FLUTe™ Flexible Liner Underground Technologies, Ltd. L.C.
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FLUTe® Air Coupled Pressure Transducer Design, Function, and Test Results

Background of the innovation

Most water level history measurements in traditional wells are performed by lowering a pressure transducer beneath the water surface to monitor the pressure history of water level changes. The multi-level sampling system in a single borehole does not allow such a simple measurement of the formation head history at different levels in the formation. Current FLUTe systems for multi-level water sampling and head measurements in a single borehole use a manual water level measurement or pressure transducers dedicated to the system and located 100 ft. below the water table in a borehole in the geologic formation. Those pressure transducers monitor the hydraulic head in the formation at many different port elevations. If a transducer(s) should fail, the entire multi-level system must be removed to replace the transducer(s). This removal can result in damage to the other functioning transducers and to the flexible liner sampling system. The current flexible liner design for the multi-level sampling system with the deep transducer location has been in use for over 12 years. A new technique allows the use of transducers at the surface to monitor water level changes at depth. This geometry allows the transducers to be repaired or reused at other locations without removal of the Water FLUTe multi-level system. Recent improvements in transducer accuracy and the addition of data recording in the transducer make this FLUTe innovation of air coupled transducers (ACT[1]) much more practical than with the earlier state of the art of transducers.

The method

The normal Water FLUTe multi-level sampling system is shown in Figure 1. Only a single port system is shown for clarity, but additional sampling intervals defined by spacers at other elevations on the liner are connected to a duplicate pumping systems and the individual pumping systems are bundled, sheathed and suspended on the tether. In this drawing, the only means of measuring the water table associated with each port is to manually lower a slender water level meter down the “pump tube” for that port.

Figure 2 shows the usual location of a pressure transducer connected to the port tube beneath the first check valve. This connection allows one to measure and record the water table

[1] This design has a US patent (8424377) and patents pending in other countries.

history at each port. The history is recovered by connecting to the transducer cable. Figure 2, is the original Water FLUTe design.

The ACT transducer is located at the surface where it is readily accessible for repair or reuse at other sites. Figure 3 shows the ACT tube extending from the spacer to the surface. As the water level in the tube rises with a rise in the water table, the air pressure in the tube increases. Therefore the water level in the tube cannot rise as much as the water table rise. However, careful measurement of the air pressure change in the ACT tube allows one to calculate the water level change in the tube and to then calculate the water level change in the formation. The resolution of the water level in the formation with the ACT design in Figure 3 is not usually as precise as with a transducer submerged in the water and connected directly to the port as in Figure 2. However, in many Water FLUTe multi-level sampling situations in fractured rock, the resolution of approximately plus or minus one inch is sufficient. The water levels in those situations often change by tens of feet.

Testing of the concept

The method was tested initially in a domestic water well. The detailed description of the test geometry is provided hereafter. The water level in the well changed dramatically with each operation of the pump in the well. The water level changes were monitored with both a transducer submerged in the water and with the air coupled tubing connection to a transducer hanging just inside the casing as depicted in Figure 4. The plots of the two transducer measurements on one second sampling intervals are shown in Figure 5. The two curves are nearly indistinguishable. A plot of the submerged transducer head measurement against the water level calculated from the air coupled measurement is shown in Figure 6. The red lines are the plus and minus quarter-inch bounds on the one-to-one curve. The green lines are the one-inch bounds off of the one-to-one line. Most of the data points fall within a quarter inch of the perfect agreement. The water table fluctuation was ~2 ft at a water table depth of 48 ft. This is considered remarkably good agreement, especially on this short time scale.

Sources of error

Because the transducer is coupled to the water level in the tube with an air column, there are various sources of possible error in the measurement. The influential parameters considered in the testing and in the design are:

1. Temperature effects on the air pressure
2. Water vapor (relative humidity) effects
3. Air leakage from the system connections
4. Air diffusion through the tubing
5. Transducer sensitivity to air pressure changes
6. Response time and hysteresis effects
7. Recalibration of the system
8. Barometric fluctuations
9. Swallowing the air above the interface during an abrupt drop of the water level in the ACT tube.

