An evaluation of precision tilt-sensors for measuring telescope position

Robert Kibrick, Lloyd Robinson, and David Cowley

UCO/Lick Observatory
University of California, Santa Cruz, CA 95064

ABSTRACT

This report describes a method for using precision tilt-sensors to measure the position of an equatorial telescope relative to the local horizontal plane. Unlike conventional systems which measure the telescope position using position encoders coupled to the telescope axes, this method avoids many sources of non-repeatable error, such as hysteresis in the telescope structure due to inelastic flexure of the fork or yoke, or random slippage in the couplings between the position encoders and the telescope axes. In this respect, it shares many of the advantages of optical gyros, but achieves these at much lower cost.

We present a design for a compact and relatively inexpensive dual-axis tilt-table whose frame is rigidly attached to the telescope's primary mirror cell. The table contains two precision tilt-sensors, aligned orthogonally with the tilt axes of the table. The sensors are used as nulling devices to close a servo loop which keeps the table level at all times. This provides a precise and stable reference against which the telescope position is measured. A high resolution incremental encoder is directly coupled to each tilt-table axis and measures the angle by which that axis rotates to keep the table level. A mathematical transform converts these two encoder readings into local hour angle and declination.

Preliminary tests of the tilt sensors and of a single-axis prototype tilt-table are reported, and future plans described. The use of tilt-tables for measuring the positions of non-equatorial telescopes is also briefly examined.

Keywords: telescope pointing, telescope position measurement, tilt sensors, tilt-stabilized platforms

1 INTRODUCTION

Accurate pointing of large and small telescopes has always been a difficult problem, rarely completely solved. With modern computers now used to control telescopes, many reproducible errors, such as those due to misalignment of the telescope axes, encoder scale factors, periodic gear errors, and elastic flexure of the telescope can be accurately modeled and reliably corrected. What remains are errors that are either non-repeatable or very difficult to measure and correct. Non-repeatable errors include items such as mechanical hysteresis in the telescope structure or slippage of friction-roller couplings between encoders and telescope axes.[1] Errors that are difficult or impossible to measure include those due to changing balance of the telescope as different instruments are installed, and changes of the mechanical shape of the telescope with rapid changes in temperature. While such errors might be corrected if they could be accurately modeled, adequate telescope time is rarely available to develop such models.

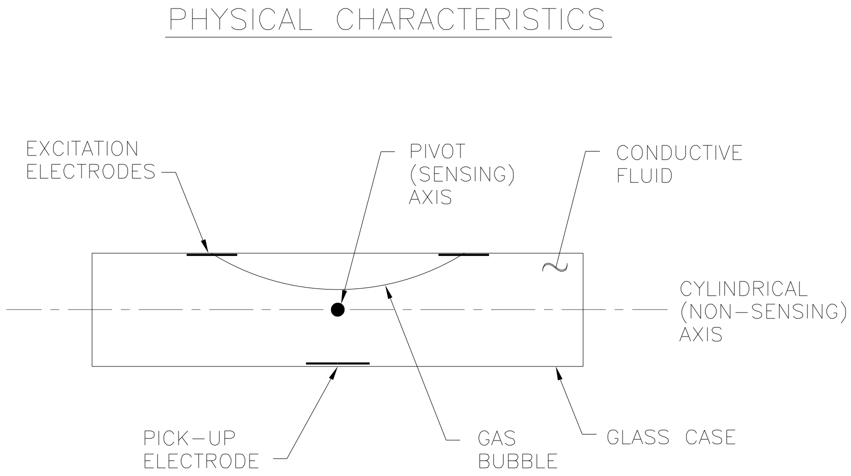

Figure 1: Tilt sensor physical characteristics

Ideally, we would like to measure the orientation of the optical axis of the telescope relative to some stable reference frame, without depending on the stability of large mechanical structures or unpredictable couplings. Some promising work has been done using inertial platforms involving laser and fiber gyros.[2] However, these systems are expensive, complex, and often subject to various problems of drift.

An alternative approach is to use a set of local horizontal axes as a reference for measuring the orientation of the primary mirror. This requires precise and stable sensors to determine the local horizontal directions, plus a mathematical conversion to derive the astronomical coordinates from the tilt of the mirror relative to the horizon. This paper describes a relatively inexpensive method to achieve such a result.

2 TILT SENSORS

Tilt sensors, or inclinometers, measure gravity-referenced angular movements. Precision inclinometers are commonly used to measure small changes in tilt and to monitor such changes over long periods of time. Many of these sensors have been developed for geotechnical applications, such as monitoring ground motion or the settling of large structures. Such devices are sometimes used on large optical or radio telescopes to monitor small variations in axis alignment or to measure deflections or deformations in the telescope structure.[3] Lower-precision inclinometers providing greater dynamic range have also been used to measure the position of dome shutters on the Keck 10-meter Telescope.

Two different types of inclinometers have been used for such applications. One type employs an oil-damped pendulum controlled by an analog servo which maintains the pendulum at a reference position relative to the local gravity vector. The torque current of this servo passes through a precision resistor generating a voltage drop proportional to the tilt angle. The other type employs an electronic spirit level, which changes its resistance as a direct function of tilt with respect to gravity.[4] Both types can be configured to provide either high resolution or wide dynamic range, but like many analog sensors, one is usually achieved at the expense of the other.

