Amateur Astronomy 71

The Essential Journal for Amateur Astronomers Around the World!

Summer 2011

Summer Astronomy

Star Party Calendar * Shorts From Down Under * Astro Trivia * Deep Sky Treasures * Golden State Star Party * Periodic Error * Laser Collimation * MSRAL * Stationary Eyepiece Project * Building A Home Observatory * Sky Sketching * Cleaning Optics *Short Subjects *Star People * Imaging With A Large Dob * Struve's Lost Nebula * WR6 * Observing SNRs * Solar Observing

As The Worm Turns

One Man's Descent Into Periodic Error

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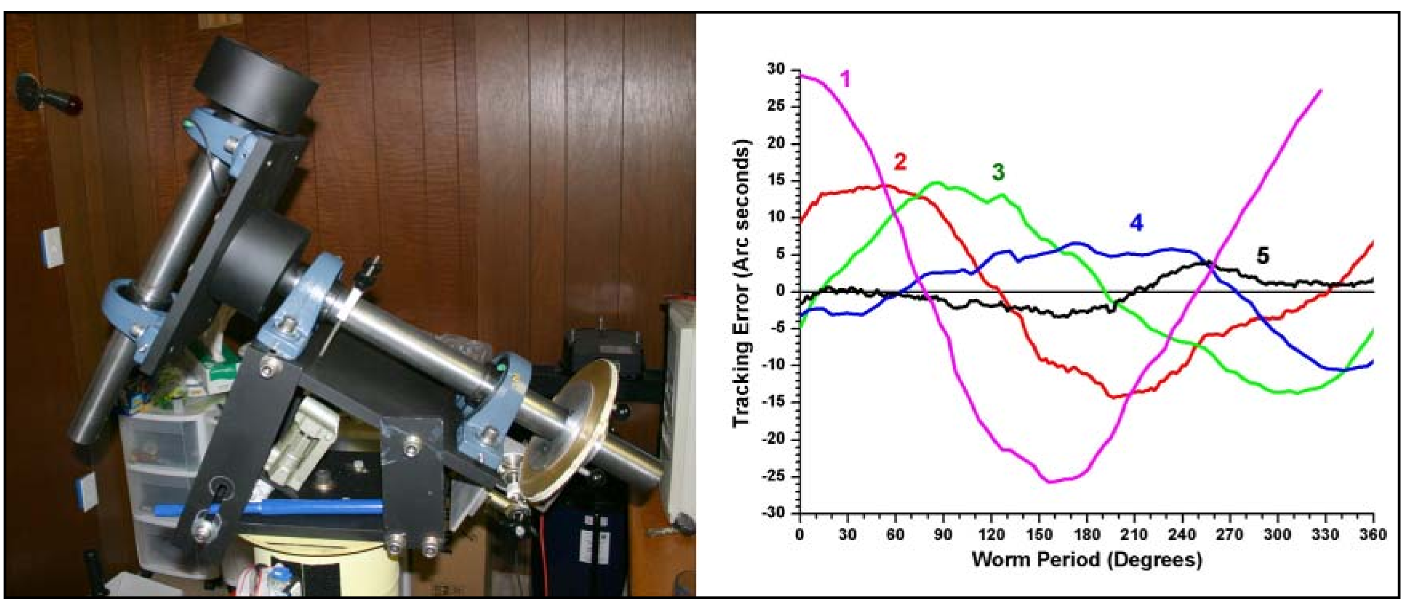
I discovered astronomy as a hobby at the comparatively late age of 38. Telescopes were something I could never afford growing up and so I never gave them much thought. This changed in 1996 with the appearance of comet Hyakutake. With absolutely zero knowledge of telescopes I purchased a TAL 4" reflector (at a time when former Soviet Union merchandise could be purchased cheap). The TAL came in a giant wooden box, complete with equatorial mount, clock-drive, and setting circles on both axes. The first lesson was that telescopes give a narrow field of view; since the comet was best observed with a wide angle (i.e. visually) I was initially disappointed. However, I was fascinated by the setting circles and the idea that cosmic objects could be found using a coordinate system. My first successful attempt utilizing setting circles was to find the Dumbbell nebula; I was at a star party where everyone else's telescope was bigger than mine, but I made them all look through my scope to see the nebula. It was at that very moment I was hooked, and priorities began to change.

