# NAVAL POSTGRADUATE SCHOOL
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# THESIS

**CALIBRATION AND EVALUATION OF WATER SPEED INDICATOR AND COMPASS FOR THE SMALL AUTONOMOUS UNDERWATER VEHICLE NAVIGATION FILTER**

by

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December 1997

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The next problem was to determine if the existing paddle wheel in use would be accurate enough for the SANS to conduct underway tests. To perform this, a mechanism had to be built to channel water and measure its speed while allowing the paddle wheel to be in the flow.

Finally, the electronic compass was found to have heading dependent errors, thus a test was designed to determine its deviation. This was performed by swinging the compass using a transit aligned with its axis. This established a deviation table that was inserted into the SANS code, further refining its directional capabilities.

As a final test for determining the effectiveness of the calibrated inputs, tests were conducted that showed that the SANS filter is capable of obtaining 3 meter accuracy with no Global Positioning Update for an excess of two minutes. This is well beyond the initial goals set for the system.

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# CALIBRATION AND EVALUATION OF WATER SPEED INDICATOR AND COMPASS FOR THE SMALL AUTONOMOUS UNDERWATER VEHICLE NAVIGATION FILTER


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# I. INTRODUCTION

## A. BACKGROUND

In the Autonomous Underwater Vehicle (AUV) community there is a need to develop small inexpensive vehicles to assist research efforts and eventually for commercial use. One of the most important subsystems involved in this platform is the navigational system. Due to intermittent submergence, the vehicle does not have continuous access to external navigational aids such as the Global Positioning System (GPS) or Loran. Thus the vehicle itself must be capable of estimating the current position from onboard sensors that measure water speed, heading, velocity and acceleration. Currently, the price of some of these sensors can be prohibitive. With this in mind, the Small Autonomous Navigation System (SANS) was developed. This system combines an inexpensive strapped down inertial measurement unit (IMU), magnetic compass, and water speed sensor. To make up for the inaccuracies of these sensors a complementary filter is used to provide a continuous positions updates, with aperiodic GPS fixes to correct for current and internal errors [Ref. 1].

## B. SURVEY OF WORK TO DATE

Tradeoff studies for various methods of underwater navigation have been addressed by previous theses and will not be discussed [Ref. 2, Ref. 3]. From these efforts, it has been shown that integrating GPS and INS into a single system makes possible production of continuously accurate navigational information even while using relatively low-cost components [Ref. 4]. The obvious benefit of this design is to correct INS errors via the aperiodic GPS fixes. However, with the aide of Kalman filtering techniques, the performance of the INS between fixes can also be improved.

Kalman filtering is a method of combining all available sensor data, regardless of their precision, to estimate the current position of a vehicle [Ref. 5]. Employing a complementary filter to bias the vehicle sensors such as angular rate sensors, accelerometers, water speed indicator and the compass provide further improvements of the systems accuracy. Thus, an integrated package of this type has improved performance, smaller navigational errors, and improved reliability over those that depend only on one expensive sensor. [Ref. 4]

Bachmann and Gay [Ref. 5] demonstrated the use of the complementary filter technique by combining low-frequency orientation data from accelerometers and magnetic compass with high frequency angular rate information to estimate heading, attitude and position. From this, position was obtained by integrating high frequency water-speed data. GPS data was used to reinitialize the system each time a fix was obtained and to develop an error bias expressed as an apparent ocean current. The current was summed with the velocity and integrated to correct the system between GPS fixes. In the first working prototype, this concept of using a relatively inexpensive IMU with limited accuracy, coupled with differentially-corrected GPS, was proven to be a viable solution to the challenge of shallow-water AUV navigation. However, it was also found that the system suffered in performance due to a slow sampling times.

The hardware of the current configuration was developed by Walker [Ref. 2] and was designed to cover the deficiency of under sampling. In addition to this, it was also found that the IMU exhibited noise that, if left unattenuated, would induce large errors in drift via the subsequent integrating stages.

The emphasis of Walker's work was to get a small integrated system operational [Ref. 2]. This was successfully completed; however there was not a clear understanding regarding the value of gains used in the complementary filter. Roberts [Ref. 3] performed this analysis and provided a methodology to calibrate the attitude sensors using a precision tilt table. With this effort the mechanism and interaction of the angular rate sensors was understood and the gains used in the attitude estimate portion were put on firm theoretical ground.

## C. RESEARCH QUESTIONS

Now that attitude mechanism is understood, the position estimation capabilities can be investigated. In order to properly assign the gains used in the filter at various stages the speed and directional sensors must be characterized. Up to this point the possible error that could be induced has not been thoroughly analyzed. To this end this thesis will examine the following research topics:

- Develop a method to provide ground speed to the SANS navigation filter for golf cart testing.
- Evaluate the current waterspeed sensor, and if possible develop a characteristic curve that can be used for an indication of water speed.
- Develop a method to calibrate the onboard compass.

## D. SCOPE, LIMITATIONS AND ASSUMPTIONS

This thesis reports part of the findings of the sixth year of research in an ongoing research project. The scope of this thesis is to develop and evaluate SANS capabilities for eventual installation as a replacement for the older technology gyros now used on board the NPS Phoenix AUV.

## E. ORGANIZATION OF THESIS

The purpose of this thesis is to present the development of a prototype system intended to meet the mission requirements of the SANS. In this thesis the term AUV is understood to include any small underwater vehicle (including human divers) which can easily carry such a compact device. The term "towfish" refers to the test vehicle used to evaluate the SANS during at-sea testing.

This thesis provides an evaluation of the hardware and software used to provide accurate navigation for the NPS AUV. The major thrust of the thesis is to develop and evaluate the ground/water speed and directional measurement capabilities of the SANS both statically and dynamically in a laboratory environment.

Chapter II reviews the current state of the hardware and a short explanation of the theory used in the complementary filter. Chapter III describes the development of a speed sensor for the golf test vehicle. Chapter IV describes the development of and testing of the onboard water speed sensor. Chapter V describes the testing and calibration of the electronic magnetic compass. Chapter VI discusses the test results following ground speed and directional sensor calibration. Finally, Chapter VII presents the thesis conclusions and provides recommendations for future research.

## II. SYSTEM CONFIGURATION

### A. INTRODUCTION

The current configuration of the SANS hardware remains the same as developed by Walker [Ref. 2]. As shown in Figure 1, all components are physically mounted in one project box with the exception of the GPS/DGPS antennas. The only external input required by the system is the power source (a 12 VDC battery) thus the system is very portable and compact. This was very helpful in performing the various calibration tests this thesis involved. Due to the experimental nature of the project, a monitor and keyboard are attached to the unit. These are not needed for the system to run independently.

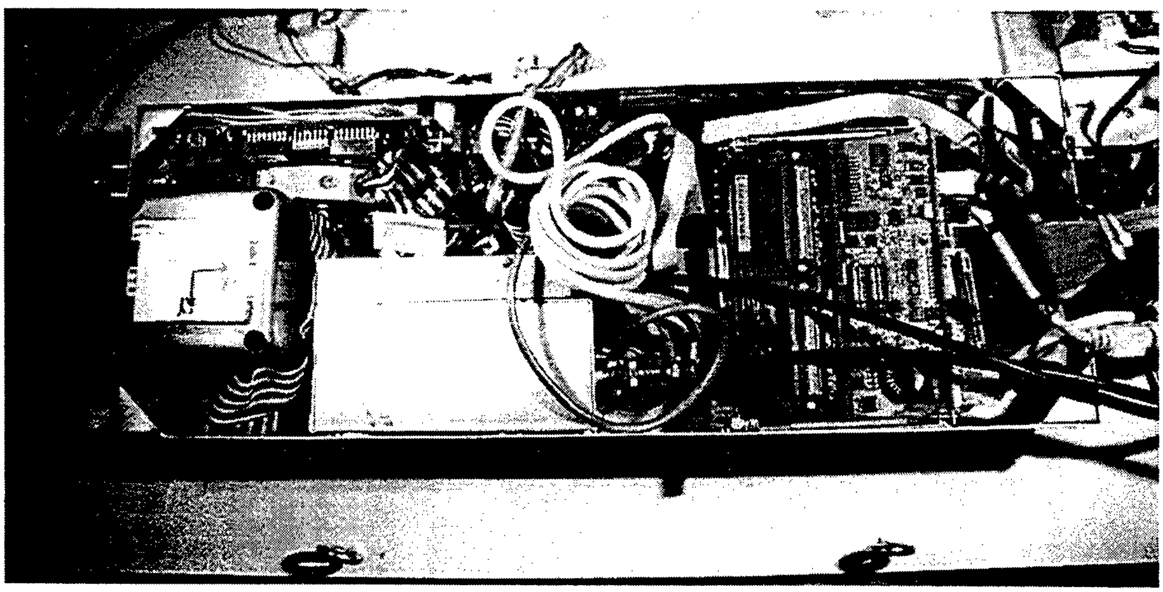

**Figure 1. SANS Unit**

### B. HARDWARE

Figure 2 is a block diagram of the SANS hardware configuration. The central processor is a 486SLC DX2 CPU module that provides all the computational capabilities necessary to implement the navigational filter. In addition to this, the CPU module provides

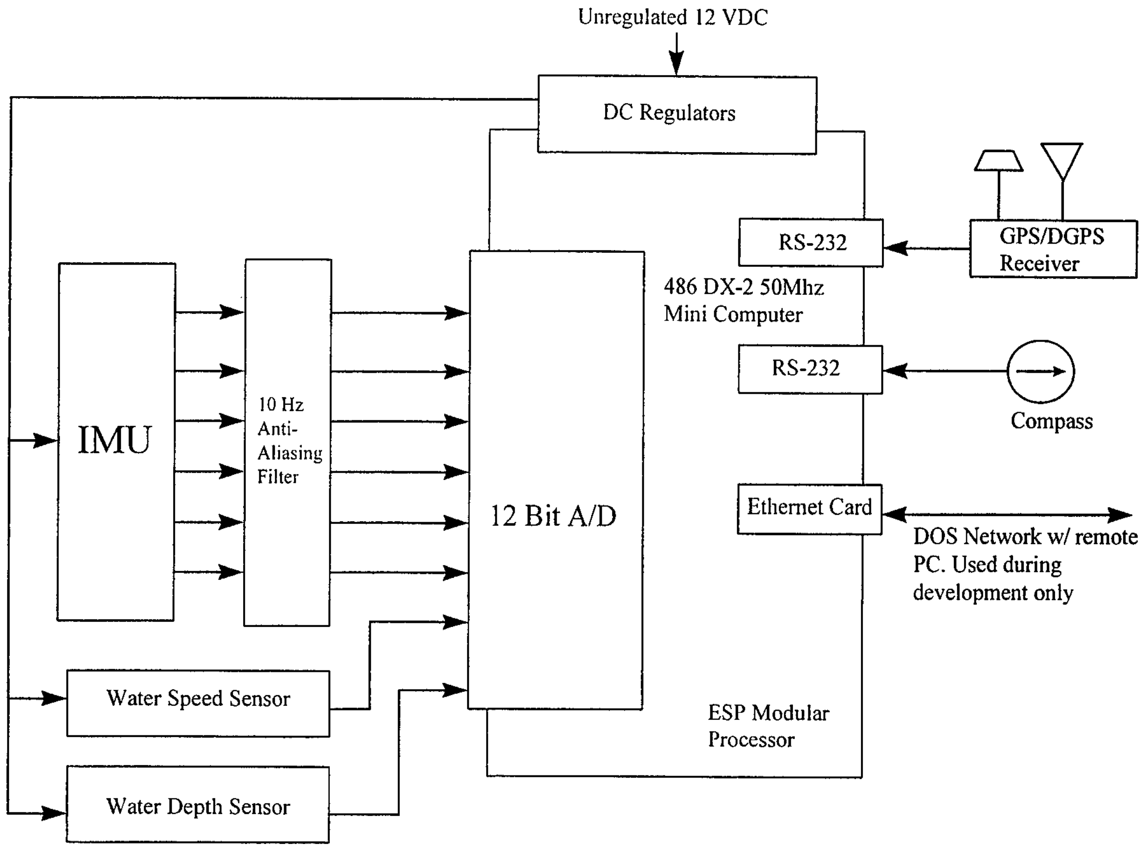


**Figure 2. Block Diagram of SANS**

the interface for a standard keyboard, the Flash ROM containing the system BIOS, two serial ports, interface for the 12 bit A/D converter, and interface for a network adapter [Ref. 7].

The A/D converter is respor:·ʰle for converting all of the analog voltages of the Inertial Measurement Unit (IMU), and waterspeed sensor to a digital representation. There is also the ability to sense depth, but the current filter algorithm does not use this input. The A/D converter has the capability to provide 8 differential or 16 single ended input channels at 12 bit resolution. The SANS uses 8 single ended inputs thus the other 8 are not used and are left open. The sampling rate for single ended inputs is 33khz with an input range of +/- 1.25mV to +/- 10V [Ref. 7]. The connection to the A/D converter is through a 34-pin external connector.

Between the IMU and the A/D Converter lies a 4-Pole, active, anti-alising low pass Butterworth filter with a bandwidth of 10 Hz. Analysis of the IMU's signal led to the discovery of a significant amounts noise in the angular rate sensors as well as low frequency noise in the accelerometers [Ref. 2]. The filter bank eliminates this undesirable signal noise and provides a large improvement in reducing the drift experienced with the first prototype SANS [Ref. 1]. The filters used are model DP-74 and are packaged in a standard 16-pin dual in-line package(DIP) [Ref. 8]. These filters feature low-harmonic distortion and come factory tuned to a user-specified corner frequency. They require no external components or adjustments, and operate with a dynamic input voltage range from non-critical +/-5V to +/-18 power supplies [Ref. 8]. The filter bank is mounted on a double sided printed circuit board (PCB). Both the input and output of each filter are connected to a LM234 opamp. This opamp is configured as a voltage follower providing input and output circuit protection. All components are mounted in sockets and easily removable making it easy to change out a filter.

The IMU is a Systron-Donner Model MP-GCCCQAAB-100 "Motion Pack" inertial sensing unit. This is a self-contained unit providing analog measurement in three orthogonal axis of both linear acceleration and angular velocity. The accelerations and angular rates are measured by clusters of three accelerometers and three "Gyrochip" angular rate sensors respectively.

The waterspeed sensor has taken two forms in this thesis. On board the Towfish enclosure, the water speed sensor is a paddle wheel device. Part of this thesis is devoted to analyzing the capabilities of this onboard paddle wheel system. The capabilities of this sensor are discussed later in Chapter IV. The other form is a bicycle wheel device used for land testing the system on a golf cart. This device was developed for this thesis and will be discussed in detail in Chapter III. Both sensors provide a DC signal representative of the linear velocity experienced by the SANS.

The SANS unit has two built in serial communication ports. One of these ports is devoted to communications with the GPS/DGPS receiver pair. This receiver is an

ONCORE 8-channel receiver which incorporates an imbedded DGPS capability [Ref. 9]. The receiver is capable of tracking up to eight satellites simultaneously. It can provide position accuracy of better than 24 meters Spherical Error Probable (SEP) without Selective Availability (SA) and 10 meters (SEP) with SA. Typical-Time-To-First Fix (TTFF) is 18 seconds with a reacquisition time of 2.5 seconds [Ref. 9].

The other serial port is dedicated to the compass. The compass is a Precision Navigation model TCM2 Electronic Compass Module. It employs a three-axis magnetometer and a high performance two-axis tilt sensor [Ref. 10]. The tilt sensor is not used in the implementation. The magnetometer has the capability of providing readings of the surrounding magnetic field strength. This is helpful in calibrating the compass and determining the effect of local magnetic anomalies on its performance.

The SANS package also has an ethernet network adapter. The network adapter can be used for downloading new versions of the filter code and for monitoring the status of the filter during testing. To provide these functions the built in disk controller, keyboard and monitor interfaces are used.

Power for the SANS is provided by a DC-DC converter and distribution block. The regulator portion consists of a DATEL model BWR-15/330-D12 DC-DC converter. This unit is used to convert the unregulated 12 VDC battery input to the regulated +/-15 VDC needed to power the low pass filter and IMU. Though the DC-DC converter ensures a low noise/ripple in the output signal, the converter is also augmented with additional capacitors in parallel with both the input and output of the device. These capacitors suppress any high-frequency radio frequencies (RF) that may be induced into the circuit by surrounding components and filter high-frequency switching noise from the converter itself. Since both the CPU and GPS/DGPS operate at 12 volts and both contain their own regulator, unregulated 12 VDC is distributed directly to each of them.