For our application, we selected the electronic spirit level because of its small size, low-cost, low-maintenance, mechanical simplicity, and high resolution. This level (which is also sometimes called an electrolevel or an electrolytic tilt sensor) consists of a small, sealed, cylindrical glass vial containing a conductive fluid (electrolyte)

Total Range	±1 degree
Resolution	0.1 microradian (0.02 arc second)
Repeatability	1.0 microradian (0.2 arc second)
Linearity	within 0.1 arc minutes over ±10 arc minutes of travel
Scale factor at 20° C	7.2 mV/arc minute/volt excitation ±20%
Change in scale factor with temperature	-0.25% per °C
Excitation voltage	3 to 5 volts, peak-to-peak, 400 Hz to 10KHz
Temperature range (operating)	-30° C to +70° C
Humidity Range	0 to 100%
Weight	80 grams (2.8 oz.)
Dimensions	38.44mm diameter cylinder x 31.8mm high

Figure 2: Tilt sensor specifications

in contact with three metal electrodes (See Figure 1). Two of these electrodes apply an input signal to the electrolyte, while the third is used to sense an output signal. The vial is only partially-filled with the electrolyte, so that a small air bubble occupies the unfilled volume. As in any spirit level, this bubble will always be bisected by the vertical gravity vector. The electrodes in this vial are arranged so that changing the sensor's tilt will change the amount of contact between the electrolyte and the two excitation electrodes. Tipping the sensor to one extreme will cause the electrolyte to completely immerse one electrode while uncovering the other, and tipping it to the opposite extreme will do the reverse. The pick-up electrode remains immersed in the electrolyte at all times, and it senses the AC signal that results when a constant AC voltage is applied across the two excitation electrodes. This signal varies linearly with changes in the tilt angle of the sensor.

The device used in our tests is a Series 755 Model 1326 dual-axis tilt sensor and Model 781 signal conditioning unit manufactured by Applied Geomechanics, Inc. (AGI), of Santa Cruz, California. The manufacturer's specifications for this device are listed in Figure 2, and are consistent with independent measurements made at the VLA.[3] While this device provides excellent resolution and repeatability, it has various limitations. First, its total dynamic range is extremely limited. Second, it suffers from significant scale factor variations with temperature (although its small size would make it easy to enclose in a thermally-controlled housing). Third, it also responds to acceleration, so that slewing the telescope will introduce transient errors in the tilt measurement. Fourth, its dynamic response is relatively slow. Following a moderate step motion of approximately 45 arc seconds, the tilt sensor output requires about one second to provide a correct reading. The tilt sensor also has a recovery time of several minutes following large changes in tilt angle, due to the time required for the electrolyte to drain off the walls of the glass cylinder. The residual error is of the order of 1% of the change in angle, making rapid measurements of large angular changes rather difficult.

To utilize the tilt sensor's high resolution and repeatability while avoiding most of its limitations, we use it in a servo loop that attempts to keep the sensor level at all times. This avoids the recovery-time effect, although the servo problem is still made difficult by the slow response time of the sensor and its sensitivity to acceleration. This approach also avoids exceeding the limited dynamic range of the tilt sensor, since it is always maintained close to level. Finally, since it is used simply as a nulling device (rather than as a device for measuring absolute tilt magnitude), and since its zero point is relatively temperature invariant, we avoid concerns involving the sensor's scale factor variation with temperature.