I mapped out the exact center of my back yard and sunk three round pavers, precisely leveled, and at the correct location for the tripod legs of the TAL (facing north). I then attempted to connect my 35mm camera to the eyepiece and try some astrophotography. Suddenly, precise polar alignment and accurate tracking became important issues. Not long after, I purchased a Meade 12" LX200 (spending a sum of money previously unfathomable for something other than a car). One night while attempting to place the OTA on the mount it fell and hit the ground. I thought I might vomit. Upon inspection, however, the only damage was a dent to the front metal lens cover (which, thankfully, I left on the scope). Without this cap the corrector plate would almost certainly have shattered. I vowed to build a permanent installation for the scope and never carry it in and out of the house again.

I decided on a roll-off roof design and started building a foundation. Then, one by one, framed walls went up. It was at this point that the president of the neighborhood homeowner's association casually strolled by and asked what I thought I was doing. He was apparently tipped off by neighbors who were frightened by a hideous large box I was building in my backyard, and which appeared to be permanent. The best time to think about looking at the rules of the homeowner's association is before, and not after, the construction of a permanent observatory in your backyard. In this case, there were two relevant clauses: 1) outbuildings must not be visible when looking directly from the front of the house, and 2) they must be finished in the same material and color as the house itself. Time to go to the front of the house and see if I can see the observatory… It would be no exaggeration to say that the observatory location met rule #1 by less than an inch (good thing I picked the exact center of the back yard). As far as the second requirement, I would have to learn how to apply stucco and architectural shingles. Stucco is the art of smearing wet sand on a vertical surface; in short, most of the stucco ended up on the ground, but I got through it. Shingles are devilishly complicated. You have to

Figure 1. My home-built mount (left) and its periodic error (right; curve #1). Specific adjustments to a set of orthogonal worm gear set screws that affix the worm gear to its shaft (see Fig. 2) allowed substantial improvements (curves #2-5) and were based upon introducing offsetting sine or cosine functions.



