Electronic Crosstalk and Linearity in the Acoustic Travel-Time Current Meter, MAVS

Albert J. Williams 3rd
Woods Hole Oceanographic Institution
MS#12, 98 Water St
Woods Hole, MA 02543, USA
awilliams@whoi.edu

Archie Todd Morrison III
Nobska Development, Inc
12 Nobska Circle, Box 308
Woods Hole, MA 02543, USA
Nobska@compuserve.com

Abstract **– Differential travel-time measurements of bi-directional transmission of sound between two fixed transducers underwater is the principle of the travel-time acoustic current meter. Sound is transmitted simultaneously in opposite directions and the difference in arrival time is a measure of the component of flow velocity along the axis of propagation. Electronically, the detection of this difference in arrival time involves voltage comparators and fast switching. Leakage of switching current into the detection circuit may bias the measurement of arrival time when the delay between the two directions of acoustic propagation is comparable to the propagation delay in the detection circuit. In 1980 such an effect was detected and removed in the Benthic Acoustic Stress Sensor, BASS, by careful separation of power and signal grounds. In 2003 a slight relaxation of this ground separation appeared to have caused another instance of this effect in the Modular Acoustic Velocity Sensor, MAVS. The detection circuit, a voltage comparator with a TTL output, has a 17 ns propagation delay causing a voltage 'glitch' to appear on the ground line 17 ns after the first signal crosses zero. This 'glitch' distorts the second signal to arrive at the moment of its zero crossing when the speed of current measured along the acoustic axis is 20 cm/s in MAVS. Electronically simulated errors in speed have been as much as 12% near 20 cm/s, returning to 0.5% by 60 cm/s. The search for a cure revealed that a totally different cause was responsible for this non-linearity and the story of this search bears repeating.**

I. INTRODUCTION

Non-linearity and noise are undesirable in a current meter [1]. Non-linearity makes calibration complex or ineffective and uncorrected non-linearity can produce error in current direction as well as the obvious error in speed. Noise is a broad degradation in performance that reduces bandwidth or resolution and may create an effective dead-band below which neither speed nor direction can be reliably determined. Acoustic travel-time current meters are inherently free of non-linearity and any introduction of such an error is correctable electronically. By contrast, mechanical sensors of velocity depend on lift or drag, both inherently non-linear, and therefore such an error is inevitable at some speed near the stall speed. The Modular Acoustic Velocity Sensor, MAVS, uses four acoustic axes to obtain a water velocity vector with differential acoustic travel-time measurements. Differential travel times for forward and reversed measurements are subtracted for removal of electronic drift [2]. The resulting measurement is linear within one half percent of full scale over the entire range of the instrument (except near zero where this ratio is poorly defined) and has a noise level that is equivalent to about 0.04 cm/s standard deviation. However, some MAVS3 instruments, introduced by Nobska in 2000, showed electronic noise above this value and attention was directed towards a specific transistor where modifications in the circuit reduced the noise to an acceptable level. Then in a current meter intercomparison test in 2002, an offset in speed in the MAVS3 measurements relative to several other current meters near 12 cm/s drew attention to a possible non-linearity, assumed to be from crosstalk between the signals from the two transducers in an acoustic-axis pair. This is the story of the search for this problem, and its surprising cure.

II. MODULAR ACOUSTIC VELOCITY SENSOR

A. Circuit

i) Differential travel-time - Sound travels through water at the group velocity, which is essentially equal to the phase velocity, C. This is 1500 m/s within 5% for most salt water and somewhat less for fresh water. Sound transmitted in opposite directions simultaneously along a common axis is delayed differentially by the component of flow along the axis by the difference in travel-time $\delta t = \frac{2dv}{C^2}$ where v is the velocity of the fluid. In MAVS3, d, the distance between transducers, is 10 cm so the travel-time difference is 89 ns/cm/s. This small time difference is measured by steering an electric current from a current sink to a capacitor when the first pulse arrives and back to the sink when the second pulse arrives. The voltage increase on the capacitor is a measure of the time the current was charging the capacitor. Actually, there are two such current integrating circuits, each connected to the receiver of one of the transducers of a pair. Each current integrator starts when the acoustic signal is received at the transducer to which it is connected but both current integrators turn off together when both pulses have been received.

