RADAR WATER-LEVEL MEASUREMENT FOR OPEN CHANNELS

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ABSTRACT

The U.S. Geological Survey is investigating the performance of radars used for water-level measurement. This paper presents data collected using the Design Analysis Associates H-360 radar sensor in the laboratory and in the field. (The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.) Radar water-level measurements at field sites were compared either to pressure sensor or float measurements by using simple statistical comparisons and frequency analysis with Fourier transforms of the data. Laboratory testing checked the performance of the radar sensor over the operating temperature range. Field data comparison and laboratory temperature testing indicate that the unit has an accuracy of about 0.03 feet except for windy conditions, when errors of -0.30 feet can occur.

INTRODUCTION

Water-level (or stage) measurements are used to compute discharge by the U.S. Geological Survey (USGS) at over 7,000 streamgaging stations throughout the United States (Hirsch and Costa, 2004). The discharges are computed from relations between stage and discharge that are used by managers to issue flood warnings and manage water supply. The accuracy and performance of stage instrumentation at these stations directly affect the quality of the discharge computed. Because of the importance of water-level measurements, the USGS has an accuracy requirement of 0.02 feet (ft) or 0.2% of reading (whichever is largest) for water-level measurements (Office of Surface Water, Technical Memo 93.07).

Several standard types of water-level instrumentation are used at USGS gaging stations: (1) a float with shaft encoder in a stilling well (float-well), and (2) two types of pressure systems– nonsubmersible pressure-transducer bubbler systems and submersible pressure transducer systems. A newer method, radar, has recently been installed at a few stations.

Radar level instruments have maintenance and installation advantages over the standard instrumentation. No stilling wells or orifice lines need to be constructed for radar. Moreover, because radar is a "non-contact" measurement method, it is

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not susceptible to being obstructed by sediment or debris. Bubbler and stilling well (float with shaft encoder in stilling well) installations have orifice lines that can be obstructed and require more effort to install than a radar. Unlike acoustic water-level sensors, the accuracy of the radar measurement is not significantly affected by air temperature or by moderate rainfall (Serafin, 1990).

Little information is available comparing the performance of radar water-level instrumentation with the older, standard instrumentation. The older instrumentation has been rigorously tested for compliance with USGS accuracy requirements. Laboratory temperature testing and comparisons between field data collected by a Design Analysis Associates H-360 radar sensor and older instrumentation at two field sites are presented, herein. Differences in instrument frequency response and simple statistics also are presented.

WATER-LEVEL RADAR SENSOR

The Design Analysis Associates (DAA) H-360 (figure 1) is a continuous-wave frequency-modulated radar equipped with SDI-12 communications that operates in the X-band frequency (10 Ghz). The H-360 measures water level by propagating electromagnetic energy with an antenna. Objects in the propagation path reradiate the microwave energy back to the radar. The time it takes for the energy to return to the radar (travel time) is used to determine the distance to the object (or water level). Radar energy propagation reflects and scatters similarly to light. Unlike sound energy, the speed of radar energy is not significantly affected by air temperature. Digital signal processing software is used to process the received microwave energy into distance. The sensor used by the H-360 was designed for liquid level sensing in a tank and has been modified to use SDI-12 communications. Specifications for the H-360 are provided in table 1 (Design Analysis Associates, 2003).

LABORATORY TEMPERATURE TESTING

The DAA H-360 was temperature tested in a walk-in environmental test chamber for temperatures ranging from -40 to +20 ^{o}C. Several units were placed in the chamber and pointed horizontally at a stationary, metal target (chamber wall). The stage readings were set to give an arbitrary 10-ft reading at room temperature for the stationary target.

Initial testing done in October 2003 found that the units did not transmit data reliably to the data logger when temperatures were below 0 ^{o}C. The manufacturer addressed the communication problem and sent replacement chips for the test units, which solved the problem. However, the radar units continued to sporadically report either a very high level (>30 ft) reading or a reading of -99 when temperatures dropped below -20 ^{o}C. Some of the scatter in the data may be due to electromagnetic noise from the chiller unit in the chamber and other

Figure 1. Design Analysis Associates H-360 radar water-level sensor.

