Development of a Fine-scale Laser-based Water Level Sensor

Joshua Benjamin and David Kaplan

College of Engineering, University of Florida

Evapotranspiration (ET) is a critical component of the global water cycle. It is the process by which water is transferred from the land to the atmosphere by evaporation from soil and other surfaces (evaporation) and from the stomatal surfaces of plants (transpiration). It is a critical process, but one that is difficult to pinpoint due to a lack of accurate and affordable sensor technology. One low-cost approach to measuring site-specific ET is to take advantage of the diurnal fluctuations in surface water and groundwater driven by ET in areas where the water table is close to the surface. This method requires highly sensitive equipment that is able to accurately quantify water table variation. The goal of this work is to develop and test a laser-based water level sensor (LB-WLS) to improve the estimate of ET via diurnal variation in water level. Preliminary results indicate a high level of accuracy, with the LB-WLS generating readings that have 23.327 times less residual noise than traditional Total Pressure Transducers (TPT). Our next steps include optimizing the LB-WLS for remote deployment by reducing total power consumption and assembling the hardware necessary for field deployment.

INTRODUCTION

Evapotranspiration (ET) is a critical component of the global water balance. In Florida, ET can account for 70-95% of incoming precipitation (McLaughlin and Cohen 2013) and is strongly influenced by land-use, highlighting the need to better understand this flux in the context of projected water scarcity across the southeastern US and other locations around the world. Numerous methods for measuring and modeling ET exist, including the Simultaneous Heat and Water (SHAW) model (Flerchinger et al., 1996) , the eddy covariance method, and the Bowen ratio energy balance method (Drexler et al. 2004), but these methods are often limited by cost and/or data availability. One low-cost approach to measuring site-specific ET is to take advantage of the diurnal fluctuation in surface water and groundwater levels driven by ET in locations where the water table is close to the surface (White 1932). Critically, this method requires high-resolution data to accurately quantify daily water table or surface water level fluctuations (McLaughlin and Cohen 2011).

Current Technology

Currently, the most widely used water level sensors are total pressure transducers (TPT), which rely on atmospheric pressure compensation using separate barometric pressure transducers (BPT). These systems rely on measuring hydrostatic pressure, using the equation:

$$\frac{p}{\gamma} = h \qquad (1)$$

where p stands for pressure, γ stands for specific weight, and h stands for height. These systems are prone to errors based on installation location and media, differences in atmospheric and water temperatures, variations in solar radiation, and long equilibration times (Cain III et al. 2004). Additionally, while these systems are precise when installed correctly, they are still prone to error (>1 cm) due to factors including moisture accumulation and differential heating across the system under ambient conditions (McLaughlin and Cohen 2011). Furthermore, all of these errors are exacerbated by the need to correct the measurements from the TPT using a second sensor (the BPT), which can double potential error. Given these drawbacks, existing water level sensor systems make it difficult to achieve fine-scale resolution observations of water levels necessary to elucidate ET, particularly in surface water systems (McLaughlin and Cohen 2011) or during times with low ET rates (cloudy days, winter).

New Technology

To help mitigate the effects of these errors, we developed and tested a laser-based water-level sensor (LB-WLS). The laser used is a Leica DISTO™ E7100i (the Disto) laser distance meter (LDM). This device utilizes the phase shift method of laser distance measurement. In the phase shift method, the transmitted light intensity is modulated sinusoidally, and the round-trip time is converted into a phase-shift (Nejad and Olyaee 2006) that is produced in the received beam due to the time delay between the emitted point and target. Distance, *D,* can be obtained by measuring the phase shift using the equation:

$$D = \frac{c}{2f} \cdot \frac{\Delta\varphi}{2\pi} \qquad (2)$$

where c is the speed of light, f is the modulation frequency, and $\Delta\varphi$ is the phase shift between the measurement signal and the reference signal. For this process to function effectively, the phase-shift $\Delta\varphi$ must be measured accurately to obtain a precise distance measurement. To improve phase measurement accuracy, the auto-digital phase measurement will usually process the signals with a heterodyne method, which can convert the two high frequency signals into low frequency signals (Hu et al., 2011). These techniques help improve the signal to noise ratio (SNR) and enable mm-range resolution at distances of 0.0015 to 60.96 m with noncooperative targets[1]. Because of this, a LB-WLS is expected to perform better because it would not be subject to the oscillations in ambient temperature and pressure that plague the TPT-BPT pair.