Temperature effects and sensitivity were examined via calculations and experiment. The experimental results agreed with the calculations as expected. For large temperature effects, there is a significant error introduced into the inferred water level change. The design includes two features that reduce the sensitivity to a temperature change. The first is the transducer tube in the upper portion of the well where temperature changes are greatest is of a small diameter providing only a small portion of the system air volume subject to temperature changes. The other feature is that the transducer is located and protected so as to minimize the temperature change of the air volume in the system. Figure 4 shows the location of the transducer inside the well casing which we have measured to be only weakly coupled to the temperature changes above the surface, and the wellhead is insulated to further maintain the temperature more nearly constant inside the casing. Finally, the transducer also measures the temperature and allows a calculated correction estimate for the water level deduced from the air pressure measurement. This temperature correction has been necessary in some field applications. The correction is included in the software for the data conversion to a water level history.

Water vapor effects were observed to be measurable when the initial air in the tube was of low relative humidity in New Mexico. However, in a relatively short time the closed volume reached an essentially constant water vapor saturation.

To date there has been no evidence of diffusion through the tubing. That is aided by the relatively low pressure difference inside the tube versus atmospheric pressure. Tubing damage has caused one air leak in a system and another obvious leaks of air from the tubes have been found to be due to poor fitting connections. Over 200 of these systems have been installed in Water FLUTe systems. The above problems have been solved.

Use of a very high resolution pressure transducer for the low pressure measurements is important. The fluctuation of the water table in the test described above shows that there is minimal hysteresis on the time scale of significant water table fluctuations. The pressure transducer used is an absolute pressure transducer and so the pressure measurement must be corrected with a measurement of the barometric pressure fluctuations if such a correction is appropriate. An absolute pressure measurement is preferred to avoid any concern about the clogging of a vent tube in the cable required for a “gauge pressure” measurement.

One of the very attractive features of the use of this system with the Water FLUTe multi-level system is the ability to measure the actual water table at the port manually whenever desired for a check or recalibration of the air coupled transducer system. There is no conflict between the normal manual head measurement, and the air coupled transducer system. The sampling procedure may cause an offset in the air coupled water level measurement discussed below under “Field Experience with the System”. Such an offset is obvious in the data.

FLUTe provides a spreadsheet into which the transducer measurement of pressure and temperature is copied with the other relevant dimensions. The result is the calculated water table history. A special ACT transducer has been designed which will provide the air pressure history measurement conversion to a water table history as direct output of the transducer.

How the system is emplaced

As in Figure 3, the tube from the spacer extends upward to the surface in an interior sleeve welded to the interior of the liner. This is all done as part of the Water FLUTe fabrication procedure. After the Water FLUTe system is everted into the borehole in the usual manner from the shipping reel, the ACT tube is trimmed to the proper length to allow it to be connected to the transducer and the transducer is then lowered about 5 ft into the well casing. The transducer and tube are supported by a kellum grip on the transducer cable, and that kellum is suspended from the U bolt in the wellhead containing the pump tube, the sample tube and the air tube for that port.

A protective insulated cover is then emplaced over the wellhead assembly to reduce significant temperature fluctuations inside the casing. The insulation is prefabricated as part of the system.

Cost of the system

Generally the cost of the ACT (air coupled transducer) system is less than the price of the dedicated down-hole transducer shown in Figure 2. The cost savings are mainly in the reduced transducer cable length (~10 ft vs. 150 ft). The accessibility for repair or reuse is also a major lifetime expense reduction. The installation of the transducer at the surface adds a small amount of time to the installation procedure (~10 mins./port?). There is an attractive reduction of the risk of damage to the transducers during shipping or during emplacement of the Water FLUTe system because the transducers are not embedded in the tubing bundle.

FLUTe charges a fee for incorporating the tubing for use of this method in the Water FLUTe system. FLUTe does not warrant the transducers or cables beyond the transducer manufacturer's warranty, so the accessibility of the ACT is very attractive. Not all transducers are equally suited for use with this system. A necessary feature of the transducer is that it can be threaded into the fittings for connection to the small tubes with sufficiently small dimensions to be emplaced in the casing adjacent to the Water FLUTe tubing bundle.

Field Experience with the method

As of January 2015, the method has been tested in the laboratory and more than 200 field installations. The system has been shown to follow well the water levels in the formation with several qualifications. The practical diameter of the larger tube in which the water table fluctuates is ¼" OD versus the ½" OD tested in the domestic well. This reduces the resolution to nearer 1 inch than the ¼" observed in the domestic well.

