Tests of a precision tiltmeter system for measuring telescope position

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ABSTRACT

We have previously described a system that derives the pointing coordinates of an equatorial telescope by measuring the angular position of a dual-axis tilt-table whose frame is rigidly attached to the telescope's primary mirror cell.[1] In that system, two precision tilt-sensors aligned orthogonally and mounted in the plane of the table are used as nulling devices to close an active servo loop which holds the table level as the telescope moves. Rotary encoders measure the angle by which each tilt-table axis rotates, and a mathematical transform converts those encoder readings into telescope hour angle and declination.

Recent work has indicated the feasibility of several simplifications to that system. First, by use of suitable low friction bearings on the tilt-table axes, along with non-contacting encoders, the active servo loop is no longer needed to level the tilt-table. Rather, a simple suspended weight keeps the platform almost level, with the residual small tilt error measured by the precision tilt sensors. Second, by suitable orientation of the weight and the tilt sensors relative to the telescope polar axis, the system can measure telescope hour angle and declination directly, eliminating the need for the complex mathematical transform. Experimental results using these ideas are presented.

Keywords: telescope pointing, gravity-referenced telescope position measurement, tilt sensors, tilt-stabilization

1. INTRODUCTION

Accurate pointing of large and small telescopes has always been a difficult problem, which is rarely solved completely. 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.[2] 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.

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.[3] 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 tilt sensors to define the local horizontal plane.

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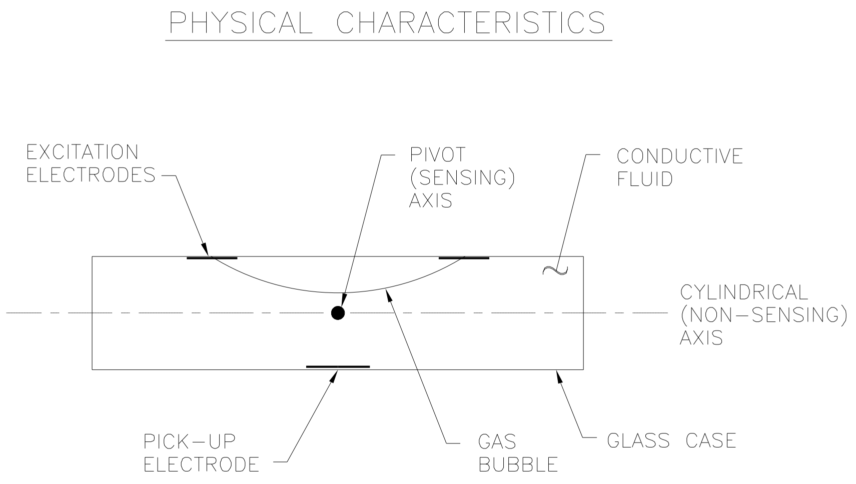


Figure 1. Tilt sensor physical characteristics

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.[4] Lower-precision inclinometers providing greater dynamic range have also been used to measure the position of dome shutters on the Keck 10-meter Telescopes.

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.[5] 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) in contact with three metal electrodes (See Fig. 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 Fig. 2 and are consistent with independent measurements made at the Very Large Array (VLA).[4] 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 can introduce transient errors in the tilt measurement. Fourth, its

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

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 mount it to a self-leveling tilt-table that keeps the sensor nearly level at all times. This avoids the recovery-time problem and also avoids exceeding the limited dynamic range of the tilt sensor. By enclosing the tilt-table and sensor in an insulated, thermally-controlled enclosure, we minimize errors resulting from the sensor's scale factor variation with temperature. (The sensor's zero point is insensitive to temperature variations.)

