Analog Output from a Differential Travel-Time Current Meter

Archie T. Morrison III, Albert J. Williams 3rd, Andrew C. Waterbury, and Colin M. Tierney
Woods Hole Oceanographic Institution
Nobska Development Corporation

Abstract

The Modular Acoustic Velocity Sensor, MAVS, measures flow components along four acoustic axes and digitizes acoustic travel-time differences that are then stored and transmitted digitally. This requires an interface to a PC or other digital data acquisition system. Analog outputs, however, free a multi-sensor data acquisition system from the timing requirements and serial input formatting requirements of an array of autonomous digital sensors. A digital to analog output circuit was added to an existing MAVS3 current meter to provide such an output for use in an array of 9 MAVS3 sensors in a wave flume. While a sequence from analog to digital to analog seems awkward, it is in fact a very simple and effective means to provide asynchronous data to an existing data acquisition system. The introduction of 1/2 bit noise in the conversion sequence is more than compensated for by the smoothing of the low pass filter on the analog output from the over-sampled digital input. Measuring at 35 Hz with a 16 Hz low pass filter provides a signal that can be digitized by the data acquisition system without degradation and at a sampling schedule determined by the logger.

I. The Differential Travel-Time Measurement

MAVS3, the third version of the Modular Acoustic Velocity Sensor, is a four axis, differential travel-time, current meter. The linearity and accuracy of MAVS and its immediate ancestor BASS, the Benthic Acoustic Stress Sensor, have been well established and characterized by members of the development teams and by independent laboratories and users. See, for example, Morrison, et al. 1993, Rowsell 1999, Thwaites and Williams 1996, Thwaites and Williams 1997, Williams, et al. 1987, Williams 1995, and Williams 2002.

To make a measurement of the component of flow along a single acoustic axis, MAVS transmits a short pulse, 15 cycles at 1.7 MHz, simultaneously from both ends of the acoustic path. The received signals are amplified in a cascode circuit and passed through a Schmitt trigger to a counter. This process provides significant immunity from noise [Williams, et al. 1987].

In each receive channel, the counter detects the 15th negative-going zero crossing of the received signal and switches an active current source to a capacitor that has previously been fully discharged. The two acoustic signals arrive differentially as a function of flow speed along the axis, so the integrating capacitors in the receive channels begin charging at different times. After the arrival of the second signal, MAVS simultaneously switches both current sources away from the capacitors. The capacitor voltages are differentially amplified and the analog difference voltage is digitized with a 12-bit analog-to-digital converter (ADC) [Williams, et al. 1987].

To further improve accuracy, each measurement is repeated with the receiver channels electrically exchanged. The results of the normal and reversed measurements are differenced in software to remove receiver bias. The result is a differential travel-time measurement, in digital form, with an accuracy in time of 40 picoseconds. Over the 10 cm MAVS acoustic path length this means a velocity accuracy of 0.05 cm/s. The full linear range of the measurement is ±180 cm/s. With this level of measurement accuracy the limiting factor becomes the disturbance of the flow created by the sensor. The sensor head was designed to minimize the distortion and provide a flat cosine response [Thwaites and Williams 1996].

Real-time MAVS3 measurements are available to an operator as a serial stream of ASCII data using standard RS-232 or RS-485 protocols.[1] Any generic PC with a serial port and running a simple terminal emulator can display and log MAVS3 data in real-time. However, a logistical difficulty arises when the requirements of an investigation make it necessary to simultaneously monitor and log the output of multiple MAVS3 sensors in real-time. The procurement of a large number of PCs is not generally an acceptable option, both because of the cost and because of the difficulties associated with merging and synchronizing the data streams to suitable precision.

The problem is well addressed by adding an analog output capability to MAVS3. Multi-channel analog-to-digital acquisition and logging systems are standard equipment in many hydrodynamics laboratories. These systems are well suited to sampling a large array of sensors and they provide the operator with real-time

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[1] MAVS3 is able to log large quantities of data internally on DOS/Windows® compatible flash cards. However, it is the case of real-time monitoring, possibly with external logging, with which we are concerned here.