The more attractive recent development is the location of the ACT tubes in the sleeves of the liner connected directly to the sampling interval (spacer) with a dedicated port and routed to the surface in the sleeves. That emplacement was described above (Fig. 3). In that case, the tube to the surface is a constant diameter and reduces the complexity of the system and therefore the cost. There is a small reduction in resolution. The resolution should still be about +- 1". This alternative routing was tested in Schkopau, Germany in 2013 and showed far superior behavior as compared to the response for the same ports in ACT tube connections below the pumps at the location of the downhole transducers.

Other applications

Because this method only requires a slender tube connection to the water level for monitoring that water level, this device can be used in monitoring water levels in various situations where the access is too limited for lowering a pressure transducer into the water or the liquid is too hostile for a pressure transducer. By attaching a pressure transducer securely to the top of any air filled tube or pipe submerged below the water table, the same algorithm used for this system can be used for calculation of the water table changes. In each case, it is helpful to the resolution of the measurement to protect the transducer and air volume from significant temperature changes or to calculate a correction for a measured temperature change. However, the focus of this improvement is for monitoring water levels in multi-level sampling systems.

Nomenclature

This system has been named the ACT system for "air coupled transducer". The main purpose is related to the Water FLUTe system enhancement. The name is the property of the FLUTe trademarked systems and the design has been patented. The method and apparatus includes the hardware design and the software developed for the reduction of the data from this system.

Conclusion

The Air Coupled Transducer (ACT) system is very simple in concept, but more complex in a useful fully tested system. The resolution of a single system emplaced in a well is ~1/4" per second in comparison with a standard submerged pressure transducer. However, temperature variations and actual emplaced geometries require a data reduction software package to convert the data to a water level history. A programming of a special transducer to convert the data as part of the output is in progress. This transducer is expected to be available by the end of 2015.

The outstanding advantage of the system is that the transducers are located at the surface. Until transducer failure rates drop to near zero and there is no interest in reusing the transducers at other sites, having the transducers at the surface is justification for extensive use of the ACT system. There is also the reduced cost of the cables to consider, which is not offset by the price of the ACT system in the Water FLUTe.

The use in other slender pipes and tubes for water level histories has not been done, but can be done easily. The ACT system does not require the air flow system of the common bubbler geometry. A common mistake is that the ACT system of measurement is a bubbler system. The savings of the bubbler constant air supply cost and the lack of bio fouling associated with a constant air flow are significant advantages of the ACT system. The trapped air in the ACT system above the water table is not a concern for modification of the sample water qualities.

The resolution of the ACT system is often not as good as a direct submerged transducer reading. However for a pressure transducer of high range (e.g., 300 psi) the ACT system has better resolution of the water table. In fractured rock environments where the typical water level variations are large, the resolution of the ACT system is sufficient. This is especially true if the aquifer is affected by local pumping.

Fig. 1 Water FLUTe Port and Pump System

(Single port system shown for clarity)