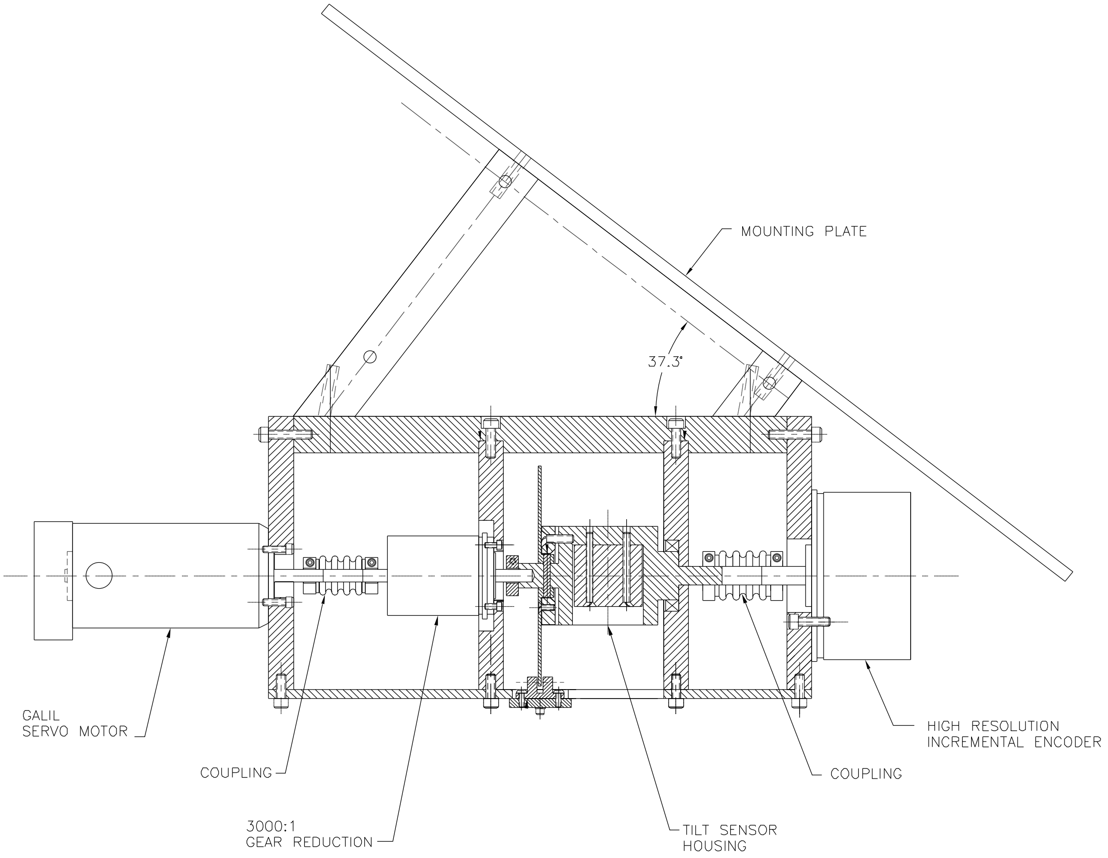

Figure 3: Single-axis prototype system

3 SINGLE-AXIS PROTOTYPE SYSTEM

To evaluate the feasibility of using electrolytic tilt sensors as the nulling device in a servo loop for a tilt-stabilized platform, we have constructed and tested a single-axis prototype (See Figure 3). The design of the apparatus is determined mainly by the characteristics of the tilt sensor, and our desire to minimize the cost of the experimental equipment by using spare parts from other projects. The main components are all commercially available, and the only custom piece is the metal framework to which these components attach.

3.1 Prototype hardware description

The prototype hardware includes a Galil servo motor controlled by a Galil DMC-700 servo motor controller, driving a gear reducer with a ratio of one output revolution for 3000 input revolutions. The tilt sensor is mounted on a metal block that is rotated by the output shaft of the gear reducer. An incremental encoder with resolution of 1.5 arc seconds is directly coupled on-axis to the opposite side of the metal block. The output of the encoder connects to the auxiliary encoder input on the Galil controller. The tilt sensor is connected to the AGI signal conditioning unit which provides the AC voltage to the excitation electrodes and receives the sensor signal from the pickup electrode. The amplified and filtered output from the signal conditioning unit is connected to an analog input on the DMC-700 servo controller. The servo algorithm firmware executing within the servo controller reads this input, and drives the motor and its gear reducer so as to keep the tilt sensor level as the telescope moves. The encoder provides a direct measurement of how much the tilt sensor had to be driven in order to stay level, and thus how much the telescope has moved. A single RS-422 serial line from the Galil controller delivers this measurement to the control room.

Initially, it was hoped that the incremental encoder would not be needed, and that the the position of the tilt sensor could be set precisely via the motor and gear reducer. The Galil motor can be controlled to 1 part in 4000 of a revolution, and the gear reducer provides a reduction of 3000 to 1, so that in principle, the position of the tilt sensor can be controlled to 1 part in 3000x4000=12,000,000. Unfortunately, the gear reducer has problems of backlash and other only partially-reproducible errors that amount to many arc seconds in the rotational position of the output shaft. If the reducer output was precise, or exactly predictable, the incremental encoder would be unnecessary, as the tilt sensor position could be determined directly from the motor position. Since the gear reducer is not precise, and since we are unaware of any gear reducer with better performance, the use of an encoder directly-coupled to the tilt sensor is necessary.

The measurement accuracy of our system is now dependent on the accuracy of this incremental encoder. Clearly, it would be preferable to have an encoder with accuracy of 0.1 arc second. Unfortunately, such encoders are currently quite costly (in excess of $10,000). However, the performance of inexpensive incremental encoders has improved steadily with time. It seems reasonable to expect that the attainable precision will continue to improve, so that upgrading the accuracy of our system may be a simple matter of replacing one encoder with a better one. Also, when the telescope is tracking, relatively high average precision should be attainable even with a 1.5 arc second encoder, since the encoder will produce about 10 pulses per second of time, and the exact position of each pulse can be measured against the sidereal clock. Depending on the uniformity and reproducibility of the encoder pulse train, it should be possible to obtain precision to a fraction of one arc second in right ascension. Our ultimate goal is to achieve a precision of approximately 0.1 arc seconds. However, an accuracy (after correction for measurable errors) of several arc seconds would be a worthwhile achievement, and that was the goal for the first trials.

For those trials, the single-axis prototype was simply bolted onto some existing brackets on the yoke of the Nickel 1-meter equatorial telescope on Mount Hamilton. While this method of attachment was far from ideal, it was adequate for our initial feasability tests, the results of which are described in section 3.3 below.