Table 1. DAA H-360 Specifications

Feature	Specification
Housing	cast aluminum
Housing dimensions	5.5 x 6 x 7.5 in. 16 in. waveguide
Weight	8 lbs
Power external	10.5 to 16.0 VDC
Power consumption Standby Measuring	 200 µA typical 240 mA typcial
Communication	SDI-12, RS-232
Radar Sensor	
Range	115 ft
Accuracy	+/-0.026 ft
Repeatability	+/-0.026 ft
Frequency	9.5 to 10.5 GHz
Antenna horn diameter beam angle	 4 in. 18^o
RF output power	1 to 3 mW
Operating Temperature	-40 to 60 ^{o} C

equipment in the laboratory. Efforts were made to determine if noise was a problem by cooling the chamber to -40 ^{o}C, turning the chamber off and letting the temperature rise back to “room” temperature in the laboratory. Some scatter was still present in those data. The manufacturer is currently working to address this problem.

Figure 2 shows data collected for one unit in the walk-in chamber. The differences in figure 2 are between the reading of the radar and the arbitrary 10 ft. Temperatures above -30 ^{o}C were collected when the chiller was off. The data show more scatter at the lower temperatures and an obvious linear trend with temperature. The range in the trend is about 0.03 ft over the tested temperature range of -40 to +20 ^{o}C. The temperature trend is possibly due to temperature sensitivity of the oscillator in the radar unit. Some of the scatter in the data is due to noise and some is suspected to be due to the instrument.

FIELD DATA COMPARISON

Two gaging stations, maintained by the USGS Mississippi District Office, were used for field comparisons: the Wolf River near Landon, Mississippi (02481510), and the Pearl River near Jackson, Mississippi (02486000). The Wolf River station

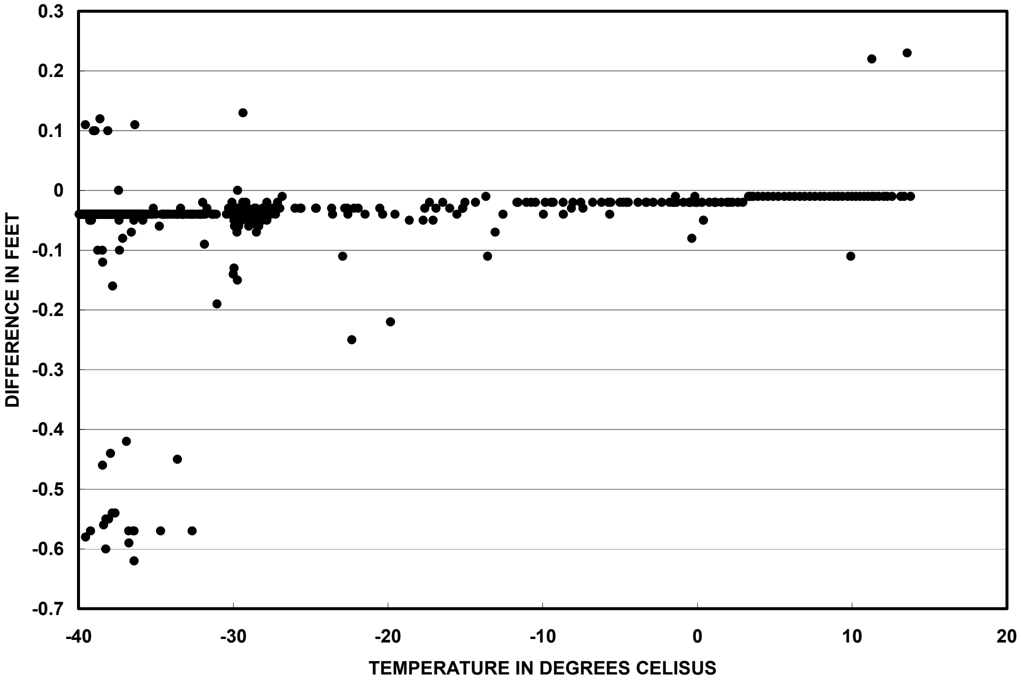

Figure 2. Difference between radar reading and initialized reading of 10 ft for the stationary target over a range of temperatures.