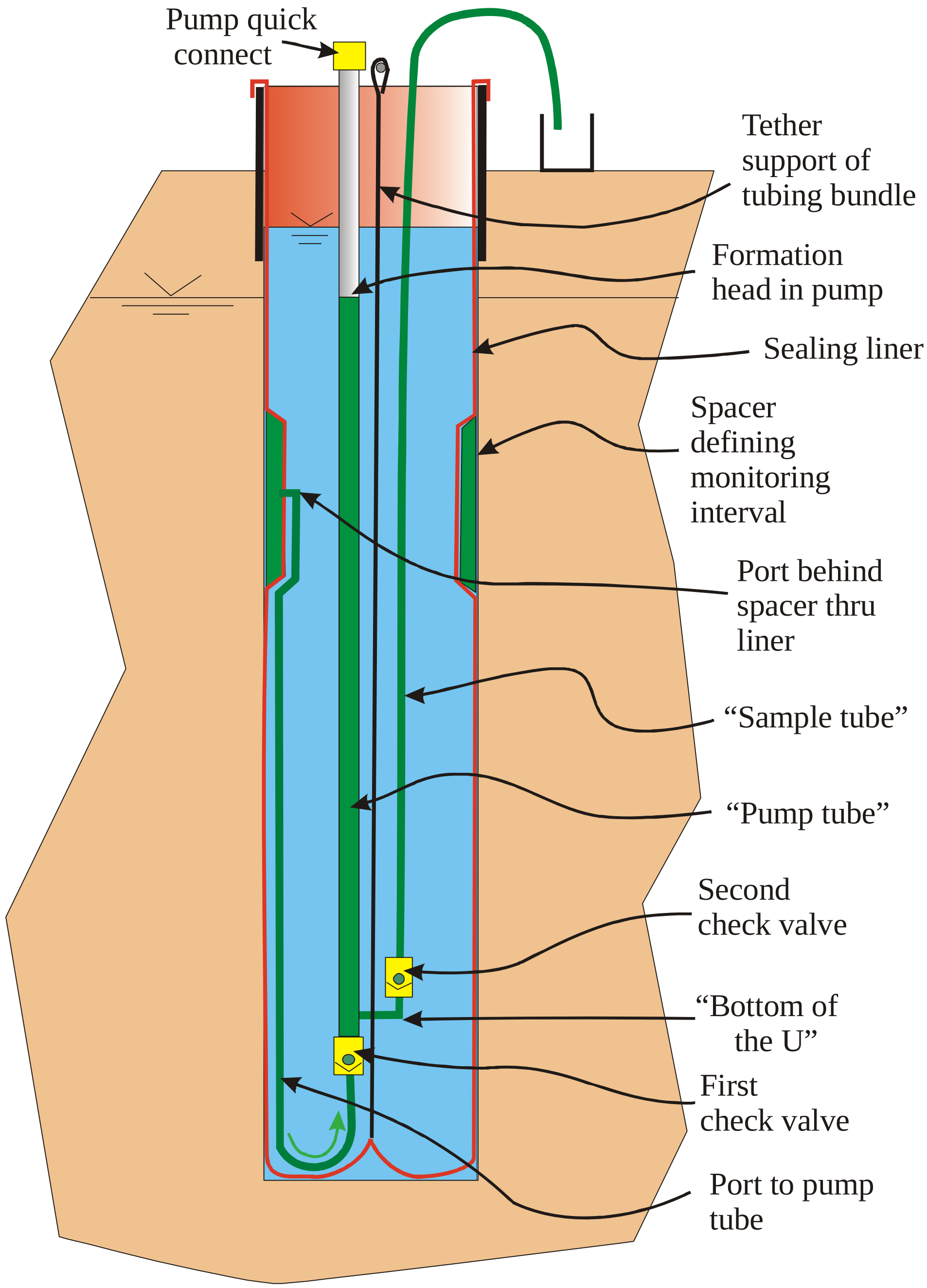


Fig. 2 Pump system with down-hole transducer

(Single port system shown for clarity)

