Methods for measuring and reducing slippage of friction rollers employed in off-axis couplings of position encoders to telescopes

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ABSTRACT

Many optical telescopes, including the Keck Observatory 10-meter and the Lick Observatory Shane 3-meter and Nickel 1-meter, employ incremental position encoders that are mounted off-axis and coupled to the telescope via friction rollers. Depending on the particular telescope, these encoders are utilized to measure telescope position and/or to provide telescope velocity feedback to the telescope drive system. A common concern in both applications is the potential for such friction roller couplings to introduce significant errors in telescope pointing and tracking. While a properly designed telescope pointing model can compensate for repeatable friction roller errors, such as scale factor and eccentricity, it cannot compensate for non-repeatable errors like roller slippage. As a result, roller slippage errors can seriously degrade telescope performance.

This report will describe instrumentation and techniques developed to study the slippage of friction rollers employed in off-axis couplings of position encoders to telescopes. (An expanded version of this report, including tables, figures, and drawings, will be issued as Lick Observatory Technical Report No. 53.) It will also examine different designs of rollers and roller mountings, and adjustment procedures for obtaining optimal alignment of the rollers to minimize slippage. Techniques will be presented for using various types of fiducials, including geostationary satellites and inexpensive opto-electronic sensors, to obtain measures of telescope position encoder repeatability and telescope hysteresis that are independent of the telescope pointing model. These techniques may also prove useful for telescopes employing other types of encoder couplings.

1. INTRODUCTION

To achieve high quality pointing and tracking, some large telescopes, such as the Multiple Mirror Telescope (MMT), employ high-precision, high-accuracy position encoders which are directly coupled to the telescope on-axis.[1] In fact, Barlow, Ulich, and Latham state:

> The direct coupling of the encoder shaft is an important feature that contributes to the MMT's excellent pointing characteristics. It improves repeatability and minimizes inaccuracies associated with the more common friction wheel and/or gear driven encoder systems.

Clearly, an on-axis coupling eliminates many potential sources of error, and thus provides significant advantages over an off-axis coupling.

Unfortunately, due to either the physical or economic constraints associated with a particular telescope, an on-axis encoder mounting is not always feasible. For example, the coudé focus light path may intersect the desired on-axis location for coupling an encoder to the hour angle axis of an equatorial telescope. While hollow, annular-shaped encoders are commercially available, they may not provide a wide enough central opening to accommodate the coudé beam. Further, to achieve even a 1-arcsecond resolution of the telescope position, the 1:1 ratio of a direct on-axis coupling requires that the encoder provide in excess of 20-bits of resolution per encoder revolution (the MMT encoder provides 26-bit resolution). Such encoders are either difficult to obtain in the desired configuration or may be prohibitively expensive (the absolute encoder unit in the MMT system cost $30,500 per axis in 1982). However, these costs are likely to decline as encoder technologies improve.

The main alternatives to on-axis couplings are off-axis couplings which employ either friction rollers, gear drives, or belt-driven systems (*e.g.*, Berg belts). The major tradeoff involves regularity versus repeatability. While gear and belt driven couplings can be designed which exhibit negligible slippage and backlash, they are often subject to significant short-term irregularities (*e.g.*, tooth-to-tooth variations) which can be difficult to model and correct. Thus, while such systems can provide relatively good long-term pointing and tracking accuracy, they may also generate very irregular short-term tracking errors, especially after such tooth-to-tooth variations have been accentuated by years of mechanical wear (as is described in the following section). On the other hand, friction rollers are virtually free of backlash and short-term irregularities, but may be subject to gradual slippage over the longer term. As a result, while friction roller couplings can provide for very smooth and regular short-term tracking, they can produce significant long-term tracking and pointing errors if no effort is made to correct for accumulated slippage. With proper design and alignment of the friction roller mounts, this slippage can be minimized. By periodic recalibration to reference fiducials, the accumulation of slippage errors can be reduced to acceptable levels.

2. THE FRICTION ROLLER TESTING SYSTEM

In early 1987, development was begun on a system for studying friction roller slippage at the Shane 3-meter Telescope. A major goal of this effort was to develop a system that could be left in place without interfering with normal telescope operations. This would allow long term studies to be conducted without the need for repeated assembly and disassembly of the test apparatus. Another goal was to reduce the cost of the test hardware by making maximum use of spare components from other systems. In fact, this friction roller testing system is a direct outgrowth of earlier work, begun in 1984, to improve the short-term tracking accuracy of the right ascension axis of the Shane 3-meter telescope. A brief summary of that work is provided next.

2.1 Friction-roller coupled position encoder for polar axle velocity feedback

The right ascension drive of the Lick Observatory Shane 3-meter telescope uses 2 worm gears: a high precision one for tracking, and a less precise one for slewing. In the mid-1970s, degradation of the right ascension tracking accuracy was first observed, with reports of 1 to 5 arc-second tracking errors that repeated at two minute intervals. This two minute period was easy to correlate with the two minute rotation period of the tracking worm gear, and was attributed to mechanical wear and misalignment accumulated over 25 years of use. Mechanical adjustments of the worm gave no lasting improvement, leading to the suspicion that the worm was damaged. Replacement of the worm was not feasible, since it would be extremely expensive, and would require that the telescope be taken out of service for an extended period.

In 1984, a friction roller was used to couple a high resolution optical incremental position encoder directly to a hardened surface on the rim of the polar axle. A hybrid hardware/software system was developed which uses the signal from this encoder to provide polar axle velocity feedback to the telescope drive controller.[2] This system adjusts the worm gear velocity in real-time to counteract the irregularities in the gear, so that the polar axle rotates at the proper sidereal rate.