has a drainage area of 308 square miles (mi^2), which is about one tenth of the drainage area of the Pearl River stations (3,171 mi^2). Mean daily flows are 628 cubic feet per second (ft^3/s) for the Wolf River station and 4,476 ft^3/s for the Pearl River station (Morris and others, 2004). Both sites have other instrumentation in addition to the radar sensor. The Wolf River site has a stilling well equipped with a float and a shaft encoder. The Pearl River site has a Sutron Accubar bubbler system. Data collected by the radar units and the other water-level instrumentation were compared by using statistics and frequency analysis.

Data sets analyzed for the Wolf River and for the Pearl River are not for the same dates or duration. Data were collected for the Wolf River over approximately 21 days during the summer of 2003 and for the Pearl River over approximately 85 days during the fall of 2002. Data were sampled at a 15-minute interval, which is typical for USGS gaging stations. This sampling rate is used because of the need to conserve battery power at remote sites and the slow rate of water-level changes at most gaging stations. The 15-minute sampling rate can under sample the water-level data because wind driven waves can have periods that are 5 minutes or less (Kinsman, 1965). For a given discharge and 15-minute sampling interval, the measured water levels affected by wind waves will be periodically high or low compared with the same water level that was unaffected by wind driven waves.

Field Data Statistics

The average water level for the data collected by each instrument was removed from the data. The resulting data are shown plotted for the Wolf River in figure 3 and for the Pearl River in figure 4. Both stations have more than one flow peak in the record studied. The plotted data for the Wolf River show that the radar periodically measured stage about -0.3 ft lower than the float well. The lower stage is likely due to the wave troughs focusing the radar energy back at the antenna and the crests dispersing the energy away from the antenna. Because the radar antenna receives more energy from the troughs, an erroneously lower water surface may be measured during windy conditions.

Summary statistics for both stations and instruments are listed in table 2. The stage data statistics show that the radar instrument has a larger range between the maximum and minimum values, from 0.16 ft (Wolf River) to 0.39 ft (Pearl River) larger than the two older instrument types. Lower minimum stages are measured by the radar at both of the stations. The minimum radar stages are lower than the older instrumentation by 0.16 ft (Wolf River) to 0.19 ft (Pearl River).

Frequency Analysis

Frequency analysis was used to help find the differences in response between the instruments. The field data for both stations were transformed into frequency data using a fast Fourier transform (Bracewell, 2000). The 15-minute sampling