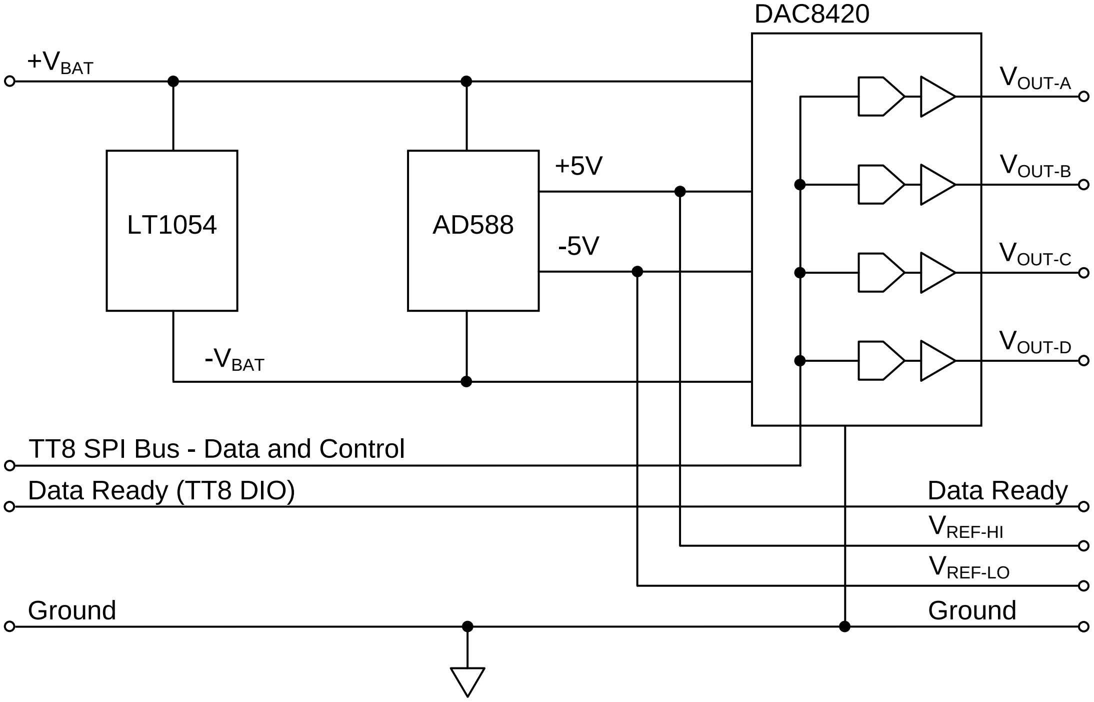

Figure 1 - MAVS3 Digital-to-Analog Circuit
The four connections shown on the left side of the diagram are a portion of the TT8/DAC interface. The eight connections shown on the right are accessible on an external connector.

data streams that have been referenced to a common time base. The digital-to-analog conversion of MAVS3 velocity measurements provides stable analog outputs that can be sampled asynchronously by the external system. Alternatively, a "data ready" pulse permits sampling synchronized to the MAVS3 measurement interval.

II. The Digital-to-Analog Circuit

A simplified schematic of the MAVS3 digital-to-analog converter (DAC) is shown in Figure 1. The circuit consists of three integrated circuits and a small number of external components (not shown). Power is provided directly from the battery or from an external supply. The circuit draws approximately 35 mA. This would be a significant drain if the instrument were used in the field. However, the analog velocity option is intended for laboratory use where multi-channel loggers and external power are commonly available.

One may reasonably ask why we have implemented a digital-to-analog conversion of the internally digitized analog voltage that is a MAVS velocity measurement. Part of the answer is that providing an output more directly from the internal analog difference voltage would have required significant changes to a carefully designed and well characterized receiver circuit. This was simply not an acceptable approach for an optional enhancement to a standard MAVS3. Additionally, each analog difference voltage is present at the output of the differential amplifier for only 12 µs to 15 µs (there is a dependence on the *in situ* sound speed) and that single output is used by all four acoustic axes in sequence [Williams, et al. 1987, Morrison 1995, Morrison 1997]. A more direct analog output would thus place a significant timing burden on the external sampling system or require that we implement a sample-and-hold circuit. The former is patently undesirable because it would restrict the usefulness of the analog velocity option. The latter is itself inherently a digital-to-analog conversion. In contrast, a precision digital velocity measurement is readily available from a standard MAVS3 and an accurate, linear digital-to-analog circuit can be easily implemented using standard commercial components. We made the obvious choice.

Several factors influenced the design of the DAC circuit shown in Figure 1. First, multi-channel analog-to-digital acquisition systems are commonly bipolar devices. They expect inputs with a symmetric voltage swing, typically ±5 V or ±10 V. This was certainly true for the first intended user of the analog velocity option. Measured fluid velocities along each acoustic axis are also bipolar, with a symmetric range of ±180.7 cm/s. This naturally suggested a simple linear mapping of velocities to voltages.

