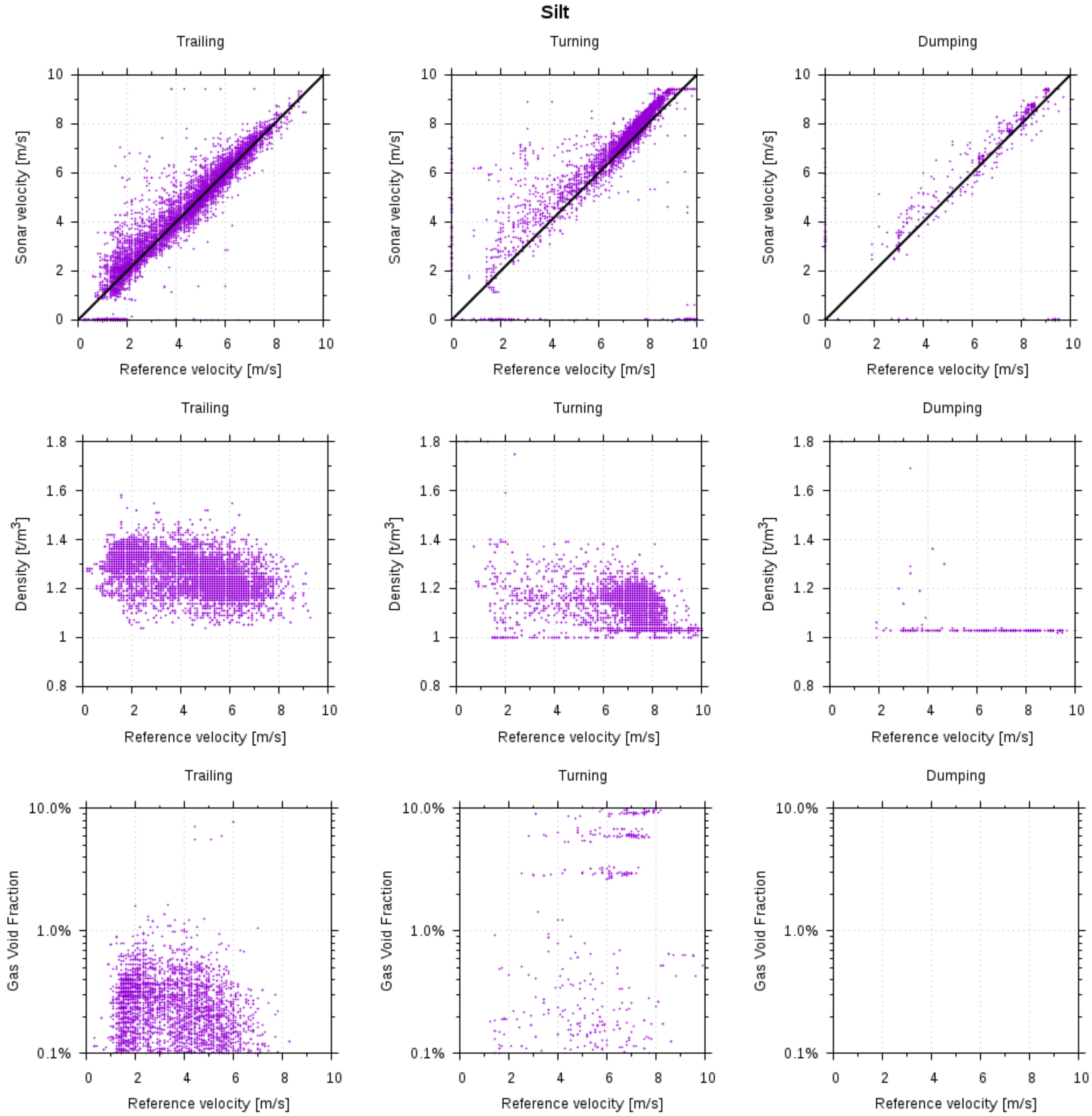

Figure 7. Comparison of velocity, density and GVF for silt.

The top row of three cross plots shares the same dependent variable, the sonar measured mixture velocity. The middle row gives density and the bottom row GVF. Observe that high levels of GVF exist during turning (with a lifted drag head) but not or rarely only during trailing or dumping. The apparent horizontal layering in the distribution of GVF across reference velocity is a result of the limited resolution of the log system which logs speed of sound to 1 m/s resolution only. Particularly at low (< 100 m/s) speed of sound, which results in high values of GVF, this results in limited resolution as is evident here.