The entire system is interconnected by a ribbon cable. This is a 25 strand cable that runs between the IMU, low-pass Filters, DC-DC Converter PCB, Analog-Digital converter, water speed sensor and the depth sensor. It is designed to reduce the amount of cabling required to electronically connect the numerous components.

## C. SANS FILTER

The purpose of the SANS filter is to utilize IMU data, heading, and water-speed information to implement an Inertial Navigational System (INS), and then integrate this with GPS information into a single-system which can produce continually accurate navigational information in real time. Details concerning the software development were discussed in previous thesis [Ref. 6],[Ref. 2], [Ref. 3] and will not be presented here. For the purpose of the understanding the work effort presented in this thesis, only a top-level discussion of the operation of the filter will be presented.

Figure 3 presents a flow diagram of the SANS navigational filter. The filter is a 12-state complementary filter in which differential GPS fixes are treated as "ground truth". This allows aperiodic reinitialization of the INS to correct for accumulated errors and develop an apparent current or error vector to compensate for them. In Figure 3, T is the body rate to Euler rate transformation matrix and R is the rotation matrix.

The purpose of the complementary filter is to bias the gain of the respective inputs using time as the determining factor. This process can be seen in the derivation of the Euler Angles depicted in the upper left corner of Figure 3. In a perfect world, (see Figure 4) all that would be needed to obtain these angles would be an integrator (a stopwatch), the angular rate readings and knowledge of our original orientation. However, with real angular rate sensors, dependable outputs are produced for only short periods of time. As time increases, they produce an error, which when integrated, induces errors which grow quadratically. To mitigate these errors, inputs from other sensors which are accurate in the long term are needed. For Euler angles, this input comes from the accelerometers using the transformation given in Figure 3. One might ask if this where so, why not just use the accelerometers all of the time to obtain Euler angle. The accelerometers have their own

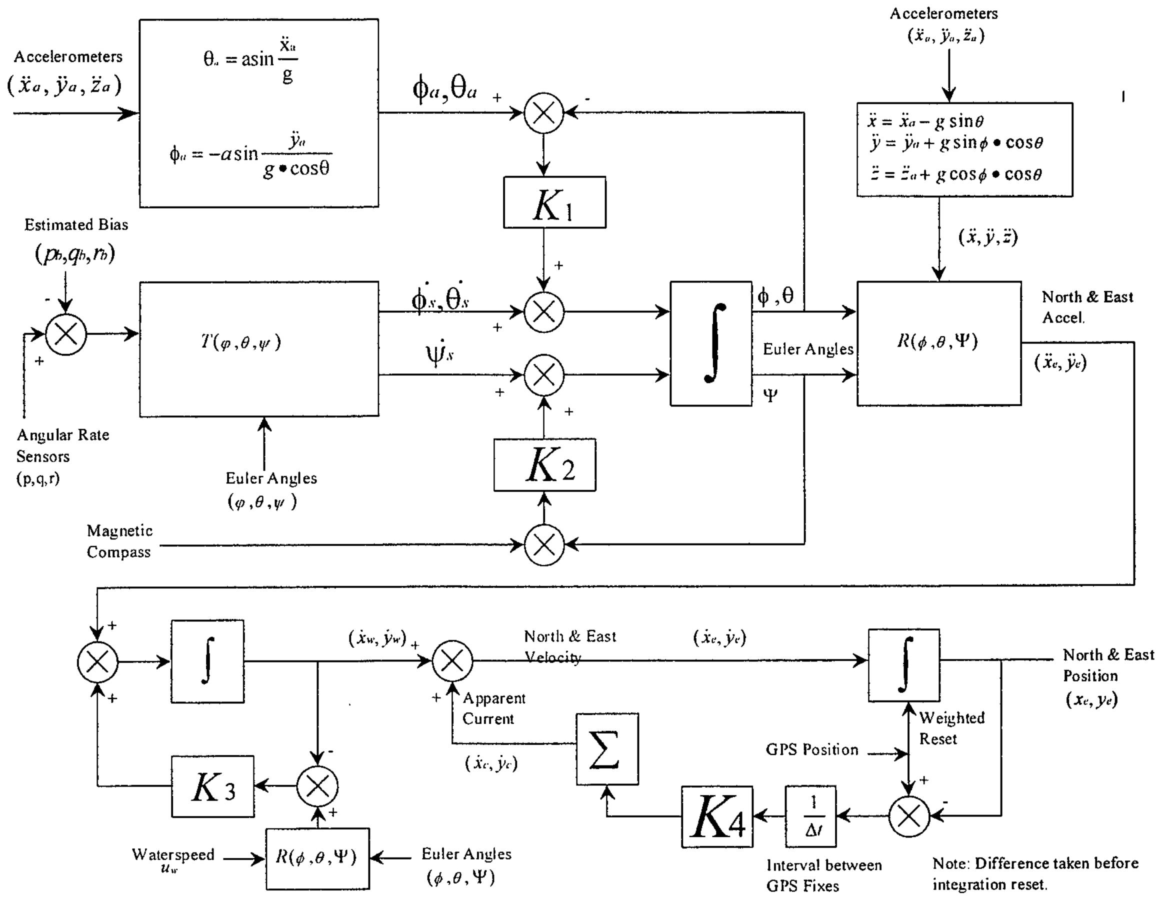


**Figure 3. SANS Filter**

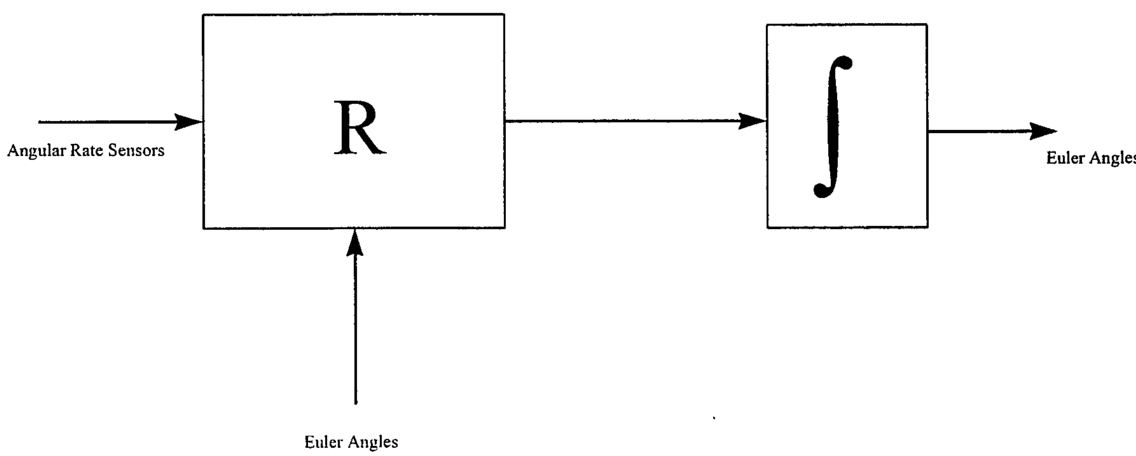


**Figure 4. Perfect World Navigation**

inherent limitations and cannot be trusted for short periods of time since a sudden acceleration in one direction does not imply an angular displacement thus accelerometers are only able to determine the "vertical" relative to the SANS over longer periods.

Therefore taking advantage of what is best from both of these sensors requires the use of a complementary filter. The complementary filter will allow the angular rate sensor to have a high gain during short time periods (high frequency) and the accelerometers to have a high gain during long time periods (low frequency). The point where the response of these two frequency curves cross is the corner frequency of the filter response and is determined by the gains K1 and K2.

Using the same methodology, linear velocity is obtained by integrating linear acceleration. However, linear acceleration can only be relied upon for short periods of time. Over time a correction is required since the outputs of these inertial sensors are noisy. This correction comes from the waterspeed sensor. The water speed sensor is susceptible to surges which do not translate to linear motion, but over time this sensor provides accurate speed information. Thus the accelerometer output goes through a high pass filter and the waterspeed sensor is low pass filtered. The corner frequency of this complementary filter is determined by K3.

Once linear velocity is obtained, it is integrated for position in a straight forward manner. However due to current or other system errors that can not be compensated for, the estimated position may not match the actual position. To compensate for this, apparent current is calculated for each GPS fix with a gain designated as K4. The magnitude of K4 determines how much weight is given to the GPS fix.

Previous work [Ref. 3] demonstrated that the gains K1 and K2 were in the correct range. The next area to be investigated involved obtaining the correct value of K3, the corner frequency of the complementary filter for the water speed estimate. This had never been looked at since there was not a test platform available that produced a signal that the existing hardware was designed to sense. The construction of this platform is addressed in the following chapter.

# III. GOLF CART SPEEDOMETER

## A. DESCRIPTION OF PROBLEM

In order to test the position prediction capabilities of the SANS navigational filter, several tests were conducted in a parking lot on campus. Initially, it was felt that due to the low speed of the golf cart test vehicle, and the apparent of levelness of the parking lot that a constant average speed would be sufficient to allow the filter to provide a rough estimate of its position. This turned out to be incorrect because the golf cart could not maintain anything close to constant speed over the course of the run. This was cause to find a mechanism to provide accurate speed over the ground to the filter since an error in this input will create a large error in the position estimate due an inaccurate current calculation.

The golf cart was designed and built to provide inputs for accurate position measurements to serve as a platform for GPS tests. However, there was no provision to provide velocity directly via any of the installed sensors. There are numerous sensors available to do this, but due to funding constraints a home-brew solution was the one pursued. Previous projects performed on the golf cart utilized a bicycle wheel (Figure 5) attached to the rear that provided distance measurement via a reed switch and two magnets placed ninety degrees apart. Removing one of these magnets (Figure 6) would provide a pulse from the wheel upon every revolution. Using this and a timing mechanism, it is possible to calculate the average velocity of the golf cart for each wheel revolution. This would provide a speed update at a rate of slightly better than one hertz at normal speeds of the golf cart over flat terrain.

From the initial tests, the average speed of the golf cart was approximately 11 feet per second while traveling around the parking lot test track. The circumference of the measurement wheel is 8 feet. Thus at normal golf cart speeds the time for one rotation is approximately 0.7 seconds. The SANS filter was designed to work in the 2-4 knot range or approximately three to six feet per second. This equates to 2.5 seconds per wheel rotation.

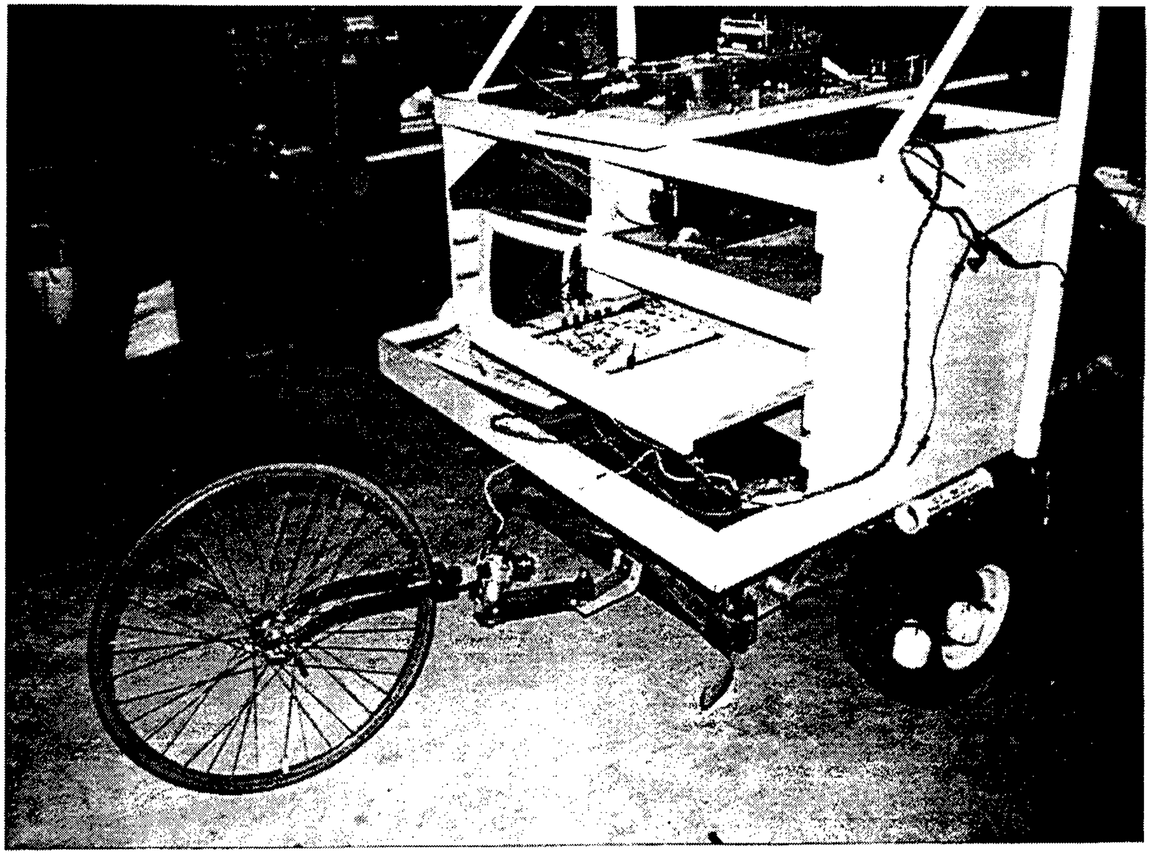

**Figure 5. Golf Cart Bicycle Wheel**

Even though it is very difficult to obtain speeds in the 2-4 knot range with the golf cart, the speed sensing device would be required to cover this spectrum in order to get as close as possible to actual underway conditions.

The water speed input to the SANS unit was designed to sense a dc voltage representing speed through the water. The voltage could be anywhere between +/- 10 volts with 204 steps per volt. In the tow vehicle, the voltage will be a direct representation of speed through the water, however in the golf cart the voltage sensed represents an elapsed time from which speed based on the circumference of the measurement wheel.

The heart of the speed sensing device design is a counter that would have as its inputs a clock and the pulse from the wheel. Using these inputs, an output representative of the number of cycles of the clock per revolution can be produced. This in turn would represent elapsed time which could be converted to speed within the software. Using a

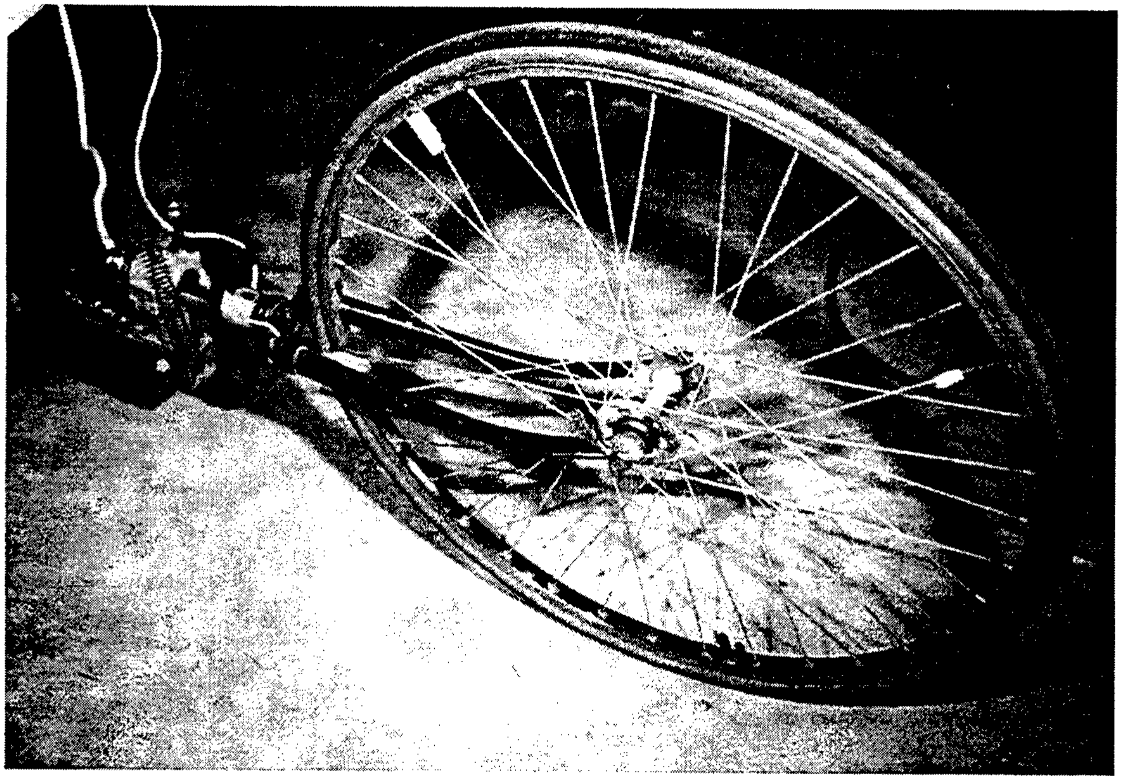

**Figure 6. Magnetic Pickups**

single magnet on the wheel, a pulse could be generated for each revolution. This would let the circuit know when the wheel made its revolution so as to start counting over again. The time counted would also be latched into a set of registers and presented to a D/A converter to provide a voltage representative of the count to the SANS unit.