2.2 Friction roller testing system summary

The polar axle velocity feedback system proved so successful in compensating for the worm gear's periodic tracking error that in 1986, a set of spare components (encoder, friction roller cylinder and mounting, electronic counter card, and single-chip microcomputer card) were obtained and assembled as a backup system. As a result, two identical high resolution position encoders were now coupled to the same rim of the polar axle using nearly identical friction roller couplings. By comparing the respective outputs from these two encoders over time, the slippage of one roller relative to the other could be continuously monitored. With the addition of opto-electronic fiducials to the polar axle itself, the slippage of each roller relative to a fixed reference point could also be monitored. The outputs of these encoders and fiducials were appropriately buffered and fed to hardware counters and to a dedicated single-chip microcomputer. This microcomputer (which contains an embedded asynchronous serial output port) acquires data from the encoders and fiducials, and outputs summary statistics via an RS-232 serial line. By connecting this line to an available serial input on any computer, these statistics can be recorded on disk or tape for subsequent off-line data reduction.

The mechanical, electronic, and software details of this system will be described next.

2.2.1 Mechanical description

The two friction rollers are 0.7749-inch cylinders that are slightly crowned. The cylinders are made of an alloy of steel that is elevated temperature drawn (ETD) and designated ETD-150. This alloy has a tensile strength of 150,000 psi, and a minimum yield strength of 130,000 psi. Although not tabulated, the compressive yield strength is known to be considerably higher than either of these values. A set of leaf springs in each roller mounting loads the roller against a hardened surface on the rim of the polar axle with a contact force of 50 pounds. These rollers have a contact length that is estimated at 0.1-inch, yielding a contact pressure of 116,000 psi. While the actual yield strength of the surface on polar axle rim is unknown, it is believed to be in excess of 130,000 psi. The diameter of this rim is 137.25 inches, providing an effective ratio of 177.12:1 between the roller and the polar axle. The two rollers are essentially identical, except that the original (1984) roller was not machined in its bearings, and has significant runout, while the spare (1986) roller was machined in its bearings, and has negligible runout. They are both located on the same side of the polar axle and are separated by a distance of approximately 12 inches.

The shafts of the encoders are mounted to the rollers by a slight press fit into a reamed hole in the back end of the roller cylinder. Each encoder is supported by an anti-torque arm assembly. To help compensate for the runout in the original (1984) roller, a .062-inch wide wand is screwed into a threaded hole in the rim of a nut which rotates with the roller cylinder at the end where the encoder attaches. This wand breaks the light beam of a stationary optical interrupter on each rotation of the roller cylinder, and thus provides a zero point for measuring the position angle of the roller cylinder. This wand also provides a means for detecting slippage at the junction between the encoder shaft and the roller cylinder. If there is no slippage at this junction, then the wand will break the beam at the same encoder count (relative to the encoder's own internal index mark) on each revolution of the encoder/roller assembly, provided that the wand is sufficiently stiff and that the interrupter itself is sufficiently repeatable.

To check for slippage between the rollers and the polar axle, a set of similar wands was attached to the polar axle. The tips of these wands are at a radius of 61.06-inches (measured from the center of the polar axle), and they break the beam of a similar optical interrupter mounted to one of the stationary support beams which are adjacent to the polar axle and anchored to the dome foundation. One arc-second of polar axle rotation corresponds to a motion of the wand tip of 7.5 microns (0.0003 inch).

In late 1989, a third friction roller assembly was mounted on the opposite side of the polar axle to evaluate a different type of roller and mounting based on a design from the Canada-France-Hawaii Telescope (CFHT). This design uses a pair of follower-rollers to apply the loading force directly to the friction roller, rather than applying the force via leaf springs through the mounting. This assembly also includes a set of stiff-felt wipers on either side of the roller, designed to catch oil and dirt so that the interface between the friction roller and the polar axle remains clean. This new roller is about twice the diameter of the previous rollers (1.56-inches versus 0.7749-inch), and is spherical rather than cylindrical. It was machined in its bearings, and the spherical curve is a 1.50-inch radius. It rolls on the same rim of the polar axle as the other two rollers and is loaded with a force of 38 pounds, yielding a contact pressure of 121,000 psi. It is fabricated from the same ETD-150 material as the other rollers, and employs an identical high resolution encoder, supported by a similar anti-torque arm. Unlike the previous design, the encoder is attached to the roller cylinder by means of a collet, rather than by a slight press fit into a reamed hole. This should simplify encoder replacement should this prove necessary.

2.2.2 Electronic description

The high resolution optical incremental encoders are all Teledyne-Gurley Model 8325-3600-CBQE (3600 lines on disc, with Model HRB-GO high resolution interpolation electronics providing a 40-fold increase in resolution), employing LED light sources and providing 144,000 pulses per revolution of the encoder. Given the 177.12:1 ratio between the original two friction rollers and the polar axle, this corresponds to an encoder resolution of 0.0508 arc-seconds of rotation of the polar axle, and a pulse rate of approximately 295 Hz when tracking at the normal sidereal rate. (For the CFHT-style roller installed in 1989, the corresponding ratio is 87.98:1, yielding a resolution of 0.1023 arc-seconds and a pulse rate of about 147 Hz.) Each encoder also provides an internal index pulse once per encoder revolution.

The signals from these encoders are buffered and fed to the inputs of a divide-by-1000 up/down counter card, and to edge sensitive input port lines on a Rockwell 65/11EB single-chip microcomputer. (These components are the same as those used in the polar axle velocity feedback system.) Encoder pulse rates of up to 5-10 kHz can easily be counted in software, which is well below the pulse rates which occur during normal tracking, guiding, and offsetting. However, when the telescope is slewed, the pulse rates from these encoders reach almost 60 kHz. To allow resynchronization of the software counters following a slew, the outputs of the divide-by-1000 up/down counter hardware are connected to additional input port lines on the 65/11EB (these hardware counters can handle pulse rates of up to several MHz). These hardware up/down counters are initially reset to zero by the respective index pulse from the encoder to which each is attached.

The signals from the optical interrupter which senses the wands on the polar axle and from the interrupter which senses the wand attached to the original (1984) friction roller are connected to appropriate thresholding circuitry to produce digital logic levels; these levels are in turn connected to additional input port lines on the 65/11EB. This allows transitions of these signals to be referenced to the current encoder positions maintained by the software running in the 65/11EB. The stability of these fiducials and associated thresholding circuitry is quite good and has been measured to be stable to at least ± 2.5 microns over a period of 10 hours, and ± 5 microns over several months.