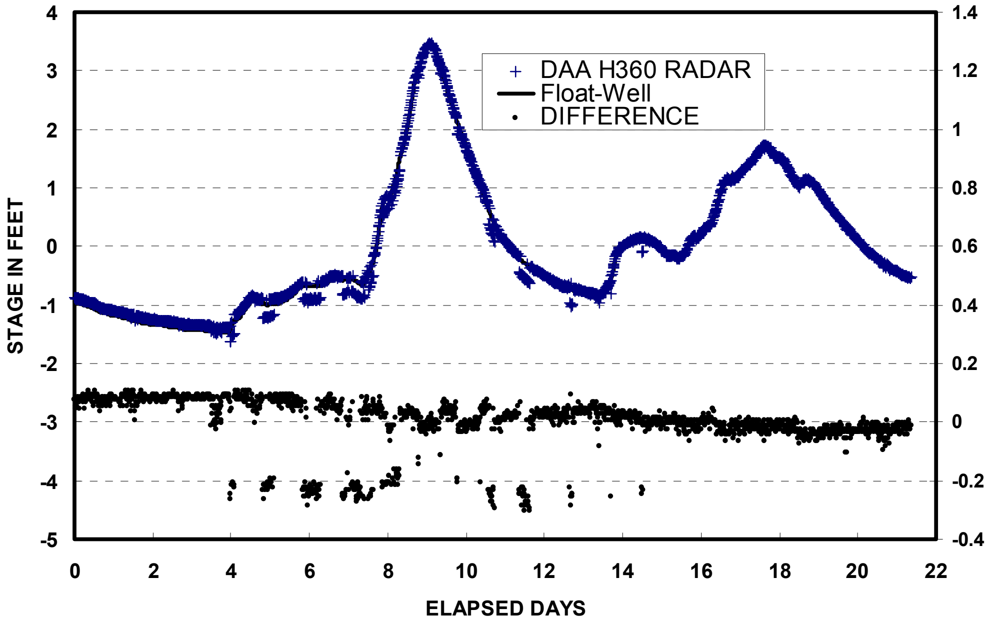

Figure 3. Wolf River water-level data for DAA H360 radar and the float encoder during the summer of 2003.

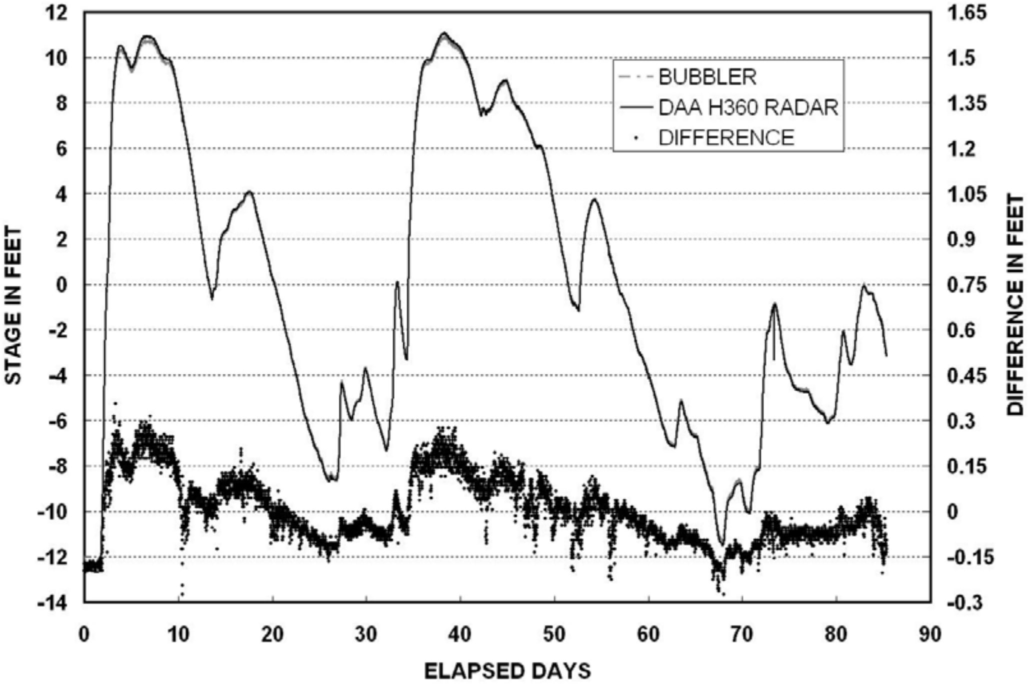

Figure 4. Pearl River water-level data for DAA H360 radar and pressure sensor (bubbler) during the fall of 2002.

interval used at USGS stations restricts the highest water wave frequencies that can be measured to 0.00055 hertz (the cutoff frequency) or a period of 30 minutes. Only the magnitude of the transform data is presented in figures 5 and 6. The magnitude is plotted as a function of period in minutes. Period, the inverse of frequency, is the time it takes for a complete wave to pass by a fixed point and is proportional to wavelength. The magnitude indicates how much energy is present for a water wave of a particular period. For river systems, most of the energy is at the larger wavelengths with periods of several hours because the response of streams to rainfall events ranges from several hours to days. However, wind-driven waves typically have periods of 5 minutes or less.

