Dynamics of the Otto Struve [2.1-Meter] Telescope

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1.0 INTRODUCTION

1.1 Purpose of Research Project

The Otto Struve [2.1-Meter] Telescope at McDonald Observatory collected it first light in 1939 and has been used for seventy years to study the night sky. During these decades of use, the telescope has gone through the general "wear and tear" expected, and has experienced several mishaps, due to the lack of a warning or safety system for much of its life.

These reasons, among several others, have caused the telescope to develop a periodic tracking error on the order of one arcsecond. This periodic tracking error can produce elliptical star images, reduce slit efficiency, and require unnecessary guiding effort by the observer. Moreover, the telescope, due to a new camera upgrade, now has the capacity to run an automatic ("auto") guiding program. To implement autoguiding without reducing slit efficiency, removal of the periodic error is essential. The periodic error is a short period variation, whereas the autoguider is in reality better able to take care of long period variations. Thus, elimination or reduction of the periodic error can improve the autoguider's performance.

The ultimate purpose of the research project was to remove or reduce the periodic tracking error, and also, to better understand the dynamics of the telescope to determine the best autoguiding parameters.

1.2 The Mechanical System of the Telescope

Tracking on any telescope goes from east to west and is done about the polar axis, an axis which points towards the celestial North Pole. The mechanical system controlling the rotational motion about the polar axis of the telescope consists of two separate gear trains: the Quick Motion (QM) and the Slow Motion (SM). The QM gear train is used for Slew and Search, whereas the SM gear train is used for Set, Guide, and Track.

Since the periodic error is a tracking error, the SM gear train is of concern. SM tracking is accomplished through a cascade of three worm gears, the final worm gear known as the 2-minute worm. The complex system of gears and worms was designed in the 1930s to essentially turn a 720-tooth bronze wheel (attached to the polar axis) at a speed of 400/399 revolutions/day, which turns out to be close to the sidereal rate. More recently, an error-sensing feedback "servo" loop has been put in place to make the 2-minute worm turn uniformly. All of the imperfections in-between the motor and the worm (the other gears and worms) are taken care of in this loop. However, the interface between the 2-minute worm and the 720-tooth bronze wheel is outside the servo loop. Imperfections in the worm cause the periodic tracking error, while imperfections in the bronze wheel cause much of the long period variations. It was estimated that approximately five (plus or minus a few) microns can cause the one arcsecond error.

1.3 Pre-load and Inertia

Two other important aspects of the telescope are the pre-load and the inertia of the telescope. The pre-load is an approximately 144-pound weight dragging the telescope to the east. It was added in 1979 to increase the contact between the 2-minute worm and the 720-tooth bronze wheel. It was observed that the 720-tooth bronze wheel tended to "float" across the worm. Thus, the pre-load was added to increase the contact and remove that movement. The inertia of the telescope is a function of instrument mass and declination. The heavier an instrument, the more inertia it has. Moreover, the farther away the telescope tube points away from the polar axis, the greater the inertia. So, when the telescope tube is pointing towards the celestial equator, the inertia is at its highest, and when the telescope tube is pointing towards the celestial North Pole, the inertia is at its lowest.

2.0 EXPERIMENTAL PROCESS

2.1 Instruments

The instruments used to study the periodic error and the dynamics of the telescope were the Sandiford Cassegrain Echelle Spectrometer (SES) and the SBIG CCD Camera (SBIG). The SES is the heaviest instrument currently used on the telescope, and including its balance weights, the telescope becomes 2000 pounds heavier than when no instrument is mounted. Thus, there is an inertia difference caused by the SES as opposed to when the SBIG is used, which only weighs a few pounds. Both instruments were used to take star images for a period of time while tracking near the celestial equator (most inertia).

2.2 Centroids

Each sequence of images from the tracking tests were converted to a time series of star centroids by using IRAF's imcentroid procedure. Imcentroid uses a 2-D Gaussian fit to find the centroids. The validity of the imcentroid procedure was in question, so a center of energy program was written. In general, imcentroid was always consistent in showing the periodic error, whereas the center of energy method sometimes showed the periodic error and sometimes did not. Thus, imcentroid was selected as the best method to take star images and convert them into a time series of centroids.

2.3 Programming

All the analysis of the data was done in MATLAB, including the center of energy method briefly described above. Approximately 2500 lines of functions and scripts were written to reduce and analyze the data.

3.0 RESULTS AND ANALYSIS

3.1 Absolute Encoder Study

Before full analysis of the tracking data was performed, a study of an absolute encoder (located on the northern end of the polar axis) was done. The study was done to assess whether the absolute encoder data could be used somehow to remove the periodic tracking error, maybe observe a feature that the star centroids method might miss.

After much data reduction of the encoder data, it could be seen that there was approximately a forty-two second sinusoidal variation in the data (caused by the relatively cheap encoder itself). Some pre-whitening of the data reduced the sinusoidal variation. When the Fourier transform of both the time series (with and without pre-whitening) were taken, it could be seen that there were several encoder harmonics. These harmonics, especially those with some band power, distorted the harmonics of the periodic tracking error. After the pre-whitening, the encoder harmonics were partially reduced in power, and the periodic error harmonics showed more power. However, the coherence between the centroids and encoder data was plotted as well with a ninety-five percent confidence level. In both, the coherence at the noise was as high as the coherence at the harmonics. The only frequencies at which the coherence was significant were very low. This meant that the absolute encoder was only good at showing the long period variations. Thus, it was determined that further use of the absolute encoder to study the periodic error was ineffective.