2.2.3 Software description

The 65/11EB software is written in 6502 assembly language and resides in a 4-kilobyte UV-erasable EPROM that plugs directly into the 65/11EB. This software maintains in RAM a set of three up/down counters for each of the two encoders monitored. These three counters are called the index counter, the 1K counter, and the X1 counter. The index counter counts transitions of the once-per-revolution index pulse, the 1K counter counts (modulo 144) the output pulses from the divide-by-1000 hardware up/down counter, and the X1 counter counts (modulo 1000) the encoder pulses directly. These counters are all incremented for clockwise (CW) motions, and decremented for counter-clockwise (CCW) motions. These software-implemented up/down counters and the divide-by-1000 hardware up/down counter are all initialized to zero when the encoder index pulse is first detected with the encoder moving CW. The software constantly checks for consistency between the index pulse, the divide-by-1000 hardware up/down counter, and the three software up/down counters, to insure that proper synchronization is maintained. If a loss of synchronization is detected (as will occur during slewing), a message is logged to the serial output line, indicating the respective counter values.

The hardware and software support two encoders. For each update of either of the 1K counters, a message is logged to the microcomputer's serial output line. This message provides the index, 1K, and X1 counter values for each of the two encoders, and also indicates which encoder produced the 1K pulse, the current direction of rotation, and the current time. Similar messages are logged whenever an index pulse is detected from either encoder and whenever transitions are detected on the signals from the optical interrupters. The message values are output in hexadecimal format (to reduce conversion overhead in the microcomputer) and encoded as printable ASCII characters, to simplify transmission to a data acquisition computer. Off-line data reduction software running on these computers combines the index, 1K, and X1 values from each encoder to form a corresponding polar axle position. Whenever this reduction software encounters a message indicating that the software has lost precise synchronization to an encoder (as occurs during slewing), it flushes further data until it detects resynchronization to a subsequent index pulse.

In an ideal case, where the two rollers are exactly identical, the relationship between the two rollers could be obtained directly by subtracting the positions reported by the encoder from each roller. In the absence of slippage (or if the two rollers slipped identical amounts), this difference would remain constant. Unfortunately, although the two rollers may be nearly identical, small scale factor and eccentricity variations will cause this difference to vary as the rollers rotate, even if there is no relative slippage between the two rollers. To avoid this ambiguity, the reduction software allows one to record, for a given motion of the polar axle, a baseline correlation between the corresponding positions reported by the two encoders. In the absence of slippage, if the the same motion is repeated, the corresponding positions reported by the two encoders should match those recorded during the baseline motion.

2.3 Friction roller parameters

Before describing the test results, it is important to identify the factors which may affect roller slippage, and the methods for measuring and adjusting these factors.

2.3.1 Slippage factors

Friction roller slippage probably results from a number of different factors, some of which are difficult to measure, to model, or to adjust.[3] For example, given the large contact pressures involved, there may be very complex micro-level deformations and interactions between the roller and the surface on which it rolls, and these will depend upon the specific combinations of materials used. Such interactions are clearly beyond the scope of this paper.

Of those factors which can be measured, modeled, and adjusted, the primary one is roller alignment. Ideally, the roller should be aligned so that its axis of rotation is parallel (in all axes) to that of the surface on which it is rolling. The alignments of interest are the skew and contact patch. (If the roller is thought of as an airplane, its rotational axis corresponds to the plane's roll axis, its skew axis corresponds to yaw, and its contact patch axis corresponds to pitch.) If the roller is misaligned in skew, this will generate an axial motion of the roller which increases as the roller rotates. This axial motion will be resisted by the roller bearings, and will give rise to an axial force. When this force exceeds the frictional force between the roller and surface, a slip will occur. This slip will have both axial and radial components, the distribution of which is difficult to model or predict. If the roller is misaligned in contact patch, the roller contact will be uneven, and besides contributing to slippage, may also result in stress or damage to the surface, the roller, or its bearings. Contact patch alignment is especially critical for cylindrical rollers, particularly those which have little or no crowning.

Other major factors over which some control may be possible are the cleanliness (or surface treatment) of the interface between the roller and the surface on which it rolls, and the roller acceleration rates, which are ultimately a function of the telescope drive system. Depending upon the type of materials used for the rollers or the surface, it may be necessary to apply chemical films to inhibit corrosion of these surfaces, and these films may reduce friction and attract dirt. If the roller/surface interface is located near hydrostatic bearings, it may also tend to acquire a film from the hydraulic fluid used in these bearings. Unfortunately, given the existing test environment, neither the cleanliness of the interface nor the roller acceleration rates are controllable. This makes roller alignment the primary controllable parameter for reducing slippage.

2.3.2 Roller alignment measurement

Roller skew alignment is usually measured by projecting a line radially from the roller and comparing it to a reference edge of the surface (*e.g.*, the edge of the polar axle rim) which is assumed to be contained in a plane that is perpendicular to the axis of rotation of that surface. Such a line can be projected either by attaching a stiff swing-arm to the roller and sweeping it from side to side by rotation of the roller, or by clamping a stiff rule to the face of the roller, assuming that face has been ground flat and is perpendicular to the roller axis. The distance between the tip of the projected line and the edge of the reference surface is measured at both extremes of the swing arm rotation, or at both ends of the rule. If the skew is properly aligned, this distance will be the same for both measures. If misaligned, the misalignment is stated as the difference between the two distances, measured over the length of the projected radial line.

The accuracy of the skew alignment measurement is constrained by a number of factors, including the length of the projected line (which should be as long as is practical), the stiffness of the swing arm or rule, and the degree to which the reference edge of the surface (and the roller face, if a rule is used) is truly perpendicular to the axis of rotation. In general, one tries to achieve a misalignment less than 0.001-inch, measured over a 10-inch radius (*i.e.*, a misalignment angle of less than 0.0001 radian). For the 0.7749-inch rollers in the test system, a 0.0001 radian skew misalignment will result in an implied axial motion of 0.00024-inch per roller revolution, and 0.0215-inch for the 88 roller-revolutions corresponding to a 12-hour angular rotation of the polar axle.