Second, the operations of a MAVS3 are directed by a Tattletale 8 (TT8) micro-controller running a flexible system control program (SCP). A serial peripheral

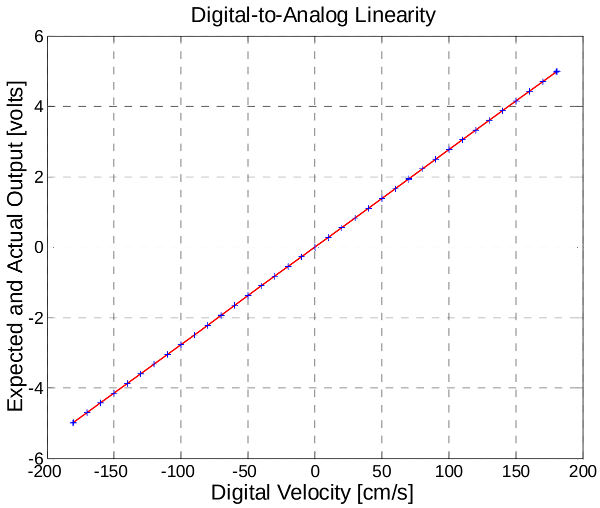

Figure 2 – Independent Response

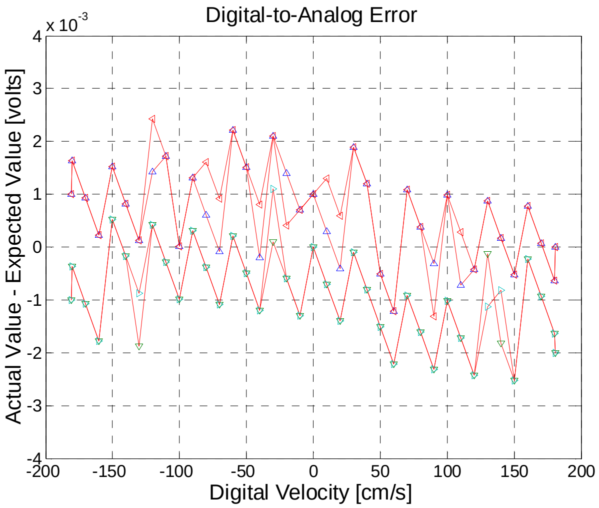

Figure 3 – Measured – Expected

interface (SPI) is native to the TT8 and already used by MAVS3. The SPI was thus accessible without significant modification of the existing MAVS3 hardware. Also accessible were several DIO pins. Both the SPI and the DIO pins are easily controlled by modification of the SCP firmware. Other hardware options would have been less easily implemented.

Third, MAVS3 velocities are internally represented by 16-bit scaled integers in the range ±32767. Because the original digitization had an accuracy of 12 bits, these can be represented as 12-bit values, ±2047, without loss of accuracy. These digital values are readily communicated through a serial interface.

Finally, interfacing an external system to the analog velocity output would be relatively easy for a potential user if all four velocities were simultaneously available at all times. An output with this characteristic would support asynchronous sampling. Support for synchronous sampling would then only require the addition of a timing pulse.

The DAC8420, a 12-bit, 4-channel, latching DAC with a SPI compatible serial input, is well matched to these design considerations. Each analog output is a linear mapping of digital values in the range ±2047 (±180.7 cm/s) to the range $V_{REF\text{-}HI}$ to $V_{REF\text{-}LO}$ (±5 V in this implementation). Each voltage is latched and buffered, remaining stable between update cycles. The duration of a four channel update cycle is only 1.55 ms. During the cycle the four channels change sequentially. MAVS3 can operate at up to 35 Hz (a period of 28.6 ms) [Morrison 2002].

For the duration of each update cycle, a logic level, normally low (0 V), "data ready" output pin, is set high (+5 V). The external ADC can use the data ready pulse to temporarily block acquisition. The logic transition from high to low can also be used to trigger synchronous conversion at the MAVS3 measurement rate. In either mode the ADC may over-sample the analog outputs and average the results to reduce the 1/2 bit noise introduced by the conversion. Although they are not shown in Figure 1, single pole, low-pass RC filters with a 3 dB bandwidth of 10 KHz are present on each analog output.

Symmetric, bipolar power supply rail and reference voltages are required to operate the DAC8420 in the symmetric, bipolar mode described above. These are provided by the LT1054 and the AD588. The LT1054 generates the negative rail from the positive supply voltage. The source of V_{BAT} will typically be an external power supply when the analog output option is used. V_{BAT} is nominally 12 V and must fall in the range +10 V to +15 V. The AD588 generates precision ±5 V reference voltages for the DAC circuit. The reference voltages and the local DAC ground are also accessible through the analog velocity port, a 10-pin connector, to support ratiometric measurement by the external data acquisition system.

III. Accuracy and Linearity of the Digital-to-Analog Conversion

We began our evaluation by measuring the response of the DAC circuit without reference to an actual acoustic velocity measurement. We accomplished this by writing fixed digital velocities to the DAC and measuring the voltages at the four analog outputs with a 4-digit multimeter. The nominal accuracy of the meter was 1 mV and the velocities spanned the full dynamic range of the velocity measurement: ±180.0 cm/s in 10 cm/s increments and the two full scale values, ±180.7 cm/s. The results are plotted for all four channels in Figure 2. The solid line is the expected response and the crosses are the voltage measurements.