3. SINGLE-AXIS MECHANISMS

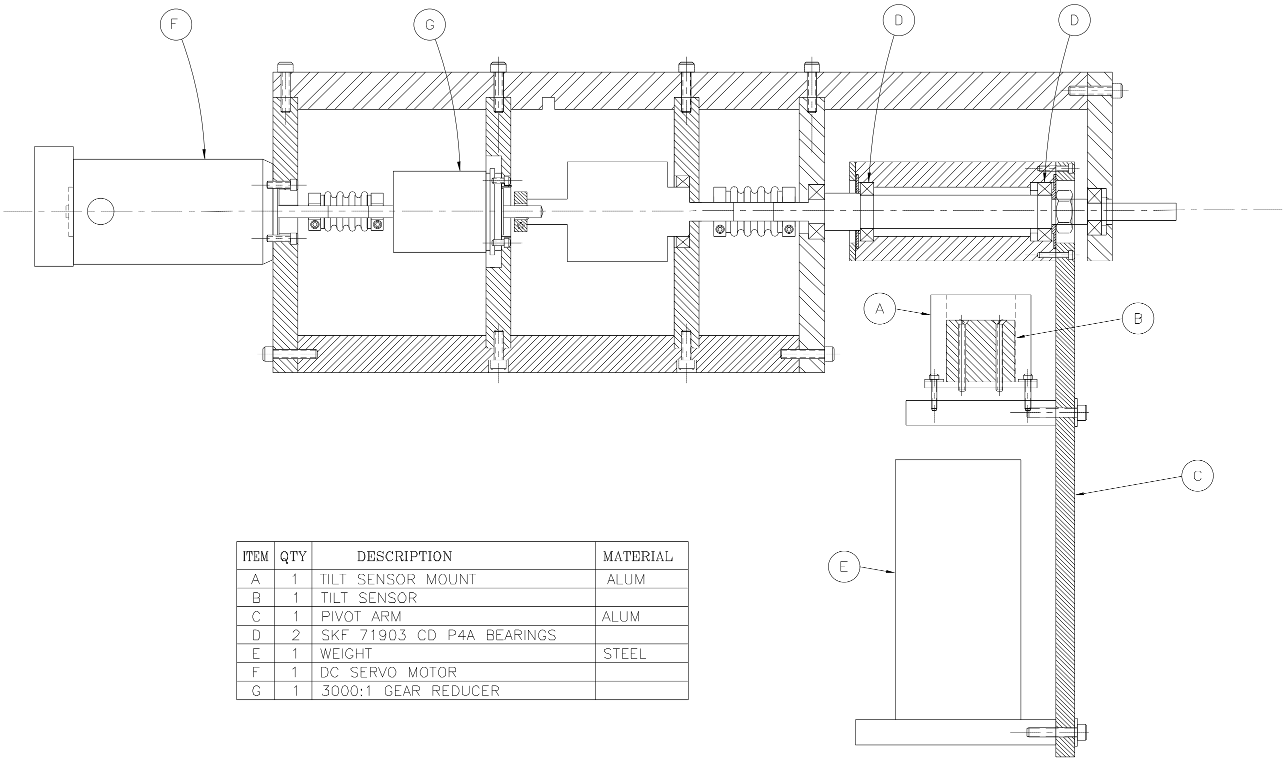
The central element of our system is a dual-axis tilt-stabilized table whose frame is rigidly attached to the telescope's primary mirror cell. The table is maintained nearly level (either actively or passively) as the telescope moves and thus provides a local reference frame against which the telescope position can be measured. Rotary encoders measure the angle by which each axis of the table rotates relative to the frame and these encoder readings are transformed into telescope position. In order to evaluate the feasibility of both active and passive implementations of this method, we constructed and tested two single-axis mechanisms: an actively-stabilized single-axis tilt-table prototype and a passively-stabilized single-axis tilt-table test apparatus.

3.1. Actively-stabilized Single-axis Tilt-table Prototype

In Ref. 1 we described an actively-stabilized single-axis tilt-table. That table was driven (via a gear reducer) by a servo motor, while the electrolytic tilt sensor mounted on the tilt-table served as a nulling device to close the table-leveling servo loop. An optical incremental rotary encoder was coupled on-axis (via a flexible coupler) to the pivot axis of the tilt-table. Tests conducted with this prototype mounted on the yoke of the Nickel 1-meter Telescope at Lick Observatory demonstrated that while the telescope was tracking, the active servo loop held the tilt-table level within 0.33 arc seconds RMS. However, the residual error in our measurement of the telescope hour angle derived from the tilt-table rotary encoder was 2.6 arc seconds RMS, due to high-frequency periodic errors within the optical encoder as well as errors introduced by the flexible coupler used to attach the encoder to the tilt-table axis.[6]

3.2. Passively-stabilized Single-axis Tilt-table Test Apparatus

A significant reduction in mechanical, electronic, and software complexity could be achieved if the tilt-table could be leveled passively. To evaluate this approach, the actively-leveled single-axis system described in Ref. 1 was modified to produce the test apparatus shown in Fig. 3



ITEM	QTY	DESCRIPTION	MATERIAL
A	1	TILT SENSOR MOUNT	ALUM
B	1	TILT SENSOR	
C	1	PIVOT ARM	ALUM
D	2	SKF 71903 CD P4A BEARINGS	
E	1	WEIGHT	STEEL
F	1	DC SERVO MOTOR	
G	1	3000:1 GEAR REDUCER	

Figure 3. Single-axis passively-leveled test apparatus

The main components of this test apparatus are all commercially available, and the only custom piece is the metal framework to which these components attach. The tilt-table consists of a metal block **A** in which the tilt sensor **B** is mounted. The block is attached to an arm **C** which pivots on low-friction bearings **D** (SKF 71903 CD PA4). A 7 lb. weight **E** is attached to the arm with its center of gravity 8-in. from the pivot. This generates a force that will tend to keep the arm aligned nearly vertical and thus hold the block and its attached tilt sensor nearly horizontal.* A DC servo motor **F**, coupled via a 3000:1 gear reducer **G**, is used to drive the inner race of the bearings **D** at various rates typical of telescope tracking and slewing. The DC servo motor is controlled by a Galil DMC-1500 servo motor 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-1500 servo motor controller, which is used both to drive the motor and capture the signal from the tilt sensor. A single RS-232 serial line from the Galil controller delivers this measurement to a computer which records the results to disk for subsequent analysis.