3.2 Transforming the tilt-table angle to local hour angle

The single-axis prototype was designed to measure only the hour angle motions of the telescope. To reduce the tilt of the sensor's cylindrical axis, the table was mounted to the underside of the telescope yoke with a beveled adapter plate machined to an angle of 37.3 degrees, which is the approximate latitude of Mount Hamilton. As a result, with the telescope on the meridian and the tilt sensor leveled, the cylindrical (non-sensing) axis of the sensor is horizontal and aligned east-west, while the sensing axis about which the sensor pivots is also horizontal but is aligned north-south. The incremental encoder is zeroed at this orientation, so that the tilt-table angle Θ that is measured by this encoder will be zero when the telescope hour angle is zero.

For an ideal equatorial telescope located at a latitude ϕ (i.e., with its instrumental pole aligned at elevation ϕ) and using a tilt sensor apparatus mounted with this orientation, the relationship between the angle Θ (i.e., the angle through which the tilt-table must be driven to keep the tilt sensor level) and the instrumental hour angle H is given by the equation:

$$\Theta = \arcsin(\cos\phi \sin H / \sqrt{1 - (\sin\phi\cos\phi(\cos H - 1))^2}) \tag{1}$$

Figure 4 shows a plot of Θ versus H for an equatorial telescope sited at Mount Hamilton. While this relationship is fairly close to linear, it is not completely so, as illustrated by figure 5 which shows the residuals to a linear fit through this curve. At this latitude, the average scale factor between H and Θ is such that one degree of hour angle motion of the telescope maps into approximately 0.73 degrees of tilt table motion. Figure 6 shows the relation between the average scale factor and the latitude of the telescope. For a telescope sited at the equator, the scale factor is 1.0, and Θ simply equals H, while for one sited at the pole, the scale factor drops to zero. Thus, this sensor apparatus becomes increasingly insensitive at higher latitudes, and at the pole, Θ no longer conveys any useful information regarding the instrumental hour angle. Since an altitude-azimuth mount looks very much like an equatorial telescope sited at the pole, this is equivalent to the fairly obvious fact that our apparatus cannot be used to measure the azimuth of an alt-az telescope.