The rollers used in this test system were all aligned using the mechanical measurements described above (swing-arm method for the 1984 and 1986 rollers, rule method for the 1989 roller). An alternative approach, which has not yet been tried, would be an iterative process of measuring the slippage and making incremental adjustments to the alignment. While this second approach would be more time consuming, it might provide better results. Another alternative would be to design into the roller mounting some type of sensitive sensor which would be able to detect the buildup of axial forces that result from rotation of a skewed roller. If this could be done, it might provide the most accurate and efficient means for making this measurement.

2.4 Friction roller test system results

Two basic classes of tests have been conducted: encoder-to-encoder tests, and encoder-to-fiducial tests. The encoder-to-encoder tests measure the degree to which two separate rollers coupled to the same surface remain synchronized to each other. The encoder-to-fiducial tests measure how well each encoder remains synchronized to fixed reference points on the common surface.

2.4.1 Encoder-to-encoder results

The encoder-to-encoder test measures the differential slippage between two encoders coupled to a common moving surface. This differential slippage may be more or less than the actual slippage of either encoder relative to the surface itself. If neither encoder slips, or if both encoders slip identically, the differential slippage is zero. If both encoders slip in the same sense, the differential slippage will be less than the actual slippage of either encoder relative to the surface. If the encoders slip in the opposite sense, the differential slippage will be larger. This test is useful in assessing the performance that might be achieved in a dual-encoder system. Also, if one assumes that the rollers are sufficiently separated (in this case by 12 inches) so that their local interactions with the surface on which they roll will be uncorrelated, then this test is also useful in looking for abrupt slips that might result from defects in this surface.

This test was performed by rotating the polar axle at "set" speed (45 arc-seconds/second) from an hour angle of $-5^{h}_{.}5$ to $+5^{h}_{.}5$, and then back to $-5^{h}_{.}5$. One of the two encoders is chosen as the reference encoder, and at each 1K pulse from that encoder (see section 2.2.3 above), the positions of both encoders are recorded. The positions recorded during the motion from $-5^{h}_{.}5$ to $+5^{h}_{.}5$ are saved as the baseline values. During the return motion from $+5^{h}_{.}5$ to $-5^{h}_{.}5$, this second set of positions is compared to the baseline to determine the differential slippage.

This test was first conducted when the skew misalignment of the 1986 roller was 0.040-inch, and that of the 1984 roller was 0.007-inch, as measured over a 10-inch radius. Upon completion of the motion from $+5^{h}_{.}5$ to $-5^{h}_{.}5$, the difference in position relative to the baseline values was +55 arc-seconds. Further, this difference increased in a roughly linear manner at an approximate rate of 5 arc-seconds per angular hour (*i.e.*, 1 angular hour = 15 degrees). The skew alignment on the 1986 roller was readjusted and the misalignment reduced from 0.040-inch to 0.002-inch. This test was repeated, and the maximum difference in position relative to the new baseline values was +35 arc-seconds. Again, this difference increased in a roughly linear manner, this time at an approximate rate of 3 arc-seconds per angular hour. This implies that adjusting the skew alignment of the 1986 roller modified its slippage to be closer to that of the 1984 roller. The other important result of these tests is that they did not identify any abrupt slips, thus verifying that the surface on which the rollers roll is in reasonable shape. This is consistent with the results obtained from the polar axle velocity feedback system.

2.4.2 Encoder-to-fiducial test results

The encoder-to-fiducial test measures how well each encoder remains synchronized to fixed reference points on the polar axle. Currently, there are two fiducial wands mounted on the polar axle, located at approximately $-0^{h}\ 30^{m}$ and $-0^{h}\ 55^{m}$ of hour angle. The separation between these two wands thus corresponds to about 6.25 degrees of polar axle rotation, or to 3.033 revolutions of the 1984 and 1986 rollers, or 1.506 revolutions of the 1989 roller.

This test is performed by rotating the polar axle at "set" speed back and forth between $-0^{h}\ 25^{m}$ and $-1^{h}\ 0^{m}$, and recording the positions reported by each encoder for each fiducial wand crossing. In all cases, the encoder positions are referenced to each encoder's internal index mark. As mentioned earlier, the optical interrupters which sense the wands provide repeatability to at least ± 2.5 microns over the time scale of these tests, and this translates to an uncertainty of less than ± 0.33 arc-second of polar axle rotation, or to ± 6.5 encoder counts for the 1984 and 1986 rollers, and to ± 3.25 encoder counts for the 1989 roller.

Although there is considerable scatter in the data obtained from this test, in all cases the worst errors observed during a series of 9 complete passes ($-0^h\ 25^m$ to $-1^h\ 0^m$ to $-0^h\ 25^m$) are under 10 arc-seconds of polar axle rotation (or about 200 encoder counts, corresponding to a 0.5 degree roller slip for the 1984 and 1986 rollers, or about 100 counts and a 0.25 degree roller slip for the 1989 roller). In many cases, the errors are considerably less. There is insufficient data collected to date to provide a convincing correlation between the measured skew misalignment and the measured slippage. Also, because the 1989 CFHT-style roller was not aligned until early 1990, there is not yet enough data to indicate a significant difference between its spherical shape and that of the 1984 and 1986 cylindrical rollers.

However, two other features that consistently appeared in the data are worth noting. First, if one looks only at the number of encoder pulses that are counted between two fiducial crossings, one will not obtain an accurate measure of the absolute slippage of the roller because both endpoints (as seen by the encoder) are slipping together. What needs to be measured is the actual encoder position, relative to its internal index mark, for each fiducial crossing. The difference between these two types of measurements is quite startling. For example, a set of 9 complete passes of the encoder-to-fiducial test indicated that the number of encoder pulses measured between the two fiducial crossings was essentially constant, while the measured encoder positions showed a progressive slip of 24 encoder counts.