Friction in the bearing causes it to act like a slip clutch, so that rotation of the gear reducer output shaft will result in small rotations of the arm that suspends the tilt-table and its attached tilt sensor and weight. Because the restoring force provided by the weight will approach zero as the arm becomes vertical, the friction in the bearing will generate a small, residual angular error from the ideal vertical alignment of the arm. The tilt sensor measures this residual error.

The test apparatus was used to measure this residual error (both as a function of motor rotation rate and as a function of bearing position angle) in order to verify that the dynamic range of the tilt sensor (±1 degree) would never be exceeded. It was also used to determine the extent to which the suspended weight would be excited into a pendulum motion during tracking or slewing of the telescope.

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*A similar scheme was first proposed by Odgers and Grundmann in 1984[7]

The results so far are satisfactory. The residual errors that must be measured by the tiltmeter are almost always less than 200 arc seconds (well within its dynamic range). Figures 4 and 5 show the deviation from horizontal as measured by the tilt meter, when the bearing shaft is rotated at speeds typical of telescope operation. The stabilizing torque was provided by a 7 lb. weight with the center of gravity 8 in. below the center of the rotating shaft. Pendulum motion is not excited at any driving speed, but it can be started by manually perturbing the arm. However, such motion damps out in less than a minute. More work is in progress to determine the minimum size of the suspended weight and a more suitable bearing lubricant, which may significantly reduce the residual tilt errors.

The bearings chosen for the test apparatus are SKF 15 degree angular contact precision bearings, P4A tolerance class, used in a two bearing assembly. For this class, maximum radial runout for shaft sizes less than 18 mm is 1.5 microns; for shaft sizes of 18 to 120 mm maximum radial runout is 2.5 microns. Because the test apparatus is not sensitive to and did not test for radial runout errors, the housing for the test assembly was not made to the high precision standards specified for these bearings. These will be important in the final design and the housings will be made to the higher standards. This lack of precision in the current assembly could be contributing to the measured bearing friction. However, we believe that the majority of the friction is a result of inadequate lubrication due to the very low rotation speed. The relative velocity of the components in the bearings is not great enough to produce the hydrodynamic film required for proper lubrication. The bearings were preloaded with Belleville springs. About 20 newtons preload is required to seat these bearings.

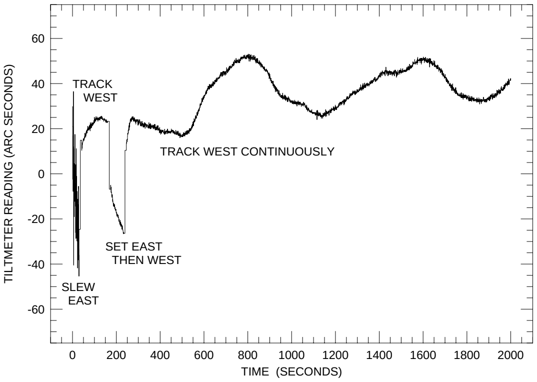

Figure 4: Tilt error over small rotation

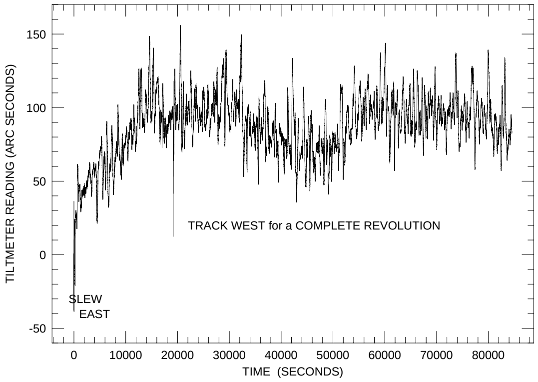

Figure 5: Tilt error over full rotation

3.3. Proposed Passively-stabilized Single-axis Tilt-table Prototype

Several modifications to the test apparatus illustrated in Fig. 3 are needed to convert it into a device capable of measuring a single axis of tilt relative to the local horizontal plane. First, the motor and gear reducer would be removed. Second, a rotary angle encoder would be added to measure the rotation angle of the arm relative to the frame. Third, the frame would be rigidly attached to the primary mirror cell of the telescope, with the pivot axis aligned east-west and leveled with the telescope pointed at the zenith. The residual error measured by the tilt sensor would be added to the angle measured by the rotary encoder to yield the true angle between the frame and the local horizontal. In this orientation, the apparatus could be used to measure changes in telescope declination along the meridian.

A key requirement is that the rotary encoder not add any additional friction to the system. This can be accomplished by using an optical tape encoder in which the encoding tape is wrapped around a small disk attached to the top of the arm and whose rotation center is concentric with that of the bearing which supports the arm. The encoder's read head is fixed to the frame and since there is no contact between the read head and the tape, there is no added friction[†]. A Renishaw model RGH 22Z optical tape encoder (with 0.5 micron linear resolution) has been tested for this application. When mounted around a 4-inch radius disk (the minimum bending radius for this tape), a resolution of 1 arc-second is achieved.[6]

Similarly, the wires (and surrounding insulation) used to convey power and signals between the tilt sensors on the pivoting arm and the sensor electronics on the frame must be extremely flexible to minimize any torques that they might apply to the pivoting arm. Laminated magnet wire proved to satisfy this requirement. If a hollow shaft is used between the bearings, it can act as a conduit for such wiring.

