# A Stand-Alone Ultrasonic Ranging System for Hydrological Water Stage Measurements

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*Abstract*—**A Stand-Alone Ultrasonic Ranging System (SAURS) was designed and applied in hydrological measurements of water levels. Ranging is carried out through air by an electrostatic ultrasonic transducer which is controlled by a microprocessor-based system. The data is collected in a 64 KByte EPROM cassette. The problems associated with temperature correction were studied theoretically and experimentally. The advantages of remote water level measurement, as compared to direct contract methods, are examined and discussed.**

## I. Introduction

Water stage of natural and artificial water bodies is one of the most critical and most measured hydrological parameters. Its central importance stems from the fact that it is used not only to gauge static water volumes but also to evaluate discharge and stream flow rates. The latter are accomplished by taking into account the hydrodynamic relationship between water level rise and flow rates in open channels and rivers [1]. In fact, this indirect method is the only practical way to estimate mean and peak discharge rates in large rivers and during floods in wadis (dry rivers).

Despite the central importance of water level monitoring in hydrological research and survey, the instrumentation technology associated with this field has been developing rather slowly. The objective of the present study was to investigate the possibility of adopting the technique of ultrasonic ranging to hydrological water level monitoring. The goal was not only to explore the metrological facet of the problem, but also to address the system aspects of data acquisition, signal processing and data processing.

## II. System Design

*General.* The Stand-Alone Ultrasonic Ranging System (SAURS) comprises two basic modules (Fig. 1): a microprocessor-based (80C31, Intel) data acquisition subsystem and an ultrasonic head. The program is stored in a 32 KByte EPROM, while a 2 KByte RAM (with a self-contained battery backup) is used for temporary storage of constants and data. The data, as well as field-derived constants, real time and housekeeping information, is eventually stored in a 64 KByte field replaceable EPROM cassette by an onboard programmer. The base module also includes an RS232 port and a two-line (16 digits each) Liquid Crystal Display (LCD) and a numeric keyboard (Fig. 1).

The electrostatic ultrasonic transducer (Polaroid, Norwood, MA) originally designed for autofocus cameras, is optimized for air coupling. It is driven by an electronics module (Texas Instrument SN28827) [2].

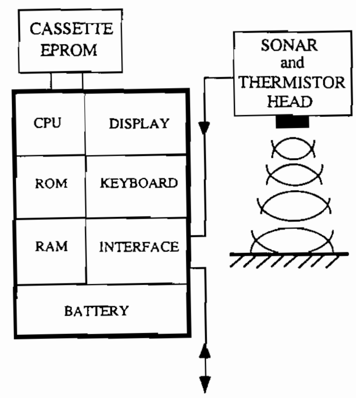


Fig. 1. Block diagram of the Stand-Alone Ultrasonic Ranging System (SAURS).

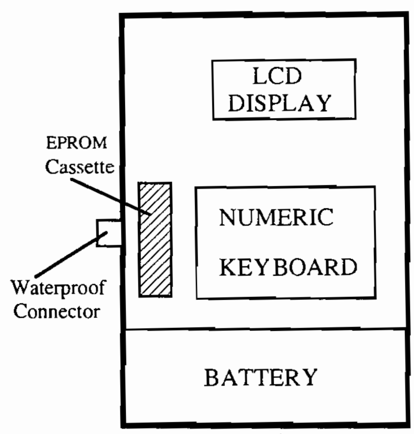


Fig. 2. Front panel of the SAURS.

*Hardware Design.* The base unit includes one printed circuit board on which all components are mounted. The front panel (Fig. 2) provides an ergonomic access to the operator. The base unit is housed in a waterproof painted-metal housing (30 cm × 25 cm × 15 cm) equipped with a watertight front door that permits access to the front panel. The head housing (Fig. 3) is machined from short sections of commercially available polyvinyl chloride (PVC) pipes.