Second, the data exhibit a curious pattern which may indicate some type of mechanical relaxation effect. In particular, the agreement between adjacent test passes measured near the end of a series of passes is much better than that between adjacent passes measured at the start of the series. For example, in one test, although the worst case slip over all 9 passes was about 8 arc-seconds (of polar axle rotation), the worst case slip over the first 4 of the 9 passes was 7.5 arc-seconds, while only 0.7 arc-seconds for the last 4 passes. Since these tests have usually been conducted in mid- to late-morning, after the telescope has been parked for at least several hours, the results obtained at the start of the series may reflect mechanical stresses in the system that accumulate when the telescope is parked, and which are relieved during the course of the test. One theory is that, given the immense contact pressures, flat spots may develop in the roller (at the point of contact) while the telescope is parked, and these spots may be rolled out during the test. Another possibility is that stresses are introduced in the roller mount when the pumps for the hydrostatic bearings which support the polar axle are turned on or off. These pumps are turned off when the telescope is parked, causing the polar axle to settle down several thousandths of an inch in response to the loss of bearing pressure. An additional theory is that repeated passes over the same area may pulverize and evenly distribute any dirt which has collected there. Whatever the case, these results suggest that more consistent data might be obtained if the telescope is "exercised" prior to the start of these tests, and this procedure will be used in future testing.

2.5 Friction roller test system conclusions

As this project has been a rather low priority at Lick, progress has been very slow and sporadic. In addition, the polar axle of the Shane 3-meter telescope has proved to be a very poor choice for a laboratory to conduct roller slippage tests. Since virtually no engineering time is available on this telescope, testing is limited to those hours of the day when the telescope is not needed by the observer and when staff are available to conduct the tests. Also, the surface to which the rollers are mounted was not designed for this purpose, and the area where the rollers are mounted is extremely crowded, making physical access exceedingly difficult. This complicates the installation and adjustment of roller mounting hardware and limits the length of the swing-arms or rules that can be used, thus making precise measurement and alignment of the roller skew very difficult. As a result, the skew alignments of the rollers are not optimal: the 1984 roller is misaligned 0.007-inch, the 1986 roller 0.002-inch, and the 1989 roller 0.001-inch, as measured over a 10-inch radius. Ideally, these misalignments should be considerably less than 0.001-inch, but given the current physical constraints this will not likely be achieved.

An additional problem is that the polar axle surface on which the rollers rotate is close to the hydrostatic bearings which support the telescope. As a result, this surface rapidly acquires a film of hydraulic fluid which in turn tends to collect dust and other contaminants. Although the CFHT-style roller mounting installed in late 1989 contains felt wipers that are designed to keep the roller interface clean, these have not proved totally effective. A further complication of the hydrostatic bearings is that variations in bearing film thickness may cause translations of the polar axle which compromise the angle measured by the encoder. This problem might be resolved by mounting 2 rollers on opposite sides of the polar axle (180-degrees apart), and averaging their readings. (This would be a problem for any encoder coupled off-axis, whether or not it was coupled via a friction roller). Finally, as noted earlier, hydrostatic bearings may result in stresses to the roller mounting as the pumps are turned on and off, and may, over time, compromise the alignment of the rollers or accelerate the wear between the roller and the polar axle surface at the position to which they are normally aligned when the telescope is parked.

A further difficulty with the current test system is its inability to collect data at slew speed, due to the counting rate limitation imposed by the microcomputer. This greatly increases the time required to collect data, and also complicates the data reduction software. The ability to acquire data at slew speed, and the addition of both more polar axle fiducials and more precise fiducials would greatly improve this test system, but would require further hardware development.

Despite all of these difficulties, the existing test system has provided a number of important insights on the behavior of friction rollers and has also provided some useful benchmarks as to how well such rollers can be expected to perform given the non-ideal conditions described above. Given more ideal conditions (*e.g.*, clean roller/surface environment, optimal roller alignment, optimal materials for surface), friction rollers may perform even better. Measurements by Melsheimer indicate that this is probably the case.[4] Nonetheless, given the unknown complexities of the micro-level interactions at the roller/surface interface and the practical difficulty of achieving (and perhaps maintaining) perfect roller alignment, the search for a slip-free friction roller coupling may prove to be as elusive as the search for the Holy Grail. If precise telescope pointing (*e.g.*, absolute pointing accuracy to the arc-second level) is required, then the design of a telescope position encoding system employing friction roller couplings should assume that the rollers will slip, and should provide sufficient numbers of sufficiently accurate fiducials to allow frequent recalibration. This is the approach that will be used for the Keck 10-meter, and it will be instructive to see what results are obtained with that system.

3. OBSERVATIONAL RESULTS AT THE LICK 1-METER NICKEL TELESCOPE

During the past year, Lick Observatory's Nickel 1-meter telescope has been used to conduct a number of tests of telescope position encoder repeatability. Unlike the Shane 3-meter friction roller test data, which was obtained during the daytime and is not correlated to any observations of stars, the data from the tests conducted at the Nickel 1-meter are based on nighttime observations of objects in the sky. This section will describe the various types of observations performed and will focus on the use of geostationary satellites in measuring telescope position encoder repeatability, telescope drive system errors, telescope structural hysteresis, and atmospheric and dome seeing effects.

