Advances in hydrostatic leveling with the NPH6, and suggestions for further enhancements

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Abstract

This paper reviews the state-of-the-art of hydrostatic leveling and tilt measurement, with an emphasis on the Pellissier H5, and the National Radio Astronomy Observatory NPH6. Details of the NPH6 design are described, experimental results are discussed, suggestions are made for further enhancements, and additional potential applications are offered.

Keywords: hydrostatic level, tilt, inclinometer, large scale metrology, Pellissier H5, NPH6, radio telescope, photogrammetry, pressure, hook gage.

1 Introduction

Hydrostatic leveling is a well established, although esoteric, method for measuring differential heights over distances of tens to thousands of meters, with a standard uncertainty of less than 0.1 parts per million–which is one to two orders of magnitude better than conventional optical leveling[1, 2, 3]. Applications requiring this degree of precision are typically limited to geophysics[4, 5, 6], accelerator alignment[7, 8, 9, 10, 11], and recently a radio telescope[12, 13, 14, 15].

Systems can be constructed by simply installing clear plastic wells to the end of a garden hose, filling with water, and reading graduation marks on the wells, by eye. Kits such as this are available from hardware stores and are commonly used for farm and home projects. However, higher precision work requires much more sophisticated techniques. The object of this paper is to discuss methods and techniques for the most demanding level and tilt measurements.

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2 Contributions to measurement uncertainty

The principle contributions to the measurement uncertainty are the U-tube error, water circulation induced errors, height transducer errors, mechanical errors, ambient pressure errors, and the astronomic error. These will be talked about in more detail in the following subsections.

Since the measurement is inherently a differential measurement, any asymmetry will introduce errors. Typical sources include: bubbles in the sense hose, dilatation of the sense hose, thermal gradients due to pumping and solenoid valve coils, improper venting (including leaks in the reservoir and water condensation in the vent line), the length measurement transducer linearity, cosine of the angle between the water surface normal vector and the length measurement transducer axis, contamination of the water surface, meniscus of the water surface, probe tip contamination, dull or damaged probe tips, vibrations and waves on the water surface, detection of the water height, mechanical, repeatability of the instrument seating, interaction of people and moving equipment, etc.

2.1 U-Tube error

The U-tube error can most easily be illustrated by considering a manometer. The two legs of a manometer are in equilibrium when

$$\rho_1 g_1 h_1 + p_1 = \rho_2 g_2 h_2 + p_2, \tag{1}$$

where ρ, g, h, and p are density, acceleration of gravity, fluid height, and ambient pressure.

This is commonly used under the assumption that

$$\rho_1 = \rho_2 \tag{2}$$
$$g_1 = g_2 \tag{3}$$

and thus the differential pressure is measured by the differential heights of the two legs. If, in addition

$$p_1 = p_2, \tag{4}$$

then the height of the two legs must be equal. If these conditions can be maintained over a distance, the manometer can be used as a level. It should be pointed out that "level" means equal height above the geoid (sea level).

If the density is not uniform in the two legs, as would be the general case for a non-uniform temperature or non-homogeneous fluid, one can not assume the legs are equal height.

In order to minimize the U-tube error, Eaton[4] flushed his system with ambient temperature water in order to ensure a uniform temperature. Pellissier[11] circulated the water in a closed circuit reservoir/hose configuration for the model H5 instrument[16]. He also jacketed the sense line with water tubes in order to buffer changes in temperature.

Hurst and Bilham[6] used a closed loop circulating system and refrigerated the water to around 4° C in order to operate in the neighborhood of the maximum density, and thus minimize the sensitivity to small changes in temperature. More will be said about the merits of using chilled water in Section 5.2.

Huggett, Slater, and Pavlis[5] proposed a two-fluid scheme using differential temperature coefficient fluids to correct for the temperature.

Outdoor measurements are typically made in the evening to avoid direct solar radiation. Indoor measurements are usually made in a much better environment, e.g., measurements of the European Synchrotron Radiation Facility were made after a 60 hour thermal stabilization period[8].

The effect can also be minimized by keeping the hose level, i.e., minimizing h.

2.2 Water circulation induced errors

Pumping the water introduces secondary problems. The pump pressure dilates the hose slightly. Pumping also heats the water, which introduces a temperature gradient down the length of the hose.