Furthermore, by taking actions such as measuring the bandwidth of the system and increasing the area of the photodiode, the measurement error within the system can be reduced dramatically (Amann et al., 2001). This gives the Disto an advantage over traditional water measurement technologies that rely on variations in pressure and temperature, as the device's optical basis enables it increased stability in dynamic environments.

We hypothesize that the advantages that come from an optical-based measurement system will allow the LB-WLS to have greater accuracy than current water level sensing technology.

METHODS

Sensor Design

The design comprises three components: a laser distance meter, a target platform, and an advanced reduced instruction computing machine (ARM)-based mini PC.

Laser Distance Meter. The laser rangefinder used for the LB-WLS was a Leica DISTO™ E7100i (Disto) (Figure 2) by Leica Geosystems (St. Gallen Switzerland). The Disto was chosen primarily for its low cost ($149.00), its high measurement accuracy (±1.5 mm), and the fact that is IP54 certified2. The Disto can also send distance measurements via Bluetooth® SMART, which makes it the least expensive Bluetooth LDM available on the market (Leica Geosystems 2016). The ability to send measurements via Bluetooth® SMART is particularly important, as it is this characteristic that allows the recording of data on an ARM-based mini PC.

ARM-based mini PC. The microcomputer that was used for the design was a Raspberry Pi 2 Model B (Pi 2B) (Figure 3) by the Raspberry Pi Foundation (Caldecote, United Kingdom). The Pi 2B was chosen for its low cost ($35.00[3]), small size[4], low power usage[5], versatility[6], and high processing power[7].

The Pi 2B was setup to run the latest distribution of Rasbian (Rasbian Jessie 4.1, March 2016). The system was then configured to run Exagear Desktop, a program developed by Eltechs (Moscow, Russia) to enable an ARM-based mini PC to run x86 applications directly on the ARM. Through this software, a remote monitoring application known as TeamViewer was installed. TeamViewer enables the user of the device to monitor and download information from the sensor remotely, which will be ideal for field applications.

Because the Disto broadcasts information using Bluetooth® SMART, Bluetooth® SMART had to be enabled on the Pi 2B. This was done by first connecting a Bluetooth® 4.0[8] radio to the Pi 2B, which in this case was the Panda Wireless Bluetooth® 4.0 USB Nano Adaptor. This adapter allows the Pi 2B to receive a Bluetooth Bluetooth® 4.0 signal. To enable the system to understand the Bluetooth signal, BlueZ was installed. BlueZ is the official Linux Bluetooth® protocol stack, and provides support for the core Bluetooth® layers and protocols.

The BlueZ protocol was used with the Bluetooth® profile description provided by Leica Geosystems to decode the signals that were sent between the Disto and the Pi 2B during operation. The signals were a combination of indicate and write without response commands. The UUIDs were found to broadcast in hexadecimal format, and were able to be read once they were converted into strings.

The information provided by this investigation was used to design a python control script we named Laser.py. Laser.py is a simple interactive control program that is used as an interface between the user and the laser. Laser.py records input variables from the user, including measurement frequency and start and end times. The program automatically records the data that is generated during the measurement period, and can be controlled autonomously using the TeamViewer function that was built into the Pi 2B.

Floating Target Platform (FTP). A floating target platform is required to take water level measurements due to the need to provide a stable non-cooperative target. The FTP was designed using the AutoDesk 123D design software package and 3-D printed using Polylactic Acid (PLA) on a Makerbot printer. The main governing equation utilized in the design process was the buoyancy equation, which is reproduced below:

$$F_b = \gamma_{fluid} \forall_{body} \tag{3}$$

where γ_{fluid} stands for the specific weight of the fluid, and $\forall_{body}$ stands for the volume of the submersed body.

The FTP went through three design iterations. The first design (Mk-I) was a simple cylindrical tube with a flat firing platform on top, and a large air-filled cavity in the center in order to make the platform stable and buoyant. This FTP was designed for a 1.50-in diameter Schedule 80 PVC pipe.

The next iteration (Mk-II) was redesigned for a smaller 1.25-in Schedule 40 PVC pipe. Further improvements included rounding the edges of the floater to make it less likely to catch on the slots in a slotted well and the implementation of a screw cap and O-ring to prevent water from leaking into the central cavity.

The third design (Mk-III) (Figure 1) implemented a magnetic retrieval system by incorporating two 0.5 in diameter neodymium magnets into the floater itself, and adding a separate magnetic retriever to the setup.