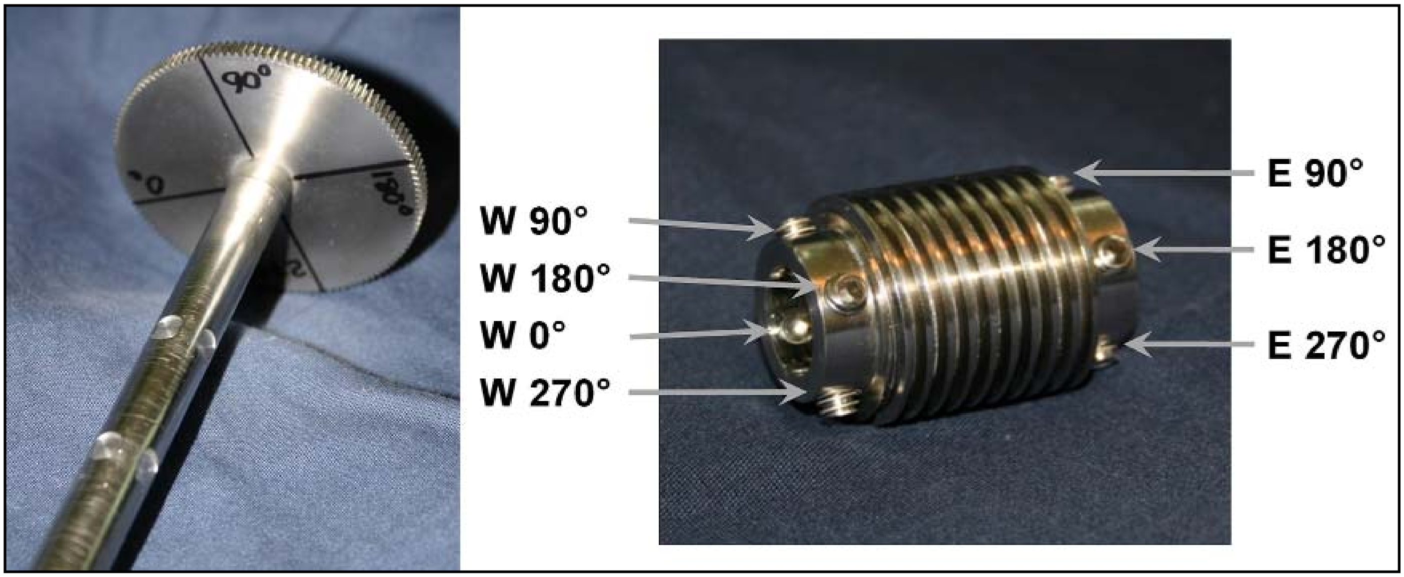


Figure 2. The mount's RA two-piece worm with orthogonal set screws that not only affix but also align the worm on its shaft (shown to the left). Each set screw has a unique identifier to enable appropriate corrections to the PE.

start at the bottom and work up. Like a lot of things, the end result was o.k. as long as you didn't get too close, or if the sun was not shining directly upon it. The neighbors complained that the observatory violated the window requirement rule. I was thinking of pointing out that when the roof rolled off it made a pretty big window; however, living in a hurricane zone I decided not to point out that the roof was not actually attached.

I moved my Meade into the observatory and lived happily for the better part of a year. Then I began to notice something that started to bother me more and more; namely, slightly oval stars. Of course, they were always there; it was a consequence of the periodic error of the Meade. But I just did not notice them when I started astrophotography; their appearance just sort of emerged as I began to perfect alignment and focusing and pursued long exposures. Given this situation I did what anyone would do; I completely disassembled the Meade mount, adjusted, tightened, re-greased, etc., and then trained the periodic error correction – averaging over a dozen worm periods. Alas, on long exposures the oval stars remained. I tried not to think about them; but failed. I then began to plot my next purchase – a mount with the precision necessary to yield round stars with long exposures.

I came to learn that, curiously, mounts (of the accuracy I needed) were more expensive than the telescope. Actually, too expensive (I could not bring myself to tell my wife how much they cost). I decided that the key component of an accurate mount was the RA gear, and perhaps I could assemble a mount with the necessary precision by only spending money on the things that mattered. I would omit a go-to system (since I was comfortable with setting circles). Having rationalized the purchase, I ordered a 9" RA gear (6" DEC gear) and a pillow-block type mount. The cost was significant, but not so great that I could not hide it from those who would be far happier not knowing.

The 8 week quote for delivery of the parts stretched to 5 months. Assembly involved another 4 months with an embarrassing sequence of partial assembly, followed by partial disassembly, correct reassembly, and then disassembly, and so on. However, after an agonizing amount of time, and a disturbing portion of the kid's college fund now missing, the magic moment arrived – first light with the new mount. I checked everything, focused and took a 5 minute exposure. Expectations and reality often don't coincide, and in this case, they missed each other by an astronomical distance. I had never seen such nasty oval stars in my entire life. The periodic error was at least twice what my Meade was. I went over the math in my head: $6,000 and about 9 months to build the observatory, another $4,000 and about 9 months to order and build the mount. Life took on a shade of gray.

I stayed away from my observatory for several weeks, thinking that a solution might present itself if I just gave it time. The only thing I could think to do was to disassemble and reassemble the mount and try again; unfortunately, it yielded the same result. While monitoring the periodic error (a whopping 50 arcseconds peak-to-peak; Fig. 1) I noticed that the maximum of the PE occurred at approximately the same time that the worm set screw passed the plane of the RA gear (my choice of where to note the start of the worm cycle). The worm was a two-piece type that was fixed to the worm shaft by a pair of set screws (one on each end of the worm gear and offset by 180°). I thought perhaps the worm gear was loose, and therefore torqued the set screws. The PE got worse; however, this gave me an idea. I loosened the set screws; and behold, the PE improved. I loosened the set screws as far as possible, and the PE improved further. I needed to adjust it still further, but could not. Motivated to improve things, I drilled and tapped another set of two set screws on the opposite side to the original two; and then proceeded to tighten those down while loosening the original two completely. I noticed that the initial PE was pretty much a large cosine wave, and the set screw adjustments I was making was removing this cosine function (or adding an inverse cosine function to the PE depending on how you looked at it). When I improved the PE as best I could with these adjustments the remaining PE no longer looked like a