Note that the range of mixture velocity is shifted down from 2 - 10 m/s in sand to 1- 8 m/s in silt. This shift down is unquestionably caused by the non-standard difficult conditions in a narrow harbor basin requiring many turns per trail.

Apart from conditioning upon the trip status no single data point was left out, discarded or thought to be "un-representative". The entire data set is plotted across each row of trellis plots. The day chosen is representative of other days when dredging in the same type of environment. Details may be slightly different but the same overall behavior is found throughout, day after day.

The trellis display below in Figure 8 gives distributions of the quantities of interest, following the same general layout as the cross plot trellis of Figure 7. The top row represents the relative deviation of the sonar measured mixture velocity from the reference. The middle row gives the distribution of reference velocity, whereas the bottom row gives the distribution of density.

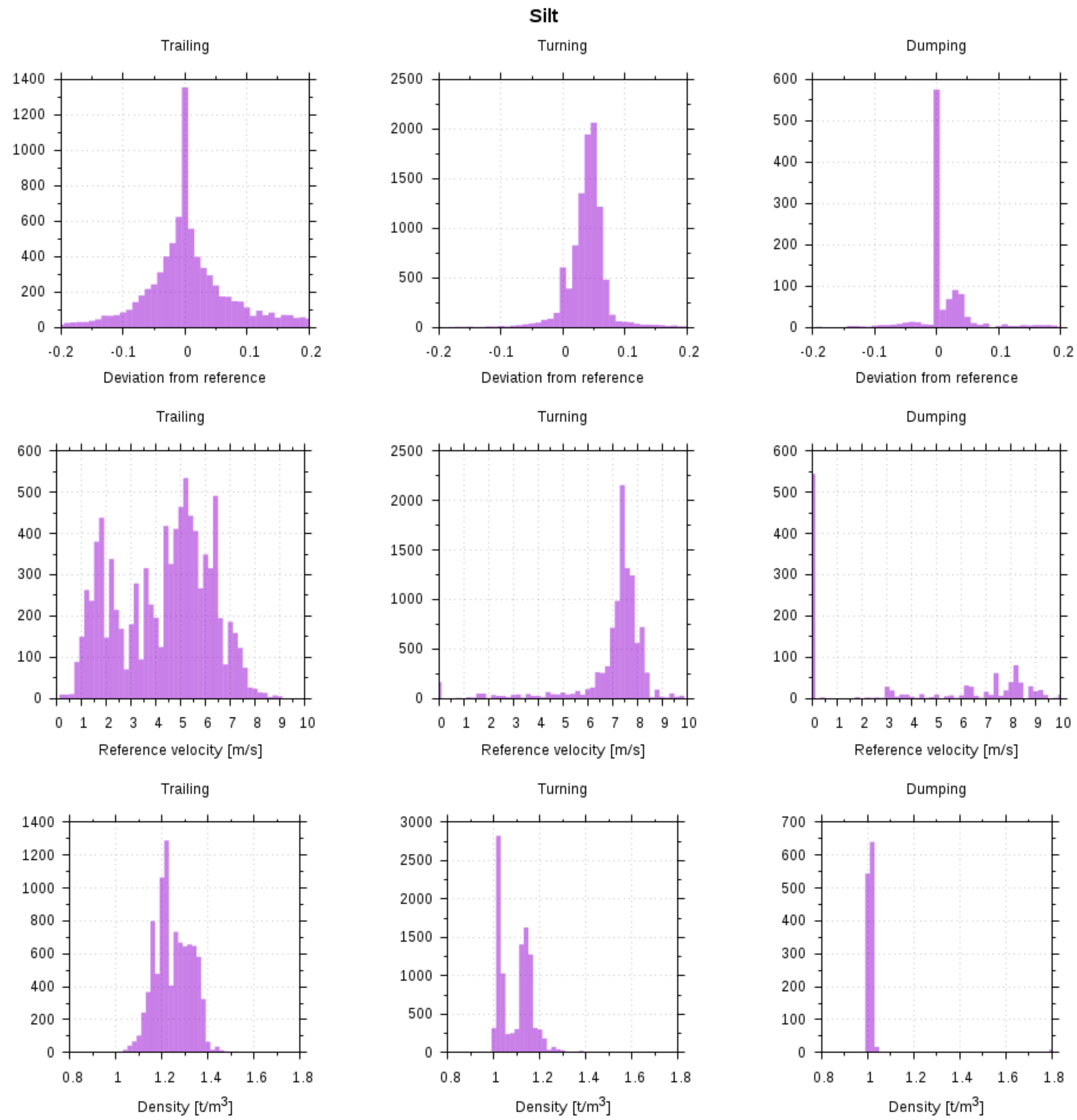

Figure 8. Histogram of deviation, velocity and density for silt.

