Tap The Sun

The SolarTrak®
Controller System

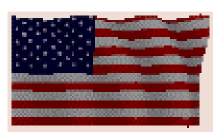
Pro-Active Sun Tracking and Peripheral System Control

Author

Timothy M. Leonard

Enhancement Electronics, Inc.
#10 Camino del Senador
Tijeras, NM 87059-7631 U.S.A.
Voice: (505) 281-0399
Fax: (505) 281-4248

www.tapthesun.com



Designed and Built in the U.S.A.

Fabrication and installation issues that affect tracking precision of mathematically-based control systems

Abstract

Mathematically-based digital microcontroller tracking technology utilizes multiple geometric reference frames related by equations of motion or by specific orientation. All reference frames involved must be adjusted to coincide with each other or conform to a known equation of motion for the mathematical approach to work.

During the fabrication and installation stages, this conformation is established through adjustment and/or measurement to produce calibrated equations for the tracking computations that will be used for motion control such that they remain valid year-round over the long term. Failing to accomplish that task will induce periodic tracking errors that will preclude the ultimate goal of continuous, uninterrupted sunlight on the receiver.

When systems are installed in large numbers, such as for solar fields, commercial office space or retail merchant applications, it is necessary to fabricate the collection device in such a way that the final mathematical calibration, which requires complex and time-consuming measurements, can be minimized or, ideally, eliminated altogether.

Some designs and fabrication methods can actually preclude proper tracking in extreme latitudes such as the tropical or arctic regions, due to mechanical range-of-motion limitations, regardless of the calibration method employed.

This document delineates the potential problems that can exist and suggests methodology for minimizing the complexity of the final field installation process.

Definition of Terms and Concepts

The following several sections define the geometric reference frames involved and terminology. The potential problems that can arise follow after that.

There are two facets to the successful implementation of the mathematical approach provided that turning motors or valves on and off is not perceived as a major issue:

- Accurate computation of the Earth's orientation with respect to the Sun and
- Accurate knowledge of the mechanical positioner's orientation with respect to the Earth.

The latter of these can be quite complex if not accounted for during the design and fabrication stages of manufacturing. Geometric asymmetry or misalignment and structural deformation contrive to make the actual position of a moving mechanical device within its range of motion hard to predict from computations made based on digital electronic feedback measurement. Looseness in any of the moving parts, especially in the position sensing components, would, quite simply, preclude proper operation by inducing a state of non-repeatability.

In a mathematically-based control system it is absolutely essential that the reported position be exactly the same each time the unit passes through any specific three-dimensional orientation with respect to the Earth.

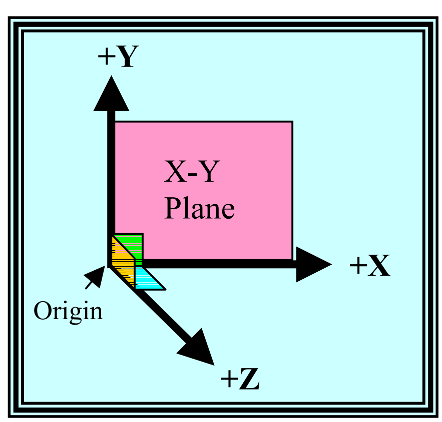
To place this process (the need for post-manufacturing adjustment) in relatively commonplace perspective, it should be considered similar to the first wheel alignment on a car after initial assembly or the first engine tune-up, neither of which can be done correctly without the right tools and neither of which can be accommodated in the manufacturing process in such a way as to not need the customary adjustment mechanisms of trim-screws and threaded tie-rod ends. To further the analogy, the structural system of the car, though stiff in the frame, relies on the mechanical characteristics of both the shock absorbers and springs to be within an acceptable range to keep the wheels in a known, relative position while at rest or while moving along on a smooth road. If either should begin to fail, the alignment performed will no longer hold and must be redone after replacing the failed parts in order to prevent wear and tear on the various affected systems such as tires, brakes, bearings and even the road surface.

Though different in effect, the misalignment of the solar collector system and the misalignment of the automobile wheels or invalid motion equations of the tracker and poor electronic timing adjustments on the engine cause the same end result; loss of efficiency of the working components and/or increased maintenance, both of which cost money either in losses or added expense.