Since the original radiation pattern of the Polaroid transducer (Fig. 4) was considered too wide for the present application, we modified the beam pattern by a short tapered horn (Fig. 3). The beam width of the present design (Fig. 4) is a practical compromise between the desire for a highly directional beam and the wish to avoid a cumbersome and costly sonar concentrator.

Total current drain of the SAURS is 30 $\mu$A in the hibernation mode and 100 mA during sampling. The self-contained 12 V battery (8 "D" size cells) will last for about 150 days when samples are taken at the present maximum sampling rate (one sample per 5 min).

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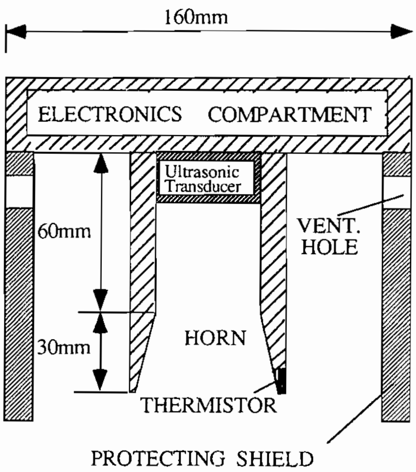


Fig. 3. Cross section of sonar head.

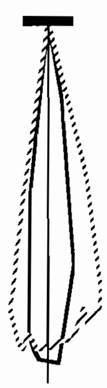

Fig. 4. Beam pattern of original electrostatic ultrasonic sensor (dashed line) and of the horn-equipped sensor (solid line).

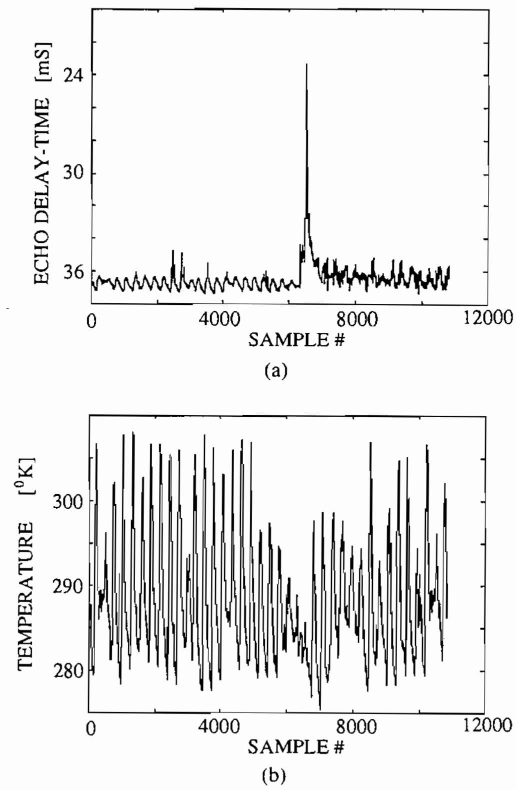


Fig. 5. Echo delay times (a) and temperatures (b) recorded by a SAURS over Wadi Zin, Negev Desert, Israel, during January 1991. Sampling interval: 5 min (288 samples per day).

*Field Installation.* In a typical field installation, the ultrasonic head is mounted on a horizontal pole which is suspended over the water body to be monitored. The distance between the head and the nominal water level ranged between 2 to 8 m. Installation locations included hard-to-access isolated desert areas.

## III. Signal and Data Processing

The typical record of Fig. 5(a) illustrates the main problems that had to be solved by signal and data processing. The plot depicts the magnitude of the ultrasonic echo delay measured before and after a flood in a dry river (Wadi Zin, located in the Negev desert area of Israel). The first section prior to the flood should have been a straight line since the Wadi was completely dry. The deviations are clearly of two kinds, noise spikes and a diurnal disturbance. The noise spikes seem to be associated with uncontrolled conditions such as coinciding electronic noise (switching regulator etc.), momentary acoustic wave deflection due to air turbulence and the like. Fortunately, the short duration of these spikes clearly distinguishes them from the real data variations which will always last more than one or a couple of sample periods. However, real data may have sharp-rising leading edges (see the flood portion in Fig. 5(a) which implies that a linear filter may not be a good solution. Tests have shown that the median filter [3] is very effective in this situation. The basic characteristic of this nonlinear filter is the ability to filter out spikes without deteriorating fast rise and fall times of the data. Median filtering is in fact a sorting procedure in which the center value in a given data window is replaced by the median data value within the window. To accomplish this, the data of a given window are sorted by magnitude, and the middle value of the resulting list is used as the center point of the window. When this procedure is repeated on all the data by a moving window, it will remove all spikes which last less than half the length of the window.