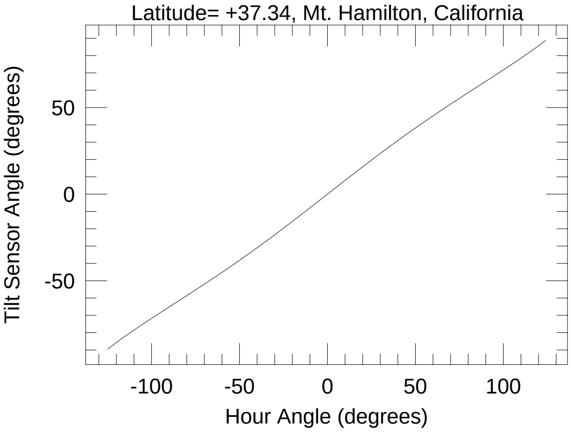

Figure 4: Transform from H to Θ

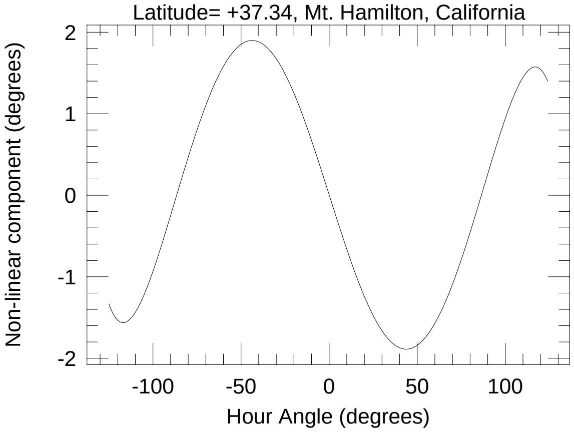

Figure 5: Non-linear component

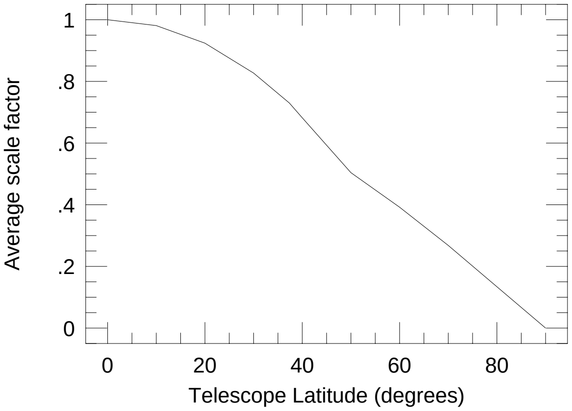

Figure 6: Scale factor versus latitude

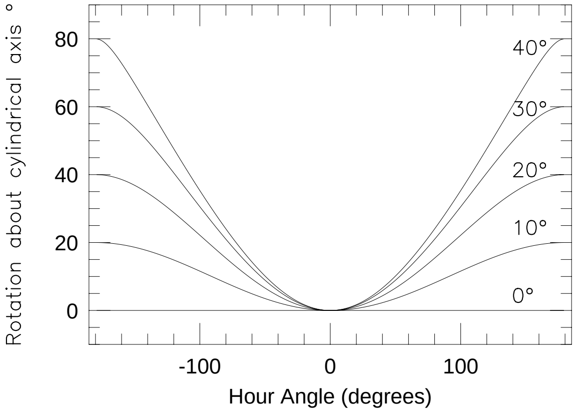

Figure 7: Rotation curves for selected latitudes

The geometry of the single-axis tilt-table is such that moving the telescope in hour angle causes rotations about both the sensing axis and the cylindrical (non-sensing) axis of the tilt sensor (see Figure 1). This is unfortunate, since the sensor is designed to operate with its cylindrical axis close to level, and since rotations about that axis alter the contact area between the excitation electrodes and the electrolyte, resulting in small shifts in the zero point of the sensing axis. To first order, these zero-point shifts will be a linear function of the rotation about the cylindrical axis of the sensor, but non-uniformities in the shape of the glass vial will introduce non-linearities in these shifts. These zero-point shifts should be quite repeatable for a given hour angle, and with proper calibration the non-linearities could be corrected. Nonetheless, these zero-point shifts present an unpleasant complexity for a single-axis system, but one which will be eliminated in the dual-axis tilt-table system described in section 4.

Figure 7 illustrates the magnitude of the rotation about the cylindrical axis of the tilt sensor for a single-axis system as a function of hour angle for telescopes sited at various latitudes. For certain combinations of latitudes and hour angles, the rotation can be quite large. If the sensor is rotated to the point where the excitation electrodes lose contact with the electrolyte, the zero point shift will go off scale, and the sensor will not provide a meaningful result.

3.3 Experimental results

While more work remains to be done, the preliminary results from the single-axis prototype have been very encouraging. First, we have demonstrated that electrolytic tilt sensors can be used effectively as the nulling device of a very simple servo loop for a single-axis tilt-stabilized platform. This servo loop has been shown to be stable during both tracking and slewing motions over the full range of hour angles through which the telescope can move. While tracking, the platform is maintained level within 0.33 arc seconds RMS, and this can probably be improved with optimization of the servo algorithm. Second, the system is stable and not subject to any significant drifts when the telescope is parked for periods of several hours, despite changes in temperature inside the dome. Third, the magnitude of the zero-point shift induced by the rotation of the sensor about its cylindrical axis can be derived from our measurements of Θ versus hour angle. For the particular sensor used in our prototype, the sensing axis zero-point shifts by about 0.02 degrees per degree of rotation about the cylindrical axis of the sensor.

Recently, measurements of Θ versus hour angle H were obtained while the auto-guided telescope was tracking a bright star transitting the meridian, so as to minimize track rate variations due to atmospheric refraction. Once the zero-point shift has been calibrated out, the residual error in our measurement of H from Θ is 2.6 arc seconds RMS, when measured over the range from 0^h to $+5\overset{h}{.}5$. The dominant source of this error is a high-frequency periodic error whose period is exactly 80 counts of the incremental encoder and whose amplitude is about 3.2 arc seconds. This incremental encoder employs a glass disk with 10,800 rulings per revolution, and utilizes an electronic interpolator with a multiplier of 20 to generate 216,000 quadrature cycles per revolution. An additional multiplication by four results from the decoding of these quadrature cycles into encoder counts, and the product of these two multipliers (i.e., 20 times 4), exactly corresponds to the period of this high-frequency error. While it would be preferable to replace this encoder with a better one, if this error can be shown to be repeatable and if it can be adequately calibrated, it should be possible to correct for it.

4 DUAL-AXIS TILT-STABILIZED PLATFORM

The single-axis prototype demonstrated the feasibility of using a tilt sensor to stabilize a single-axis yoke-mounted platform. While a similar, independent platform could be attached to the telescope tube to measure declination, there are three problems with this approach. First, as noted earlier, on an equatorial telescope the single-axis platforms are subject to rotations about both the sensing axis and the cylindrical (non-sensing) axis of the tilt sensor. The rotations about the cylindrical axis induce small shifts in the zero-point of the sensing axis, and these will be difficult to calibrate precisely. Second, the yoke-mounted platform used to measure hour angle is still located far from the optical axis of the telescope, and is subject to various sources of non-repeatable errors from the yoke structure and its bearings. Third, the tube-mounted platform used to measure declination will sense tilt variations that result from telescope motions in either the declination or hour angle axes. To calculate the telescope declination, the readings from both platforms must be combined. However, since the platforms would be located at different points on the telescope structure, and since that structure may flex, twist or deform in unpredictable ways, it would prove extremely difficult to combine the readings from these two platforms into a meaningful result. All of these problems can be resolved by combining the two single-axis platforms into one dual-axis platform that is mounted to the back of the primary mirror cell as close as possible to the optical axis of the telescope.