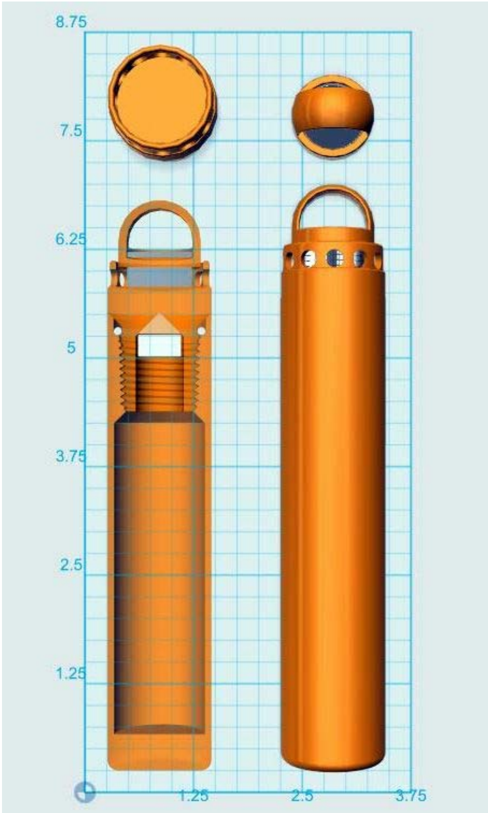

Figure 1. The final design for the FTP (FTP Mk-III). The top left is the target platform, the top right is the Magnetic retriever, the bottom left is a cutaway view showing the central cavity, screw-cap, magnets, and O-ring, and the bottom right is the entire assembly.

The retriever itself underwent two design revisions, with the first design relying on superglue to attach the magnets to the retriever, and the second design implementing magnets on both sides of the retriever's central disk to prevent the magnets from slipping[9].

Experimental Setup

Two different experimental setups were tested in this investigation. Comparisons were conducted between the laser-based water level sensor (LB-WLS) and the TPT-BPT pair. The LB-WLS was composed of the Disto, the FTP, and the Pi 2B. The TPT used was a Solinst Levelogger® (accuracy = 0.3 cm, precision/resolution = 0.005 cm) and the BPT was a Solinst Barologger® (accuracy = 0.1 cm, resolution = 0.003 cm).

In the first setup (Figure 2) a graduated cylinder was filled with 1 L of water, and both the TPT-BPT pair and the LB-WLS were installed (the FTP Mk-I was used in this setup) in order to stimulate stagnant water with only ambient evaporative effects. The experiment took measurements every fifteen minutes for 24 hours.

In the second phase (Figure 3), a graduated cylinder was filled with 0.75 L of water. A 0.9793 m long section of 1.25 in schedule 40 slotted PVC was then inserted into the cylinder to simulate a well. The FTP Mk-III and the Levelogger were placed inside of the well, and then the Disto was placed inside of a specially built enclosure inside of the well cap. The barologger was placed inside of a nylon sleeve in order to simulate the buffered conditions that were investigated by McLaughlin and Cohen (2011). The experiment was run for 24 hours, with measurements every 15 minutes.

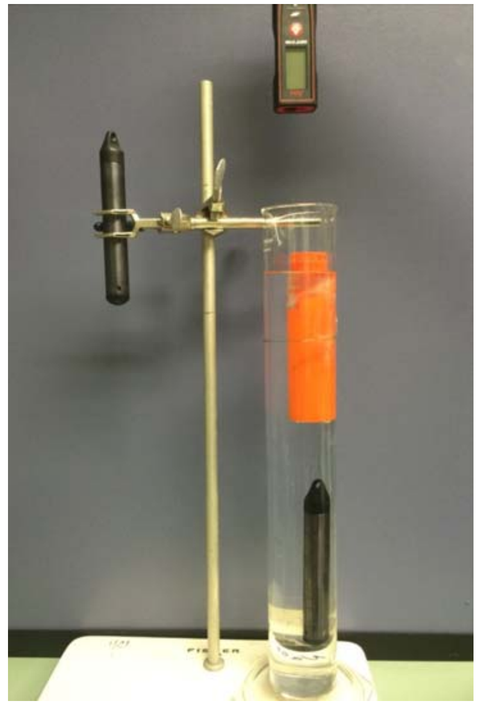

Figure 2. The experimental set-up for the stagnant water column comparison tests. The Solinst Barologger® is on the far left, the Disto is hanging at the top, the FTP is in the center, and the Solinst Levellogger® is on the bottom.