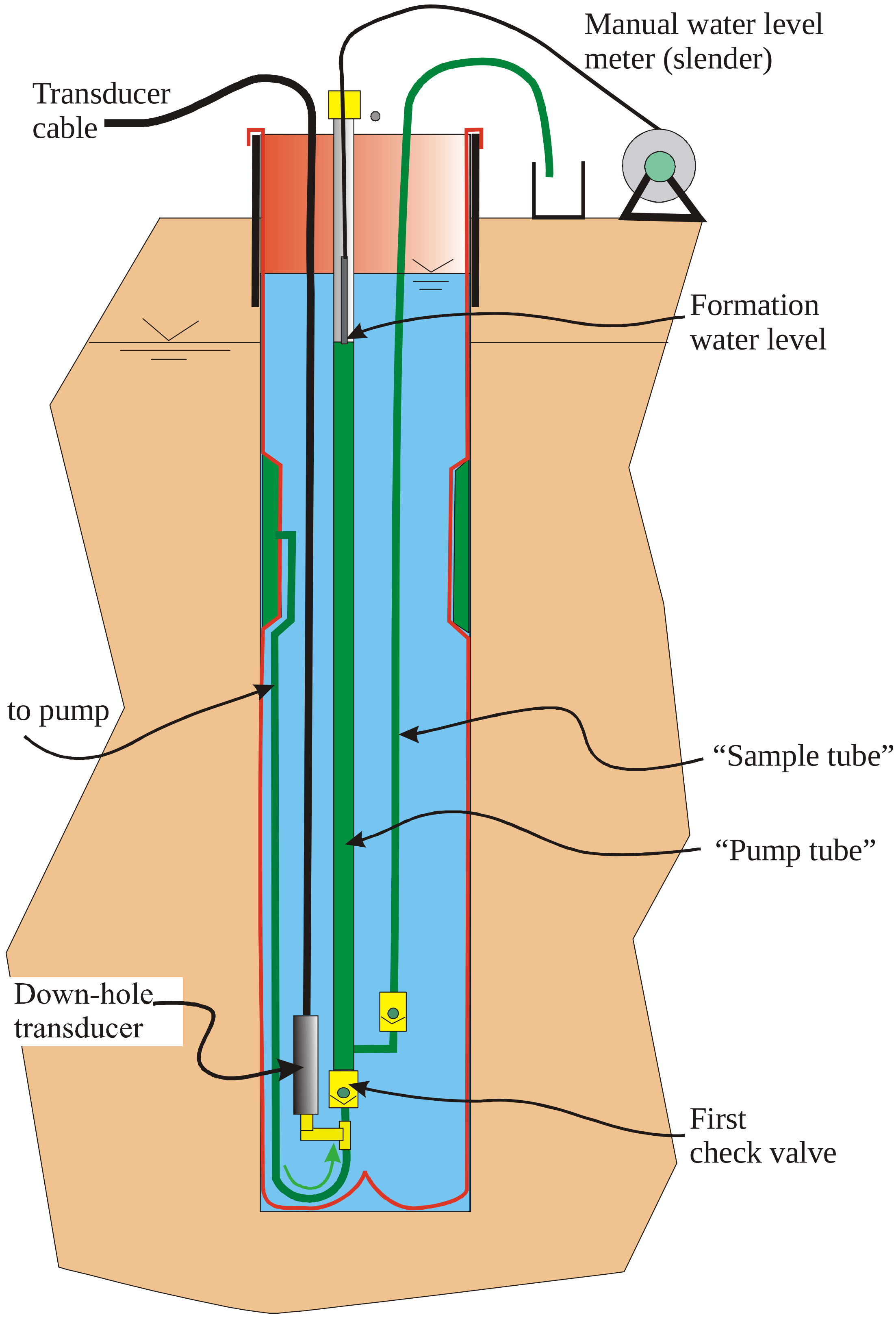


Fig. 3. Pump system with air coupled transducer

(Single port system shown for clarity)