[†] A similar result can be achieved using an annular glass-disk optical encoder where the disk is mounted to the arm and the read head mounted to the frame.

We believe that the tilt sensors can be calibrated to an accuracy of about 1%, and the tape encoder to significantly better accuracy. By enclosing the entire measurement mechanism in an insulated, thermally-controlled enclosure, errors resulting from thermally-induced changes in the tiltmeter scale factor or in the alignment of the various mechanical components can be minimized. The tiltmeter calibration could be checked continuously while the telescope is tracking, by measuring changes in apparent telescope position as a function of the tiltmeter reading. Assuming that flexure of the weight bearing assembly, bearings and attachment to the telescope can be calibrated, an overall measurement accuracy on the order of one arc-second seems feasible using this relatively simple and inexpensive technology. While not adequate to close a high-frequency telescope-tracking servo loop, a tilt-stabilized platform for measuring telescope position could still provide significant improvements in telescope pointing and target acquisition.

4. DUAL-AXIS TILT-STABILIZED PLATFORM

The single-axis actively-stabilized prototype and the single-axis passively-stabilized test apparatus have demonstrated the feasibility of using a tilt table, tilt sensor, and rotary encoder to precisely measure changes in tilt over a large dynamic range. However, there are several reasons why such single-axis tables cannot be used directly to measure the pointing coordinates of an equatorial telescope. First, on such telescopes single-axis platforms are subject to rotations about both the sensing axis and the cylindrical (non-sensing) axis of the tilt sensor (See Fig. 1). 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, a yoke-mounted or fork-mounted platform used to measure hour angle is located far from the optical axis of the telescope and is subject to various sources of non-repeatable errors from the yoke or fork structure and its bearings. Third, a 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 ways that are difficult to model, 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.

4.1. Actively-stabilized Dual-axis Platform

While an optimal mechanical design for a dual-axis platform is not yet complete, a *conceptual* design for an actively stabilized platform was presented in Ref. 1 and is reproduced here as Fig 6. 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.

4.1.1. Transforming tilt-table angles to instrumental hour angle and declination

The actively-stabilized dual-axis platform shown in Fig. 6 is attached to the back of the primary mirror cell so that with the telescope parked at the zenith and the inner table leveled, 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 and the inner table is level.

In Ref. 1 it was shown that for an ideal equatorial telescope located at a latitude ϕ (i.e., with its instrumental pole aligned at elevation ϕ) and using an ideal dual-axis platform mounted with this orientation, the equations which

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[‡] Rotations about the tilt sensor's cylindrical (non-sensing) axis alter the contact area between the excitation electrodes and the electrolyte. The resulting zero-point shifts are, to first order, a linear function of rotation about the cylindrical axis and are typically 0.02 degrees per degree of rotation. There are also low-level non-linearities due to imperfections in the shape of the glass case.