3.1 Mechanical and electronic description

The friction rollers at the Nickel 1-meter are considerably older (1981) and somewhat different than those at the Shane 3-meter. The rollers which couple the hour angle and declination position encoders to the telescope are made of 17-4-PH-900, a stainless steel alloy which is hardened after machining to a Rockwell C hardness of 45. These rollers roll on the main hour angle and declination friction drive wheels which are both 37.463-inches in diameter and made of carbon steel #C1144, heat-treated to a Rockwell C hardness of 55. To inhibit corrosion, these wheels are coated with Dayton Dem-Kote Industrial Spray Type 4X597-A Anti-Rust Film. The friction roller used to couple the declination encoder is 0.5874-inch in diameter with a 0.0002-inch crown (corresponding to a crowning radius of 156-inches), while the roller used to couple the hour angle encoder is 0.4390-inch in diameter, and is not crowned. Both rollers employ mountings similar to those used for the 1984 and 1986 rollers at the Shane 3-meter. A set of leaf springs in each mounting loads the roller against the corresponding drive wheel with a contact force of 50 pounds, yielding a contact pressure of 45,000 psi for the declination axis, and 55,000 psi for the hour angle axis. Unfortunately, these older roller mountings do not provide a convenient means of adjusting the roller skew alignment, and records of the skew alignment (performed during installation in 1981) are no longer available.

Both axes use a Disc Instruments model 736FR-2540-OBLP-X4-HTL+15-LD optical incremental encoder providing 10,160 counts per revolution (2540 lines on glass disk, with times-4 quadrature decoding). This provides a resolution of 2 arc-seconds per encoder count in the declination axis, and 0.1 seconds of time in the hour angle axis. Unfortunately, neither of these encoders provide an internal index pulse.

3.2 Telescope pointing tests

In late 1987, a formal series of telescope pointing tests was conducted, using a selected set of SAO catalog stars. To provide rapid selection of the stars to be observed, software was developed by Allen to graphically display a current map of these stars on the sky, along with the corresponding telescope limits. An interactive cursor is used to select a star from this map, and the software generates a predicted position for setting the telescope, based on the current version of the telescope pointing model. This system allows stars to be acquired every 3 to 4 minutes given the current slew speed of the Nickel 1-meter.

These telescope pointing observations were reduced using the TPOINT telescope pointing analysis system developed by Pat Wallace of Starlink.[5] After accounting for all of the canonical telescope misalignments and errors (*e.g.*, polar axle misalignment, encoder index errors) and for the friction roller scale factor errors, the residual RMS pointing error was still disturbingly high, on the order of 60 arc-seconds. Even more distressing, the distribution of errors was extremely puzzling, and did not seem correlated to any obvious flexure model. More thorough analysis, performed outside of the TPOINT system, indicated that the errors were correlated with the order in which the objects were observed, and that the error growth was roughly linear with time.

Although this type of error was observed in both axes, the errors were much worse for right ascension than for declination. At first, a drift in the sidereal clock was suspected, but this was specifically ruled out. A more likely explanation was a lack of repeatability in the position encoders, either due to friction roller slippage or to electronic noise corrupting the signals from the incremental position encoders or some combination of both. Because these particular encoders do not provide an internal index pulse (a serious oversight!), it is impossible to prove that some encoder counts are not getting lost or spurious pulses added. However, given the quality of the encoder signals measured, this does not seem likely, and friction roller slippage is probably the cause. The manner in which the error grows and the overall error magnitude are consistent with the roller slippage results measured at the Shane 3-meter.

In this case, regardless of whether the cause is electronic noise or roller slippage, what one is really trying to confirm is that the residual errors in the pointing model are due to lack of repeatability in the telescope position encoders. Lacking an accurate mechanical or opto-electronic fiducial on the telescope itself, a test of telescope position encoder repeatability might be attempted using observations of a star. Conceptually, this is quite simple. First, one would acquire a star in the telescope's acquisition camera, align it with a reticle or other reference mark, and record the displayed telescope position. The telescope would then be slewed sufficiently far (perhaps some tens of degrees) to have a high probability of causing roller slippage, or electronic noise in the encoder signals. Finally, the telescope would be slewed back to the recorded position, and the acquisition camera would be checked to see if the star was recentered on the original reference mark.

In practice, this procedure has some limitations. If the slew speed is relatively slow, this procedure could easily take one minute or longer. Unfortunately, to detect small drifts that are typical of roller slippage, one might have to repeat this process many times before the drift was large enough to measure on the acquisition camera field. By the time one has finished repeating this test a sufficient number of times, the reference star will have moved some many minutes of time (or several degrees of arc). If, at that point, it is not quite recentered on the reference mark, is it because the position encoders have slipped, or because the telescope pointing model is inaccurate? Of course, we already know the pointing model is inaccurate, since that is what started us looking for the position encoder repeatability problem in the first place! This problem would be easier to resolve if the Earth did not rotate, and the positions of the stars remained fixed on the sky. Unfortunately, the only star whose position appears to remain fixed is the pole star, which is not helpful in this case, for two reasons. First, Polaris provides no useful information for a position encoder repeatability test in the right ascension axis. Second, Polaris is inaccessible to the Lick 1-meter, because its yoke mount prevents it from acquiring objects North of +65 degrees declination.

3.3 Geostationary satellites as "fixed fiducials on the sky"

While there are no adequate stars whose positions remain fixed on the sky, there is a significant class of objects whose positions do remain fixed, or at least, nearly so. These are geostationary satellites, whose orbital periods match the sidereal day, and whose orbital planes are nearly parallel to the Earth's equatorial plane. Although these satellites are relatively faint (visual magnitudes ranging from 11 to 16.5, depending on satellite size, shape, construction, and angle between Earth, satellite, and sun), they are easily observed by telescopes with apertures 1-meter or larger, especially if equipped with sensitive CCD TV guide cameras, such as that used at the Nickel 1-meter.[6,7] In fact, the telescopes used by U.S. Space Command's Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) system to monitor deep space satellites are typically 1-meter class.[8]

Unlike pole stars (*e.g.*, Polaris), which for an equatorial telescope cannot provide any useful information for a position encoder repeatability test in the hour angle axis, geostationary satellites are conveniently located near the equator, where both the hour angle and declination axes map to equal scales on the sky. This makes geostationary satellites equally suitable for position encoder repeatability tests in either axis.