Figure 3. The experimental set-up for the artificial well comparison tests. The Solinst Barologger® is in the corner inside of the nylon sheath. The Disto, FTP, and Solinst Levelogger® are inside the well, and the Pi 2B is at the nexus of all of the cables in the bottom of the image.

Once data collection was complete, the data from the TPT-BPT was compensated using the Solinst Levelogger Software 4.1.2, and the data from the LB-WLS was compensated by subtracting the measured data and the height of the target platform from the total height of the water column in order to showcase the total water level. Next, both the data from the TPT-BPT and the LB-WLS were transferred to Microsoft Excel for analysis.

Data analysis involved taking the initial water level from each trial and subtracting it from each cumulative measurement in order to determine total variance in mm. After that, a linear model was derived by taking the linear trend line from the LB-WLS, with the linear model assumed to be the "true" water level. A linear model is necessary because even though water level was relatively static, it was still subject to minor evaporative losses[10]. The model was based on the LB-WLS because it had a lower level of variance compared to the TPT-BPT pair, which gave a more linear trend and a higher R^2 value. Next, values were subtracted from the linear model and placed into absolute terms in order to calculate the residual noise from the linear model.

RESULTS

Overall, the LB-WLS had much lower residual noise than the TPT-BPT pair (Figures 4 and 5).

Water level measurements between the LB-WLS and the TPT-BPT pair were substantially different. The LB-WLS had an average absolute residual of 0.110 mm (Table 1) while the TPT-BPT pair had an average absolute residual of 2.566 mm (Table 2).

The minima and maxima between the two models show the true extents of the increased accuracy that is provided by the LB-WLS, with results indicating that the LB-WLS can differ from the linear model by up to 0.666 mm. The value is even lower when not including the well trial, at 0.279 mm. This is because the well cap used in the well trial impacts the constant evaporative flux that was seen in the static water column trials. This removed that constant linear effect and made the well more subject to factors such as Brownian

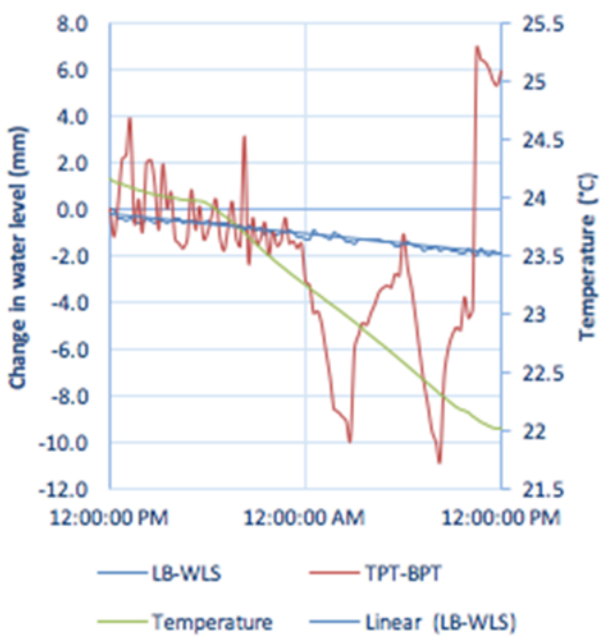

Figure 4. Trial one change in water level. The results from trial one show that the laser based water level sensor is far less variable than the total pressure transducer-barometric pressure transducer pair, and follows a linear evaporative model.

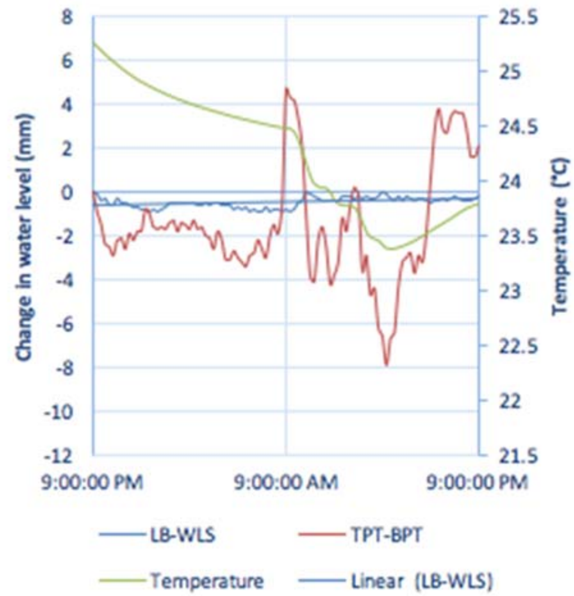

Figure 5. Trial three change in water level. The results from the well trial show that even under buffered conditions, the laser based water level sensor is far less variable than the total pressure transducer-barometric pressure transducer pair.