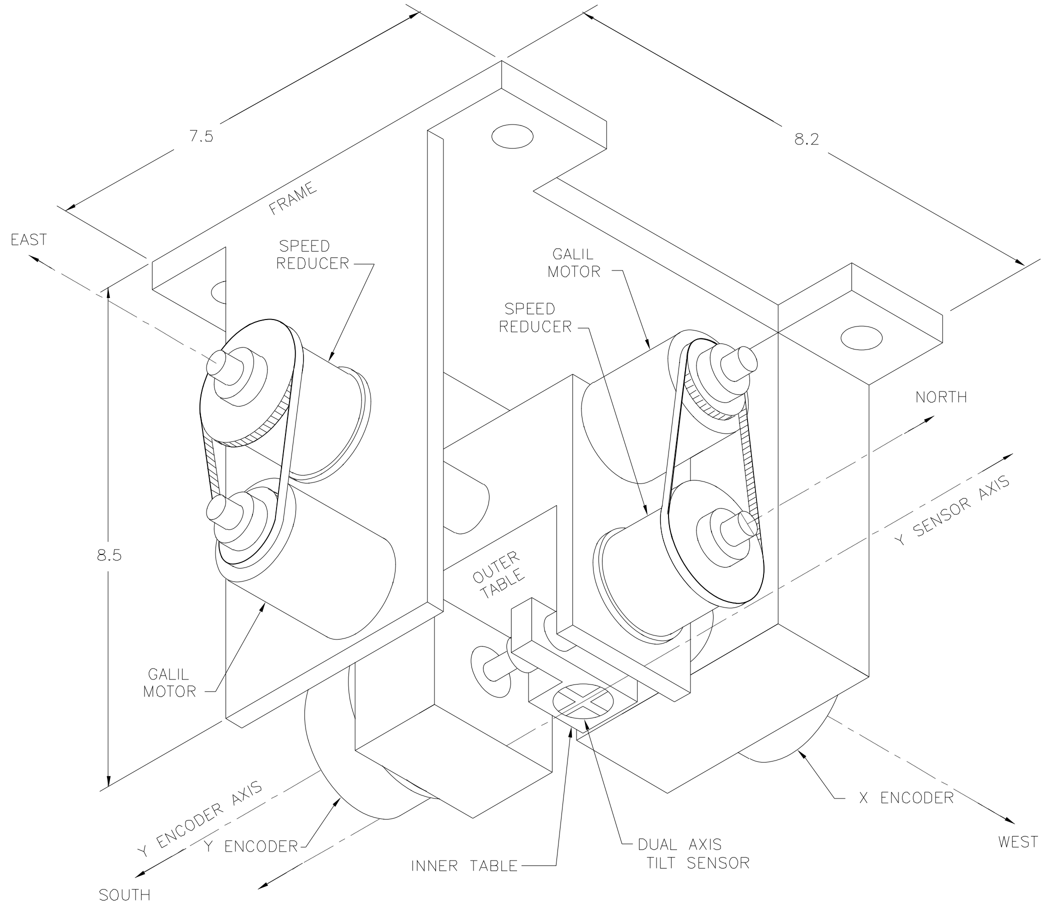

Figure 6. Actively-stabilized dual-axis tilt table, telescope pointing at zenith, both tables leveled

relate the angles X and Y to the instrumental hour angle H and declination D are as follows:

$$X = -D + \arctan(\sin\phi / \cos\phi \cos H) \tag{1}$$

$$Y = -\arcsin(\cos\phi \sin H) \tag{2}$$

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

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

$$D = -X + \arctan(\sin\phi / \cos\phi \cos(\arcsin(\sin -Y / \cos\phi))) \tag{4}$$

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.

Fig. 7 shows a plot of Y versus H for an equatorial telescope sited at Mount Hamilton (latitude +37 degrees). This relationship is fairly close to linear between -3^h and $+3^h$, but the scale factor begins to roll off outside this range, and is quite attenuated at $\pm 6^h$. Also 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 $+6^h$. Fig. 8 shows the relation between the average scale factor (over the range -3^h and $+3^h$) and the latitude of the telescope; it is 1.0 at the equator and decreases with increasing latitude, dropping to zero at the pole.

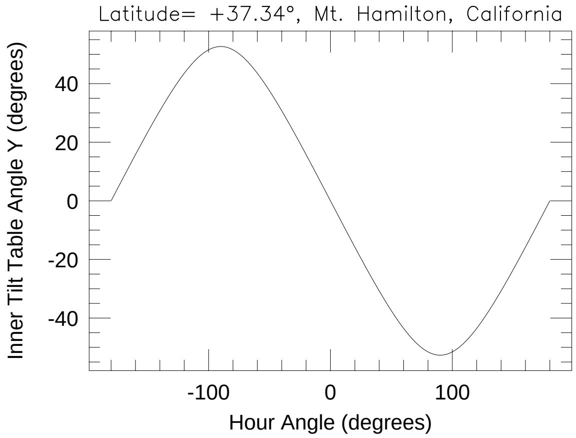

Figure 7: Transform from H to Y

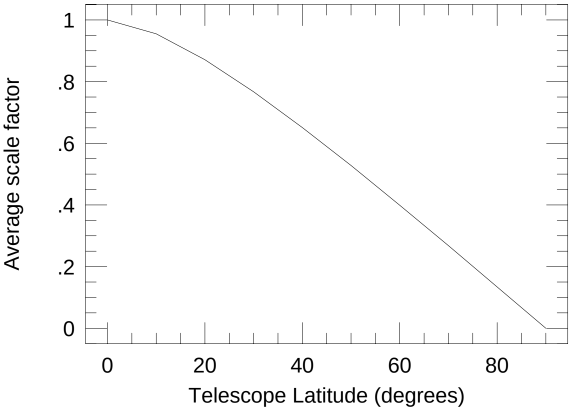

Figure 8: Y:H Scale factor versus latitude ϕ

4.2. Passively-stabilized Dual-axis Platform with Re-aligned Y Tilt-Sensor Axis

As noted in the preceding Section and illustrated in Figs. 7 and 8, there are several operational problems that arise from the relationship between H and Y: quadrant ambiguity, Y scale factor variation with H, and Y scale factor variation with latitude. While Ref. 1 described methods that address some of these problems, they added further complexity to the overall system.

Alternatively, several of these problems can be reduced or eliminated and the overall dual-axis system (as shown in Fig. 6) significantly simplified by switching to the design that is conceptually illustrated in Figs. 9 -12. (In all four figures, both tilt sensors are level, and the latitude of the telescope site is +37 degrees.)