Circuits of this type are highly dependent on the clock speed and the size of the register used to save the count per revolution. To determine the clock rate required, the following calculations are helpful. Let $x$ be the number of feet per second required. Then $x/8$ would represent the number of times that the wheel would revolve per second. The reciprocal $8/x$ would represent the seconds required for wheel to revolve once. Thus if $C$ represented the clock frequency, in cycles per second, then $C(8/x)$ is the number of cycles that would occur per revolution of the bicycle wheel, or in other words, the count that would be fed in to the D/A converter.

The aim of the speedometer was to create a circuit that was both simple and inexpensive. This led to an eight bit D/A converter that was readily available in the electronic lab. Eight bits allows for a resolution of 256 levels. Thus $C(8/x)<=256$. In our case x ranges from 3 to approximately 20 feet per second (a guess on how fast one can safely go in a golf cart). Solving for *C*, the frequencies that could be used range from 96 to 640 Hz. Since the golf cart would be operating in the lower end of this spectrum and for ease of human interpretation of the values out of the counter, a clock speed of 100 Hz was chosen.

## B. DESCRIPTION OF CIRCUIT

A block diagram of the proposed circuit is found in Figure 7. The speedometer consists of a clock, counter, zero detector, signal conditioner, and a latch/reset circuit. On every revolution the counter is reset to $FF and starts counting down. The clock is set to

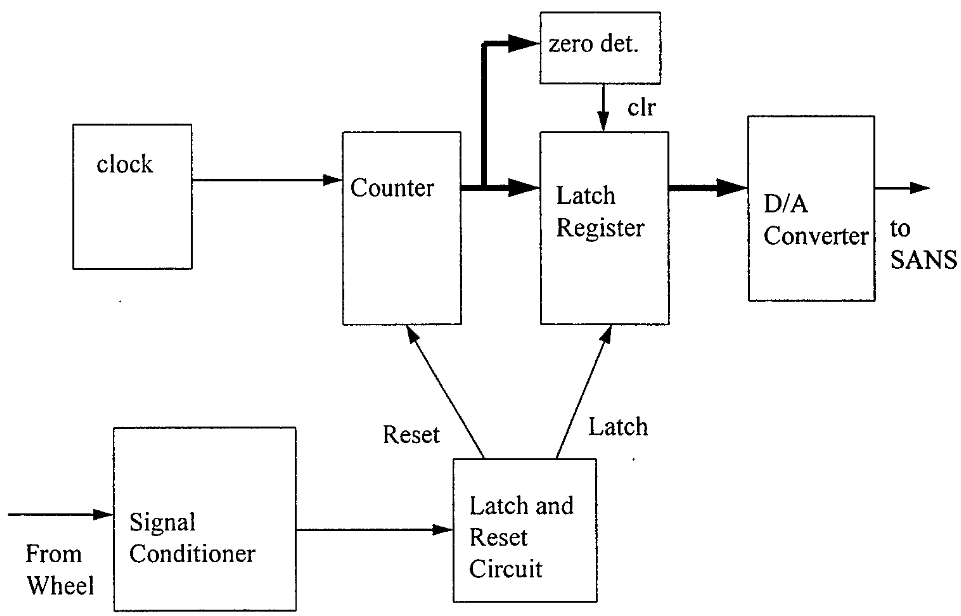


**Figure 7. Simplified Block Diagram of Speedometer**

run at 100 Hz. Thus, the least significant bit represents one hundredth of a second. Upon sensing the next revolution, the current count is latched into the latch register which then presents this count to the D/A converter for conversion.

On the input side, the signal conditioner cleans up the pulse from the bicycle wheel creating a clean square wave. The latch and reset circuitry establish the timing required to latch the current count prior to resetting the counter. The idea is that the current count will be latched into the registers, followed by a reset to start the next counting cycle. This takes a minimal amount of time so that the counter will not miss a clock cycle.

The circuit used to implement this was developed using readily available TTL components. Figure 8 is the schematic diagram of the circuit.

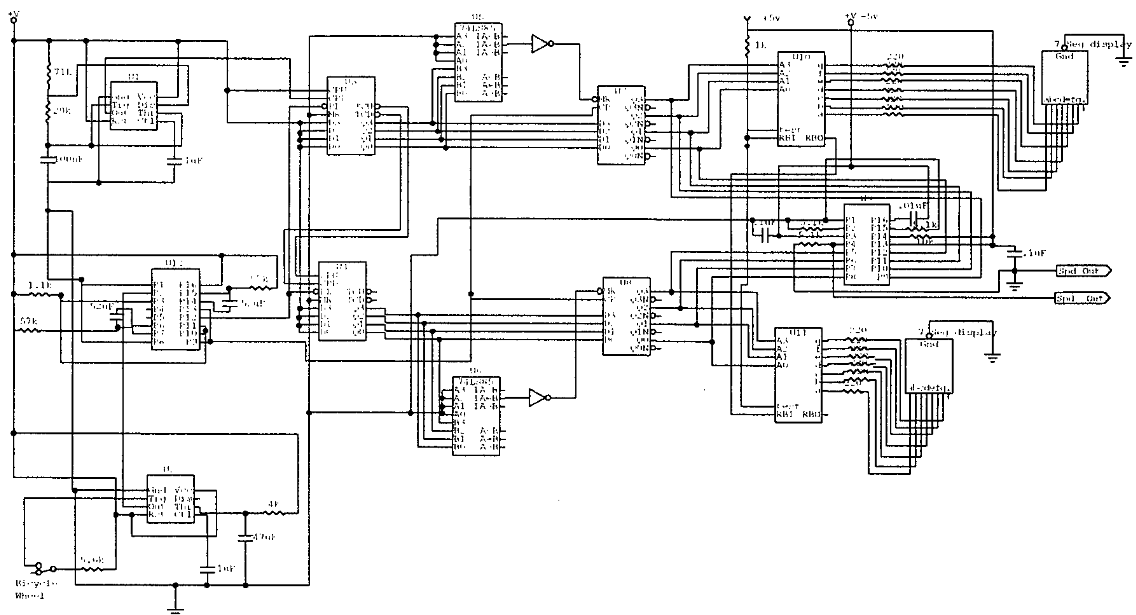

**Figure 8. Schematic of Speedometer**

## C. THEORY OF OPERATION

U1 is the system clock and consists of a 555 timer configured to operate at 100Hz. The combination of the 71K Ω, 29KΩ resistors and 100nF capacitor make up the RC timing required for the 555 to produce this clock speed [Ref. 11] . The clock pulse is asymmetric. This is not a problem however, since the logic of the counter uses only the low to high transition of the clock to change states [Ref. 12].

U3 and U4 are a pair of 74LS192 Synchronous Binary Up/Down counters configured to count down only. The reset pulse from the reset/latch logic is tied to the load input where the count $F is loaded into each counter. U3 holds the four low order bits and U4 the high order bits. It is possible to get a miscount for the first rotation since there is no procedure to make sure that the first count of the timer and position of the magnet on the wheel are synchronized. However, the SANS software averages the waterspeed prior to using it for its calculations, thus this error will be corrected as more data is obtained. Since all tests have to take place over a period of several minutes this error in minuscule. There is also a problem when maximum count is exceeded. This happens when the wheel is revolving very slowly or is stopped (very slow being more than 2.5 seconds per rotation which is approximately below 2 knots). To overcome this, a zero detect circuit is used to assert a reset on the latches holding them at $00 when this occurs. A count of $00 is then interpreted as a speed of zero in the software.

U7 and U8 are a pair of 74LS17 Quad D-Type Flip Flops with clear, which make up the latch that will hold the count for the D/A converter for each rotation. Upon receipt of the latch signal from the reset/latch circuitry, the U7 and U8 will load the current count from the Q0...Q3 lines of U3 and U4. During times of very slow speeds, the counter will wrap around and continue counting from $FF. This really only comes into play when the vehicle is stopped, since it is near impossible to move at such slow speeds with the controls available on the golf cart. For this reason, U5 and U6 monitor the output of the clock. If the clock reaches $00, it will send a master reset signal to U7 and U8 forcing all output lines low.

As just mentioned, U5 and U5 are a pair of 73LS85 4 bit Magnitude Comparators which make up the zero detect circuitry. All of the B inputs are hardwired to ground so that when the A input reaches $0, the A=B output goes high. They are cascaded together with U5 detecting a zero on the low order bits and U6 detecting a zero on the high order bits. This is done with the A=B input on U6. Both circuits must detect zero for a reset pulse to be sent to the latch circuitry.

Once the count has been latched into U7 and U8, it is immediately sent on to U9, a DAC0800 8 Bit Digital to Analog Converter [Ref. 11]. The input to this chip is a binary count representing the time of rotation of the wheel. U9 will use this count to provide specific current out to pins 2 and 4. These two pins provide a complementary output, i.e. when pin2 is at maximum, current pin 4 is at minimum. In the configuration used, the full scale current out is dependent on the reference current at pin 14. The reference current is given by ohms law as $V_{rev}/R_{ref}$. In our case, $V_{ref}$ is 5 volts and $R_{ref}$ is 10kΩ. This makes $I_{ref}$=.5mA. From the data sheet, the full scale current is then $I_{ref}$ * .996=.498mA. This makes a voltage drop of 2.54 v across the 5.1kΩ resistor off either pins 2 or 4. The actual value was found to be 2.45 volts. A plot of voltage out pin 4 to ground is found in Figure 9. This figure shows that the output is fairly linear across the scale and is operating as described in the data sheets. The voltage for the least significant bit turns out to be 9.55mv. The SANS A/D board precision is 5mv, thus it is possible to be accurate to within one hundredth of a second. It should be noted since the D/A converter is a current source and the output resistors are referenced to ground. The voltage out across the resistors is -9.55 volt/bit.

U2 is the signal conditioning circuit. It consists of a 555 timer that is configured as a monostable multivibrator. Since the signal from the reed switch on the bicycle wheel is noisy and changes in size depending upon the angular velocity of the wheel, this circuit takes what ever the reed switch generates and produces a pulse that is .2ms in duration. This is sufficient for a the U12 to generate a latch and reset signal.

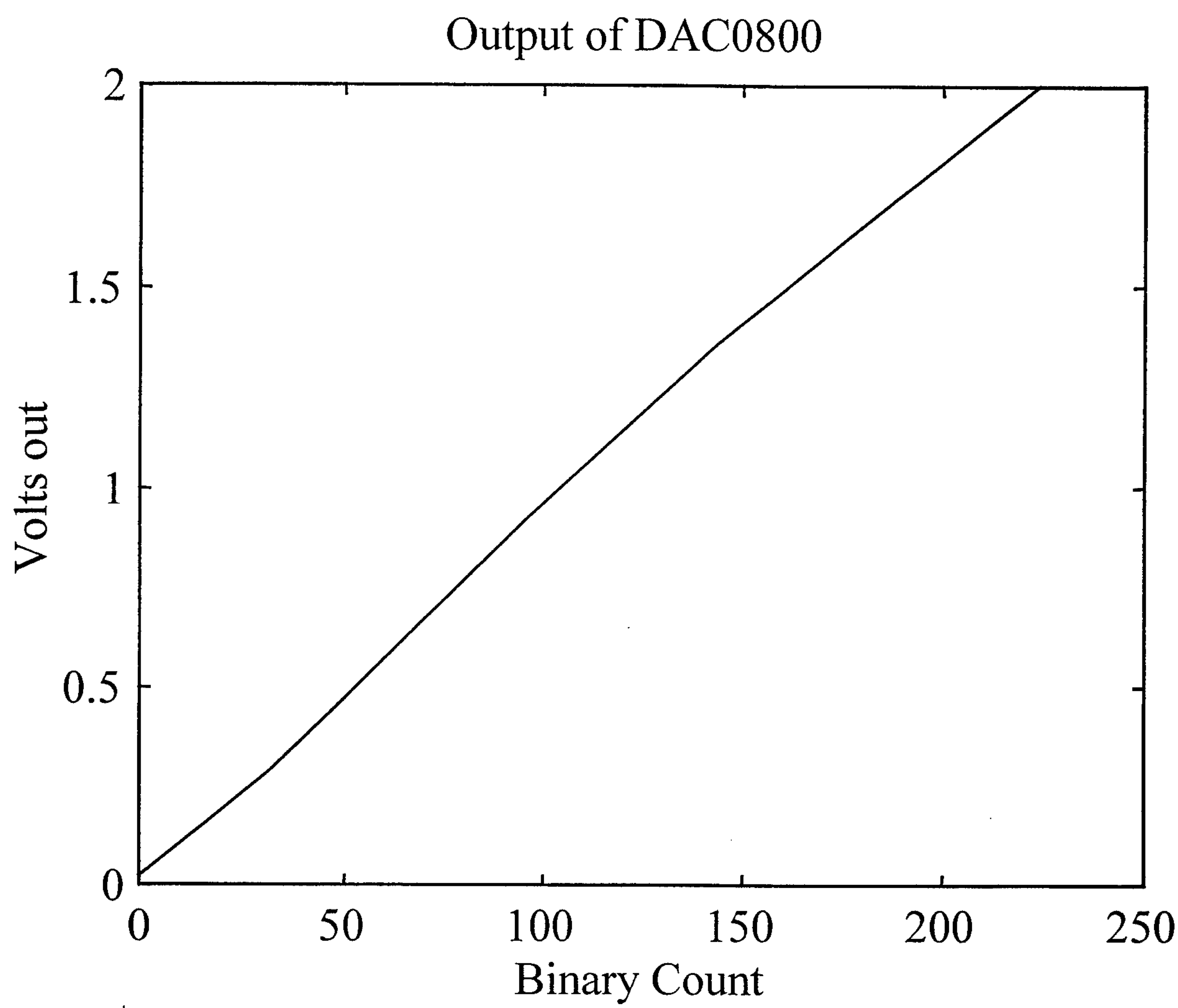


**Figure 9. Actual Voltage out of D/A Converter**

The reset/latch circuitry is made up of U12 which is a 74LS123, Dual Retriggerable Monostable Multivibrator. Each side of this IC works similar to the 555 timer used above, in fact a 555 could have been used here, but to reduce chip count on a already crowded bread board the 74LS123 was used. Both of these monostable multivibrators are configured to produce a 3ms pulse out upon reception of an input pulse. What makes this circuit work is that the input of the first monostable multivibrator is the output of the signal conditioning 555 circuit mentioned above. The output of this circuit then goes to two places. The first is what has been called the latch signal which is sent on to the Quad D flip flops to save the current count of the counter. The second is to the input of the other monostable multivibrator. This second multivibrator again produces a 3ms output that goes to the counter chips to load in $FF so another round of counting can be initiated.

The last part of the circuit is a visual display of the count. This is composed of U10 and U11, a pair of 74LS48 7-segment LED drivers and the respective 7 Segment LED. This IC takes a 4 bit binary number and converts it to the correct signals to drive a 7 segment display. This circuit is not necessary for the operation of the speedometer, however it provides an indication that power is applied and the circuit is working. On the actual speedometer mounted in the golf cart, there is another set of LED drivers and LED displays connected to the output of the counter. Again, these are there only as troubleshooting aids and were not included in the schematic.

## D. TESTING

As stated above when discussing the D/A converter, the precision of the A/D converter in the SANS unit has a resolution great enough to measure times to within one hundredth of a second. As would be expected, the relationship between time and voltage out is very linear. The first test of the speedometer was conducted on a test bench with the wheel mounted in the air so that it was free to rotate. Another circuit was built to measure the elapsed time for three rotations. The schematic for this is shown in Figure 10.