ii) Reversing switch - Since the time delay within the voltage comparators that detect the time of arrival of the acoustic pulse is long compared to the time differences being measured, there are two measurements made for each axis. The first is made with the top transducer connected to the top comparator and the bottom transducer connected to the bottom comparator. The second is made with the top transducer connected to the bottom comparator and the bottom transducer connected to the top comparator. These are termed normal and reversed measurements. The two resulting digitized voltage differences, the normal and reversed measurements, are subtracted, doubling the signal and canceling the offsets of the comparators. The reversing switch uses a set of four transistors, two of which are turned on for normal, and the other two turned on for reversed. The output of this reversing switch is a pair of transistors in a cascode configuration. Each cascode transistor has a "grounded base" in which the base is held at 4 volts and the current at the emitter is expressed as essentially the same current at the collector. The collector has a resistive load so that the changes in electric current at the emitter become changes in voltage at the collector and these are the input to the voltage comparator. The circuit is shown in Fig. 1.

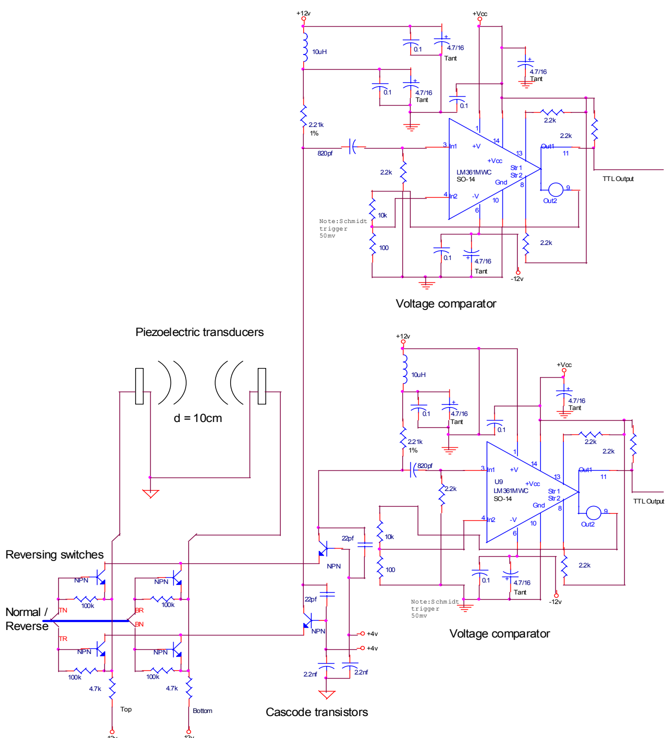

Fig. 1. MAVS receiver circuit showing transducers, reversing switch, cascode transistors, and voltage comparators. Two transistors in the reversing switch are turned on at a time, one pair for normal connection, and the other pair for reversed connection. The cascode transistors clamp the voltage of the reversing switch outputs by their "grounded base" configuration so that crosstalk between the two signals is minimized. The voltage comparators are configured as Schmitt triggers to detect positive signals of 50 mv and trigger on negative going signals when they cross 0 volts.

iii) Acoustic burst - There are some refinements to this description, one of which has some importance to this description. The received acoustic signal is actually a burst of 15 cycles at 1.8 MHz. The first half cycle is negative going so the voltage comparator has been configured as a Schmitt trigger with a positive trigger point set nominally to 50 mv and the negative trigger point at 0 volts. This allows the negative-going half cycle to be ignored while the first positive-going signal is reliably detected, generally being between 100 mv and 200 mv. But the Q of the piezoelectric transducers is about 5 so the amplitude increases through the burst from 200 mv to about 2 volts peak to peak. A counter following the Schmitt trigger voltage comparator enables clocking of a JK flip-flop on the 14^{th} cycle and this flip-flop is triggered by the 15^{th} negative-going transition of the signal, an event that is very steep and is not strongly influenced by the amplitude of the signal. Electronic noise of 10 mv, the Johnson noise of the circuit, introduces a time jitter of only 1 ns. This is equivalent to 0.01 cm/s; a practical limit set by thermal noise. Typically we see a noise level about 4 times this.