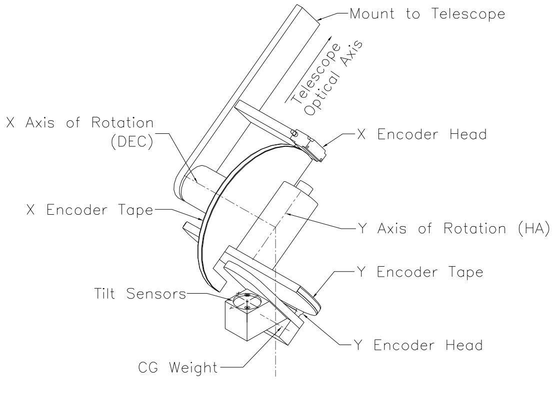

Figure 9: Passive table, telescope points at N pole

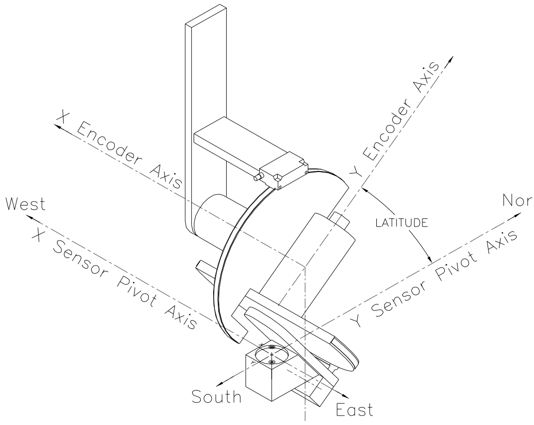

Figure 10: Passive table, telescope points at zenith

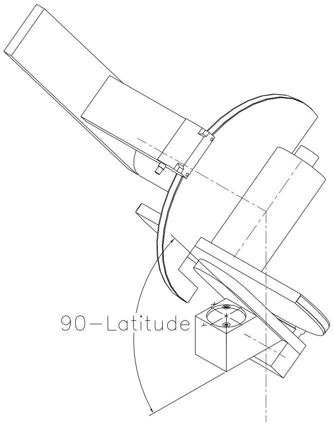

Figure 11: Passive table, telescope points at equator

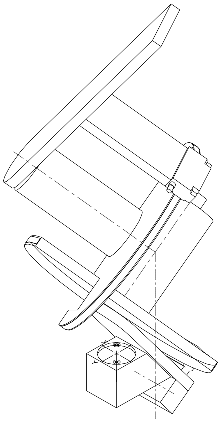

Figure 12: Passive table, telescope at -3,^{h} +37d

The passively-stabilized dual-axis system (Figs. 9-12) differs from the actively-stabilized system (Fig. 6) in several important respects. First, the motors, gear reducers, and active servo system have been eliminated. Second, the on-axis, flexible-coupled encoders have been replaced by frictionless, non-contact encoders[§]. Third, extremely low-friction bearings are used on both rotation axes. Fourth, the pivot axis of the Y tilt sensor is no longer parallel to the pivot axis of the Y encoder. Rather, these two axes are offset by an angle equal to the latitude of the telescope site.

This last modification is the most significant, since it allows the X and Y encoders to respectively measure instrumental declination and hour angle directly, provided that both tilt sensors are level. The difference in alignment of the Y tilt sensor pivot axis is most easily seen when comparing the Fig. 6 (active system) and Fig. 10 (passive system), both of which show the telescope pointing at the zenith. In Fig. 6, by definition, the pivot axes for both the Y encoder and the Y tilt sensor are parallel to a north-south line contained within the horizontal plane, and are thus parallel to each other. It is clear from Fig. 6 that (barring mechanical fabrication and alignment errors) these two pivot axes will remain parallel at all orientations of the mechanism.

By comparison, in Fig. 10, the pivot axis of the Y tilt sensor is parallel to a horizontal north-south line, while the pivot axis of the Y encoder is parallel to a north-south line that is inclined to the horizontal by an angle equal to the latitude of the telescope (i.e., it is parallel to the telescope's polar axis). Further, Figs. 9-12 illustrate that (barring mechanical errors) the pivot axis of the Y encoder will remain parallel to the telescope's polar axis for all orientations of the telescope, provided that both tilt sensors are level. When that condition is met, the Y encoder will measure the instrumental hour angle. Because the axis of the X encoder is defined to be perpendicular to the axis of the Y encoder, the X encoder will consequently measure the instrumental declination.

It should not be surprising that the device pictured in Figs. 9-12 bears considerable resemblance to an equatorial telescope mount. In fact, this device can be thought of as an "inverse" equatorial telescope mount when considered from an appropriate perspective. The operation of a normal equatorial mount can be viewed as a sequence of rotations that are applied to an initially horizontal primary mirror (i.e., one with its optical axis pointed at the zenith) so as to align the mirror's optical axis with a selected point in the sky.

That sequence of rotations consists of 3 steps:[¶] Step 1 is always the same, and consists of a fixed rotation about an East-West horizontal line drawn through the plane of the mirror (i.e., the plane perpendicular to the primary mirror's optical axis) and intersecting its optical axis. The magnitude of this rotation is equal to the latitude of the telescope site, and corresponds mechanically to the fixed inclination of the telescope's polar axle. Step 2 consists of an arbitrary rotation about a north-south line drawn through the plane of the mirror and intersecting its optical axis. This rotation is equal to the telescope's hour angle and the north-south line corresponds to its polar axis. Step 3 consists of an arbitrary rotation about a line in the mirror plane that is aligned perpendicular to the axis of rotation used in step 2 and which intersects the optical axis. This rotation is equal to the telescope's declination and the axis of rotation corresponds to the telescope's declination axis.