Table 2. Summary statistics for radar and older instrumentation data measured at the Wolf River station and the Pearl River station. The mean value was removed from the data.

	Wolf River Station		Pearl River Station	
	Radar	Float-well	Radar	Bubbler
Median (ft)	-0.31	-0.26	-0.78	-0.73
Standard deviation (ft)	1.15	1.17	6.63	6.53
Maximum (ft)	3.48	3.48	11.11	10.91
Minimum (ft)	-1.63	-1.47	-12.70	-12.51
Sample size	2048	2048	8192	8192

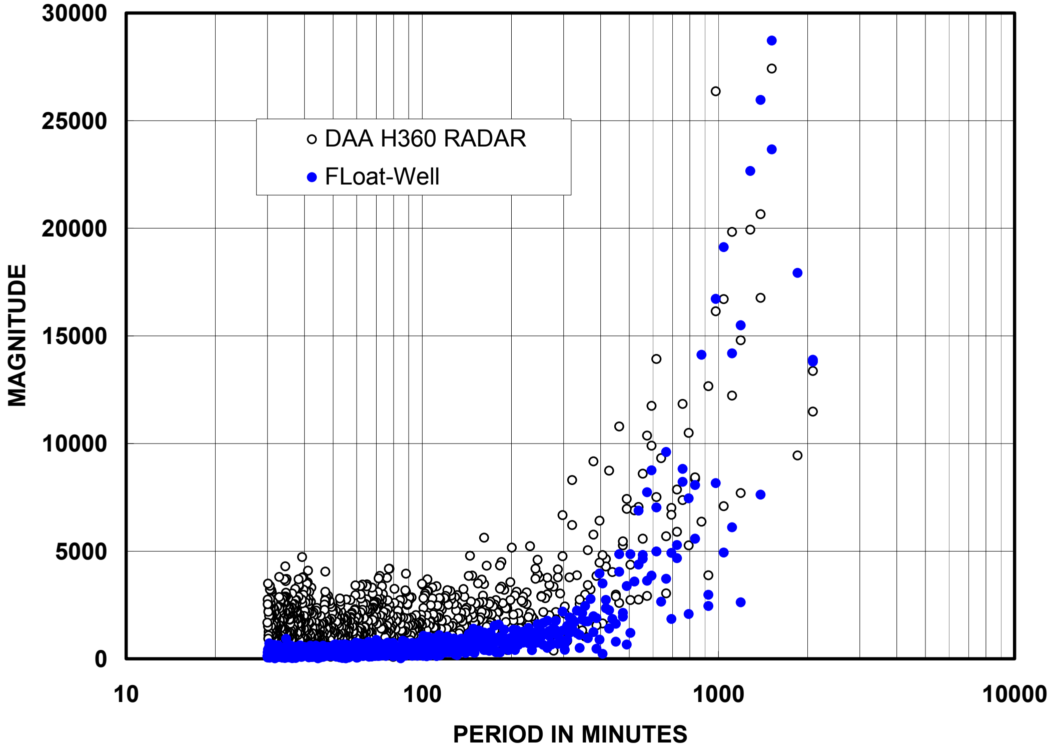

Figure 5. Wolf River water-level data for radar and float encoder instruments transformed into frequencies.

The frequency data for the float-well instrument (Wolf River) had considerably smaller magnitudes (about 1/3 less) than the radar for periods shorter than about 200 minutes (0.005 hertz). Because a stilling well acts as a low-pass filter, it damps out the shorter period (or higher frequency), small surface waves that are produced by wind or other small flow disturbances. The resulting water level is closer to the local (in time) average water level. The bubbler instrument (Pearl River) was slightly less variable and had slightly lower magnitudes than the radar for periods shorter than 150 minutes (0.0067 hertz frequency). The column of air in the bubbler line, similar to a stilling well, damps out some of the smallest surface waves.