For the purpose of this evaluation, the top row is again the most important one. In trailing, a very strongly peaked unimodal distribution of some skew is observed. The peak is located at 0.0 indicating no bias of the sonar mixture velocity with respect to the reference. The tails of the distribution are longer when compared to the tails of the distribution of the same quantity during dredging of sand mixtures. During turning a bias of about 5% is observed, whereas during dumping, which is essentially just water being discharged, no bias exists. Observe however how in both turning and dumping a fair number of very low reference velocity points occur.

Contrary to dredging in sand, with less frequent turns per trail, the distribution of density during turning shows a large amount of points taken at densities appreciably higher than the density of pure water.

DYNAMICS

The dynamics of the sonar flow meter mixture velocity measurement in response to variations in pump speed or flow rate are important for control purposes. Figure 9 below shows a compound plot of a zoomed in time record of half an hour exactly giving pump speed, reference and sonar mixture velocity for sand and silt sediment dredging.

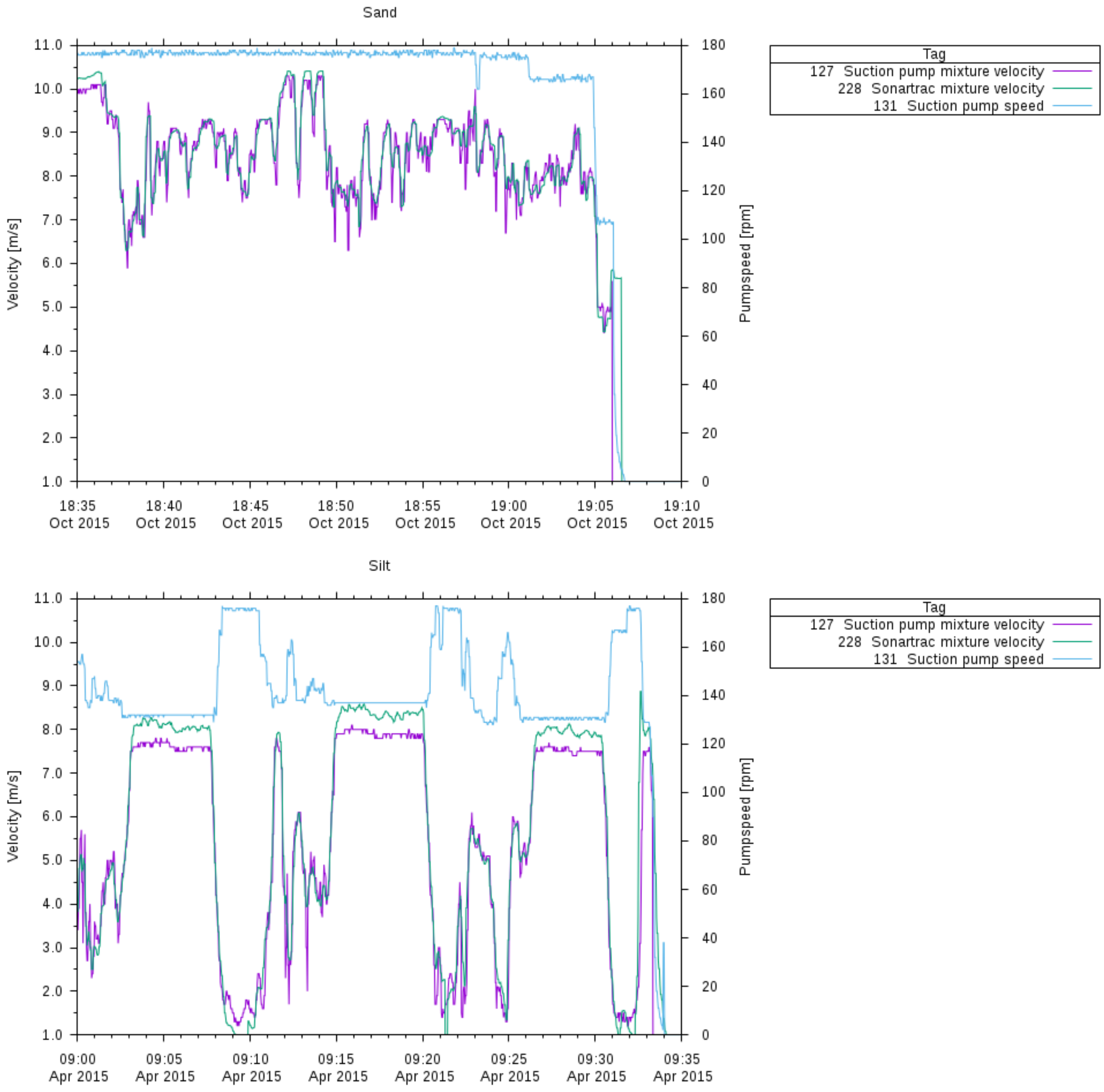

Figure 9. Dynamical behavior in sand and silt.

As is apparent from these there is virtually no delay between the sonar and reference measured velocity over a wide range of measured velocities. At the end of a trailing run, however, when the pump is shut down, the reference velocity drops to zero before the pump has come to a complete stand still. This is not possible in reality, as long as the pump's impeller turns there must be positive flow. Since a pump is not shut down until the suction and discharge lines have been flushed so as to replace any mixture with water this zero drop is not caused by any physical effect. The zero drop is enforced by the control system as soon as the command to unclutch the pump is issued. The angular momentum of the impeller then causes the pump to coast down which results in a fluid velocity measured and recorded by the sonar based flow meter but not by the reference. This, by the way, explains the long tails in the distribution of the relative deviation between the sonar and reference mixture velocity measurement.

DISCUSSION

A discussion of results obtained, either for accuracy or dynamic response must include the four main considerations about the flowing conditions and their impact on the meter and reference responses as mentioned previously. Accuracy, i.e. the degree to within the sonar measured mixture velocity agrees with the reference is much dependent on the dynamics in the case of unsteady flow as occurs in practical field conditions. Only in an ideal case of zero delay between the reference and the sonar meter under test can a direct comparison be made. Likewise estimating the response delay between the reference and the sonar meter under test requires a high degree of correlation between the two. If there were no correlation at all it would be impossible to determine a delay.

Accuracy