After pumping; the hose relaxes, which reduces the volume of the hose and thus raises the water height in the wells, i.e., h is time dependent. Moreover, if the pump is not symmetrically located near the center of the hose, there is a pressure gradient down the line and the resulting movement of water is not symmetric, which can result in a time lag for the distant well. Pellissier minimized this effect by using a larger hose, a low pressure pump, and using spiral wire reinforced hose for the sense line.

2.3 Height transducer error

A number of methods have been used to measure the height of the water with respect to the physical bench mark. Pellissier used a digital depth micrometer, such as the Mitutoyo 329-711-30, with a sharp platinum tip probe and an electronic circuit to detect contact with the water. This was used to measure the height of the water with respect to an invar mounting that is located on a 12.700 mm tooling ball bench mark, i.e., the micrometer measured down to the top of the water. This method has a lot of merits, e.g., the digital depth micrometer is easy to interface to a computer, the measurement is based on an internal glass scale, and the calibration is certified by the instrument manufacturer. Experience has verified that, with reasonable care, it works reliably.

Some designs use micrometers measuring from below the water[4, 6]. This method has some disadvantages. Since the probe is always in contact with the water, automated electronic detection is not an option. Measurements must be made manually, which can jiggle the instrument. The measurements are somewhat subjective and require some skill to determine when the point pierces the water surface. This is compounded by the requirement that two people are required to make the measurements. Adjusting the micrometer screws introduced additional volume into the well, and thus introduces a transient in the water level–unless both operators work in close synchronization. The micrometer seal must be made against water instead of air, which can add contamination to the water.

The Fogale Nanotech HLS (the only commercially available hydrostatic level known to the authors) uses a capacitive sensor. This design has obvious advantage for automation and multiple wells, and the European Synchrotron Radiation Facility employs a system of 288 of the instruments[8]. Calibration is less direct than the digital instruments employing glass scales.

An optical system, which uses total internal reflection off the air/water interface, has been developed for the Argonne Advanced Photon Source[10]. This would also facilitate automation and multiple wells, but calibration may be a little more difficult.

All mechanical methods are sensitive to the cosine theta error, i.e., the measurement axis must be aligned along the true vertical. For mechanical probes, this is a secondary error and tilt of the instrument is absorbed into the cosine theta error. Methods that rely on reflections off the water-air interface are not subject to the cosine theta error, since the water surface is always correct with respect to the vertical. Note that the linear displacement of a laser reflecting off the water-air interface will be a linear function of the tilt of the instrument, and thus much more care must be taken to eleminate the tilt error. This probably makes field use of the optical method impractical.

Common problems with probes are that they detect the crest of a wave, are sensitive to dust and contamination on the surface, and are sensitive to contamination and defects of the probe tip. All of these are fairly easy to detect in the data. For example, vibrations will show up as outlying high readings and contamination will show up as outlying low readings, i.e., a spec of dust floating on the water will be harder to pierce by the probe. Barbs on the tip will make contact and release erratic.

2.4 Ambient pressure error

The pressure is typically held constant by connecting the two wells with a common vent line which is vented to the atmosphere at the midpoint of the instruments. The vent port should be muffled to avoid dynamic changes in pressure due to wind.

Note that extreme care must be taken to ensure that the wells are well sealed and vented only through the vent line. Even a small shunt leak can introduce a differential pressure, due to static pressure differentials, as well as dynamic effects due to wind. This is best assured by pressurizing the wells and soap bubble testing before use. Care must also be taken to ensure water or condensate does not collect in the vent line.

2.5 Mechanical errors

An often overlooked problem with repeatability is mechanical stability of the bench mark[17]. Note that a standard sheet of printer paper is 100 microns thick, and typical hydrostatic level resolutions are a few microns. A spec of dust, or the slightest movement of the instrument location on a rough or inclined surface, will dominate the non-repeatability. Pellissier used 12.700 mm tooling balls firmly mounted or epoxied to the measurement points. The H5 coupling is an invar cone that kinematically rests on the tooling ball, with leveling screws to minimize the cosine theta error. The NPH6 uses a 19.050 mm tooling ball on the instrument, which fits into a rigidly-fixed cone mounted on the bench marks.

Due to the extreme sensitivity of the instrument, interactions with other influences are often overlooked. For example, even a concrete warehouse floor is clearly deflected by the presence of a person standing beside the instrument.