iv) Current source - The electric current from a "source" that is steered from a sink to an integrating capacitor and back is expected to remain steady during this steering. To obtain an accurate and stable velocity calibration, this current source must be insensitive to temperature, aging, and voltage supply variations. But most importantly, it must adjust rapidly to slight changes in conditions as the steering circuitry varies voltages to turn transistors on or off. In 1990, an application for BASS [2], a predecessor of MAVS using this circuitry, had an unusually long integration time. The path length was long, 1.5 meters, and the velocity was high, thus producing a long differential time delay. The response was calibrated with a new nanosecond delay box containing more than 100 meters of coaxial cable to simulate these long differential delays. We found the calibration to be non-linear beyond about 60 ns delay. The cause was slow response of the electric current source [1]. Removing superfluous parts, an operational amplifier and a Darlington transistor, solved the problem and restored linearity to better than 0.5% of full scale over the full range (except near zero where the ratio is poorly defined).

v) Cascode transistor - While the cascode transistor has been described, its reason for existence has not. Acoustically generated electronic signals on the two transducers and associated receiver components (the four reversing transistors) must not be able to influence one another. Such coupling, termed crosstalk, could influence the detection of a zero crossing because the opposite transducer was receiving its own waveform at that moment. The cascode transistor prevents these changes in current in one received circuit from generating a voltage fluctuation that could capacitively couple to the other circuit. This had given trouble in a much earlier version of travel-time current meter. But that is not the only place where crosstalk can be troublesome. When the voltage comparator detects a transition and changes the state of the output, a pulse of current from the power supply is required to change the TTL outputs. This can shift the reference point on the input to the other voltage comparator and cause a premature or delayed detection of the transition there. The propagation delay of the voltage comparator, LM361, is 17 ns, about the differential delay produced by a 20 cm/s current. The TTL output of the voltage comparator is at the end of this propagation delay. This would have the second comparator detecting a zero crossing when the first comparator output pulse was generating crosstalk. Attention to ground separation between signal and power ground is the best way to prevent this problem. Because there was a problem in MAVS3 at about this current speed, attention fell on this form of crosstalk and the investigation started with grounding and power isolation on the LM361 voltage comparators.

B. Performance

i) Intercomparison of four current meters - Fig. 2 shows current measurements from MAVS3, a VACM mechanical sensor, an FSI acoustic travel-time sensor, and an Aanderaa acoustic Doppler current meter obtained near Bermuda at 4000 meters depth in 2002. MAVS in this example tracked the others but at 1 cm/s greater speed. This was not observed at lower speeds or at higher speeds so it looked like crosstalk. In fact, as shown in Fig. 3, at lower speeds, the mechanical VMCM sensor was stalled and "over speeding" by MAVS was really under reading of the VMCM [3].

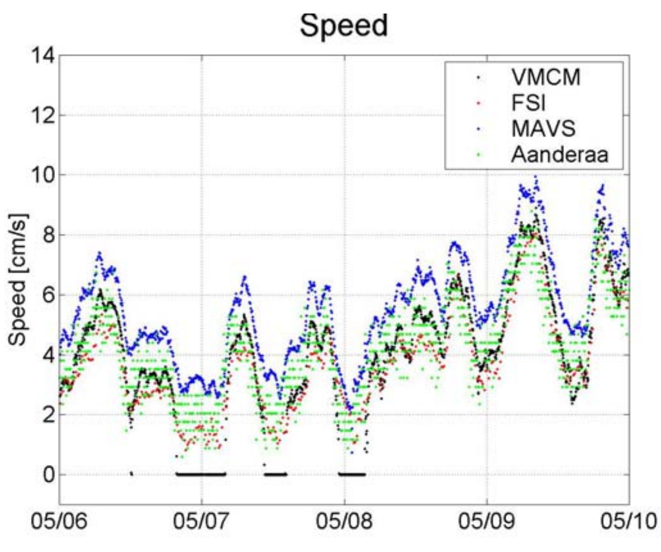

Fig. 2. Intercomparison of four current meters at 4000m depth near Bermuda where MAVS3 (in blue) is uniformly 1 to 2 cm/s higher than the mechanical VMCM, acoustic travel-time FSI, and acoustic Doppler Aanderaa. Note that the VMCM stalls below 2 cm/s.