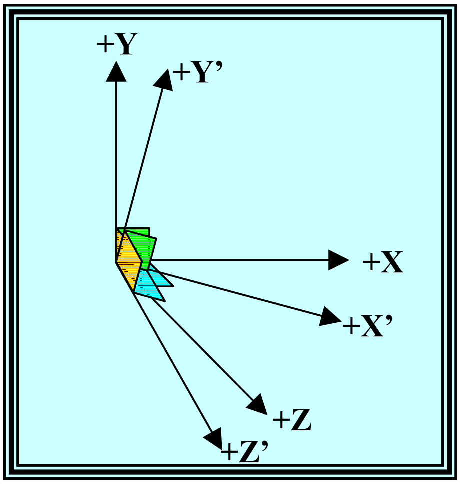
Reference Frames

A reference frame can be associated with any physical body moving or at rest and is composed of three orthogonal (mutually perpendicular) axes (pronounced: ax'-ease) of reference (three-dimensional space). There are a total of six degrees (types or directions) of freedom of motion with those being the three discrete directions of translation (motion without rotation) and rotations about each of the three axes. These three axes are the references for the local coordinate system used for measurement of translation or rotation with respect to the place where the three axes meet in space, known as the **origin**. The three axes are generally labeled X, Y and Z and rotations about each of the axes follow what is conventionally known as the “Right-hand Rule” where, using the right hand with the thumb extended and with fingers together and bent slightly, the thumb represents the positive direction of an axis and the fingers represent a positive rotation about that axis. A further convention is that a positive rotation about the X-axis rotates from the Y-axis towards the Z-axis, rotations about the Y-axis go from the Z-axis towards the X-axis and those about Z rotate from X towards Y such that the following labels apply and the square or parallelogram constructs indicate a right angle:

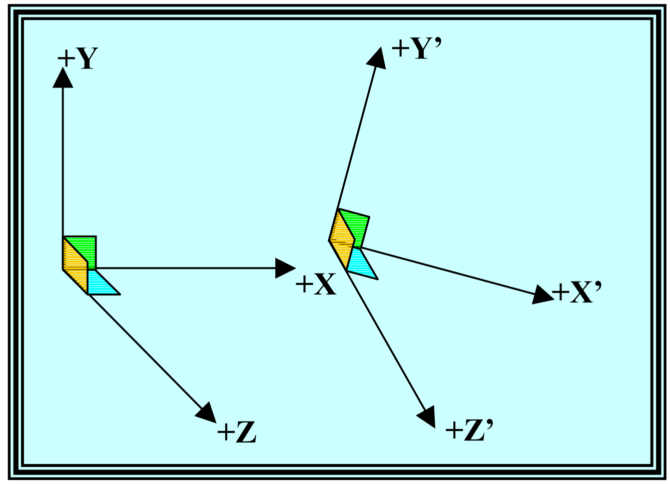
Orthogonal Reference Frame



Multiple Reference Frames

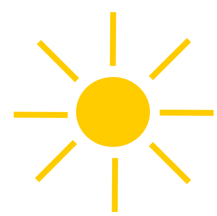


Coincident Reference Frames with Relative Rotation

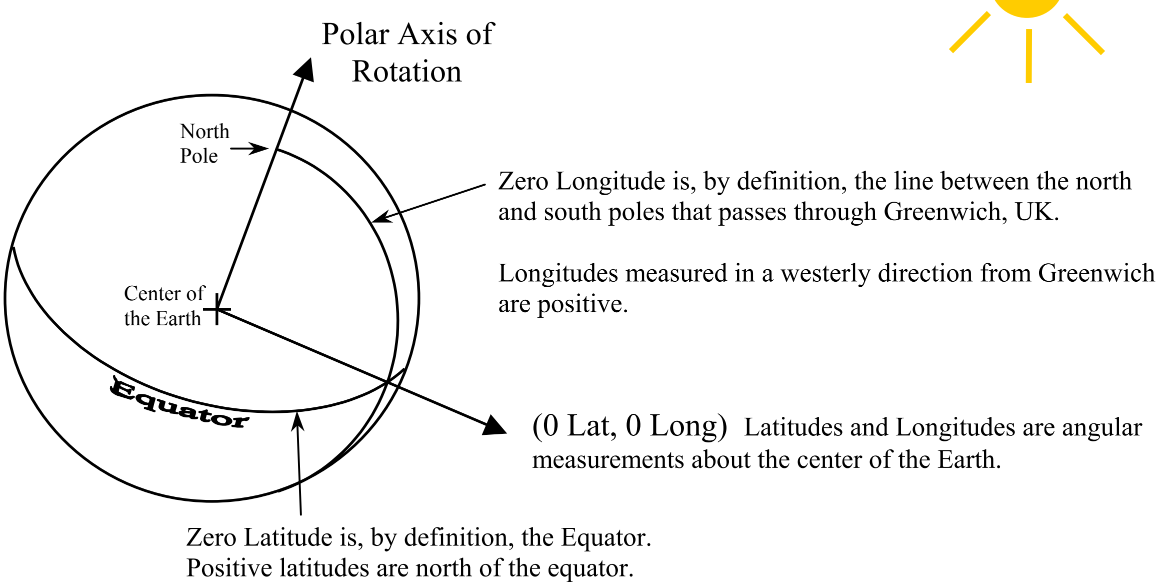


Non-Coincident Reference Frames with Relative Rotation

The above illustrations show both coincident and non-coincident reference frames with relative rotation. 'Coincident' means that the origins are either actually or effectively (mathematically) the same.



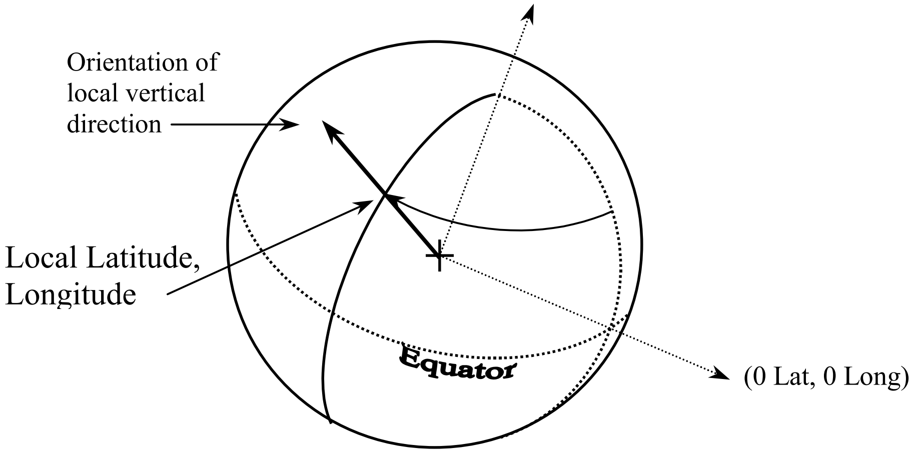
Tracking Control Reference Frames



Mathematical tracking control is based on high-precision equations that characterize the relative motion of the Earth with respect to the Sun. The Sun itself is moving through the Milky Way galaxy at some 18,000 miles per second but other than our orbit around the Sun we are effectively moving with it in the same reference frame such that the Sun defines the origin and we move around it.