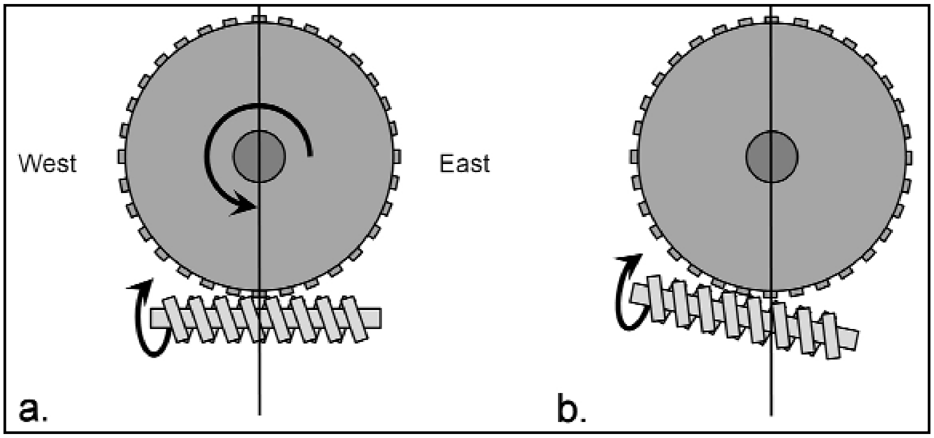


Figure 3. Fundamental mechanical elements of a worm gear utilized in a telescope's RA drive. Panel a: A rotating worm gear held in a fixed position causes the clock gear to rotate and compensate for the Earth's rotation (the RA axis is aligned to the celestial pole, which in the northern hemisphere points north with an altitude equal to the latitude). Panel b: the rotating worm will travel around a stationary clock gear if the worm is not held in a fixed position relative to the gear.

cosine function; rather, it looked like a comparatively small sine wave. It was not possible to remove a sine function with the set screws I had on the worm. So, I drilled and tapped a series of additional set screws at 90° (i.e. orthogonal) to the original set (see Fig. 1). Adjustments to these set screws permitted the introduction of sine (or inverse sine) functions into the PE.

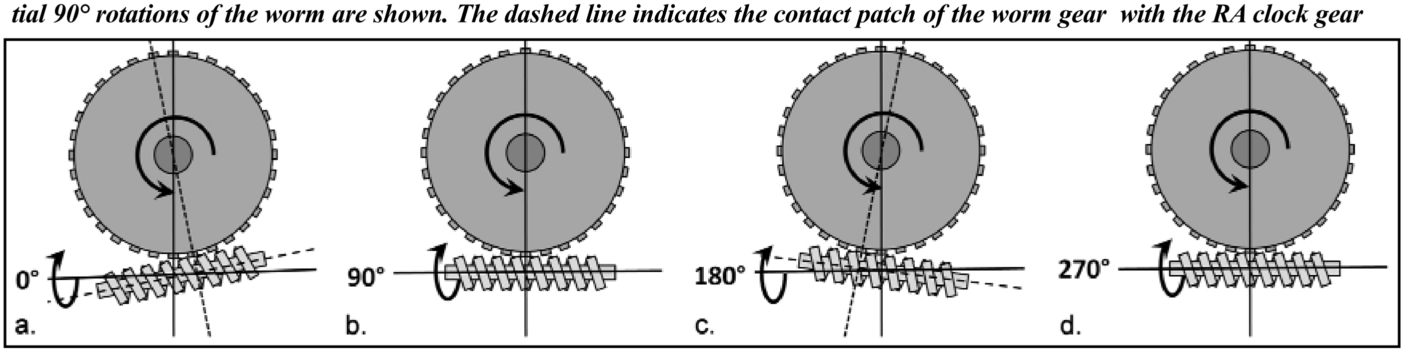
Misalignment of the worm axis relative to its rotational axis

Figure 3 provides the starting point for understanding the source of the PE. If the worm gear is not held in a fixed position when it is rotating, then the worm can travel around the circumference of the clock gear (and the clock gear remains stationary instead of being driven). This would be an extreme case, but provides a clear understanding that a slight movement of the worm around the perimeter will affect the rotational rate of the clock gear. In Figure 3 the movement of the worm around the clock gear results in a decrease in the clock gear speed.