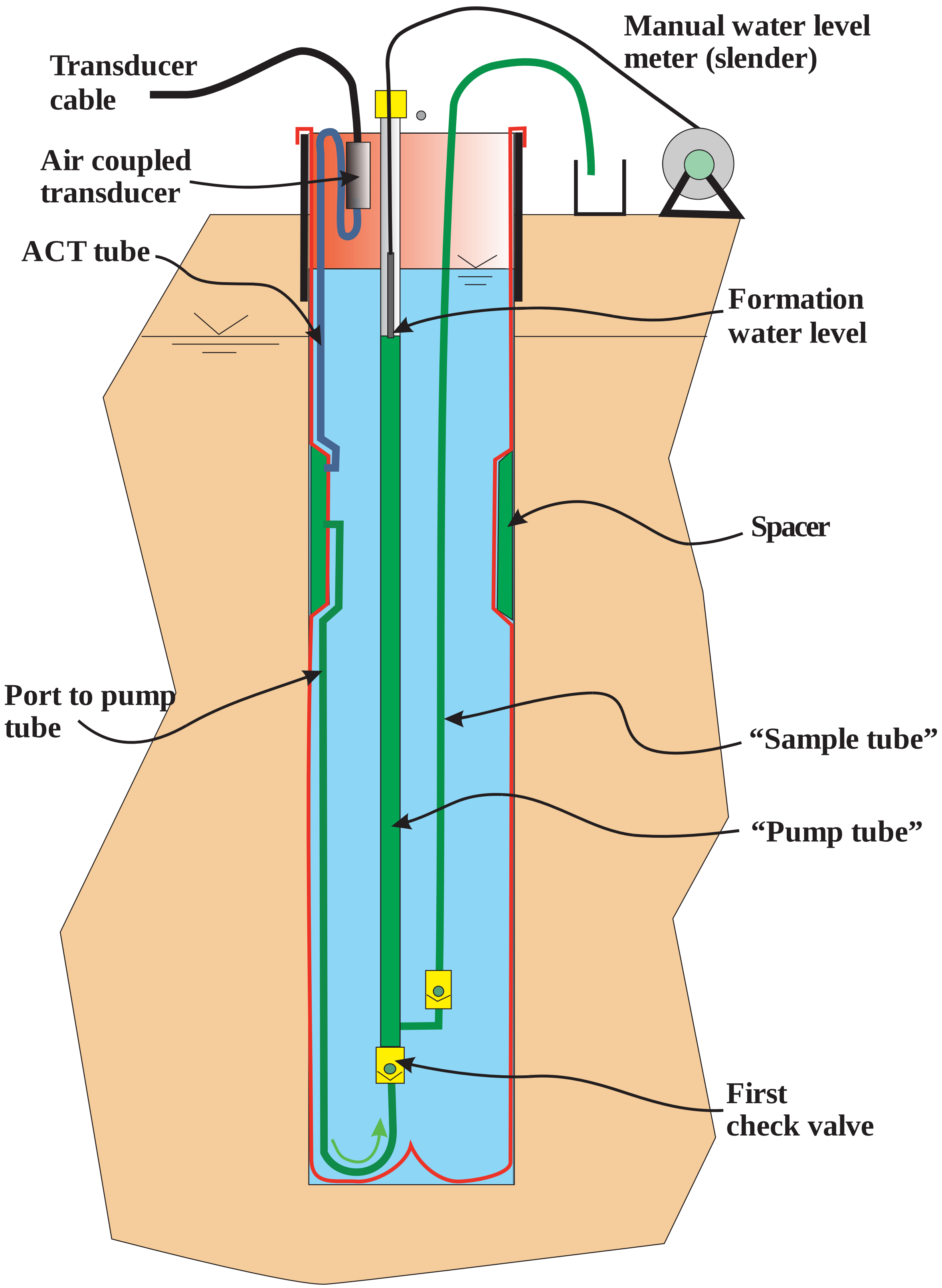
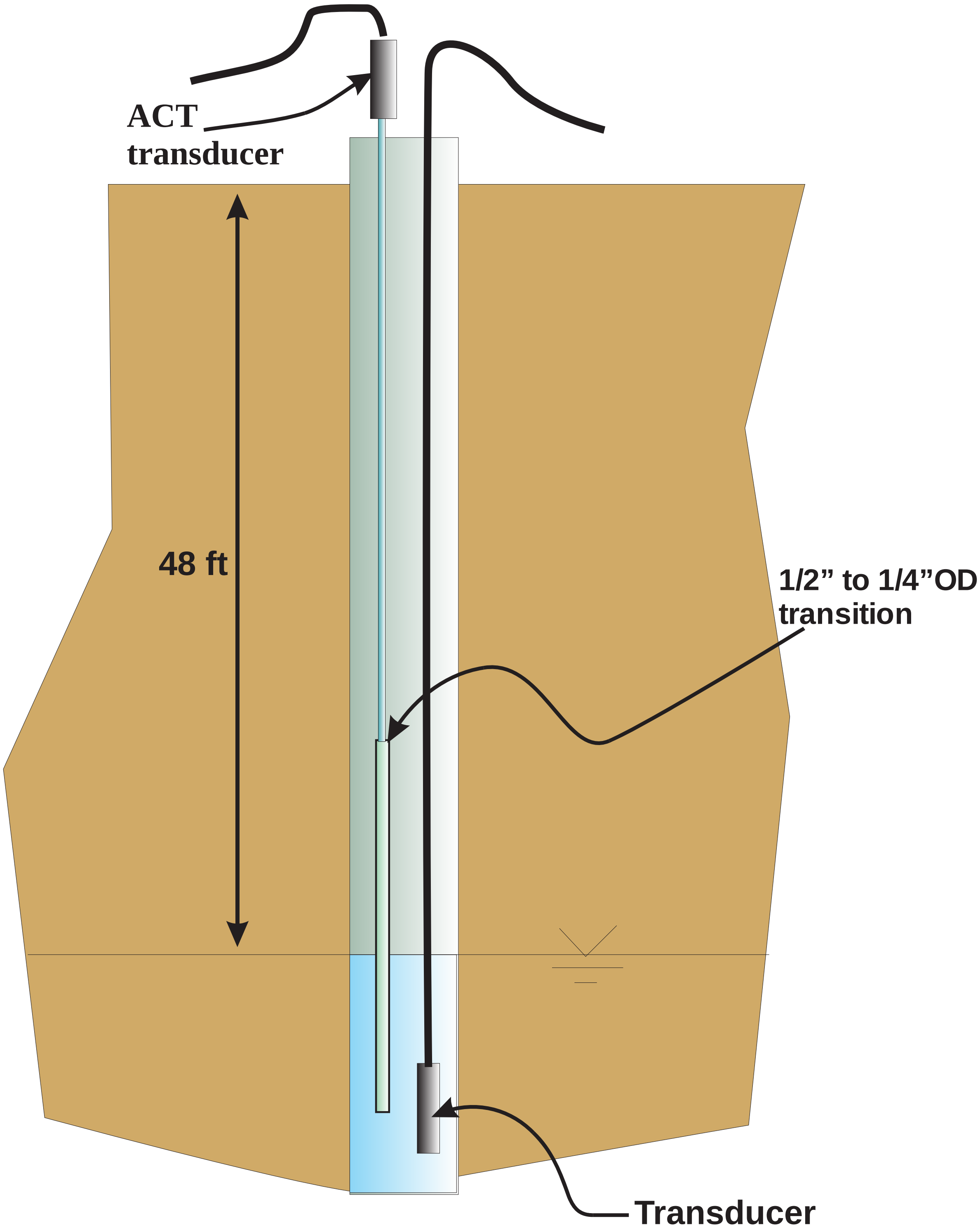