Table 1. Laser Based Water Level Sensor Residual Noise (in mm)

Trial #	Minimum (abs)	Maximum (abs)	Mean (abs)
1	0.002	0.279	0.099
2	0.001	0.234	0.067
3	0.005	0.666	0.163
Mean (#1-2)	0.001	0.256	0.083
Mean (All)	0.003	0.393	0.110

Note. All values are absolute. Trial 3 data is treated separately due to the difference in experimental conditions.

Table 2. Total Pressure Transducer-Barometric Pressure Transducer Residual Noise (in mm)

Trial #	Minimum (abs)	Maximum (abs)	Mean (abs)
1	0.085	9.153	2.865
2	0.070	6.287	2.532
3	0.184	7.519	2.303
Mean (#1-2)	0.077	7.720	2.698
Mean (All)	0.113	7.653	2.566

Note. All values are absolute. Trial 3 data is treated separately due to the difference in experimental conditions.

motion, density variation, and molecular diffusion. The TPT-BPT was off by as much as 9.153 mm, which verifies the claim stated by McLaughlin and Cohen that TPT-BPT pairs can be off by 1 cm (McLaughlin and Cohen 2011).

It is important to note that when using a buffered BPT as suggested by McLaughlin and Cohen (McLaughlin and Cohen 2011), the temperature difference between the BPT and TPT decreased (Figure 6). This trend indicates that using a nylon sheath to buffer the BPT is a useful technique. The absolute mean residual that was demonstrated by trial 3 was the lowest among the three trials at 2.303 mm, with the inclusion of the buffered trial lowering the mean absolute residual from 2.698 mm to 2.566 mm. Due to this effect, it is recommended to use a buffered BPT when conducting future trials, as the lower temperature difference between the TPT and the BPT (Figure 6) correlates with lower absolute residual noise.

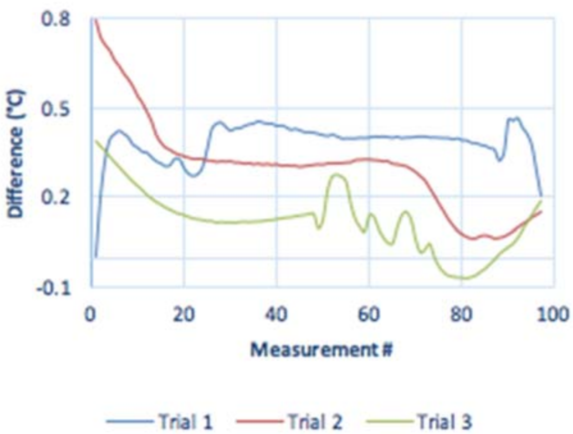

Figure 6. Temperature differences between the TPT and the BPT across all three trials.

DISCUSSION

On average, the residual noise from the LB-WLS was 23.327 times lower than the residual from the TPT-BPT pair. This number was calculated by taking mean absolute residual noise of the TPT-BPT pair and dividing it by the mean absolute residual noise of the LB-WLS. This is mainly due to the inherent inaccuracies that are a product of the TPT-BPT's reliance on fluctuations in temperature and atmospheric pressure. These fluctuations do not play a large role in macro-scale observations, but minute changes in these conditions can affect the indicated water level.

The LB-WLS is not affected by these variations, because as seen in Equation 2, the main parameters that determine the measurement distance are the modulation frequency f and the phase shift between the measurement signal and the reference signal $\Delta\varphi$. These parameters are measured against a nonvariable medium (the speed of light), and are processed using a heterodyne method, which is shown to highly improve SNR (Hu et al., 2011) and overall give a higher level of accuracy and a lower margin of error than the TPT-BPT.

It can be concluded that the LB-WLS has demonstrated superior capabilities in the lab setting, with great promise for field deployment.

Future Objectives

Future objectives for this investigation involve improving the central algorithm in laser.py and modifying the design for field deployment.

In regards to the algorithm, there is a certain degree of lag time that can cause up to seven seconds of temporal drift per day, which can be a large source of error in a month-long trial. Furthermore, an error exception loop still needs to be implemented to prevent Laser.py from freezing in event of a misfire.