Figure 4 shows a situation where the worm is fixed in relationship to the clock gear (so it cannot travel around the circumference) but is misaligned on its rotational axis. The reference point for the start of the "worm period" is 0° and at this angle in Figure 4 the misalignment is at its extreme (i.e. the misalignment is entirely in the 0°-180° plane of the worm rotational axis). In this example when the worm rotates to the 90° position there is no relative misalignment (i.e. there is no component of the worm misalignment in the 90°-270° plane of the worm rotational axis). Rotating another 90° (reaching the 180° mark) the misalignment is again at an extreme but in the opposite direction. Rotating the worm to the 270° position again introduces no misalignment. Another 90° rotation brings the worm position back to 0°.

In Fig. 4 note that although the worm is held in a fixed position relative to the RA clock gear its contact patch with the clock gear is moving back and forth along the circumference. Starting at 0° and moving to 180° (i.e. Figure 4, panels a-c) the relative movement of the worm's contact patch results in a relative decrease in the speed of the RA gear. Subsequently, moving from 180° to 360° (i.e. 0°) the relative movement of the worm contact patch results in an increase of the clock drive gear relative to normal (i.e. Figure 4, panels c-a). During the worm's rotation the correct RA clock gear speed is realized at the 90° and 270° position (where the worm contact patch with the RA is not affected by the worm misalignment). The effect of the worm's apparent motion in Figure 4 upon the RA clock gear speed is illustrated in Figure 5, and describes a cosine function. This function will repeat itself with each turn of the worm (i.e. each worm period) and describes a periodic error in tracking rate. If the worm period is assigned a different start/end point it is manifest as a phase shift of the above function. For example, if we choose 90° as the starting point of the worm period the effect upon the clock gear speed will look like an inverse sine function; if we choose 180° as the starting point the effect upon the clock gear speed will look like an inverse cosine; and if we choose 270° as the starting point it will look like a sine function. Conversely, if we keep the start of the worm period at 0° but have a misalignment along a different axis (e.g. the 90°-270° axis of the worm rotational axis) the periodic error will be a sine or inverse sine function (depending on the direction of the worm axis misalignment). Random misalignment can therefore be described by some combination of (inverse)sine/(inverse)cosine functions.

Figure 4. Effects of misalignment of the worm relative to its rotation axis. The misalignment in this example is exclusively in the 0°-180° plane of the worm's rotational axis (where 0° marks the start of the worm period). Effects of this misalignment for sequential 90° rotations of the worm are shown. The dashed line indicates the contact patch of the worm gear with the RA clock gear



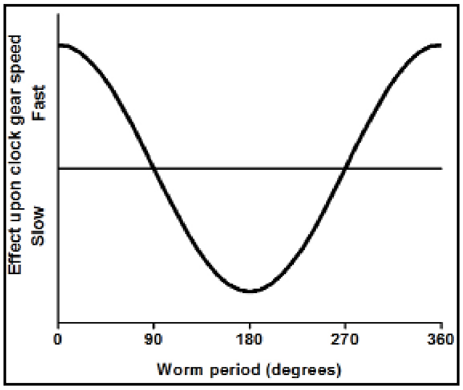


Figure 5. The effect of the worm misalignment in Figure 4 upon the clock gear speed. The horizontal line represents the nominal clock gear speed.