An additional process that had to be applied is temperature correction since velocity of sound in air ($V_s$) is temperature dependent. The theoretical dependence is of the form:

$$V_s = K_1 \sqrt{T} \tag{1}$$

where $K_1$ is a constant, and $T$ is air temperature in °K. Hence, the temperature dependence of the measured delay ($t_d$) for a given ranging distance ($L$) should be:

$$t_d = \frac{K_2 L}{\sqrt{T}} \tag{2}$$

or:

$$L = K_3 t_d \sqrt{T}. \tag{3}$$

When this theoretical temperature correction was applied to the filtered data it was found to accurately compensate the night-level readings of the dry Wadi but not the day readings. To examine the reasons for this discrepancy, the measured echo delays of the constant-level section were plotted against ($T$) in a Log–Log scale (Fig. 6). For a constant distance ($L$), the relationship of (2) should plot as a straight line with a slope of ($-1/2$):

$$\text{Log}\,(t_d) = K_4 - \tfrac{1}{2}\,\text{Log}\,(T). \tag{4}$$

This presentation of the experimental data (Fig. 6) clearly indicates that many of the data points follow the relationship of (2) whereas some points do not. The deviation can be explained by a wrong

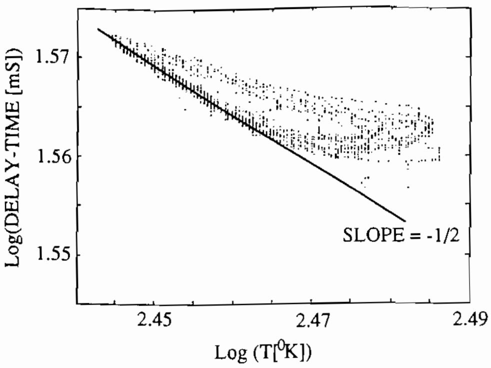


Fig. 6. Log-Log plot of first section (dry Wadi) of Fig. 5(a) data after median filtering.

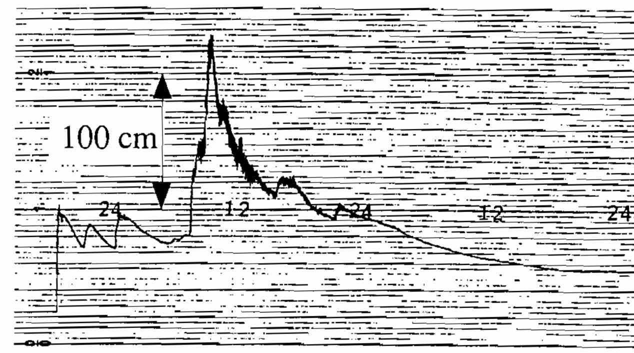


Fig. 8. Wadi Zin flood as recorded on paper by a mechanical float-type water stage instrument. Vertical scale: 2 cm/division.

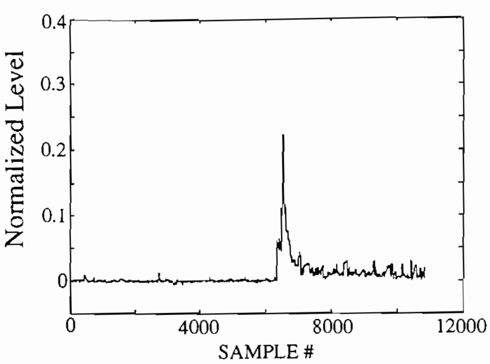


Fig. 7. Normalized level of Wadi Zin data of Fig. 5(a) after fitting the first (dry) section to the model of (5).