Unfortunately, the apparent positions of geostationary satellites on the sky are not perfectly fixed. In fact, each day, geostationary satellites will move in either a figure-eight or an elliptical pattern that may extend up to several arc-minutes in each axis.[9] Rates of motion in each axis will vary from near zero to several arc-seconds/minute depending on the position within the orbit at which the observation is made. However, if the geostationary satellite's orbit is fairly close to nominal (*i.e.*, orbital eccentricity near zero, orbital inclination near zero, and orbital period nearly equal to a sidereal day), and if the satellite can be observed at elongation, its apparent position in the sky can remain stable to within 1-2 arc-seconds for periods of up to 45 minutes or more, which is plenty of time to perform many tests.

3.3.1 Applications

In addition to providing fiducials on the sky which are useful for telescope position encoder repeatability tests, geostationary satellites may prove useful for measurements of atmospheric seeing and dome seeing. Because geostationary satellites can be observed (once acquired) with the telescope parked, they can be used to obtain seeing measurements that are not contaminated by telescope tracking errors or by heat radiated from telescope drives. Although a pole star could be used for this purpose on those telescopes capable of acquiring one, a pole star only allows sampling of one point in the sky. For telescopes located closer to the equator (such as the Keck 10-meter), the pole star will be located at a rather large air mass. Approximately 30 geostationary satellites with nearly optimal orbits are visible from most sites in the U.S., and these are fairly evenly distributed in longitude, allowing sampling over a wider range of air masses.

Geostationary satellites can also be used when trying to distinguish periodic tracking errors resulting from vibrations in the telescope/dome building (as might result from cycling of pumps, compressors, dome drive motors, etc.) from tracking errors resulting from the telescope drive train or electronics. By comparing observations of geostationary satellites (obtained with the telescope parked) with observations of nearby stars (obtained with the drives powered up and the telescope tracking), periodic features that appear in both will likely be due to vibrations present in the building, while features appearing only in the stellar observations will be due to drive system errors.

If accurate and precise mechanical or opto-electronic fiducials are available on the telescope axes themselves (*e.g.*, similar to the fiducial wands installed on the Shane 3-meter polar axle), then observations of geostationary satellites might also be used to distinguish telescope position encoder repeatability problems (*e.g.*, friction roller slippage) from problems of hysteresis in the telescope structure itself. If, following repeated slews, the observed position of the geostationary satellite remains consistent relative to the axes fiducials but the telescope position reported by the encoder has changed, then the problem is lack of repeatability in the encoders. If, on the other hand, the axes fiducials and the encoders remain consistent and the observed position of the geostationary changes, then the problem is most likely due to some sort of hysteresis in the telescope structure, or possibly in the primary or secondary mirror supports.

More specialized applications for observing these satellites will likely arise. For example, during the initial checkout of the Keck 10-meter Telescope, it may prove useful to test the active mirror control system using light from a "real" object (as opposed to some test source in the dome), but with the telescope parked. This could help to isolate any mechanical or electronic cross-coupling between the telescope drives and the mirror control system.

3.3.2 Requirements and constraints

The use of geostationary satellites for the applications described above is subject to the following requirements and constraints. First, one needs a telescope of sufficient aperture and an acquisition camera of sufficient sensitivity. Second, one needs to be able to predict the location of the satellite at a given time with sufficient accuracy that it can be rapidly acquired. Third, one needs to be able to predict at what time and location the points of orbital elongation will occur for the given satellite, and to predict the length of time over which the satellite's position will be sufficiently stable to conduct the test in question. These last two requirements reduce to the ability to generate accurate ephemerides for geostationary satellites.

Ephemerides for geostationary satellites can be generated, using appropriate orbital prediction software, from a current set of orbital elements for these satellites. Orbital elements for most satellites, including geostationary satellites, are publicly available from NASA Goddard Space Flight Center (NASA/GSFC)[10]. There is currently no charge for this service, and elements can be requested for up to 20 satellites. Since these elements are currently distributed by U.S. mail, they will be a few days old by the time they arrive. For those with connections to the Internet network, orbital elements for some geostationary satellites are available via the Usenet news groups and from other sources via electronic mail. NASA/GSFC is currently considering establishment of an electronic bulletin board for distribution of these element sets. Appropriate orbital prediction software is available from a number of sources, including the Steward Center for Orbital Mechanics, and such software can be run on a personal computer (*e.g.*, IBM-PC equipped with 8087 floating point coprocessor). More accurate orbital elements and orbital prediction software might be available from the geophysical research community, which has observed these satellites for geodetic purposes for some years.[11] However, such data are not as publicly available as that provided by NASA/GSFC, and the corresponding software probably requires a significantly greater computing capability.

The quality of the ephemerides produced is subject to 5 basic limitations. First, the orbital elements distributed by NASA/GSFC are generated by a number of different sources using a variety of observing sites and instrumentation, so the resulting quality of the element set provided is somewhat variable.[12] Since no uncertainties or error bounds are provided with the element sets, there is no obvious way to determine the quality of a given set. Second, the orbital models used to generate these element sets do not account for all of the various orbital perturbations (such as solar radiation pressure effects).[13] Third, for those perturbations which are modeled (*e.g.*, lunar-solar perturbations, inhomogeneities in the Earth's gravitational potential), the models used are not the most recent or accurate.[14] Fourth, the delay incurred by sending the element sets by U.S. mail further degrades their accuracy, by an amount estimated to be roughly 5 to 10 arc-seconds/day.[15] Fifth, (and currently the most difficult to do anything about) is the possibility that the geostationary satellite will execute a station-keeping maneuver (*i.e.*, fire its thrusters) in order to reposition itself toward the center of its allocated position window. Since most geostationary satellites with nominal orbits are in fact communications satellites, they are required by the International Telecommunication Union (ITU) to maintain their positions within a range that is typically ± 0.05 degree. If a station keeping maneuver is executed after the element set is generated, the ephemeris produced will be inaccurate. Such maneuvers are generally executed every 2 to 8 weeks, depending upon the size of the satellite's nominal position window and the location of the satellite in longitude relative to the stable and unstable nodes in the Earth's gravitational potential.[16]