The independent response appears to be gratifyingly

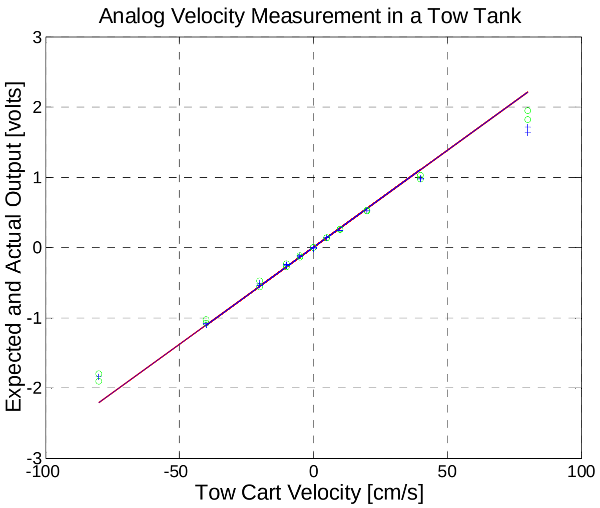

Figure 4 – Tow Tank Results

linear and accurate, but the scale of the plot hides small deviations. More informative are the errors, measured voltage minus expected voltage, of each channel, which are plotted in Figure 3. The deviations are generally less than 2 mV. Nowhere are they greater than 2.5 mV. The accuracy of the MAVS3 DAC, independent of the acoustic velocity sensor, is ±0.05% of the ±5 V full-scale analog output voltage. In terms of velocity, this is approximately ±0.09 cm/s, which is comparable to the nominal 0.05 cm/s electronic noise floor of MAVS.

IV. Physical Flow to Analog Velocity

The results of a series of tow tank runs are shown in Figure 4. A MAVS3 system with an integrated DAC was mounted on the tow cart with the acoustic axes approximately 30 cm below the surface. The sensor was positioned so that two of the axes lay in a vertical plane parallel to the direction of cart motion. The axes were angled 45° above the horizontal. All results reported here have been corrected for axis geometry (projected onto the direction of cart motion) and sound speed (fresh water tank, 22ºC). The measurements have also been referenced to a nano-second delay calibration circuit [Williams 1995].

We towed the sensor in both directions at 5 cm/s, 10 cm/s, 20 cm/s, 40 cm/s, and 80 cm/s. We also made measurements with the cart motionless. The tows were conducted in order from slow to fast and we allowed time for significant residual motion in the tank to decay before starting each run [Thwaites and Williams 1997].

Digital MAVS3 velocity measurements for each acoustic axis were recorded to the hard disk of a laptop PC in real-time. The analog outputs of the two axes aligned with the run were instrumented with digital multimeters and “averaged by eye” over the course of a tow. The analog outputs were also instrumented with a two channel digital oscilloscope, recording in real-time. Our limited familiarity with the apparently extensive statistical capabilities of the oscilloscope was not sufficient to allow a quantitative calculation of average voltage during a tow. The oscilloscope measurements did, however, qualitatively confirm the accuracy of the multimeter measurements.

The solid line in Figure 4 is the expected output of the analog velocity channels after the geometry corrections and other manipulations described above are applied. The mapping from velocity to voltage is simply 5.0/180.7 V/cm/s. The circles are derived from the digital velocity measurements. Data from the portion of each record during which the cart was in motion were averaged, corrected for geometry and sound speed, and mapped from velocity to voltage. The crosses are the visually averaged measurements read from the digital multimeters. The measurements were made by one of us while walking beside the cart during the tow. Events which transpired during the first 80 cm/s tow (the multimeter observer had trouble getting around some obstructing equipment) lead us to believe that those two measurements are somewhat less accurate than the others.

As expected, the agreement between the analog and digital MAVS3 measurements is high throughout the tested range. Disagreements are well within the error bounds of the visual averaging processes associated with the measurements. The analog outputs are an accurate presentation of the MAVS3 velocity measurement. The agreement with the tow velocities is also very good. Below 40 cm/s the MAVS3 velocity measurement accurately reflects the cart speed. The divergence from the cart speed at higher velocity is an effect of the increasing value of the Froude Number,

$$F = U \big/ \sqrt{gL}$$

As the cart speed increases the proximity of the sample volume to the surface becomes an increasingly important determinant of the flow distortion. Had the sensor been placed deeper in the tank, the divergence would have been significantly less.

VII. Conclusions

The MAVS3 digital-to-analog circuit performed well in tests, accurately mirroring the standard digital velocity measurements. The relatively high current drain of the DAC will generally restrict this option to use in the laboratory. As this is the likely province of multi-channel acquisition systems, this is not a sever constraint. The DAC is well suited to this use, enabling users to more easily integrate the measurements of an array of MAVS3 sensors into a common data stream.

Acknowledgments

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