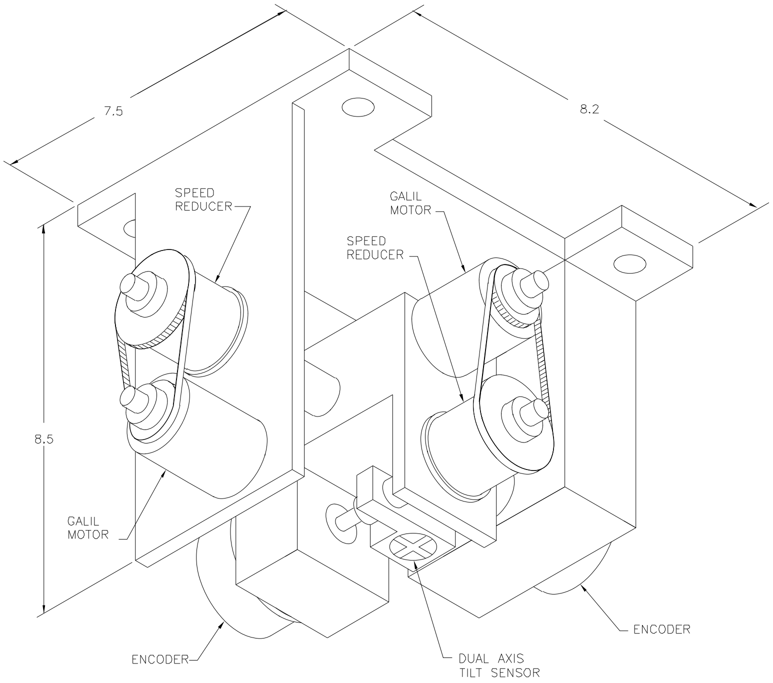

Figure 8: Dual-axis tilt table

4.1 Hardware description

While an optimal mechanical design for such a platform is not yet complete, a conceptual design is illustrated in Figure 8. The platform contains an outer table, which is supported by the framework which bolts to the back of the mirror cell. This outer table in turn supports an inner table, whose pivot axis is aligned orthogonally with that of the outer table. The inner table contains two tilt sensors, mounted orthogonally to each other. One of these sensors senses tilts about the pivot axis of the outer table, while the other one senses tilts about the pivot axis of the inner table. The servo loop for each table is closed by its respective tilt sensor. Since the inner table which contains both tilt sensors has two degrees of freedom, it is always possible to keep the plane of this table parallel to the local horizontal plane. As a result, when the servos are holding the inner table level, there will be no rotations about the cylindrical axes of either sensor, and that source of zero-point shift is eliminated, thus solving the first problem. Since both tables attach to the telescope at the same point, and since that point is near the optical axis, the second and third problems are also addressed.

The detailed design for the dual-axis platform should aim for a mechanism that is as light, compact, and rigid as practical. The servo motors and gear reducers, especially the one for the inner table, should be sized as small as possible, since the tables are not massive and the gear reductions are very high. The limiting factor on motor size is likely to be the resolution of the integrated motor encoder. To minimize thermally-induced variations in the platform structure, it should probably be enclosed in an insulated and thermally-controlled box. Since the overall size of this mechanism should be well under 1.0 cubic foot, this should not be difficult. This enclosure could also provide electrical shielding, to minimize pickup of electrical noise by the tilt sensor electronics.

4.2 Transforming tilt-table angles to local hour angle and declination

The dual-axis platform is attached to the back of the primary mirror cell so that with the telescope parked at the zenith, the pivot axis of the outer table is horizontal and aligned east-west, while the pivot axis of the inner table is horizontal and aligned north-south. We define the angle X to be the angle measured by the incremental encoder attached to the pivot axis of the outer table, and Y to be the angle measured by the encoder attached to the pivot axis of the inner table. Both encoders are zeroed when the telescope is aligned to the zenith.

For an ideal equatorial telescope located at a latitude ϕ (i.e., with its instrumental pole aligned at elevation ϕ) and using a dual-axis platform mounted with this orientation, the equations which relate the angles X and Y to the instrumental hour angle H and declination D are as follows:

$$X = -D + \arctan(\sin\phi / \cos\phi \cos H) \tag{2}$$

$$Y = -\arcsin(\cos\phi \sin H) \tag{3}$$

The reverse transforms used to compute H and D directly from X and Y are then:

$$H = \arcsin(\sin -Y / \cos\phi) \tag{4}$$

$$D = -X + \arctan(\sin\phi / \cos\phi \cos(\arcsin(\sin -Y / \cos\phi))) \tag{5}$$

The angle Y depends only on H. This is because the outer table is used to precisely counteract any motions in declination, so that the inner table is only sensitive to changes in hour angle.

The derivation of these transforms can be best understood by defining a right-angled spherical triangle whose vertices, sides, and angles are as follows: Vertex A is on the same meridian as the star but northward of the star by the angle X, vertex B is at the zenith, and vertex C is at the pole. Side a is then $90-\phi$, side b is $90-(D+X)$, and side c is $-Y$. Angle A is 90 degrees, and angle C is the hour angle, H. The formulae for a right-angled spherical triangle[5] can then be applied to derive the relationships between H, D, X, and Y. These relationships can be visualized as follows. To determine the tilt angles X and Y which correspond to the position of a star at a given hour angle H and declination D, one first aligns both the inner and outer tables so that a vector that is normal to the plane of the inner table points towards the star. The outer table is then pivoted by the angle X in order to reach a declination $D+X$ where a movement of only the inner table (i.e., a movement purely in Y) is required to align the normal vector with the zenith. At that point, the plane of the inner table will be parallel to the local horizontal plane.