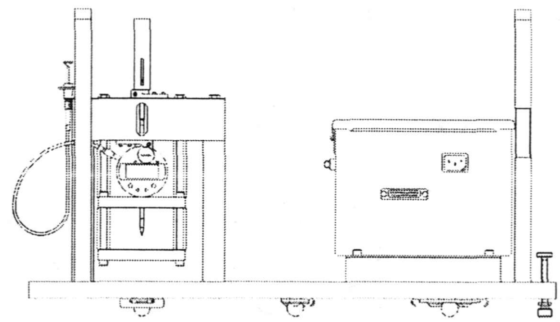

Figure 1: Hydrostatic level head.

2.6 Astronomic error

For conventional surveying over several hundred meters, we normally assume the gravitational field is both spacially and temporally invariant. However, for the most precise work, there is a slight spacial nonuniformity, due to the moon and sun, which must be accounted for. This is < 0.1 mm/km[18], or 0.1 ppm. Software to make the astronomic corrections is available from the National Geodetic Service, and will be discussed later.

3 The NPH6

The National Radio Astronomy Observatory (NRAO) purchased a Pellissier H5 level to set the elevation of a 32 meter radius track for the Robert C. Byrd Green Bank Telescope (GBT). This produced excellent results[12], but the fixed 14 meter hose length was a limitation for another job measuring the elevation of 12 monuments on a 62 meter spacing. Unfortunately, Pellissier became ill and died before a 62 meter instrument could be built. The GBT Antenna Metrology Group had worked with Pellissier and he shared much of his experience, so NRAO decided to build on the H5, and Pellissier's experience, and built the NPH6 (NRAO/Pellissier Hydrostatic level model 6)[19].

3.1 Features

While preserving the design philosophy of the H5, the NPH6 incorporates a number of additional features. See Figure 1 for the mechanical, Figure 2 for a schematic of the hydraulics, and the drawing control sheet[20] for additional details.

The fixed 14 meter hose was replaced by a removable, variable-length hose incorporating quick disconnect double-shutoff hydraulic couplings, in order to

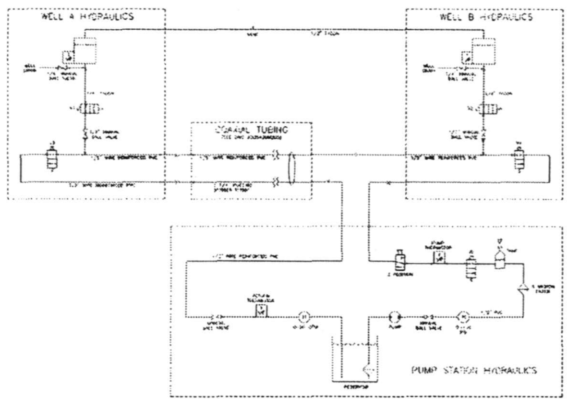

Figure 2: Hydraulic system schematic.

retain the hose charge and minimize air bubbles for knockdown and setup. The wire reinforced sense line was retained (12 mm ID), but the outer jacket (32 mm ID) was made into a true coaxial system, with an insulated outer hose and special end fittings to break out the two hydraulic circuits. The two heads were made identical, and the pump and reservoir were made much larger to handle the increased volume.

Since it was to be used on the site and access to power was not a concern, the electrical system was designed to operate on 120 VAC, instead of 12 VDC batteries. The probe movement was totally automated. The H5 was motor-driven down, but manually returned, which required two operators and touching the instruments could introduce vibrations and waves in the wells. Low pressure (for minimum solenoid power and heat), full port, electric solenoid valves are used for all operational functions (manual valves were retained to secure the wells for movement of the instrument). All solenoid valves operate in the deenergized state, for measurement operations, in order to eleminate solenoid valve heating and possible AC hum.

A filtration cartridge, bubble trap/sight glass, flow meter, and pressure gages were incorporated into the hydraulic system. Temperature sensors were incorporated into the wells, pump output, and return lines. All of this was controlled from a handheld computer over a multidrop RS485 serial bus which connects the two measurement heads and pump station.

One problem we had with the H5 probe was that the probe rotates with the depth micrometer, which requires a slip ring arrangement for the electrical connection to the probe tip. This was prone to maintenance problems. The digital depth micrometer was replaced by a digital indicator (Mitutoyo 543-252B), which does not rotate as it is plunged.

The digital indicator was mounted "upside down" on an invar bridge connected to the kinematic mounting point, i.e., the nominal plunger pointed up and the shaft nominally hidden under the protective dust cap pointed down.