ii) Nanosecond delay measurements - The nanosecond delay measurements that verify linearity and that are run on every MAVS did not reveal such a glaring non-linearity. They are taken at 20 ns intervals from 0 ns to 160 ns to cover the full-scale range of a standard MAVS (+/-188.7 cm/s). It had been noted, however, that sometimes there had been an elevated value observed for the calibration point at 20 ns. Fig. 4 shows a composite of 42 such curves from product delivered in 2002. The MAVS3 of the intercomparison had been calibrated at 20 ns intervals and produced the curve in Fig. 5. In this figure, a serious non-linearity shows up at 20 ns. This effect was not visible in MAVS2 instruments, one example of which is shown as Fig. 6.

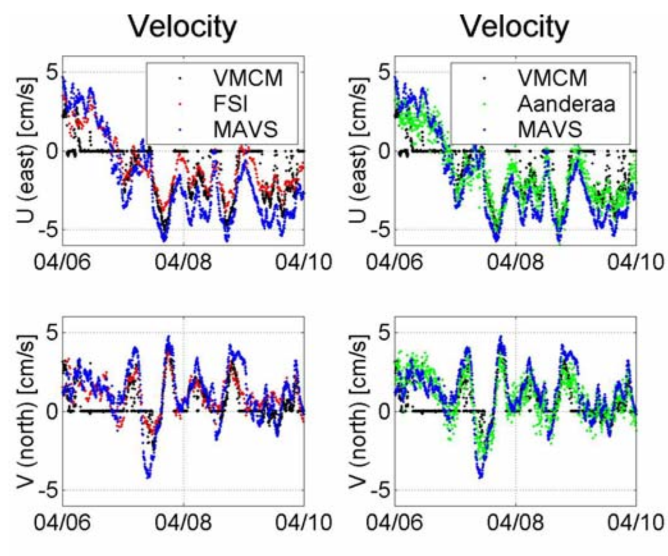

Fig. 3. Vector display of intercomparison of four current meters at lower flow rate than in Fig. 2. VMCM is stalled more often and the difference between the FSI, Aanderaa, and MAVS3 is reduced over that in Fig. 2.

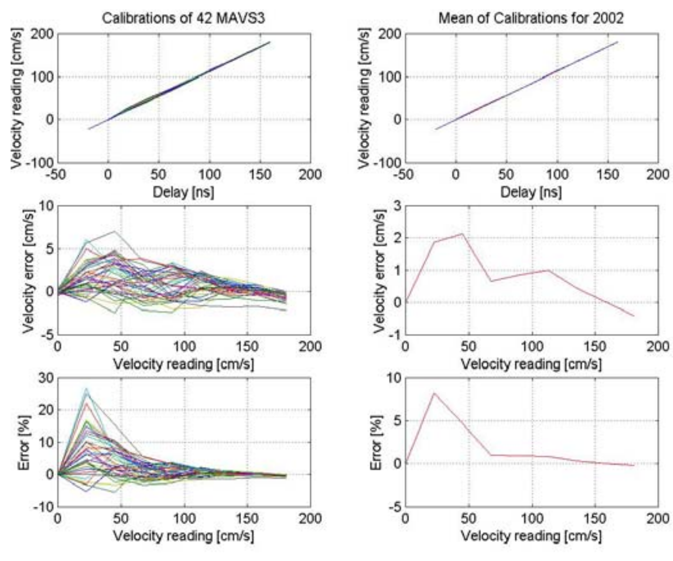

Fig. 4. Non-linearity of 42 MAVS3 instruments calibrated in 2002 with the average showing 8% over-reading near 20 cm/s.

C. Electronic Modifications

i) Separation of power ground from signal ground - MAVS3 has been optimized for machine assembly with surface mount components. It differs from MAVS2 in layout details but has the same circuit in what was assumed to be the critical elements. So, effort was directed towards the crosstalk, produced by a transition in output of the first voltage comparator, at the instant when the second voltage comparator is detecting a zero crossing. Fig. 7 shows the 'glitch' on the received waveform when the delay between the two received signals is 17 ns, the same as the propagation delay of the voltage comparator. To remove this effect, the power capacitors were disconnected from the signal ground pins of the voltage comparators and tied to the power ground pins of these devices. This removed the 'glitch' of Fig. 7 but this had no effect on the non-linearity. With this change, no improvement was achieved as shown in Fig. 8.