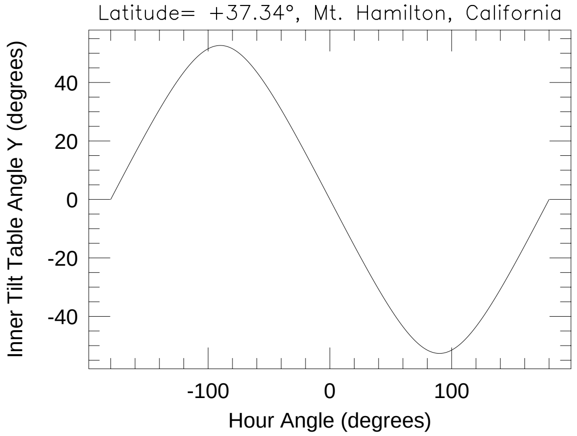

Figure 9: Transform from H to Y

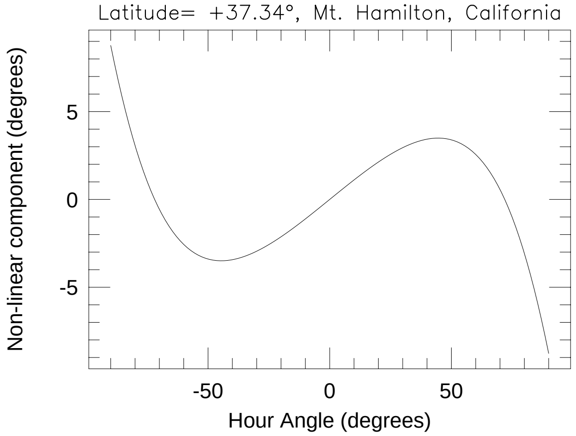

Figure 10: Non-linear component

Figure 9 shows a plot of Y versus H for an equatorial telescope sited at Mount Hamilton. Note that there is quadrant ambiguity, in that a given value of Y corresponds to two different possibles values of H. This ambiguity exists regardless of the telescope latitude, and correctly reflects the actual operation of the inner table of the dual-axis platform; the relative motion of this table slows and reverses direction as the telescope tracks through the points -6^h and +6^h .

For telescopes capable of hour angle motions greater than $\pm 6^h$, this quadrant ambiguity needs to be addressed, and at least two options exist. In the first option, the control system can simply take note of the quadrant crossing when it occurs, and switch to the appropriate transform. Alternatively, the control system can transform the current (X, Y) readings into two sets of (H, D) coordinates, one set for each of the two possible quadrants. For each set, it can then compute an instantaneous declination velocity by subtracting the corresponding declination that was obtained during the previous time step. The velocity derived from the coordinates from the correct quadrant will be stable and equal to the expected declination drive rate, while the velocity derived from the coordinates from the incorrect quadrant will be variable and not equal to the drive rate. Computer simulations covering the full range of H, D, and ϕ confirm that this second method will select the correct quadrant for all possible telescope positions above the horizon and for declination rates less than or equal to the lunar rate.

Within the hour angle range between -6^h to +6^h , there is no quadrant ambiguity, and a given reading of Y transforms to a unique value of H. Since the telescopes on Mount Hamilton have cable-wrap constraints which limit their hour angle motions to within $\pm 6^h$, this quadrant ambiguity was not a concern for us. Figure 9 shows that the relationship between H and Y is fairly close to linear between -3^h to +3^h , but the scale factor begins to roll off outside this range, and is quite attenuated at $\pm 6^h$. Figure 10 shows the residuals to a linear fit through this curve. At the latitude of Mount Hamilton, the average scale factor over the central portion of the curve is such that one degree of hour angle motion of the telescope maps into approximately 0.683 degree of tilt in Y. Figure 11 shows the relation between the average scale factor and the latitude of the telescope. It follows a similar pattern to that shown for the single-axis platform in Figure 6, namely, that the scale factor is 1.0 at the equator, decreases with increasing latitude, and drops to zero at the pole.