The spring loaded indicator was operated by a motor driven optical translator operator (Oriel Corporation "Motor Mike") pushing on the nominal probe shaft, with an insulated platinum tipped probe attached to what would normally be the shaft under the protective cap. A simple jumper, without the need for a slip ring, between the insulated platinum tip and an insulated feedthrough in the well housing, was used for the contact detection circuit. Since the shaft did not have to rotate, this also made sealing easier by using a simple bellows.

It was discovered that even with the large gear reduction of the micrometer drive, dynamic breaking was necessary in order to stop the travel of the probe repeatabibly and thus lock-in the proper reading on the digital indicator. The motor drive and contact detection was all incorporated into a custom-designed circuit board. The RS485 control of the pump, valves, and temperature sensing is all done with commercial modules. With the increase in size and hose length, large spools and a cart were built to transport the hoses.

The instrument is fully controlled by a handheld computer which can perform individual operations, such as opening and closing valves, as directed by the operator[21, 22, 23]. Common operations which require multiple actions and handshaking, such as circulating the water or taking measurements, are handled by routines. The computer synchronizes the motor operations in an attempt to synchronize the two probe contact times, and thus minimize the hose relaxation problem.

Repeated measurements are made at the rate of about 2.5 per minute. The computer records the time, micrometer readings, and the temperature of each well. Data is typically taken for around 30 minutes, and the water is circulated again. This is repeated several times.

The calibration of each instrument head includes an unknown constant. Eaton describes a reversal technique, whereby the two unknown constants vanish for a differential height measurement, and the difference between the two constants can be obtained[4]. If there is any question, the data is taken off and plotted for analysis before swapping ends with the measurement heads and repeating the process. The field instrument constant is compaired to the constant obtained in the lab as a check.

In the final analysis, the data is plotted and checked for anomalies. The difference between well A and well B is plotted, as well as the sum of A and B. The

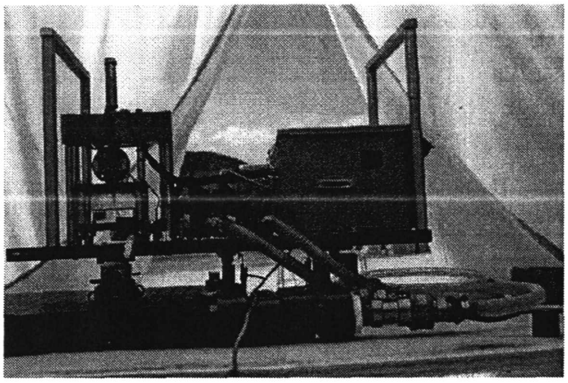

Figure 3: Measurement head on laser monument.

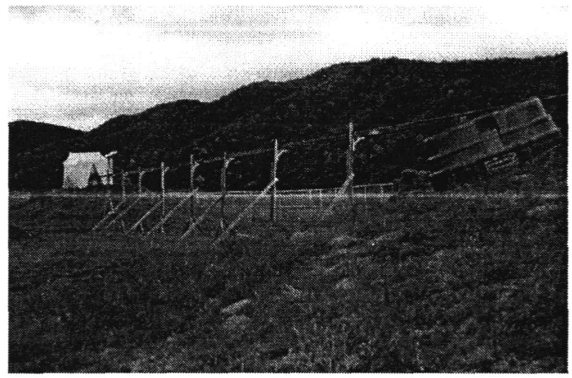

Figure 4: Typical 62 meter run. Note the elevated hose support.

difference, plus the instrument constant, is the differential height between monuments. The sum reflects the change in the total volume in the wells and clearly shows a characteristic decaying exponential increase as the hose relaxes. Solenoid valve leaks are detected by a constant rate change in A + B. In principle, A + B could be calibrated to measure temperature changes. A histogram of A-B is a good measure of the best value and flags readings with poor repeatability.

4 Experimental Results

Between November 1999 and October 2001 the NPH6 was used for four measurement campaigns[13, 14, 15]. These included partial measurements of the GBT track foundation and four of the laser monuments in 1999 and 2000, and a complete measurement of all 12 laser monuments and 8 points on the track foundation, in both loaded and unloaded conditions, in 2001. The measurement of the 12 laser monuments is the best illustration of the instrument, but the other measurements are also reported in the cited internal reports and are suggested reading for anyone building or operating an instrument.