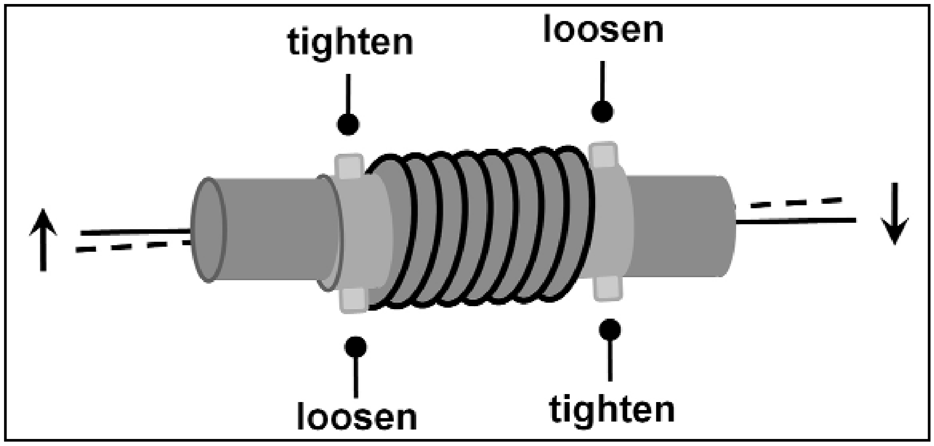


Figure 6. Set screws on a two-piece worm permit adjustment to align the worm on its shaft. In this figure the adjustments would correct for the misalignment corresponding to that shown in Fig. 2a.

For a two-piece worm the set screws can be utilized to align the axis of the worm along its rotational axis. In Figure 6 the worm shaft rotation axis is indicated by the solid line and a misalignment of the worm gear on its shaft is indicated by the broken line. Correct alignment can be achieved by adjusting the set screws as indicated. The misalignment in this case is conveniently in the plane defined by the set screws (and so their adjustment is able to completely correct the misalignment). If the worm misalignment is orthogonal (i.e. coming out of the plane of the page) these set screws could not correct it; however, a second group of orthogonal set screws would enable correction of this orthogonal misalignment.

As explained above, misalignment of the worm relative to its rotational axis is expected to result in some combination of (inverse)sine, (inverse)cosine functions as regards clock gear deviations from nominal speed (i.e. PE). Conversely, such PE can be eliminated by appropriate adjustment of orthogonal set screws (i.e. via the introduction of offsetting functions). Thus, if the observed PE is a sine function, the set screws are adjusted to input an inverse sine function, etc. The effects of the set screw adjustments upon the PE would look like the functions shown in Figure 7.

Correcting the alignment of my mount's RA worm on its axis proceeded by characterizing the PE and identifying the appropriate offset function to be introduced by the set screw adjustments. The initial periodic error (Figure 1, curve #1) looked a lot like a cosine function, and so adjustments to introduce an inverse cosine function (i.e. the orthogonal set screw adjustments shown in Figure 7c) were performed and resulted in reduction of the PE to approximately 30 arc seconds peak-to-peak (Figure 1, curve#2). The new PE after this adjustment looked intermediate between a sine and cosine function, so the prior (inverse cosine) adjustment was increased further. The result (Figure 1, curve #3) did not substantially reduce the PE, but the new PE function was now a well-defined sine wave. Set screw adjustments described in Figure 7d were performed to introduce an inverse sine function and resulted in reduction of the PE to approximately 20 arc seconds peak-to-peak (Figure 1, curve #4). The new PE still looked somewhat like a sine function, so the prior adjustment was increased and resulted in reduction of the PE to approximately 8 arc seconds peak-to-peak (Figure 1, curve #5). While the remaining PE might be removed by addition of a sine function, the adjustments to the set screws are so slight at this point that it is difficult to introduce such a small correction without over-correcting. The results, however, are clear – the majority of the PE in the mount was due to worm gear misalignment on its rotational axis, the RA clock gear itself is reassuringly precise. Furthermore, the resulting PE of ± 4 arc seconds (with no electronic PE correction) is on par with mounts costing in excess of $5,000. Tapping orthogonal set screws allow you to precisely align the RA worm, and thereby eliminate a substantial contributor to the PE; in doing so, the full accuracy of the main clock gear can be realized. This, in turn, permits nice round images of stars.

Figure 7. Effects upon RA clock drive speed with the indicated orthogonal set screw adjustments (referencing Figures 2 and 6).