There are several modifications that need to be made to the LB-WLS before it is ready for field deployment, with the main focus being on power supply. An external power supply needs to be designed for the Disto, as its current power source of two AA-batteries can only last up to three-four days at most. One option for improving the Disto's operating time is to design an alternate battery cover that has external cathodes and anodes that can then be connected to a solar cell. The solar cell could in turn be connected to a charging circuit that could power both the Disto and the Pi 2B. Modifications will need to be made to the Pi 2B itself in order to reduce power consumption. The most viable option for this would be to simply replace the Pi 2B with a less power-hungry ARM-based mini PC, such as a Raspberry Pi Model A+ by the Raspberry Pi Foundation, or a CHIP by Next thing Co (Oakland, California).

ACKNOWLEDGMENTS

I would like to thank my mentor, Dr. David Kaplan, for his guidance and leadership during this project, as well as my parents Arnold and Lorraine Benjamin and my girlfriend Kylie Chapman for their help and support. John Loeffler for helping me with the FTP design, Johannes from the Disto Support Team for providing me with the Disto Bluetooth service documentation, and my friend Jackson Benfer for his assistance during the programming phase of the project.

REFERENCES

Amann, M.-C., Bosch, T., Lescure, M., Myllyla¨, R., and Rioux, M. (2001). "Laser ranging: a critical review of usual techniques for distance measurement." *Optical Engineering*, 40(1), 10–19.

Barchers, JD. (2011). "Non-cooperative laser target enhancement system and method."

Cain III, S. F., Davis, G. A., Loheide II, S. P., and Butler Jr., J. R. (2004). "Noise in Pressure Transducer Readings Produced by Variations in Solar Radiation." *Groundwater*, Groundwater, 42(6), 939–944.

Drexler, J. Z., Snyder, R. L., Spano, D., Paw, U, and Tha, K. (2004). "A review of models and micrometeorological methods used to estimate wetland evapotranspiration." *Hydrological Processes*, Wiley Online Library, 18(11), 2071–2101.

DSM&T CO., INC. (2011). "IP Rating."

Flerchinger, G., Hanson, C., and Wight, J. (1996). "Modeling Evapotranspiration and Surface Energy Budgets Across a Watershed." *Water Resources Research*, 32(8), 2539–2548.

Hu, P., Tan, J., Yang, H., Zhao, X., and Liu, S. (2011). "Phase-shift laser range finder based on high speed and high precision phase-measuring techniques."

Leica Geosystems. (2016). "Leica DISTO E7100i."

McLaughlin, D., and Cohen, M. (2011). "Thermal artifacts in measurements of fine□scale water level variation." *Water Resources Research*, 47(9), n/a–n/a.

McLaughlin, D., and Cohen, M. (2013). "Realizing ecosystem services: wetland hydrologic function along a gradient of ecosystem condition." *Ecological Applications*, 23(7), 1619–1631.

Nejad, SM, and Olyaee, S. (2006). "Comparison of TOF, FMCW and phase-shift laser range-finding methods by simulation and measurement." *Quart. J. Technol. Educ*.

White, WN. (1932). "A method of estimating ground-water supplies based on discharge by plants and evaporation from soil: Results of investigations in Escalante Valley, Utah."

ENDNOTES

[1] A non-cooperative target is a target in which no laser beacon is provided directly by the target for wavefront sensing. This means that no laser beacon is available from the target except that obtained from the target itself or from the atmosphere (Barchers 2011).

[2] IP54 certification implies that a device is protected from limited dust ingress and protected from water spray in any direction (DSM&T CO., INC. 2011). These protections make the Disto ideal for field deployment.

[3] Not including price of the 5V power source, case, external monitor, mouse, keyboard, and Ethernet connection, all of which can increase the cost significantly.

[4] 85 mm x 56 mm – about the size of a credit card.

[5] 3 to 9 W depending on usage.

[6] The Pi 2B contains 4 USB ports, 1 HDMI port, an Ethernet port, and a Micro SD card slot.

[7] Supplied by a 900Mhz quad-core ARM Cortex-A7 CPU, which is suitable for running a full range of ARM GNU/Linux distributions.

[8] For the purposes of this device, Bluetooth® SMART and Bluetooth 4.0 are essentially the same thing.

[9] The original retriever design had the magnets attached to the PLA using superglue. This caused the retriever to fail, as the magnets were stronger than the superglue and ended up breaking the bond from the glue, which caused them to slip off of the retriever.

[10] This is why a linear model is necessary as opposed to a flat line, because ambient effects such as evaporation and Brownian motion are highly noticeable in fine scale measurements, and could be a significant source of error if not taken into account.