3.3.3 Observations

A variety of observations of geostationary satellites has been conducted using the Lick 1-meter telescope. These observations have been obtained using the thermo-electrically cooled CCD TV acquisition camera developed by Robinson and Osborne,[17] and the high speed CCD photometer system (HSP) developed by Stover and Allen.[18] The CCD TV system provides a 5 arc-minute field of view, which is adequate to acquire these satellites given the accuracy of the satellite ephemerides and the (current) 1 arc-minute pointing accuracy of the Nickel 1-meter. The CCD TV camera is sufficiently sensitive that camera integration times of 1 to 2 seconds are adequate for visualizing these satellites. Once the satellite is acquired using the CCD TV, a precise offset of the telescope allows the satellite to be acquired by the HSP. This system employs a cryogenically-cooled 576 row by 386 column GEC CCD configured to operate in frame transfer mode. The HSP can generate a continuous series of 1-second exposures of a 40 row by 40 column unbinned subsection of the CCD. (Since the size of this subsection is constrained by the readout speed of the CCD, a larger subsection can be used if the integration time is increased or if the image is binned on the chip.) For this application, the HSP is configured for an image scale of 0.25 arc-seconds per CCD pixel, which provides a high-resolution 10 arc-second square window within which the satellite can be observed. This high spatial and temporal resolution of the HSP system have made it extremely useful for measuring short-term seeing effects, periodic errors in the telescope drive system, and drift rates of geostationary satellites.

The observations of geostationary satellites conducted to date using the Nickel 1-meter have demonstrated that these satellites are a valuable tool for use in telescope engineering tests. These observations have confirmed the suspected source of error in the telescope pointing model. They have confirmed that periodic image motion observed in HSP images is in fact due to periodic errors in the telescope drive system, rather than in either the telescope or building structure, or the HSP itself. These observations have also provided the first measures of seeing (at the 1-meter) which are not biased by errors in the telescope drive, and this has significantly improved our understanding of short-term seeing effects and their impact on both imaging and autoguiding. Finally, these observations have demonstrated that existing orbital prediction software can be used in conjunction with the orbital element sets provided by NASA/GSFC to generate ephemerides of sufficient accuracy to allow rapid and routine acquisition of these satellites by telescopes such as the Lick 1-meter.

As a tool for telescope engineering tests, geostationary satellites may be considered a publicly-available resource. These satellites can be observed by any moderate to large optical telescope situated within a reasonable range of latitude. Aside from brief (*i.e.*, 70 minutes or less) periods of eclipse which only occur during 42-day windows centered around the equinoxes,[19] these satellites can be observed all night long, every night of the year (weather permitting). Unlike some schemes developed for telescope seeing and other specialized engineering tests,[20] the observation of geostationary satellites does not require the addition of *any* special hardware or instrumentation to the telescope or dome. Rather, it requires only the availability of modest computing resources and the installation of a small amount of existing software.

4. ACKNOWLEDGMENTS

Many dedicated individuals contributed to the results described here, and their contributions are gratefully acknowledged:

UCO/Lick engineers Jack Osborne, Fred Mueller, and Bruce Bigelow developed the mechanical designs for the various friction roller mounts. These were machined in the Lick Instrument laboratory by Jeff Lewis and Terry Pfister. Lewis and Mueller, along with Neal Jern and Erich Horn, performed the installation and alignment of the various roller mountings, under very difficult conditions. Terry Ricketts of the Lick Electronics laboratory developed the electronic design for the friction roller test system. Telescope technician Mike Owens developed and installed the mountings for the polar axle fiducials. Technicians Barry Alcott, Keith Baker, Jim Burrous, Wayne Earthman, and John Morey, assisted both with the installation of the test system wiring, and the operation of the telescope during the collection of the friction roller test data. Bill Cruise, of the Canada-France-Hawaii Telescope, provided many useful suggestions, and provided copies of drawings for the CFHT friction roller design. Dr. Frank Melsheimer, of DFM Engineering, provided many helpful ideas on the design and testing of friction rollers.

Graduate student Melinda Weil and telescope technician Jim Burrous assisted with the observations of the geostationary satellites. Weil also assisted with the telescope pointing observations, and with the reduction of the data generated by these observations. A number of Lick astronomers also helped in this effort. Burt Jones and Dave Rank aided in the first attempts to observe these satellites at the 1-meter, and it was Rank who generated our first crude ephemeris using very rough satellite coordinate data. Lick research astronomer Richard Stover helped test out his high speed photometer system for use in observing these satellites, and Arnold Klemola provided a number of helpful ideas on how they might best be observed.

Pat Wallace of Starlink made available his TPOINT telescope pointing analysis system, and provided many helpful suggestions on its use. CFHT's Bill Cruise and John Brewster (now with Hewlett Packard) provided much useful information on sources of satellite orbital prediction software. Dave Harvey of the Steward Center for Orbital Mechanics provided a great deal of information on geostationary satellites, and made available his "Kepler" package, which was used to generate the ephemerides for the geostationary satellites observed with the Lick 1-meter. Jonathan

McDowell of the Smithsonian Astrophysical Observatory provided considerable information on satellite orbital element sets. Dr. T. S. Kelso, of the U.S. Air Force Institute of Technology, provided a tremendous amount of assistance in obtaining current orbital element sets for geostationary satellites and in providing sources of information about these satellites. Dr. Kelso, Dr. H. Beat Wackernagel, of the Astrodynamics Division of the U.S. Air Force Space Command, and Dr. Felix Hoots, co-author of the NORAD SDP4 deep space model, offered much useful information on the accuracy of the NASA/GSFC orbital element sets and the models used to generate them. Mark Trueblood and Dave Whalen, of Ford Aerospace, provided significant details regarding the operational aspects of geostationary communications satellites, as did David Dunham of Computer Sciences Corporation. Dr. Gordon Taylor, formerly with the Royal Greenwich Observatory, offered many useful suggestions on techniques for observing geostationary satellites, as did Paul Maley, of the Johnson Space Flight Center.

There are probably others, whose contributions we have overlooked, but their efforts are no less appreciated.

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