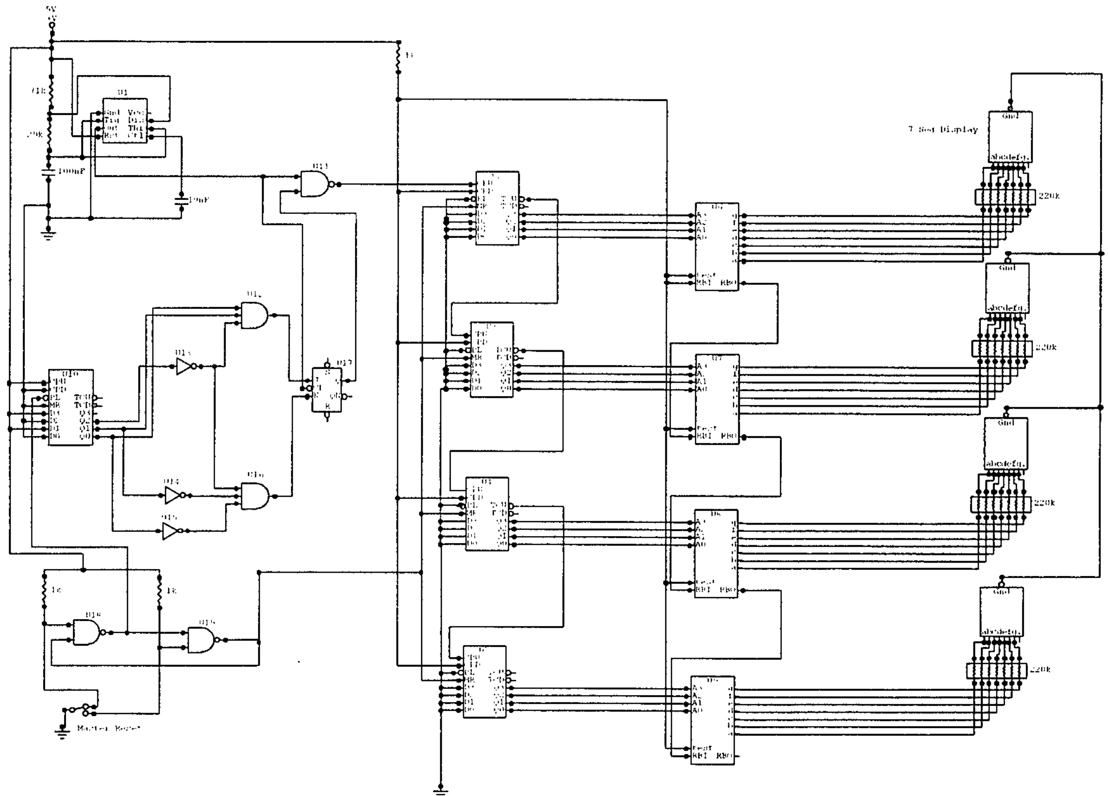

**Figure 10. Gated Timer**

The operation of this is fairly straight forward. It is essentially a timer that has a control gate to determine when to start and stop. U1 is the system clock and consists of a 555 timer configured to operate at 100 Hz. The output of this is sent to U11 that acts as a gate to the clocking signal. When the correct signal is asserted on its other input it will allow the clock signal to pass through to the counters. U2 through U5 are a set of 74LS193, Synchronous Decade Up Counters. Once the clock signal gets through U11, this bank of counters will count up to the maximum limit of 2000 which equates to 20 seconds. The output of the counters is sent on to U6 through U9, a set of 7448 BCD to 7 Segment Decoder which in turn drives the 7 segment display.

The control of the gating signal is completed by U10 through U17. U10 is another 74LS192 configured to count down. When the circuit is reset, a binary five is loaded in. Then as the bicycle wheel rotates, it sends a signal to the count down input. Once the counter gets to a binary 3 which has been decoded via the three input AND gate U12, there will be a 1 on the J input of U17. Thus at the next clock cycle from U1, a 1 will be out on the Q output of U17 enabling the clock signal to be gated through U11 and onto the main bank of counters. This will continue until a binary zero is detected by U16. Once a zero is detected it will reset the J-K flip flop on the next clock cycle of U1 and thus block the clock pulse to the main bank of counters. This effectively locks in the time it took the wheel to rotate three times.

The initial test showed that the relationship between time and volts out is linear as shown in Figure 11.

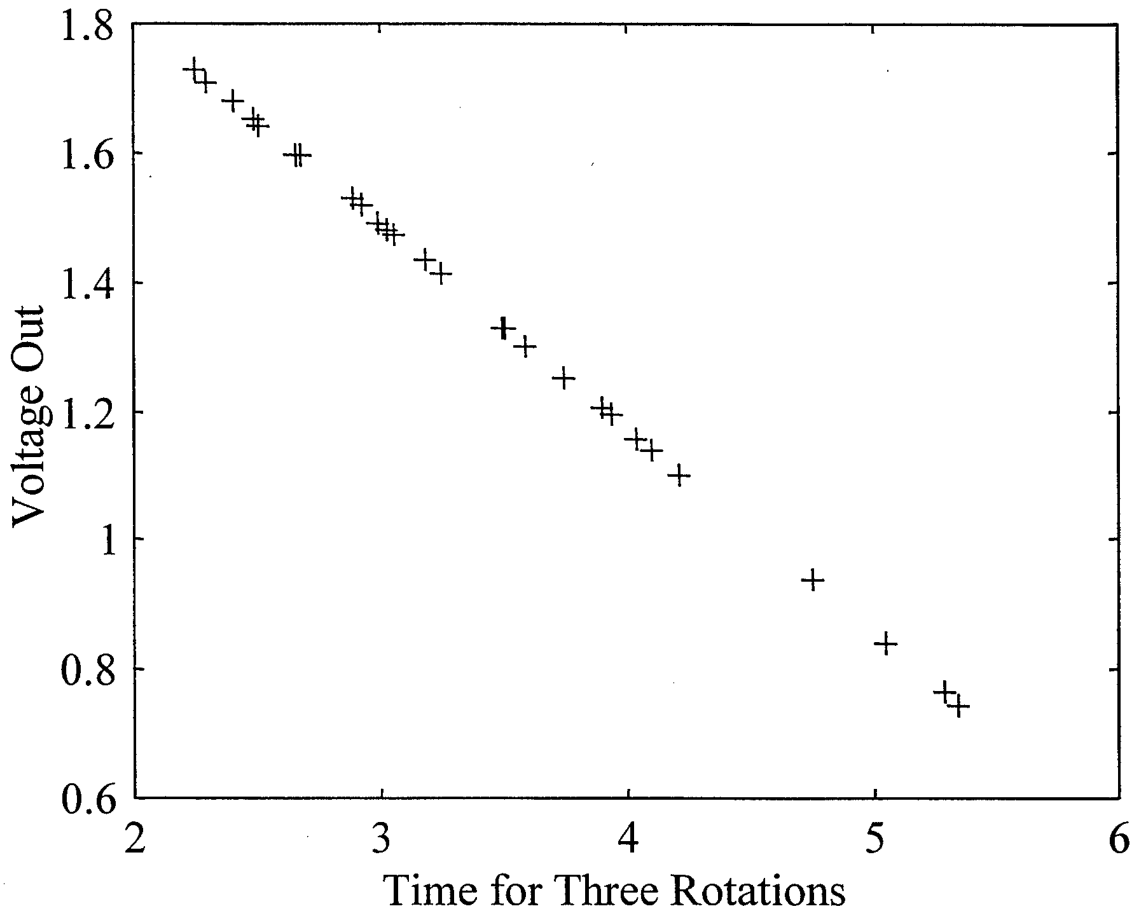

**Figure 11. Bench Test Voltage Out**

## E. CONVERSION FROM ELAPSED TIME TO LINEAR VELOCITY

The conversion from elapse time to speed is straight forward. The output from the speedometer is a voltage representing elapsed time for one rotation. This has the form:

$$Speed = \frac{1563.9}{SANS\_OUT - 2047}. \quad \textbf{(1)}$$

Equation (1) is determined from the following derivation. Let Γ be the circumference of the wheel and K be the count from the speedometer. Then the velocity (ν) is given as:

$$v = \frac{\mathrm{K}(feet\ /\ rotation)}{\Gamma(\mathrm{sec}/\ rotation)}. \quad \textbf{(2)}$$

Looking at the units only, rotation cancels out thus the result is feet/second = velocity (ν). Recalling that the speed count is in hundredths of a second, the conversion to linear velocity results in a formula of the form:

$$v = \frac{8}{\frac{\mathrm{K}}{100}} = \frac{800}{\mathrm{K}}. \quad \textbf{(3)}$$

The counter counts down so that the actual time per rotation is 256 - K on the counter. However, the output comes off the inverting pin of the D/A converter and thus for the discussion that follows, the speedometer count can be thought of as an up-counter with an output value K.

As previously mentioned, the output of the D/A converter has the following relation to the voltage out (V):

$$V = -.00955 \times \mathrm{K}. \quad \textbf{(4)}$$

Solving for K results in:

$$\mathrm{K} = \frac{V}{-.00955}. \quad \textbf{(5)}$$

Substitute equation (5) into equation (3) results in,

$$v = \frac{800}{\frac{V}{-.00955}} = \frac{-7.64}{V} \quad \textbf{(6)}$$

Looking at the problem from the SANS point of view, the A/D converter has a conversion in the ratio of 204.7/volt. Since the converter converts 0 volts to a digital value of 2047, -10 volts to 0, and +10 to 4096 there is an off set to consider. Let T be the value the SANS filter reads out of the A/D converter. The conversion from volts to this value is:

$$\mathrm{T} = (V\_in \times 204.7) + 2047 \quad \textbf{(7)}$$

Solving for volts in results in:

$$V\_in = \frac{\mathrm{T} - 2047}{204.7} \quad \textbf{(8)}$$

Volts out of the speedometer is the same as volts in to the Sans unit, so to obtain the conversion, substitute equation (8) into equation (6).

$$v = \frac{7.64}{(\frac{\mathrm{T} - 2047}{204.7})} = \frac{1563.9}{\mathrm{T} - 2047} \quad \textbf{(9)}$$

It may seem possible that there is a divide by zero error at some point in the code, however this will not happen due to the physical constraints of the system. A value of 2047 received by the SANS system means that there is zero volts out of the D/A converter of the speedometer. It is possible that this could happen if the wheel were rotating at speeds greater than 800 feet per second. This is not a realistic possibility. The only other way to get zero volts out is to cut the wire. This actually did happen while testing and the program crashed with a divide by zero error.

Another limitation of this system is the slowest speed detectable. The slowest speed is represented by a rotation every 256 seconds which corresponds to a speed of 3.13 feet per second. Below this the speedometer will consistently report a speed of 3.13 feet per second. Unfortunately this also includes when the cart is stationary. This will have to be recognized as a limitation of the design thus when the speed goes below an certain value the software will have to report zero speed.

## F. SUMMARY

The speedometer described in this chapter is made to input elapsed time for one rotation of a bicycle wheel. The conversion from time to speed is performed in the filter software. A different conversion will be needed if another sensor is used or when the SANS unit is placed in the UAV. This circuit allowed further testing of the filter to be performed with the assurance that the software was receiving a better representation of its velocity. This was useful in finding the software error described in Chapter VI.

# IV. WATER SPEED INDICATOR

## A. INTRODUCTION

Another goal of this thesis was to determine if the paddle wheel water speed is accurate enough to support at an sea test of the SANS unit. One of the requirements of the SANS project is to have a sensor that can detect speed with the accuracy of 1 knot. The reason for this is that during periods with no GPS fixes the filter depends upon its constant gain Kalman filter to estimate position. In the complementary filter, the water speed indicator is believed over long time periods. That is, small impulses in speed change will be filtered out, but the speed inaccuracies from the speed indicator will be integrated into the position estimate creating large errors.

The water speed sensor mounted on the towfish enclosure is a paddle wheel that uses a magnetic pickup for the mechanical to electrical conversion of water speed. As water flows past it, the paddles rotate creating an A/C signal that is about 1 volt peak to peak and varies in frequency with the rotational velocity of the wheel. This type of sensor is designed to provide inexpensive speed estimates for motor boats. Under normal conditions, vessels using this type of sensor are going much faster than 2-4 knots with the understanding that the water speed indicator is not expected to supply a precise water speed readout. Thus, the question that needed to be answered was, "is the water speed indicator good enough for the SANS, if the SANS knew and was able to compensate for its limitations."

Originally the paddle wheel was connected directly to the D/A converter in the SANS unit. However was incorrect since the paddle wheel is an A/C signal and the SANS filter needs a DC signal representing speed, or something that speed could be derived from. Thus a decision needed to be made concerning the conversion of the time varying A/C signal to a D/C signal. It was decided that an IC device that was designed for the purpose of converting a frequency to a voltage should be used.

## B. DESIGN OF FREQUENCY TO VOLTAGE CONVERTER

The IC selected was the LM2907 frequency to voltage converter. The circuit used is shown below in Figure 12.

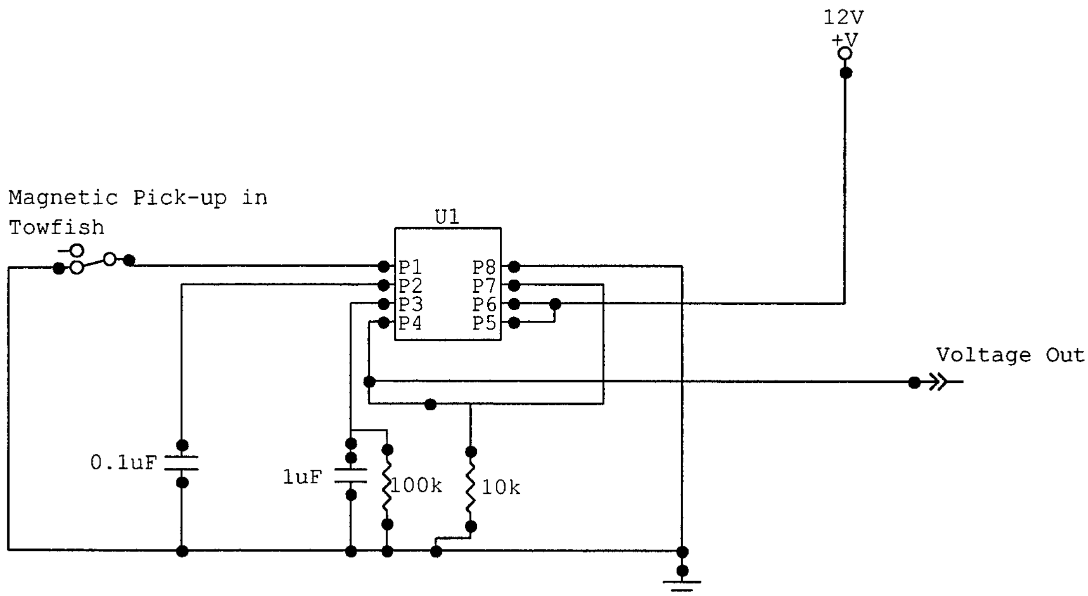


**Figure 12. Frequency to Voltage Converter**

The output of the circuit is determined by the product of $F_{IN}*V_{CC}*R_1*C_1$. Where $R_1$ is the resistance seen on pin 3 and $C_1$ the capacitance seen on pin 2. The circuit in Figure 12 is found in National Semiconductor databook [Ref. 12] and produces a voltage out of 0.5 volts for an input frequency of 10 Hz. This is the lower limit of the paddle wheels rotational capability. That is, the internal friction of the paddle wheel will not permit slower rates of rotation. For low Rpm's, the circuit was found to have lower that expected voltage out however, the signal was very reliable. Therefore, this output provides information concerning the sensitivity of the paddle wheel.

## C. TESTING

The method used to test the waterspeed sensor was via water flowing through a water trough. The source of the water was a large tank that was approximately 20 x 20 x 8 feet in size. This supplies enough water to maintain a constant velocity for several tests of the sensor. The water from the tank was throttled using a gate valve and carried to the trough via a 2 inch pipe(see Figure 13). Here it was discharged into the trough where the waterspeed sensor, mounted on the towfish unit, was placed in the water flow. The voltage and frequency of the sine wave produced by the sensor was measured along with the output of the circuit in Figure 12.

Just downstream of the towfish enclosure were two flashlights that illuminated two photo resistors (see Figure 13). These light beams acted as a start and stop gate for a timer circuit similar to that used to time rotations of the bicycle wheel in Chapter III.