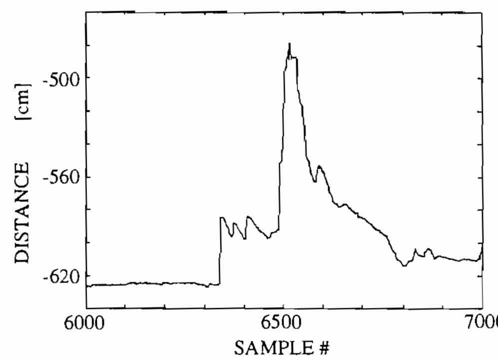


Fig. 9. Wadi Zin flood as registered by the SAURS (zoom on Fig. 7).

(too high) temperature reading. During nighttime, the two temperatures are practically the same which explains the good temperature correction of the night-level readings. This observation is also consistent with the fact that the residual temperature error is not detected during the (clouded) rainy days of the flood period.

To further explore the temperature correction question, we have separated the day data from the night data of the first section (constant level) of the Wadi Zin record. The day data was then fitted to an experimental model in which sound velocity was assumed to follow the polynomial relationship:

$$V_s = K_1\sqrt{T} + K_2 T + K_3 T^2 + K_4 H + K_5 H\sqrt{T} + K_6 H^2\sqrt{T} \quad (5)$$

where $H$ is the hour in the day based on a 24-h clock.

The rationale for this fitting was to attempt to take into account the extra temperature rise of the sensor due to sunlight. The temperature rise was assumed to be a nonlinear function of the temperature and the azimuth of the sun which is a function of the hour in the day. This procedure was found to reduce the error level to about 0.5% (Fig. 7).

## IV. Results and Discussion

Ten SAURS were deployed in various geographical regions of Israel. In some locations, a SAURS and a float-type water stage recorder (Paper Strip Chart Recorder, The Hydrological Service, Jerusalem) were placed side by side. The agreement was found to be very good (Figs. 8, 9). The discrepancies between the two are due to the fact that the response time of the SAURS is much shorter than that of the float-type instrument. The main reason for the sluggishness of the mechanical instrument is the need to install the float in a protecting vertical pipe which is anchored to the (river) floor. The pipe includes a series of peripheral openings at the floor base to permit water exchange with the main body of water. This hydraulic "low-pass filter" causes a marked damping of the dynamic response of the float-type instrument and, in fact, is the reason for its frequent malfunction. Sand, pebbles and debris which accumulate in the pipe distort the water-level record and eventually clog the pipe altogether. Indeed, the trailing edge of the record duplicated in Fig. 8 shows evidence of clogging when compared to the SAURS record of Figs. 7 and 9. This comparison clearly reveals the advantages of remote ultrasonic water-level monitoring over direct contact methods.

The ranging error due to temperature inaccuracy can be estimated from the basic relationship of (3). The relative error of the measured distance ($L$) can be estimated from (3):

$$\frac{\Delta L}{L} \simeq \frac{\Delta T}{2T} \quad (6)$$

and for "normal" air temperatures ($T \simeq 300°K$):

$$\frac{\Delta L}{L}(\%) \simeq 0.17\Delta T. \quad (7)$$

That is, an overall temperature accuracy of about 0.6°C is required to maintain a 0.1% ranging precision.

The experimental data of this study seem to suggest that the temperature correction issue is the main limiting factor of the SAURS' precision. In the case of the Wadi Zin record, the total distance between the sonar head and dry Wadi floor was about 600 cm (Fig. 7). When temperature compensation was correct (during nighttime), level fuzziness was less than 1 cm, independent of night temperature fluctuation. This corresponds to an overall precision of better than 0.2%.