The 12 laser ranging monuments are equally spaced on a 120 meter radius around the GBT[24, 25]. The adjustable bench mark elevations were set within a few mm of level, using conventional optical leveling techniques and an N3 level. Due to the natural slope over the site, the monuments vary between about 0.5 to 3.5 meters above grade. The elevated portion of the monuments are cased with a 1.07 m ϕ pipe and earth-bermed to provide more uniform environmental conditions. The cardinal point on each 0.91 m $\phi \times 6.09$ m concrete monument is a cup fitting in the center of the monument, attached to a 25.4 mm anchor bolt, that matches a 19.050 mm tooling ball on the laser ranging instrument. Since this was the principle reason for building the instrument, the base of the NPH6 was built to match the laser rangers and therefor fit directly on the monuments. See Figure 3.

Prior to the field measurements, the instrument calibration constants (zero offsets) were measured in the lab. This is a relatively simple method whereby the instruments are swapped on fixed monuments to yield the instrument constant. The digital indicators retain an absolute zero, but readings were recorded for each indicator with the Motor Mike retracted in order to recover from an indicator battery failure.

The hose was supported on 6 m Unistrut sections, which were leveled via a line stretched between monuments and attached with velcro straps. For the lower elevations, this was simply done using telescoping pipe stands. For the higher spans, the plant maintenance group had to be called in to build temporary supports. See Figure 4. The hose and instruments were typically set up during the day, with pop-up work tents to protect the instrument.

All measurements were made in the evening, taking a minimum of 2 sets of data in the initial configuration and then permutating the two measurement heads and taking a minimum of 2 sets of data. This allows the instrument constant to be used as a check of the validity of the measurements. Since the hoses and instruments were out in the sun most of the day, ice was added to the reservoir. The water was circulated through the system until the return water was stable at near the ambient evening temperature. Typically, one pair of monuments were measured, two-three times, in each configuration, each evening.

The twelve measurements took slightly more than a calendar month. The final closure error for the 744 meter loop was 0.030 mm, i.e., 0.04 parts per million, or equivelent to 0.008 arc seconds.

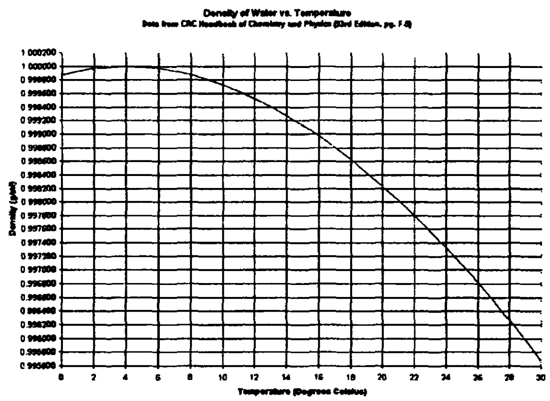

Figure 5: Density of water vs temperature. Note the relative insensitivity around 4° C, as compaired to the steeper change at higher temperatures.

5 Enhancements

As remarkably accurate as the technique can be, there are still several enhancements that could be brought to bear.

5.1 Astronomic correction

The moon, and to a smaller degree the sun, introduces a perturbation to the gravity vector. This is discussed in detail by Balazs and Young[18], and is incorporated in the National Geodetic Survey REDUC5 software package. In 2002, we obtained the astronomic correction C++ source code, ASTRO5, from Ed Herbrechtsmeier[26], and a command line program was written to use ASTRO5[27]. Unfortunately, the instrument has not been used since then, and the corrections have not yet been tested.

5.2 Chilled water

In addition to circulating the water and holding the hose level to minimize the U-tube error, there is another option. Figure 5 shows the density of water vs temperature. Note that the density is a maximum at 4° C, but more importantly, anywhere in the neighborhood, $\Delta\rho/\Delta t$ is small compared to higher temperatures. This strongly suggests that the instrument could be made even less sensitive to the U-tube error for operations close to 4° C. Hurst and Bilham built a refrigerated system for geophysical measurements[6]. Short of building a fully refrigerated system, one can still take advantage by planning high precision measurements for cool fall or spring evengs, and by using ice to cool the water to ambient conditions.

5.3 Hose dilation

The hose dilation problem could be further minimized by using high pressure hydraulic hose for the sense line and/or placing the pump in the middle of the system in order to make the expansion symmetric.