3.2 Least Squares Subtraction

After performing the imcentroid procedure, the tracking data was plotted onto two time series of the displacement in right ascension and in declination. The two minute periodic error could be clearly seen on the right ascension plot. The Fourier transform of the plot clearly showed the spectral lines associated with the periodic error. In general, all of the tracking data showed five harmonics that stood above the noise, while some of the data even showed up to nine harmonics.

In order to remove the long period variations that occur during tracking, a nearly linear or mildly inflected curve of data was selected and a least squares solution was fit after the data was rotated to account for the tilt in the camera when the data was taken. This least squares solution was then used in other tracking tests to simply subtract out the periodic error. However, the results of the subtraction resulted in inverted curves, and much of the times, curves that did not seem to follow any general trend. It was discovered that the very shape of the periodic tracking error curve itself depended on the instrument. SES had a smaller peak-to-peak periodic error than the SBIG. More inertia meant less error.

Several tests were done by subtracting the least squares solution multiplied by some smaller amplitude scale factor. These, in general, gave smaller peak-to-peak values with the best results being a 43 percent reduction for SES and a 57 percent reduction for the SBIG.

3.3 Transfer Function Analysis

Since simple subtraction failed to remove much of the periodic error, the transfer functions of the system were studied. A transfer function is a representation of the relation between the input signal and the output signal of a linear time-invariant (LTI) system. The assumed model used in the least squares subtraction was that the input of the worm is uniformly present and causes the periodic error. This led to one equation and the subtraction inputs led to another equation. With two equations and the two unknowns (the worm's input and the transfer function), an equation was derived for the worm's input, which in turn was enough to solve for the transfer function. Using the equations and the using the fact that the least squares solutions (with five harmonics) could be used to represent the known functions, the transfer function was solved by finding the amplitude and phase at each of the five harmonic frequencies.

The results of this analysis showed that the system is nonlinear, at least partly. The worm's input functions all varied, especially in amplitude, but had similar curves (similar phases essentially). The transfer functions were plotted as an amplitude and phase (for the five harmonics) in compass plots. All of them had similar orientations, just greatly different amplitudes. The impulse response functions were plotted as well, and they showed the same feature, greatly varying amplitudes and slightly varying phases.

3.4 Step Functions

Step functions were input into the telescope to better understand the transfer function results, and also because autoguiding is based on steps. One arcsecond steps were input and it was observed that while steps to the west and east overall went the same amount in distance, the steps to the east tended to overshoot and then oscillated back to the commanded distance. This was better observed in a differences plot (somewhat like a derivative) where the differences to the west were about one arcsecond while the differences to the east were about one and a half arcseconds. This meant that the rate of change was higher in the east.

3.5 The Pre-load Effect

Since the steps to the east occurred at a faster rate, the only reason which could be attributed to the occurrence was the pre-load. Thus, a tracking test was done with half the pre-load off in order to see the effects. The results showed that the tracking error was three times worse with random oscillations and spikes in the data. This analysis proved that even just without some of the pre-load, the 720-tooth bronze wheel would float across the worm. The pre-load is the cause of the nonlinearities in the system, but ironically, also keeps the periodic tracking error on the order of one arcsecond, instead of almost non-periodic errors at much greater amounts.

3.6 Jump at the Meridian

Another peculiar tendency of the telescope was noticed in one of the tracking data sets, which did not occur in any of the other data sets. At the meridian, a sudden jump to the east and then another jump to the west were observed. Moreover, after the jump, tracking deteriorated in the west, where the root-mean square (rms) of the periodic error increased by fifty percent. Possible reasons for the jump could be a shift of the primary or secondary mirror (unlikely because such a shift would not cause the rms to increase in the west). More likely, it could be a telescope balance issue or damage in the self-aligning ball bearings at the south end of the polar axis. Perhaps, once in a while, one of the worn ball bearings catches on the telescope, causes a jump, and jitters along in the west.

4.0 CONCLUSIONS

4.1 More Realistic Modeling

After analysis of the transfer functions and understanding the effect of the pre-load on the telescope, it can be seen that a more realistic model is necessary to correct for the periodic error. The original model (simple subtraction) was a simplistic model, where a linear system was assumed to exist between the worm and the sky. A more complex model would account for the effect of the pre-load, and would be seen as a partly linear and partly nonlinear system. Instead of the transfer function (classical) approach, a state-space (modern) approach can be taken. In such an approach, it would be easier to solve for nonlinear systems, but more detailed dynamical modeling would be necessary, such as having an actual numerical estimate for the inertia, etc.

4.2 Autoguiding Recommendations

After the study performed here, it can be seen that in order for autoguiding to improve long period tracking without losing slit efficiency, there can be several steps taken. First, autoguiding steps must be reduced to lower values than required to correct for the errors. Second, steps to the east must be scaled lower than steps to the west (due to overshoot). Finally, all the autoguiding steps should be scaled depending on the position of the worm.