A major conclusion of this study is that the theoretical temperature dependence of sound velocity is valid in air-ranging applications. Hence, one can use the theoretical relationship of (3) rather than a look-up table [4]. Furthermore, it appears that air turbulence, rain, and winds have little effect on ultrasonic ranging in air. The original design of the SAURS described here could not provide accurate day temperature due to direct sunlight heating of the sonar head. This problem has been rectified in an advanced design of the SAURS in which the thermistor probe is suspended in a well-ventilated and sunlight-protected housing.


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# An Automated Thermocouple Calibration System

Mark D. Bethea and Bruce N. Rosenthal

***Abstract*—An Automated Thermocouple Calibration System (ATCS) was developed for the unattended calibration of type K thermocouples. This system operates from room temperature to 650°C and has been used for calibration of thermocouples in an eight-zone furnace system which may employ as many as 60 thermocouples simultaneously. It is highly efficient, allowing for the calibration of large numbers of thermocouples in significantly less time than required for manual calibrations. The system consists of a personal computer, a data acquisition/control unit, and a laboratory calibration furnace. The calibration furnace is a microprocessor-controlled multipurpose temperature calibrator with an accuracy of ±.7°C. The accuracy of the calibration furnace is traceable to the National Institute of Standards and Technology (NIST). The computer software is menu-based to give the user flexibility and ease of use. The user needs no programming experience to operate the systems. This system was specifically developed for use in the Microgravity Materials Science Laboratory (MMSL) at the NASA LeRC.**

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## I. Introduction

This paper describes the efficient calibration of large numbers of thermocouples via a program link between a digital computer and a thermocouple (TC) calibration furnace. In the present case, type K (Nickel Chromium vs. Nickel Aluminum) thermocouples were calibrated for use in a specially designed crystal growth furnace, [1] but the technique is general in nature and may be applied to other types of temperature measurement or calibration systems. This system was developed to provide an efficient way to calibrate the large number of TC's used in the MMSL and NASA LeRC. A commercially available temperature calibrator is used as the temperature comparison source together with a computer, which is used to control setpoint changes, record data, and keep a calibration history of each TC. This history will enable a user to chart the error of a given thermocouple and be able to compensate if necessary by using various statistical techniques. The analysis of the data is left for the user in an ASCII file format. This is done to let the user graph the results using an individual or industry graphical analysis package.

The purpose of calibration, as referred to in this paper, using the system developed, is to determine if the thermocouples being tested are within the ASTM/NIST standard limits of error for the specific type of thermocouple used.

The calibration of a thermocouple consists of the determination of its electromotive force (emf) at a sufficient number of known temperatures so that with some means of interpolation, its emf will be known over the temperature range in which it is to be used. This process requires a standard thermometer to indicate temperatures on a standard scale, a means for measuring the emf of the thermocouple, and a controlled environment in which the thermocouple and the standard can be brought to the same temperature [8].

The approach used for calibrating thermocouples using the equipment described in this paper involves that of the temperature comparison method. In the comparison method, the thermocouple to be calibrated is placed in a temperature-controlled environment (the calibration furnace). The reference junction of the furnace is an RTD sensor (platinum resistance thermometer). The RTD sensor is considered a secondary standard, the calibration of which is traceable to NIST. The temperature-controlled environment is set to one of the selected temperatures and stabilized so that the electromotive force (emf) of each thermocouple may be measured [2], [3]. The emf is measured by the data acquisition/control unit and converted to temperature by a computer algorithm.

Since the opening of the MMSL at the NASA LeRC in September 1985, the number of projects and experiments has steadily increased. The need to obtain accurate thermocouple measurements for qualitative/quantitative data has also steadily increased. Many MMSL projects and experiments use thermocouples to measure temperature inside the various furnaces and experimental apparatus in the lab. What follows is a description of the calibration system developed for use in the MMSL.

## II. System Description

To calibrate thermocouples by the temperature comparison method, the thermocouples are placed in a special calibration furnace which provides a stable, repeatable environment [4]. The heating block inside the furnace has a high thermal conductivity and is heated by resistance elements. The temperature is controlled by a precision platinum resistance thermometer (RTD sensor) and a closed-loop circuit. A typical calibration run involves placing a