5.4 Motor operated ball valves

Low-pressure, direct-acting, full-ported solenoid valves were used for the NPH6. In order to protect the wells, a normally-open solenoid valve was placed between the sense line and the well, as shown in Figure 2. Normally-closed solenoid valves were placed on each end of the sense line to isolate the sense line from the outer jacket of the coaxial system. The pumping cycle first energized the well protection valves to close them, and then energized the sense-to-outer jacket valves to open them. Water can then be pumped through the circuit.

The solenoid valves introduced three problems. The solenoid coils generate heat. Movement of the plungers introduces an impulse disturbance into the system due to the volume change. Solenoid valves are inherently two position, and thus two valves are required to achieve the equivalent three port (well, sense, return) combination of xoo, xxx, oox (x=closed, o=open) for pumping, isolating, and measuring respectively.

Three-position motor actuated ball valves could significantly improve the performance. Since they would only be energized for the move, the heat load would be much less. Rotation of a ball would not change the volume, and thuse there would not be an impulse disturbance when switching.

5.5 Natural frequency

Eaton and Goldman both calculated the dynamic response and developed the equations for the optimum critical damping[4, 28]. Since the NPH6 was to be automated, and the setup time far exceeded the measurement time anyway, little attention was given to optimization. Experience indicates the combination of hose size, length, and well diameter chosen is over damped, and some improvement could be enjoyed by optimization to the critically damped criteria.

5.6 Symmetric water circulation

In order to make the hose dilation and temperature gradient symmetric, it would be advantageous to put the pump midway between the measurement heads. In order to ensure symmetric flow between the two circuits, a flow regulation device would probably be required. This could easily be designed using a pair of cavitating venturies built by Fox Valve Development Corporation of Dover, New Jersey. These venturies, developed for bipropellant rocket engines and the aerospace industry, deliver a preset flow rate over a large range of downstream pressures.

5.7 Bubble detection

After setting up the NPH6, a jumper hose is connected between the sense and return lines at the far end and water is circulated to sweep any trapped air from the system. With the pump running, the hose is "milked" by lifting a loop to capture any trapped air at the top of the loop. Starting at the pump end, the loop is systematically advanced to the other end, thus collecting all trapped air from the sense line.

This can be time consuming and labor intensive. An alternate means of detecting a bubble would be useful. One possibility would be to close the well valves and measure the compressability of the fluid, e.g., by injecting a known volume of water into the closed sense line and measuring the pressure vs volume. A pure fluid should show a repeatable linear response, whereas a bubble would be a lower nonlinear response. Something could possibly also be devised using acoustic or conductivity measurements.

6 Additional applications

Historically, most applications of precision hydrostatic leveling have been in the geophysics and accelerator fields. NRAO has expanded the field to radio telescope construction.

Several other possible applications suggest themselves. When doing photogrammetry measurements, such as the 300 m diameter Arecibo radio telescope surface[29], known geometric artifacts are included in the pictures to be used as constraints and to set the scale factor. The physical size of the artifacts are limited and are much smaller than desirable, and the absolute orientation is not a constraint.

In the case of the Arecibo reflector (since it is fixed to the ground), it would be relatively straightforward to establish a network of fixed elevation bench marks which could be used to absolutely constrain the photogrammetry measurements in the vertical direction. For circumferential networks, the hose could follow contours of the main reflector, and would not require hose support or offset adapters. Radial networks would be a little more trouble due the the required hose support and larger differential height. The same application could be applied to movable radio telescopes at a single fixed orientation.

Many radio telescopes incorporate tilt instruments into their pedestals in order to try to model the pointing. This is inherently error prone due to the fact that the tilt instruments are very small, and one must extrapolate the localized tilt hundreds of times greater than the length being measured, in order to infer the differential heights between the actual points of interest. The advantage of a hydrostatic level measurement is that the measurements can be streatched out to the actual points of interest without extrapolation. For example, the 45 m spaced elevation bearings on the GBT would be an excellent application.

It would seem that there should be applications for structural health monitoring of civil structures, such as measuring the deflection of bridges, foundation settling, subsidence, pilings, deflection of ships, roof deflection, etc.

It should also be pointed out that the system could be used as a differential pressure instrument by venting each well to pressure ports of interest, instead of the common vent line. This could be used as an automated, and more accurate, replacement for the Dwyer 1420 Hook gage or the Dwyer 1430 Microtector.

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