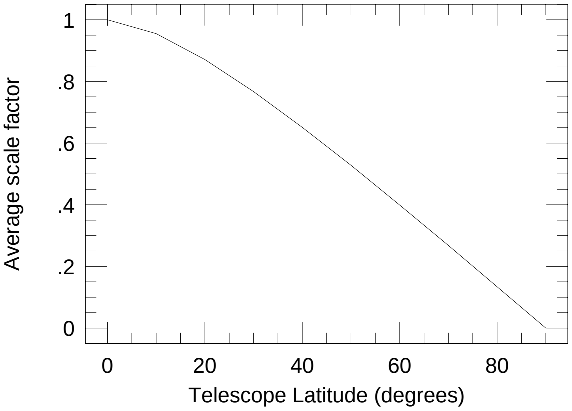

Figure 11: Scale factor versus latitude ϕ

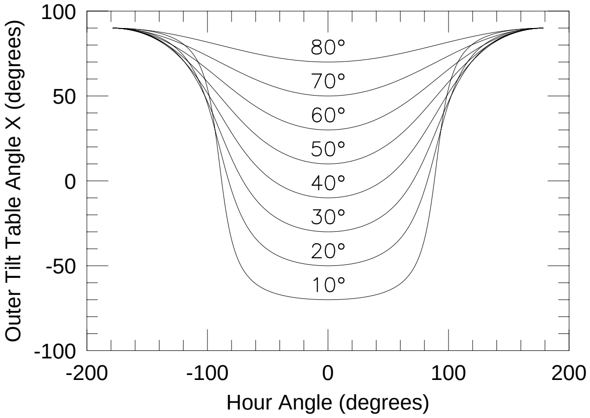

Figure 12: X as a function of H for $D = 90 - \phi$

From equation 2 it can be seen that X varies linearly with the declination D, and that the scale factor is constant at unity. For a fixed declination D, the outer tilt-table angle X will vary with changing hour angle H, following the curves shown in Figure 12. Thus, changes in hour angle simply shift the zero-point of the X scale, without altering the 1:1 relationship between X and D. The magnitude of this zero-point shift varies with the latitude of the telescope.

Equations 2 through 5 describe the case of an ideal telescope and tilt table. In practice, these transforms will need to be used in combination with a formal telescope pointing analysis, to derive a pointing model which accurately corrects for the various misalignments of both the telescope and tilt table.

5 APPLICATIONS TO NON-EQUATORIAL TELESCOPES

The tilt table platforms described above were designed to work on equatorial telescopes sited at low to moderate latitudes. However, such platforms may have application to other types of telescope mounts.

5.1 Altitude-Azimuth telescopes

As noted earlier in section 3.2, tilt table platforms cannot be used to measure the position of the azimuth axis of an alt-az telescope. However, a single-axis platform is well suited for measuring the position of the elevation axis of such telescopes. Such a platform would be mounted to the bottom of the primary mirror cell, such that its table pivot axis is aligned parallel to the elevation axis of the telescope. The tilt angle Θ would then directly map into the elevation angle of the telescope.

5.2 Altitude-Altitude telescopes

An altitude-altitude mount is similar in appearance to an equatorial telescope sited at the equator. While such mounts are uncommon, they are sometimes employed on telescopes used for satellite-tracking applications. A dual-axis tilt sensor platform is ideally suited to measuring the positions of both axes of such telescopes. If we label these axes as H and D (even though they do not actually correspond to hour angle and declination), then we can treat the alt-alt mount as if it were an equatorial telescope at the equator, and by substituting $\phi = 0$ in the equations 4 and 5 we obtain the result that $H = -Y$ and $D = -X$. Thus, the dual-axis platform provides a direct measurement of the positions of the major and minor axes of an alt-alt telescope.

6 CONCERNS

Our analysis of the single and dual-axis platforms, and our experiments with the single-axis prototype have addressed nearly all the concerns raised in section 1. However, two remain, and are worth noting here.

First, while the dual-axis tilt sensor platform avoids many of the sources of non-repeatable telescope position error (such as mechanical inelastic flexures of the telescope fork or slippage of friction roller encoder couplings), it is still subject to various error sources that it cannot sense, including dynamic polar axle misalignments in azimuth, shifts of the primary mirror within its cell, structural deformations in telescope tube, and variations in the position of the secondary mirror, any of which can alter the orientation of the optical axis of the telescope. A more direct coupling between the platform and the primary mirror itself could address the second problem, while careful design of the telescope tube can minimize the third problem. Fortunately, the deformations associated with the Serrurier truss design typically used for telescope tubes are less of a problem than those deformations (e.g., fork flexure and tyne rotation) that occur in telescope forks.[6] Also, many modern telescopes provide control and readout of the secondary mirror tilts, so that their effect on the optical axis can be compensated for.

Second, the small shifts of the sensing-axis zero point that are induced by rotations about the cylindrical axis of the tilt sensor translate into low-level (i.e., about 2% of signal) cross-talk between the servo systems controlling the inner and outer tables of the dual-axis platform. This cross-talk, combined with the sensor's sensitivity to accelerations, will require careful adjustment of servo parameters to insure that the servo loops for this platform remain stable.

7 CONCLUSIONS

We have shown how the position of both axes of an equatorial telescope could be measured relative to a dual-axis tilt-stabilized platform that is kept aligned with the local horizontal plane, and have identified the various advantages and limitations of this technique. We have also demonstrated that inexpensive electrolytic tilt sensors can be successfully employed as nulling devices in a servo loop used to maintain a single-axis tilt-stabilized platform.

While this paper has emphasized the use of resistance-based electrolytic tilt sensors as the sensing element of the active servo system, there are other types of sensors (e.g., capacitive) which might be used. In addition, we have only explored in detail one orientation for mounting the dual-axis platform relative to the primary mirror cell. Other orientations might provide useful capabilities, and should be explored. Finally, it might also be worth exploring the possibility of a passive, self-stabilized platform which requires no tilt sensors nor any active servo system. Such a platform would require virtually frictionless bearings for its pivot axes and for the incremental encoders.[7] Were such a passive platform possible, the transformations between tilt angles and telescope axes positions derived above would be equally applicable to it.

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