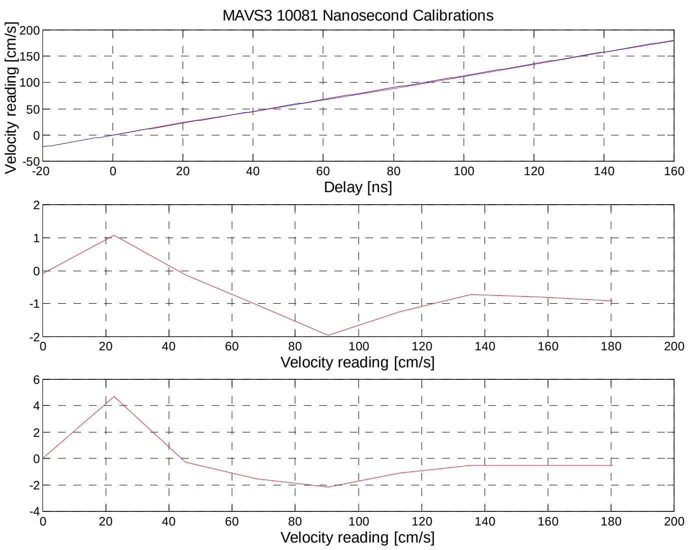

Fig. 5. Non-linear behavior of the MAVS3 used in the Intercomparison.

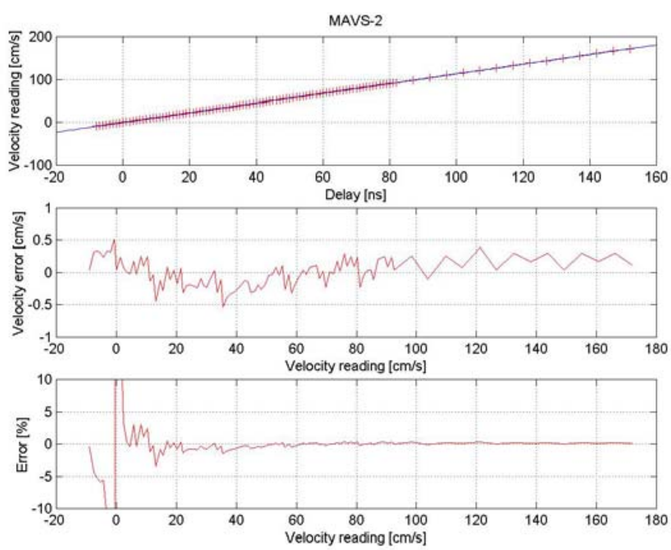

Fig. 6. Calibration of MAVS2 without evidence of non-linearity.

ii) Cascode transistor - In the unraveling of this mystery, the story must be told of the cascode transistor introduced earlier. The cascode transistor need not be very fast and in BASS and in MAVS1, this transistor is an NPN switching transistor, 2N2369A. This has a current gain-bandwidth product, f_T, of 500 MHz and a small signal gain, h_{FE}, of 20. But Motorola did not have a surface mount 2N2369A in 1997, when the circuit was prepared for surface mount, and in the effort to reduce the variety of parts for automatic assembly, an RF NPN transistor, MMBR901LT1, was substituted for the 2N2369A. In the first production run of the MAVS2 board, this RF transistor in the cascode location oscillated and was only tamed by adding a 22-pf capacitor between the collector and the base, sort of an external Miller capacitance. The capacitor was dropped on top of the transistor and soldered to the transistor leads. This solved the problem and MAVS2 has as low a noise as MAVS1.

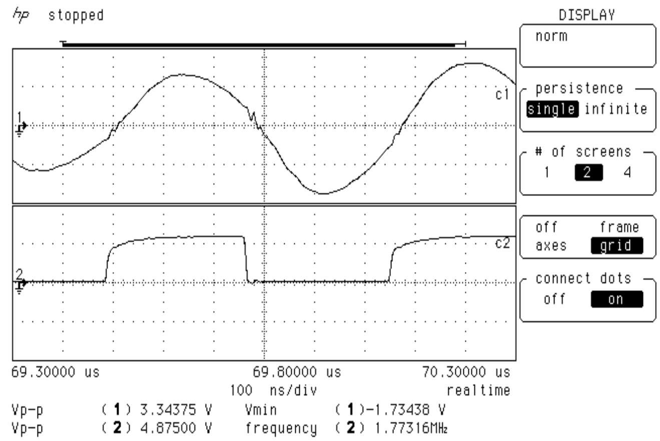

Fig. 7. 'Glitch' in received waveform in top trace when the voltage comparator output shown in the bottom trace changes state. This is a potential cause of non-linear behavior.