Low-pass filtering (removing the higher frequencies from the data) also was tried in an attempt to reduce the differences between the radar data and the float-well data. However, after low-pass filtering, the radar data had larger magnitudes for the higher frequencies than the float-well because the 15-minute sampling interval "aliased" the data collected. Aliasing of data results when water levels are sampled at a rate that is slower than the frequency of periodic water-level changes. Waves occur in the collected data that do not exist in the actual water levels and result in the large magnitudes at the higher frequencies, even after low-pass filtering. Similar to the radar, the bubbler system also had large magnitudes

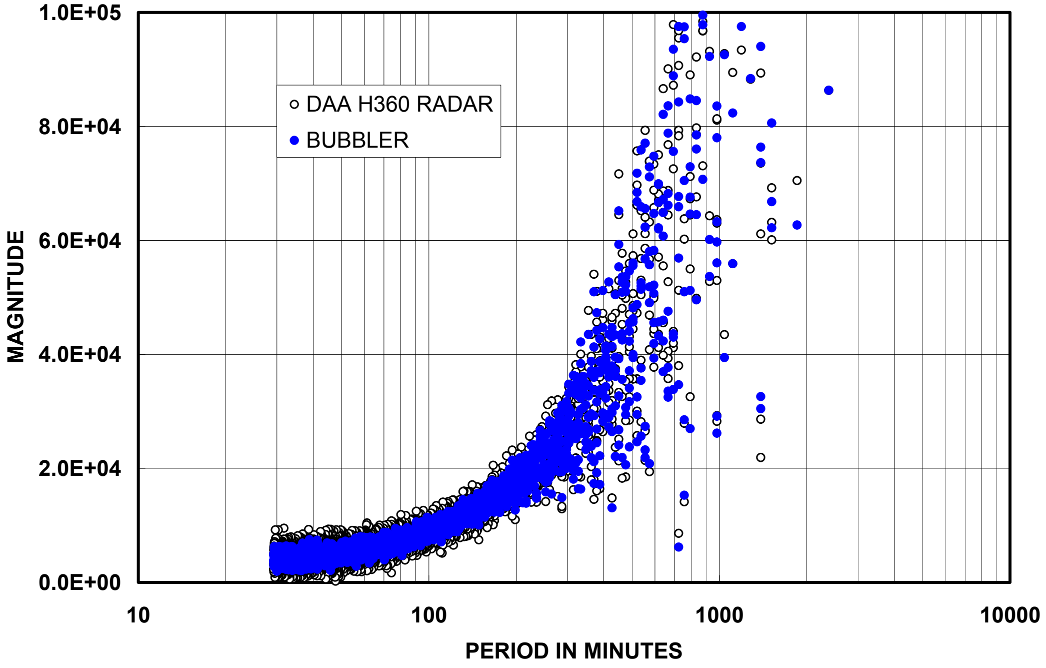

Figure 6. Pearl River water-level data for radar and bubbler instruments (pressure sensor) transformed into frequencies.

at the higher frequencies when compared to the float well. Because the radar and the bubbler sample at a 15-minute interval, the instruments may collect data that are influenced by wind-driven waves, resulting in a value that is either too high or too low.

SUMMARY

Radar instruments are a promising new tool for measuring water levels. Radar water-level sensors require less construction to install than traditional contact water-level sensors. However, radar accuracy may be affected by oscillator sensitivity to temperature changes. Units tested in the laboratory were found to vary 0.03 ft over -40 to +20 ^{o}C temperature changes. Additionally, field data indicate that currently available radars may have negative bias when surface waves are present. Wave troughs act to focus energy back at the radar and wave crests act to scatter energy away from the radar, biasing the stage reading low. Frequency analysis of the field data with Fourier transforms found some aliasing in the data collected at 15-minute intervals for the radar and bubbler systems.

Changes in sampling rates and appropriate filtering of the data may enhance the accuracy of radar water-level measurements and may enable radar water-level sensors to approach the accuracy of well-float systems. The noncontact methodology used by radar water-level sensors makes the unit tested useful for sites at which sensor fouling is a problem for traditional contact type sensors and where an accuracy of 0.03 ft is adequate.

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