The "inverse" equatorial telescope mount, which is rigidly attached to the back of the primary mirror's cell (i.e., to a plane that is parallel to the plane of the primary mirror), simply applies these three rotations in reverse order so that the tilt-sensor plane is restored to horizontal (and thus parallel to our initial orientation of the primary mirror). For the inverse mount, step 1 consists of rotation about its X encoder axis, which effectively counteracts step 3 of the normal mount. Inverse step 2 consists of rotation about its Y encoder axis, thus counteracting normal step 2. Inverse step 3 consists of a fixed rotation (applied by a bevel on the block holding the tilt sensors; see Figs. 10 and 11) of the tilt sensor plane about its X sensor pivot axis so that its Y sensor pivot axis is offset from the Y encoder axis by the latitude of the telescope site, thus counteracting normal step 1.

4.3. Impacts of Re-aligning the Y tilt-sensor Pivot Axis

There is a major advantage to re-aligning the Y tilt-sensor axis so that it is aligned with the telescope's polar axis (as shown in Fig. 10) rather than with the Y encoder axis (as shown in Fig. 6) because it allows the X and Y encoders to measure instrumental declination and hour angle directly (provided the tilt-sensor plane is level). Unfortunately, because the two Y axes are no longer parallel, this realignment results in a larger and variable cross-coupling between the X and Y tilt sensors. This coupling is zero when the tilt-sensor plane is level, but it increases with increasing tilt of the Y tilt sensor.

[§] This same modification could also be made to the active system.

[¶] Prior to starting the sequence the mirror is translated vertically to sufficient height to avoid collisions with the ground.

When the two Y axes (i.e., the tilt-sensor Y axis and the encoder Y axis) are parallel (as shown in Fig. 6), the pivot (sensing) axis of each tilt-sensor is parallel with its respective table rotation axis. Since the two table rotation axes are orthogonal to each other, as are the two tilt-sensor pivot axes, a rotation about the pivot axis of one tilt sensor corresponds to an identical rotation about the opposing sensor's cylindrical axis. A rotation about a sensor's cylindrical axis alters the contact area between the excitation electrodes and the electrolyte, inducing a small shift (approximately 0.02 degrees per degree of rotation) in the zero point of its sensing axis (See Fig. 1). Aside from small non-linearities resulting from imperfections in the shape of the sensor's glass case, this zero point shift is essentially a linear function of cylindrical rotation angle, except for extreme rotations that result in a loss of contact between the sensor's electrodes and the electrolyte. Thus, when the two Y axes are parallel, there is only minimal and relatively linear cross-coupling between the two tilt sensors.

When the two Y axes are not parallel (as show in Fig. 10), the pivot (sensing) axis of the X tilt sensor will be parallel to X table rotation (and X encoder) axis only when the Y tilt sensor is level. As the Y tilt sensor is displaced from level, the non-parallelism between the X tilt sensor pivot axis and the X table rotation axis increases nonlinearly, as does the cross-coupling between the X and Y tilt-sensors. Thus, the cross-coupling between the two tilt sensors is significantly worse for the non-parallel alignment of the two Y axes.

The consequences of these differences (in tilt sensor cross-coupling) between the parallel and non-parallel alignments of the two Y axes are different depending on whether the dual-axis tilt table is leveled actively or passively.

4.3.1. Active case

In the case of an actively-leveled platform, the implementation of the two servo loops become more difficult because of the increased cross-coupling between the tilt sensors that results from the non-parallel alignment of the Y axes. As long as both tilt sensor axes are maintained close to their respective null points, the cross-coupling is minimal, and the servo loops should remain stable. For moderately larger displacements from level, there may be some advantage to processing each axis sequentially, closing the loop first on the Y tilt sensor axis and then on X. However, because the cross-coupling increases non-linearly with increasing displacement from level, for very large displacements as might occur at initial system start up, it might be necessary to manually level the tilt sensor plane prior to closing the servo loops.

Despite these added concerns regarding the servo loops, the non-parallel alignment of the Y axes affords significant advantages for the actively-leveled platform. Because the servo system should always hold the tilt sensor plane level, the tilt error signals will be held at zero and thus don't need to be added to the encoder readings. Accordingly, the X and Y encoder readings should transform directly into instrumental declination and hour angle, and the complex mathematical transform isn't needed.

4.3.2. Passive case

In the case of the passively-leveled dual-axis platform, the tilt sensor plane is not held precisely level, rather, it is only maintained close to level. As a result, the X and Y encoder readings do not map precisely into instrumental declination and hour angle, since that relationship only occurs when the tilt sensor plane is precisely level. Similarly, in this configuration where the two Y axes are not parallel, the X and Y tilt sensor readings do not correspond directly to the residual errors of the encoder readings (i.e., errors resulting from the incomplete leveling of the tilt sensor plane), since the axes about which the sensors measure their respective tilts are not parallel to the corresponding encoder axes.