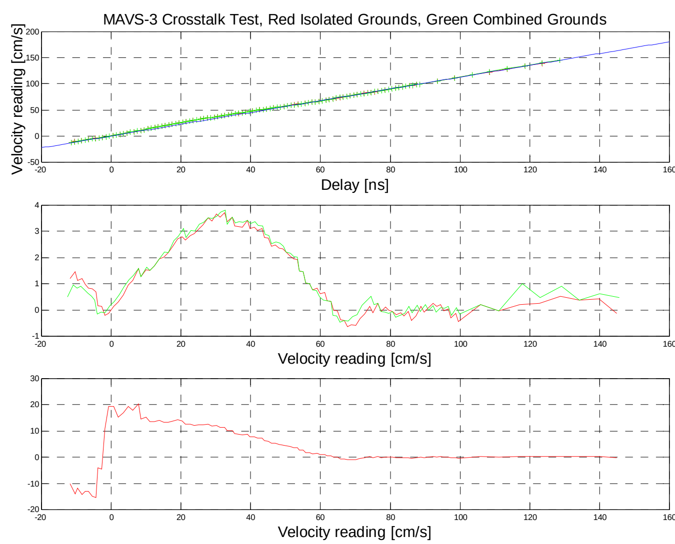

Fig. 8. Evidence that crosstalk from power and signal grounds are not the cause of non-linearity. The red curve results from separated grounds in which the 'glitch' of Fig. 7 is gone while the green curve results from common grounds where the 'glitch' is evident. There is no improvement due to separating the grounds.

iii) Displaced solder pads - In the revised layout of MAVS3, this 22-pf capacitor was added to the layout with pads near the RF transistor but with enough space for automatic placement. In the second year of production of MAVS3, one instrument exhibited greater noise than was acceptable, which was traced to an incipient ringing of the cascode transistor on the second, reversed, measurement of an acoustic axis. More “Miller” capacitance did not help but a piece of #26 bus wire on top of the 1/8” foil run to the 22-pf capacitor solved the problem. At the ringing frequency of the RF transistor, the inductance of the 1/8" foil was high enough to form a tuned circuit with the 22-pf capacitor. Adding the relatively fat wire lowered this inductance. The effect of quenching the ringing is shown in Fig. 9. While our effort had been directed at lowering the noise, serendipitously it cured the non-linearity.

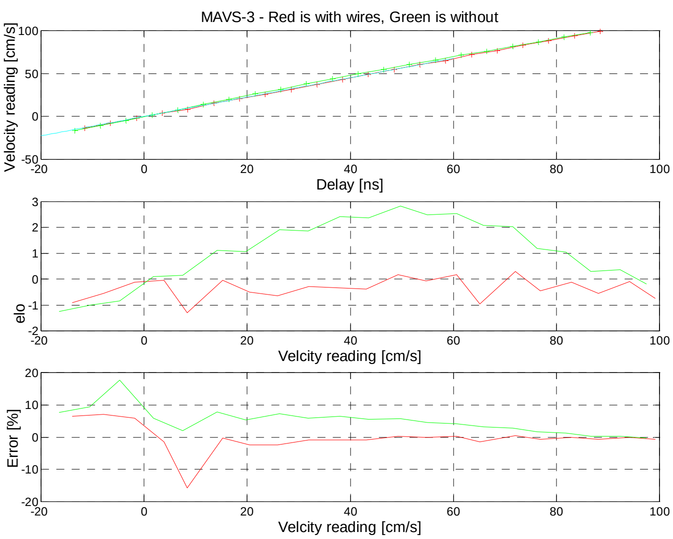

Fig. 9. Non-linearity is corrected with a short length of #26 bus wire laid on top of the 1/8" foil run to the "Miller" capacitor of the cascode transistor.