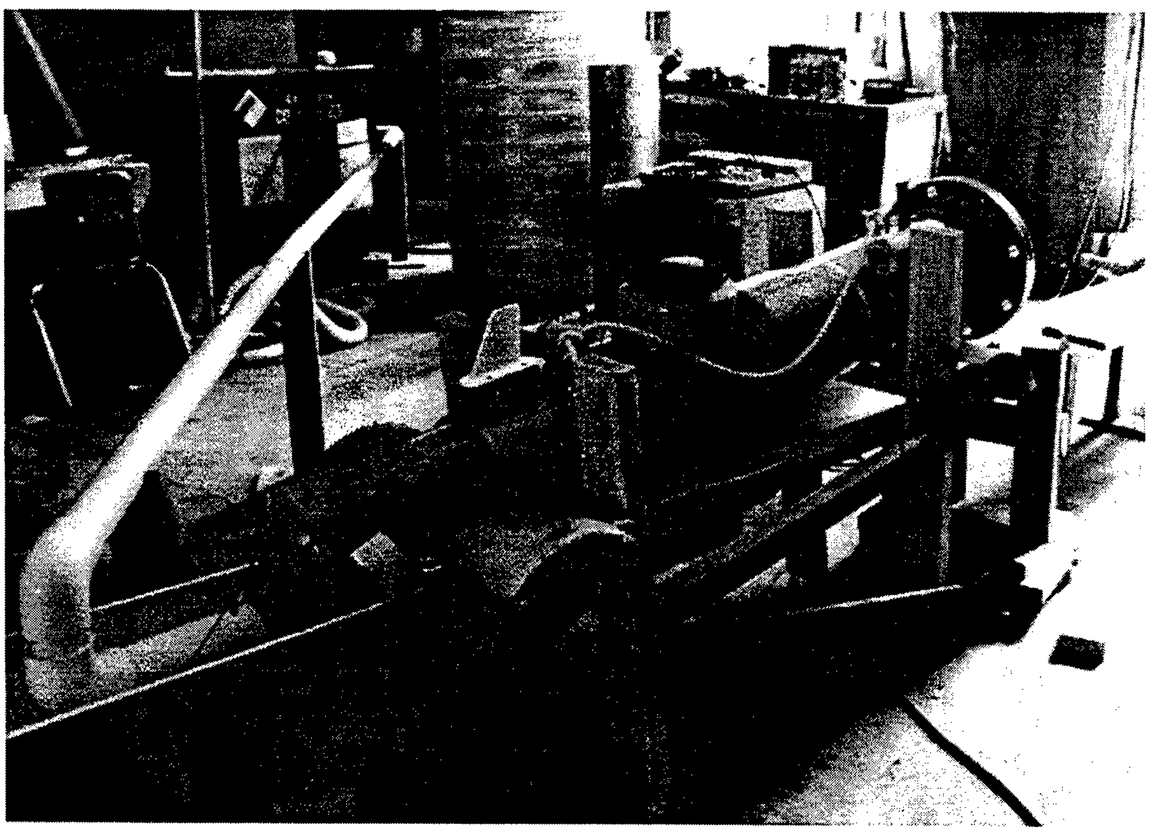

**Figure 13. Water Speed Sensor Test**

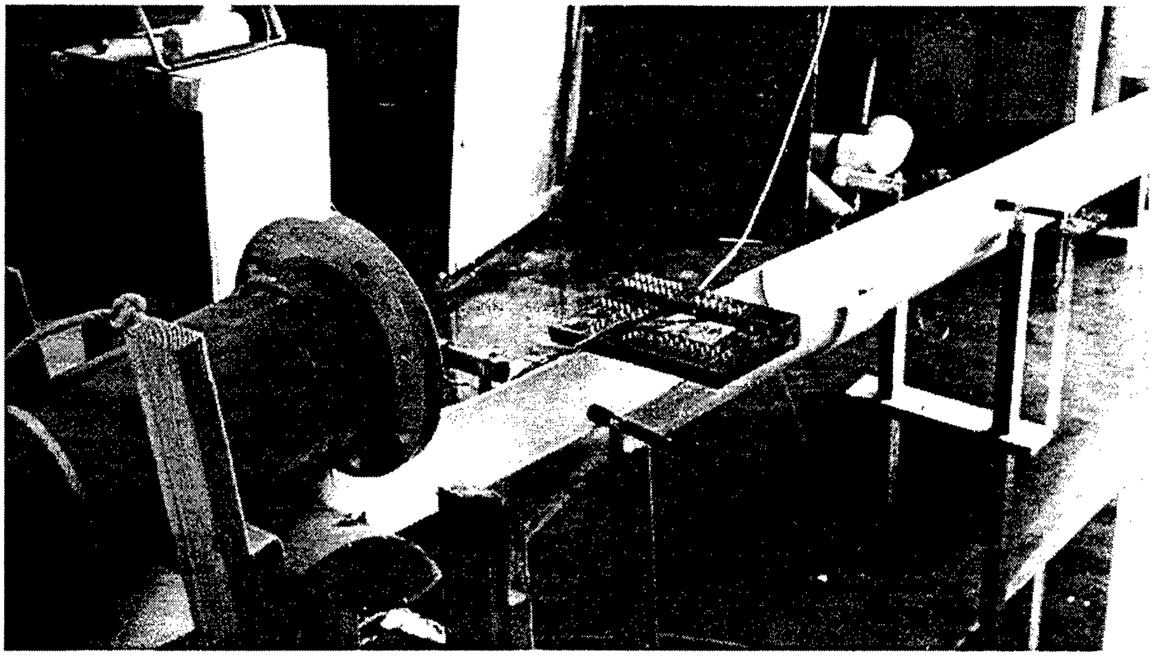

**Figure 14. Start and Stop Light Gate**

The circuit used is shown in Figure 15 and operates as follows. U1 is a 555 timer functioning as the system clock operating at 100Hz. U2 is a NAND gate that permits the clock pulse to be seen at U3 through U6 if enabled. The enabling signal comes from the latch formed from U11 and U12. As the rubber duck goes down the trough, it first passes the start light beam. When this beam is interrupted, the latch is set causing a high to be felt on the bottom input of U2. This in turn will cause the timing pulse to pass through. When the rubber duck interrupts the finish beam, the latch resets, causing a low to be asserted on U2 cutting off the timing pulse. The rest of the circuit works exactly like the one described in Chapter III. U3 through U6 are a bank of 743192, decade up/down counters that count the elapsed time in hundredths of seconds. U7 through U10 are 7447, 7 segment drivers that convert the binary decimal code to a set of signals that can be used to display the result on a 7 segment LED. The reset circuitry consists of U13 and U14 which form a signal conditioner to debounce the reset switch.

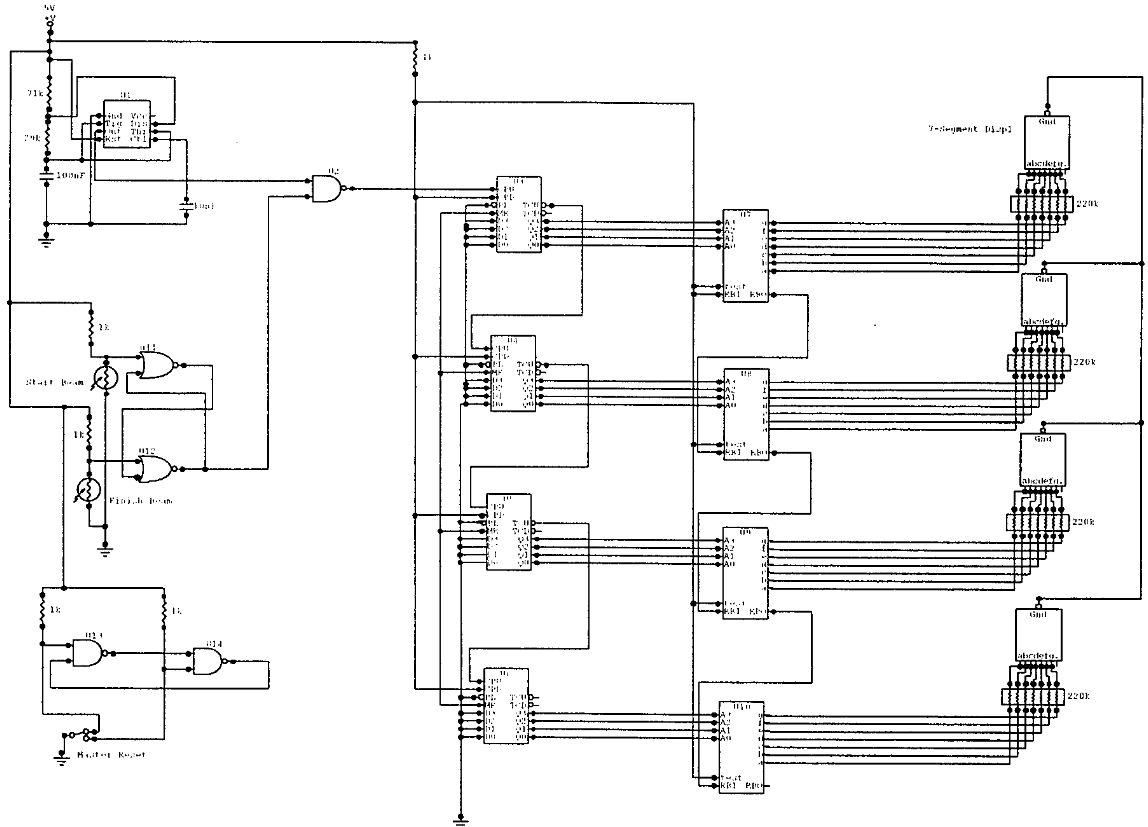

**Figure 15. Timer Circuit**

Velocity of the rubber duck is determined in the obvious manner using the distance traveled divided by time to traverse the distance interval.

The idea behind this experiment is that the flow of water past the paddle wheel is very close to the velocity of the water in the speed gate that the rubber duck would ride in. Thus, a correlation can be made between the velocity of the duck and the voltage out of the paddle wheel. This will provide an insight into the performance of the paddle wheel sensor.

## D. RESULTS AND CONCLUSIONS

Figure 16 shows the data obtained from the testing which clearly indicates that the paddle wheel sensor's characteristics are not consistent enough to be modeled with a curve or even interpolated with a look up table to determine the speed of the water flow past it.

Thus the paddle wheel does not have the characteristics needed to provide speed to the SANS filter. An alternate method must be found.

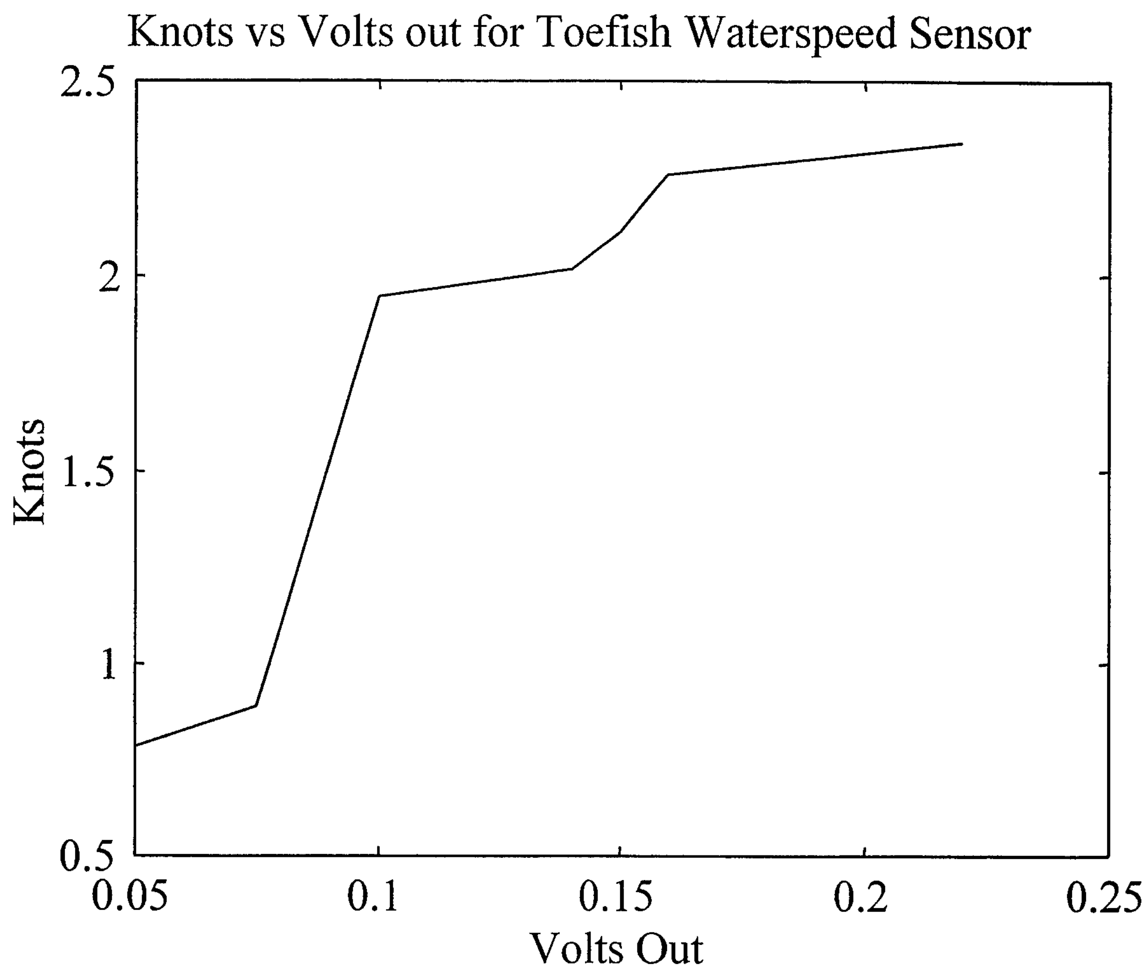


**Figure 16. Results of Water Speed Sensor Test**

# V. COMPASS CALIBRATION

## A. INTRODUCTION

The final sensor analyzed in the SANS system was the digital compass. The instrument is a Precision Navigation model TCM2 Electronic Compass Module. It uses a three axis magnetometer and a high-performance two axis tilt sensor to determine heading and orientation. The goal [Ref. 2] is to have a directional measurement device that can sense headings to within one degree of the actual heading. Earlier tests demonstrated that even though the direction of position estimations were correct, greater precision was needed meet the goals of the project.

Figure 17 shows a typical run of the parking lot test track with GPS updates every 10 seconds. The sawtooth like edge of the northerly run is evidence that the filter is not receiving the accurate directional information. The cart starts out on a heading of 260 (west) and turns north to 350 (north). Figure 18 shows the filter heading as recorded by the filter. The filter shows that it is heading approximately 260, the correct value. However the turn to 350 is overshot by 3-6 degrees. This trend is continued up the entire leg of the run causing a fairly large correction upon every GPS fix. Two areas seemed the most obvious sources of the problem. One being the interference produced by the golf cart electric motor and the other being compass deviation of the TCM-2 itself. The investigation presented takes a look at both of the these sources of error.

## B. INTERFERENCE CAUSED BY ELECTRIC MOTORS

The TCM-2 has a self calibration routine which should be ran every time the compass is mounted at a new location. This routine is supposed to remove the effects of static magnetic fields caused by ferrous materials in the vicinity of the compass.