The single one constant “a” required in Equation 3 was found to have a value of 0.00 for sand and silt type sediment under all operating conditions, trailing, turning and dumping. The relative deviation between the reference and the sonar meter under test is in most cases well within 1% for both sand and silt type sediment in either long or short trails. The same result is obtained during dump cycles when water is being pumped. A relative deviation of 2% to 5% is found for turning in sand and silt type sediment respectively where the latter still exhibits a fluid density markedly different from the density of water. If this deviation were caused by pump jetting one would expect a similar or larger effect during dumping but our observations exclude that. During dumping the fluid flow velocity is generally higher than the same during trailing which excludes stratification of the fluid as a potential explanation. Turning is unique in the sense that it pairs a high fluid flow velocity with a relatively low pump speed as compared to either trailing or dumping. The observed deviation between the sonar based meter under test and the reference must be related to this in an as of yet poorly understood way.

Dynamics

The response time delay of a sonar based flow meter is dependent on a large number of parameters but is generally equal to one half the processing buffer length. The processing buffer length is determined dynamically based upon the actual measured velocity and other signal quality parameters. Experience has shown that the response delay is variable but generally less than 5 seconds. This response time is appreciably shorter than the response time of the radiometric density meter. The response delay can still be shortened by optimizing various processing parameters. This remains an active subject and is expected to result in adequate response delays for drag head control purposes.

CONCLUSIONS

A sonar based flow meter is a technically viable alternative to a conventional electro-magnetic flow meter for dredging applications on trailing suction hopper dredgers. Both the accuracy as well as the dynamic response are adequate for operational and control purposes.

Over and above a mixture velocity measurement a sonar based meter can evaluate gas content by volume in the flowing mixture. This quantity is determined by a measurement of the speed of sound which is highly dependent on the compressibility of the fluid and therefore strongly influenced by even small amounts of gas. This capability is new to the dredging industry. It may aid drag head and or degas system control in attempts to reduce pump wear or minimize fines carry over in the hopper. The operational value of this capability is yet to be determined.

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ACKNOWLEDGEMENTS

B. Markoja, P.Dolan and M. Fernald all of CiDRA Corporate Services are gratefully acknowledged for help with post processing raw time series data during initial and final commissioning.

B. Porte of DEME is thanked for invaluable assistance with uploading and downloading data and flow meter configuration files.