iv) Bus wire – The addition of bus wire as a solution to the cascode ringing was made standard as shown in Fig. 10. It was initially employed to reduce noise but served as well to remove non-linearity.

v) 2N2369A in a surface mount package – In 2003 a supplier for the original transistor, 2N2369A, in surface mount was found. By replacing the RF transistor with this slower switching transistor the noise was removed and the non-linearity as well as shown in Fig. 11

III. Conclusion and Lesson

Problems that have been solved or that have never come up can be engendered by layout or by component replacement. This is a lesson learned early and often by circuit designers who also build, test, and debug their designs. A good design can be sabotaged by subtle variations such as 1/8” movement of components to allow room for a placement tool. Errors introduced by such changes can hide between calibration points in a test procedure. But actual testing in comparison with other instruments may reveal the problem, which can then be analyzed and eventually isolated and fixed.

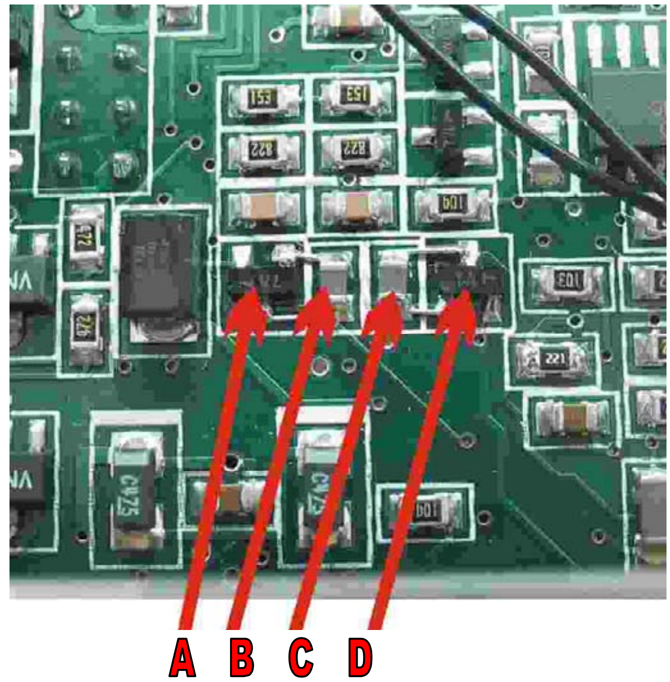

Fig. 10. A and D are RF NPN transistors that require "Miller" capacitors, B & C, for stability. However, without addition of short lengths of #26 bus wire visible between A & B and between C & D, ringing may occur producing non-linearity.

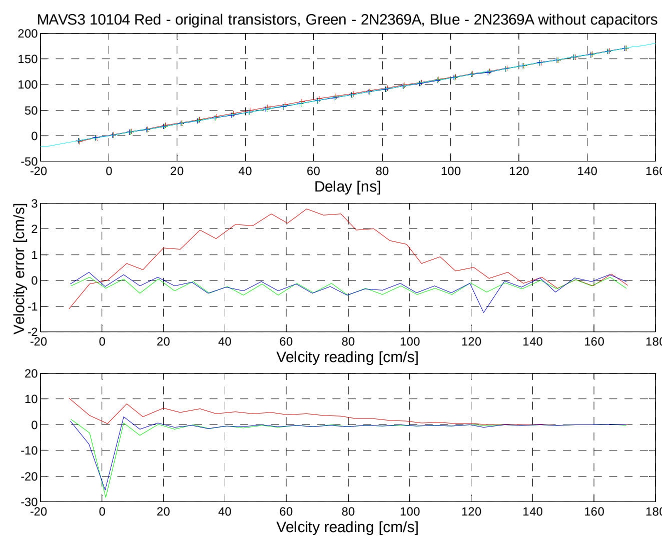

Fig. 11. Replacement of the RF NPN transistor with a 2N2369A NPN switching transistor removes non-linearity whether "Miller" capacitors are present or not. Electronic noise is also removed by this substitution.

Acknowledgement

We thank Nelson Hogg and Dan Frye of Woods Hole Oceanographic Institution for the opportunity they provided to compare MAVS to other instruments in various flow

conditions and their insistence that MAVS was “over speeding” in this one environmental regime.

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