Fig. 4. Domestic well test geometry



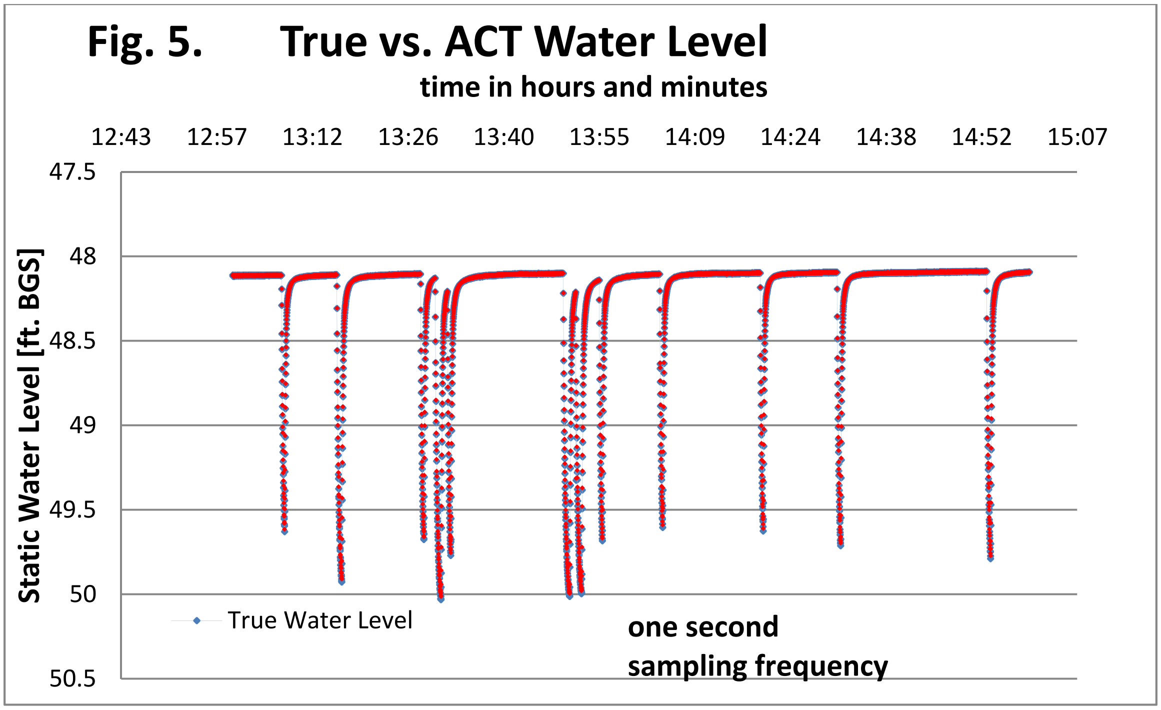


Fig. 5. True vs. ACT Water Level
time in hours and minutes
12:43
12:57
13:12
13:26
13:40
13:55
14:09
14:24
14:38
14:52
15:07
47.5
48
48.5
49
49.5
50
50.5
Static Water Level [ft. BGS]
True Water Level
one second
sampling frequency