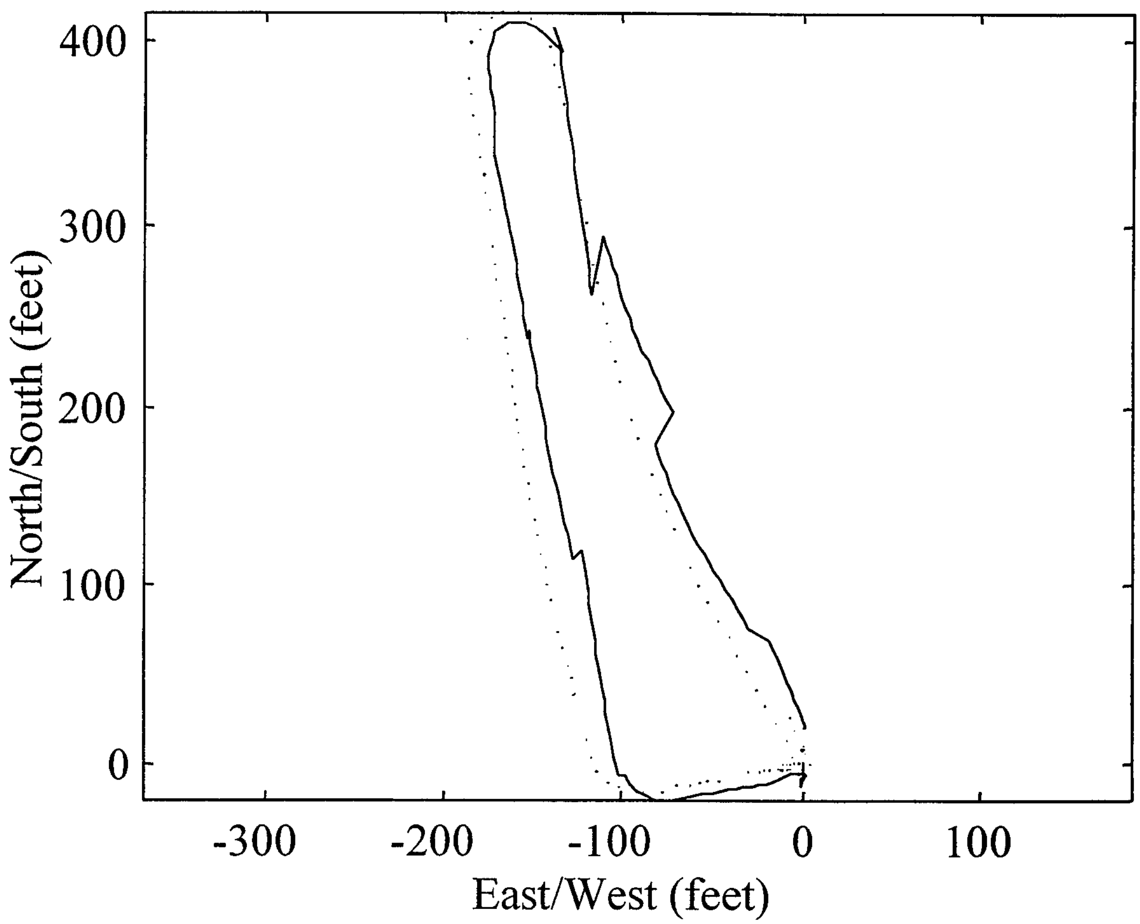


**Figure 17. Typical Run, 10 Sec GPS Updated**

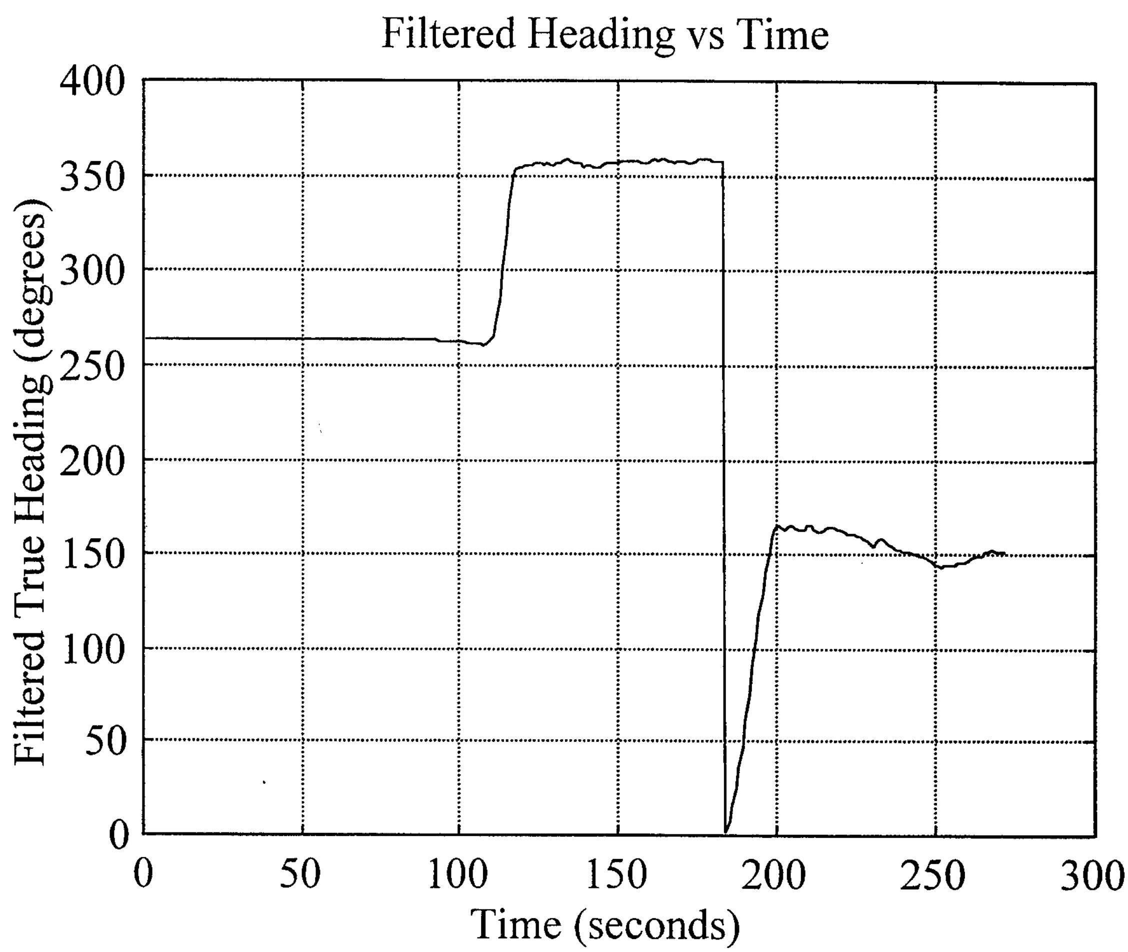


**Figure 18. True Heading vs Time**

The calibration routine is not capable of compensating for dynamic magnetic field distortions like those caused by an electric motor. To find what effect the electric motors have on the compass a series of tests was performed.

The first test involved jacking up the rear wheels of the golf cart so that they could spin freely while the motor was on. The motors were turned on for 30 second intervals followed by a 30 seconds off time. During the off time, the wheels continued to rotate for approximately 10-15 seconds until they came to a stop. This test allowed changes in heading due to motor engagement to be observed. The graphs of these tests appear in Figure 19 through 22. The same test was performed four times rotating the cart through the cardinal points.

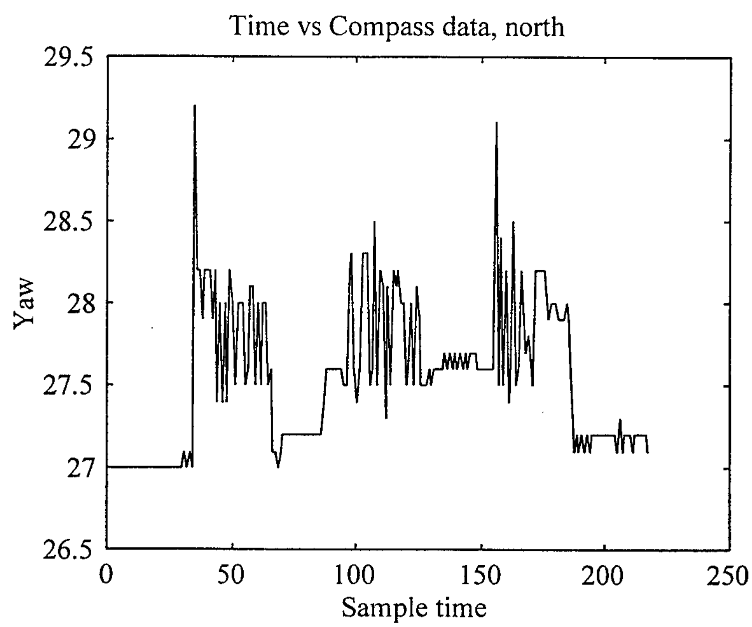

**Figure 19. North Facing Test**

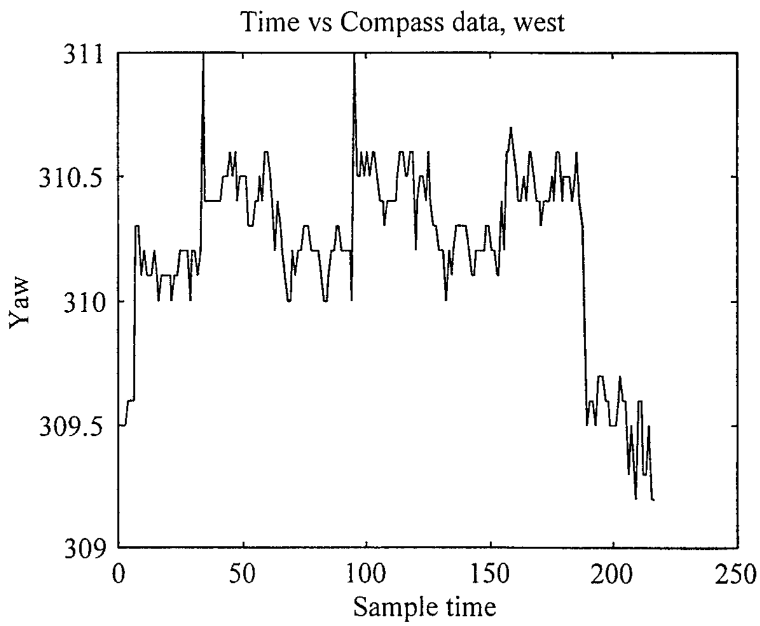


**Figure 20. West Facing Test**

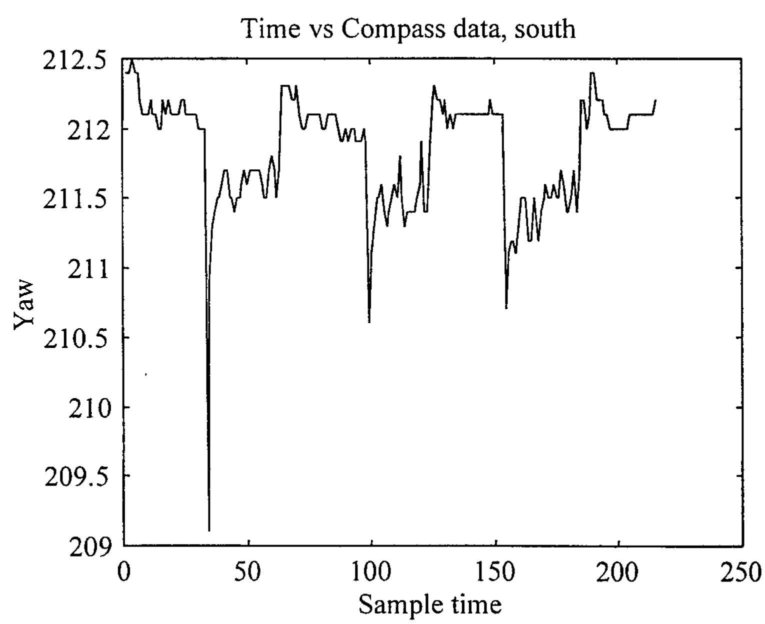


**Figure 21. South Facing Test**

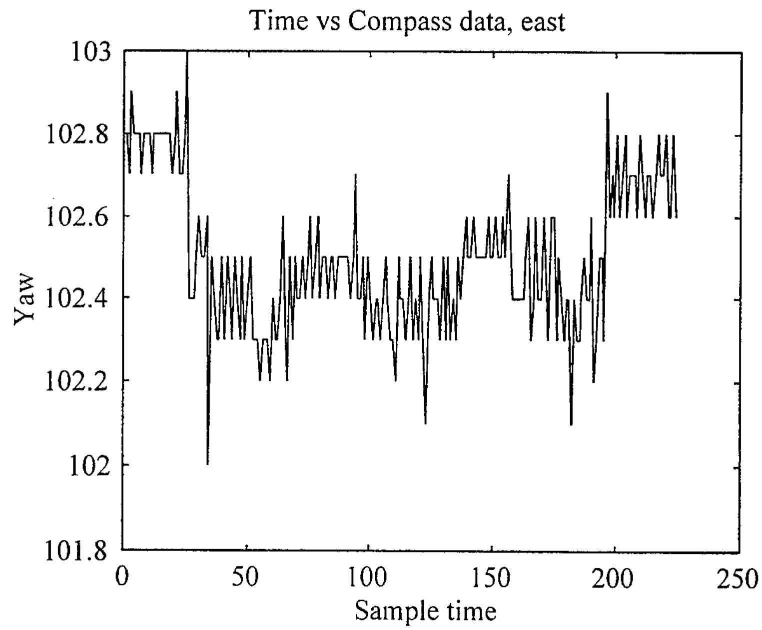


**Figure 22. East Facing Test**

The graphs indicate that there is interference, but its magnitude appears to be limited to approximately a half a degree. The graphs also indicate that the noise is at a relatively high frequency which can be compensated for with an appropriate value for $K_2$, the time constant that controls when the compass is believed more that the angular rate sensors.

The test was a good data point for use in verifying if the motors were interfering with the compass. However the loading of the motor will also effect the magnetic field. To see the effect of motor loading, the cart was driven up and down a slight hill in a straight line. At first the cart was at rest for 60 seconds to get a good representation of the system prior to engaging the motors. Then the cart was driven up (Figure 23) or down (Figure 24) a the hill.

These tests show that there are large compass deviations once the cart starts moving. However, a subsequent test shows that all interference is not coming from the magnetic field generated by the electric motors.

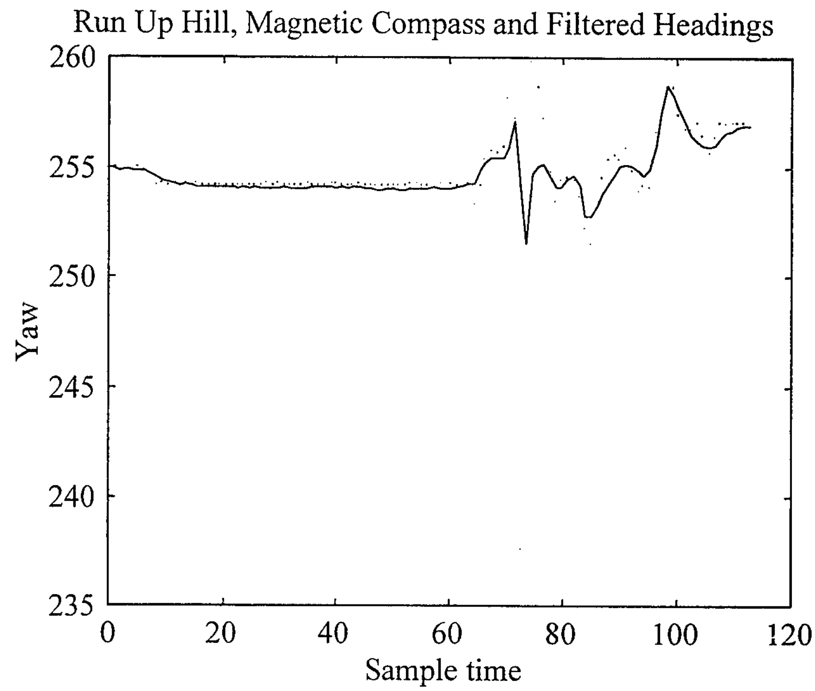


**Figure 23. Up Hill Run**

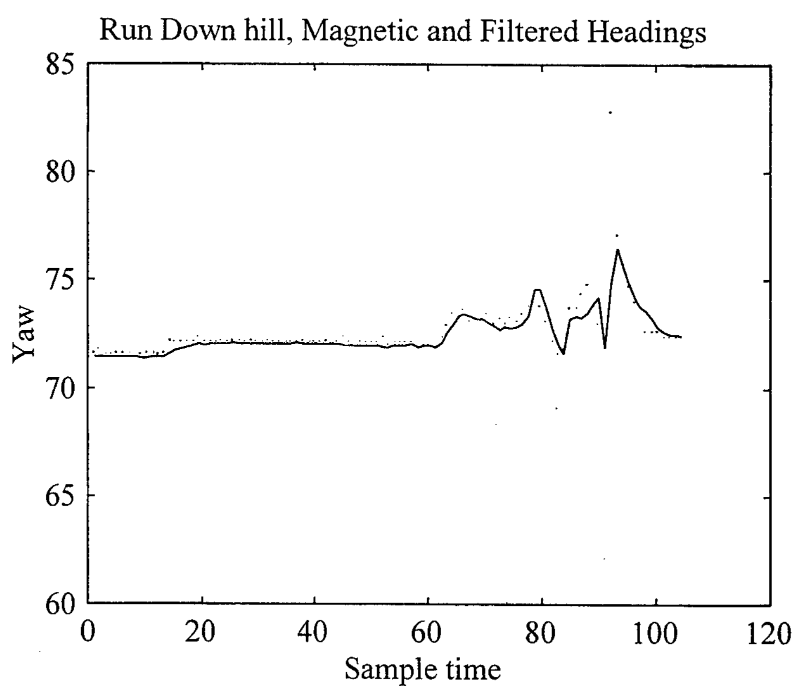


**Figure 24. Down Hill Run**

Vibration plays a much greater role in compass error than the electric motors. This can be seen in Figure 23 and 24. At the beginning of the up hill run there is a large deviation. This is the same physical location as the large deviation found at the end of the down hill run. The road that the test was conducted on was bumpy in this area.