Accordingly, the residual tilt errors measured by the X and Y tilt sensors cannot be added directly to their respective X and Y encoder readings. Rather, these X and Y tilt errors must first be mathematically transformed into the same reference frame as the encoder readings. The non-parallelism between the two X axes will be small, as will be the effect of the transform. The non-parallelism between the two Y axes is large but will consist of a large fixed component (i.e., the latitude) combined with a small variable component (i.e., the residual tilt error in Y). The result obtained from combining the encoder readings and the transformed tilt sensor readings then must be further transformed into instrumental declination and hour angle. Thus, while the passive dual-axis system is significantly simpler than the corresponding active system in terms of electronic and mechanical complexity, it is potentially more complex mathematically.

However, much of this increased complexity involves second-order effects. While the residual tilt errors of the passive system are not zero, they are still very small. In many cases, small angle approximations can be applied which reduce the complexity of the required transformations. At some level, if the residual tilt errors of the passive system can be kept sufficiently small, then negligible error is incurred by treating the X and Y encoder readings as if they map directly to instrumental declination and hour angle, even though this is not strictly the case. Whether such a small level of residual tilt error can be achieved in practice depends on the quality of bearings and lubricants ultimately employed.

4.4. Dual-axis Summary

In an ideal world with perfect, frictionless bearings, perfectly machined and aligned mountings, and freedom from external disturbances that would induce pendulum motions, the tilt sensors could be eliminated since the dual-axis platform would in theory be able to level itself without incurring any residual tilt error. Toward this end, we investigated air bearings (which have extremely low friction) but rejected them because of their high cost and mechanical complexity. However, in the real world, some bearing friction (or some other mechanism, such as the independently-suspended viscous damping mechanism described in Ref. 7) is needed to provide a damping force so that low level vibrations from the telescope do not excite pendulum motions in the table.

The detailed design for the dual-axis platform (active or passive) should aim for a mechanism that is as light, compact, and rigid as practical. To minimize thermally-induced variations in the platform structure (as well as variations in the tilt sensor scale factor, at least for the passive case), the mechanism should be enclosed in a sealed, insulated and thermally-controlled box. Since the overall size of this mechanism should be less than one 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. In addition, the enclosure could protect the tilt table from wind disturbances and the bearings from contamination with dust or dirt.

Because of the small size of the overall mechanism relative to the size of its bearings, bearing rumble is a significant concern for the dual-axis table, since it represent yet another source of cross-coupling between the table rotation axes. This source of error may be extremely difficult to measure accurately, since it is on the order of 0.25 micron. However, since the bearings rotate less than a full revolution, the elements of the bearings (both races and balls) travel fixed, repeatable paths that we should be able to model, if necessary. Accordingly, besides providing very low friction, the bearings selected must be of extremely high quality so as to minimize bearing rumble. The cost of such bearings will represent a significant part of the overall cost of the mechanism.

As noted earlier, the dual-axis tilt table bears considerable resemblance to a telescope mount, and as such is subject to many of the same imperfections (e.g., non-perpendicularity and misalignment of axes). These sources of error will need to be carefully measured and modeled. While this activity requires significant effort (similar to that required for developing a telescope pointing model), it can be performed in a laboratory during the day, and does not require time on a telescope at night. Further, this model, once developed, should remain exceptionally stable, because the dual-axis tilt table mechanism will be essentially invariant inside its sealed enclosure. Its attachment to the telescope at a single, fixed location on the back of the primary mirror cell should also remain quite stable over time. While aligning the tilt-table axes to the telescope axes will require telescope time, it should be possible to conduct this alignment during the day. Once these daytime calibrations have been completed, a formal telescope pointing analysis should be performed to derive a pointing model which accurately corrects for those error sources in both the telescope and tilt table that are not accounted for by the daytime calibrations.

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

Because there is no corresponding tilt to measure, a dual-axis tilt table cannot be used to derive 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 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. A dual-axis tilt sensor platform provides direct measurement of 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 substitute $\phi = 0$ in equations 3 and 4, obtaining the result $H = -Y$ and $D = -X$. Since we set $\phi = 0$, the Y encoder and Y tilt sensor axes will be parallel.

6. CONCERNS

Our analysis of the single and dual-axis platforms, and our experiments with the single-axis active prototype and the single-axis passive test apparatus have addressed nearly all the concerns raised in Sect. 1. However, 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: 1) the azimuthal component of dynamically varying polar axle misalignments; 2) shifts of the primary mirror within its cell; 3) structural deformations in telescope tube; and 4) variations in the position of the secondary mirror. Any of these can alter the telescope pointing. 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.[8] Also, many modern telescopes provide control and readout of the secondary mirror tilts, allowing for direct correction of any pointing errors they induce.

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 illustrated how the design presented in our previous paper can be simplified to yield a passive system which provides a direct readout of telescope hour angle and declination, and have evaluated the tradeoffs between actively and passively stabilized platforms. Initial tests of a single-axis test apparatus have demonstrated the technical feasibility of the passive design.

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