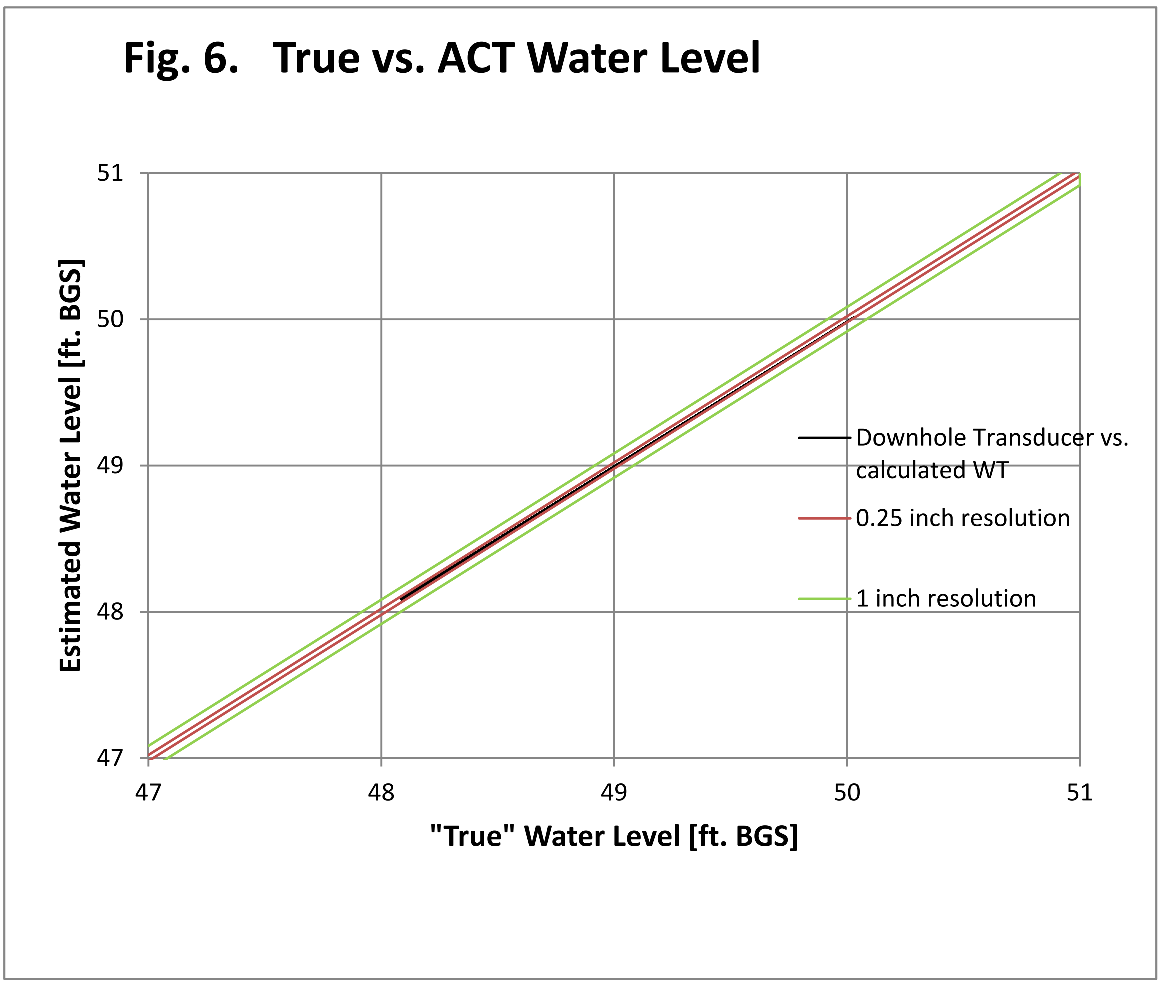


Fig. 6. True vs. ACT Water Level
51
50
49
48
47
Estimated Water Level [ft. BGS]
47
48
49
50
51
"True" Water Level [ft. BGS]
Downhole Transducer vs. calculated WT
0.25 inch resolution
1 inch resolution