To confirm this, Figure 25 shows another test conducted while the cart remained stationary and the board the compass is mounted on was vibrated by taping it lightly with a screwdriver and a finger. Figure 25 shows large deviations of 10 degrees or greater. (The largest deviations are the result of taping lightly with the screwdriver. The metal of the screwdriver is suspected of playing a major role in the magnitude of these deviations and should be ignored.) However, these deviations are high in frequency relative to the measurement of interest and should again be able to be filtered with an appropriate value of $K_2$.

## C. TCM-2 MAGNETIC DEVIATION

The next area investigated was the heading dependent nature of compass deviation. The test runs performed showed that during east-west runs the errors were not as large as the test runs that went north and south. It was also reported that deviations of up to 10 degrees were found by other users of the TCM-2. Thus testing for compass deviation was needed to ascertain the magnitude of possible error.

Magnetic deviation tests were performed by swinging the compass, comparing the indicated direction against a reference. The instrument used as the reference was a transit manufactured by W. and L.E. Gurley. This had a calibrated, balanced magnetic compass mounted within its body. By mounting this in line with the TCM-2 a comparison could be made between the two measurements to determine the TCM-2's deviation (Figure 26).

The compass was swung through the entire 360 degrees taking measurements every 10 degrees. The raw data from the TCM-2 was recorded and compared to the actual magnetic heading. Figure 27 shows the difference between the measurements of the transit and those of the electronic compass. Using this data a table lookup and linear interpolating function was added to the existing SANS filter code.

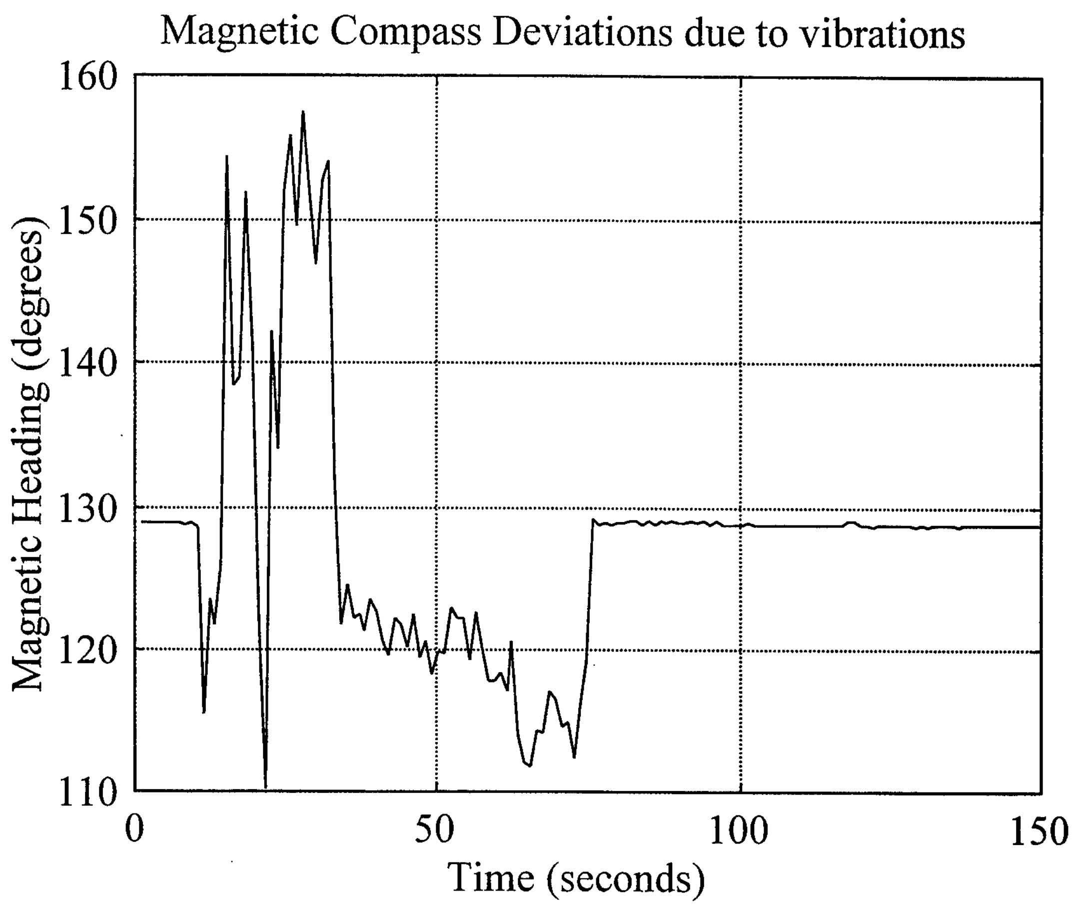


**Figure 25. Vibration Testing**

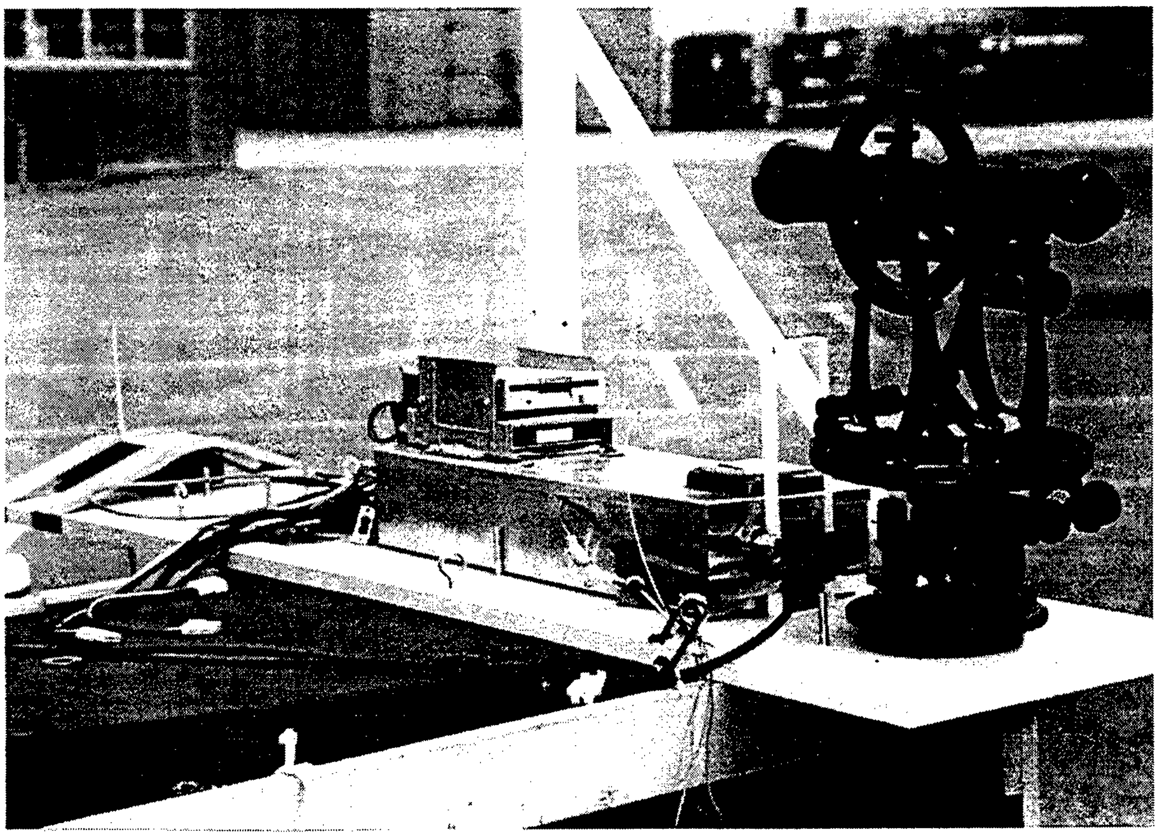

**Figure 26. Swing the Compass**

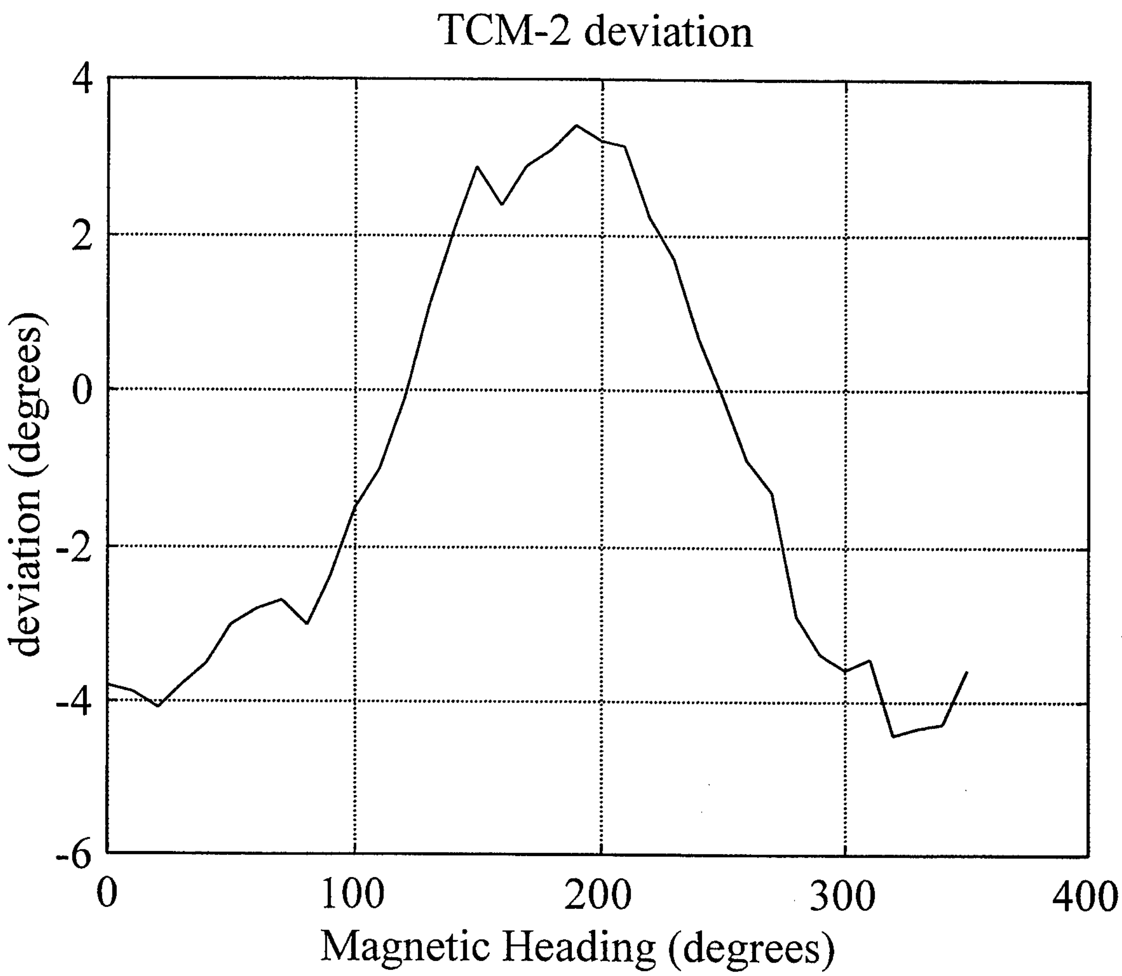

**Figure 27. Compass Deviation**

## D. SUMMARY

Magnetic deviation proved to be the major source of directional error in test runs. The tests indicated that turns from west to north over shot the actual turn consistently by about 5 to 6 degrees. The is supported in the deviation table where the correction for a westerly headings is small (less than one degree) where as the correction for northerly heading is approximately -4 degrees. Correction of this would reduce the amount of overshoot. Interference from the electric motor was considered small enough to ignore as long as $K_2$ was set to a value high enough to filter out most of the associated noise. This will also filter out the noise seen due to vibration. As previously mentioned, $K_2$ was set to 0.5 for the runs to date. This corresponds to a time constant of 2 seconds. It is felt, due to the above test results, that $K_2$ should be decreased to 0.1. This corresponds to a time constant of 10 seconds and would make the filter less responsive to the high frequency transients caused by vibration of the platform.

# VI. RESULTS

## A. INTRODUCTION

The current system in use was configured and assembled by Walker [Ref 2]. It has been evolutionary in nature in the sense that at first the emphasis was to get all of the parts put together and working. Other than the IMU, no other source of sensor error was investigated. Later the system was tested for accuracy in attitude estimates by Roberts [Ref 3] with excellent results. During this phase of testing, besides making sure the software worked correctly, a major emphasis was on determining a proper value for the gain $K_1$. Since all tests were conducted on a nonrotating tilt table the only requirement of the compass was to provide a static input. Thus K2, which determines the time constant of the compass input, was tested only in a limited sense. The goal of this thesis was to provide an accurate sensor to detect ground speed in order for land tests to be performed, investigate the existing water speed sensor and to characterize the input received from the compass.

## B. INITIAL RESULTS

All land tests were conducted in the parking lot next to the Mechanical Engineering Auditorium at the Naval Postgraduate School . The path is shown in Figure 28. The first runs showed that there were problems with the system. A plot of a typical run with continuous and intermittent GPS is shown in Figure 29 and 30 respectively. The cause of the large divergence in the position estimate was not immediately known, but the calibration of the speed inputs with the verification of the compass, showed that these inputs were not the source of the large error seen in the plots. Later it was found that the error was caused by a sign error in the east-west direction of the GPS position updates provided to the navigation filter. After these corrections, the plots were acceptable for up to 20 seconds between GPS update intervals. Figure 31 and 32 show a typical run with 10 and 20 second updates. These results indicate that the heading appeared to have deviation errors. This pointed towards the compass as a potential error source.

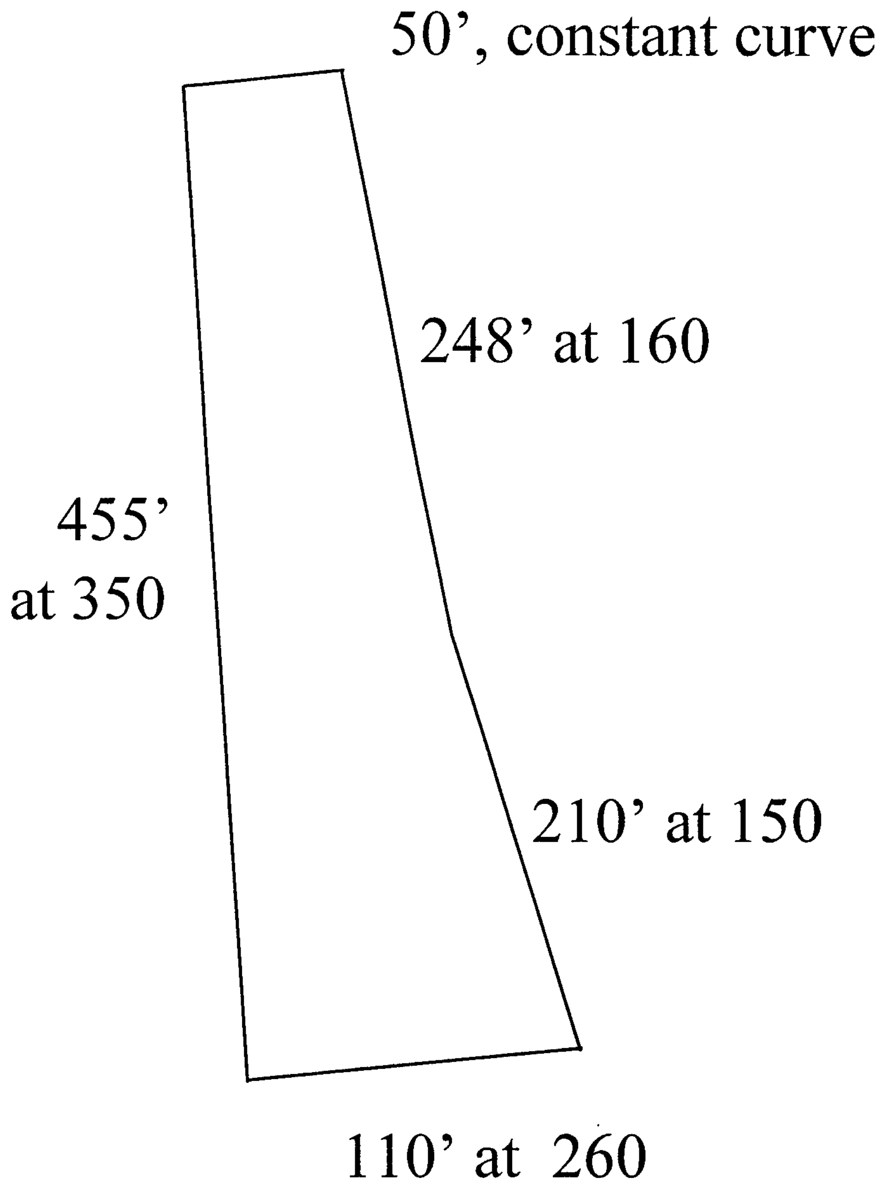


**Figure 28. Parking Lot Test Track**

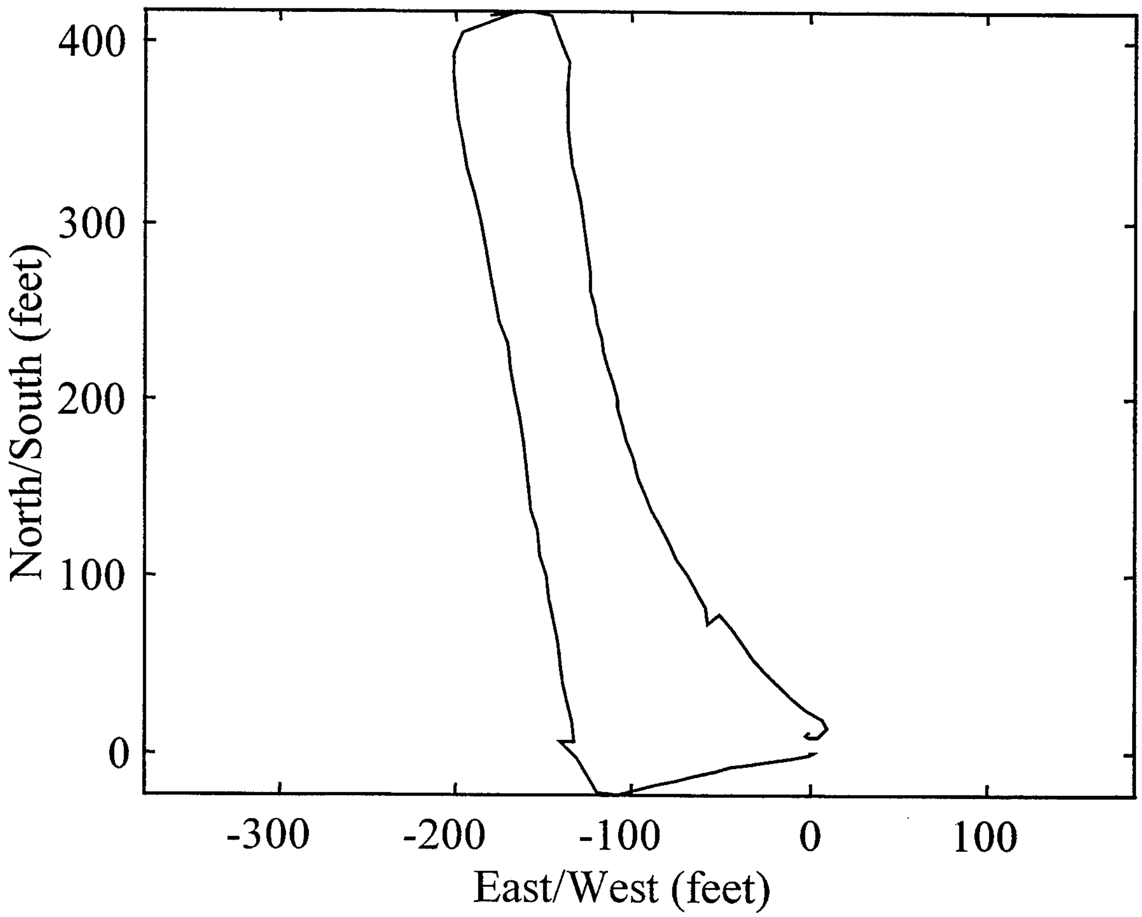

**Figure 29. Continuous GPS Position Plot**

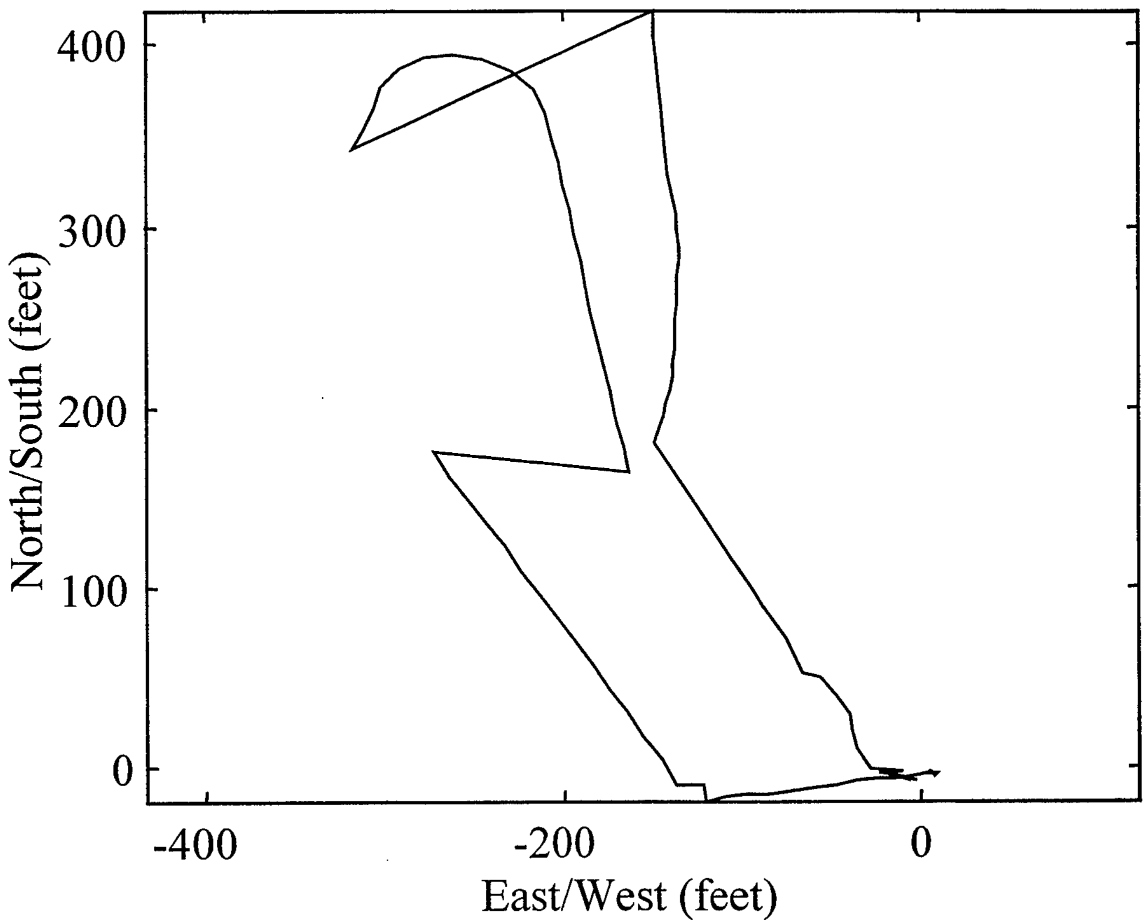


**Figure 30. Intermittent GPS Position Plot**

The tests completed prior to compass calibration indicate that the goals of the project are attainable. Figure 31 compares two runs made with updates of 20 seconds against no GPS updates (approximately 2 minutes of integration time). The run with updates of 20 seconds is well within the position estimate goals, however the goal is to have updates no less than every minute. The run with no GPS indicated that the speed wheel was passing along a value that was too large. This test was made prior to the second test of the speed wheel presented in Chapter III. Also observable in this figure are slight directional errors. The deviation correction presented in Chapter V reduces this error significantly.

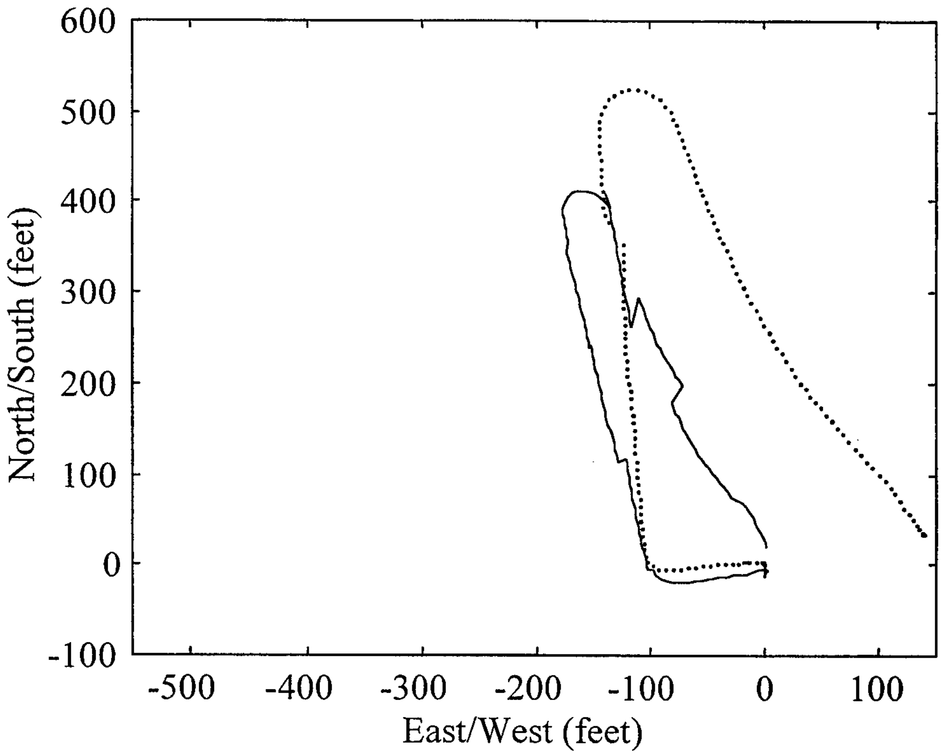


**Figure 31. Position Plot, GPS v.s. No GPS Updates**

Another test was conducted in a parking lot on the Navy Golf Course. This test, shown in Figure 32, was conducted after the compass had been corrected for deviation errors and the speed wheel given a proper gain constant. The dots represent a run with continuous GPS fixes and the line is the result of a run with no GPS correction applied. The test was over two minutes in length. As this figure shows, the result of the GPS and non-GPS tests are well within 10 meters of each other. This is much better than what was expected with this system and clearly demonstrates that given calibrated inputs the complementary filter will provide results commensurate with the goals stated for the project.

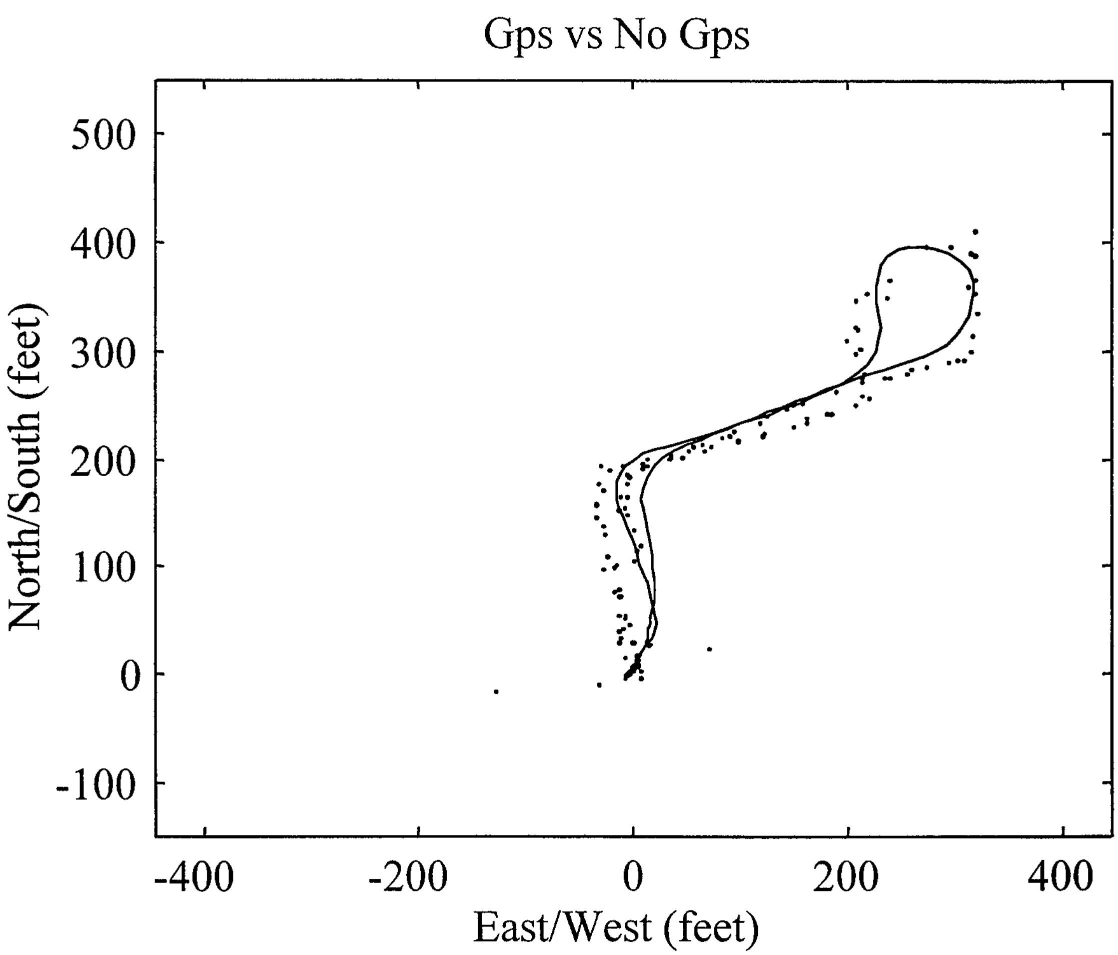


**Figure 32. Test with Calibrated Inputs**

# VII. CONCLUSIONS

## A. CONCLUSIONS

The purpose of this thesis was to test and evaluate the speed and directional sensors of the existing SANS unit and to build a system capable of accurate ground speed for land based testing. This was performed to eliminate these inputs as causes of the inaccurate position estimates the SANS unit was calculating. The speed wheel developed provides inputs well within the 10 percent tolerance the SANS filter is expected to perform under. This wheel provided input for speeds that are normally attainable using the golf cart, but are quite a bit faster than the speeds the SANS unit will be experiencing when it eventually is installed in the Phoenix. Testing in this speed domain at sea could have continued were it not for the inadequate characteristics of the speed sensor in use on the tow vehicle. The operating characteristics of the paddle wheel water speed sensor were judged as unacceptable. Thus, sea tests were not attempted. Instead, a new speed sensor that meets the required tolerances should be investigated and procured.

The directional capability of the heading sensor is now well within the required 1 degree tolerance. However the compass deviation must be recalculated following each new installation.

## B. FUTURE RESEARCH

Now that the software is operational and is expected to produce favorable results, a method of determining optimal gains should be investigated. So far the gains have been experimentally determined with the proof being whether or not the plot looked good enough.

The SANS hardware is aging and can no longer be supported when failure occurs. A new system is required so that the SANS can be inserted into the Phoenix. The Phoenix currently uses mechanical gyros that are also aging and have limited useful life left. A small navigation package like the SANS could replace at least two of these gyros at a reduced cost, weight, size, and power. What is needed in the next generation of hardware is either a large onboard storage capacity or a LAN connection to a host processor in order for data from every interation to be recorded.

The ground speed sensor is constructed out of MSI TTL circuits. A more modular and reconfigurable sensor could be built so that speed and actual distance traveled is recorded. This would create a second measurement that the SANS filter compared against.

There is still a question as how the apparent current should be calculated. Although the current method seems to be working, it is not felt that this is the best way for it to be calculated. It is felt that a 12 state asynchronous Kalman filter is needed.

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