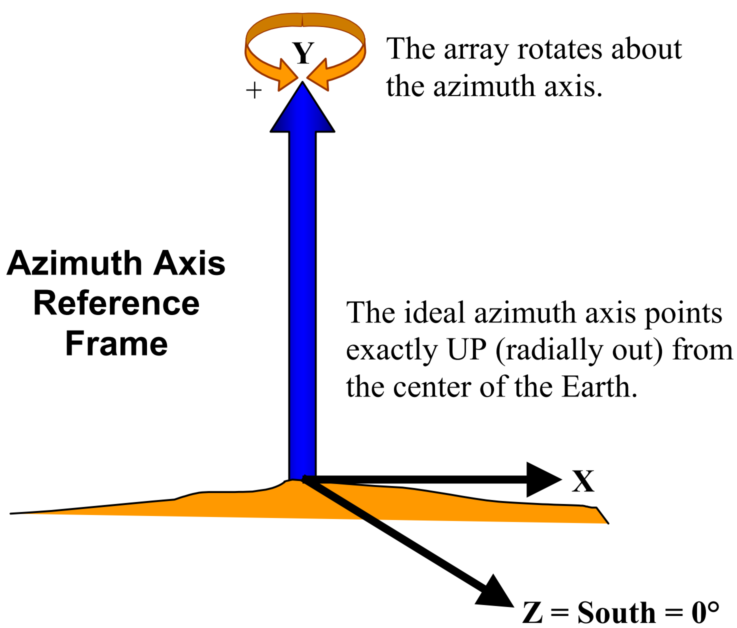
Primary Tracking Reference Frame (Axis 1)

The first stage in locating the tracker is to define the actual latitude and longitude of the installation.



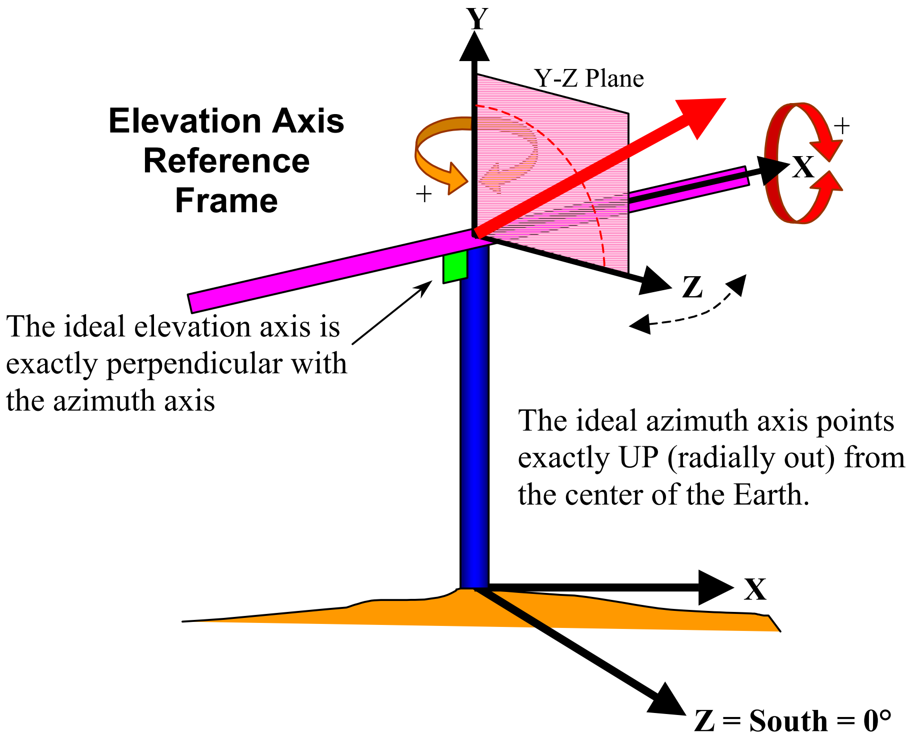
Azimuth – Elevation Geometric Configuration

There are four basic geometries used for tracking, all share the characteristic of having the primary axis fixed in its orientation to the Earth. The Azimuth – Elevation configuration is the easiest to visualize because it has the same basic orientation as a human being and will serve well for the purpose of this discussion.



The azimuth axis is attached to the Earth and will be designated as the Y-axis of the primary reference frame. The Z-axis will be defined as being oriented to point due South in the northern hemisphere and represents an azimuth angle of zero degrees. These definitions will play a role in discussion further on relating to direction of misalignment errors.

Secondary Tracking Reference Frame (Axis 2)



The Y-axes of the primary and secondary reference frames must remain coincident and aligned (zero rotation of both the secondary X-axis and Z-axis). Relative rotation of the two Y-Axes is identically the azimuth angle. The secondary Z-axis will always point at the horizon (zero elevation) and the Y-axis always points straight up (zero zenith = 90° elevation).

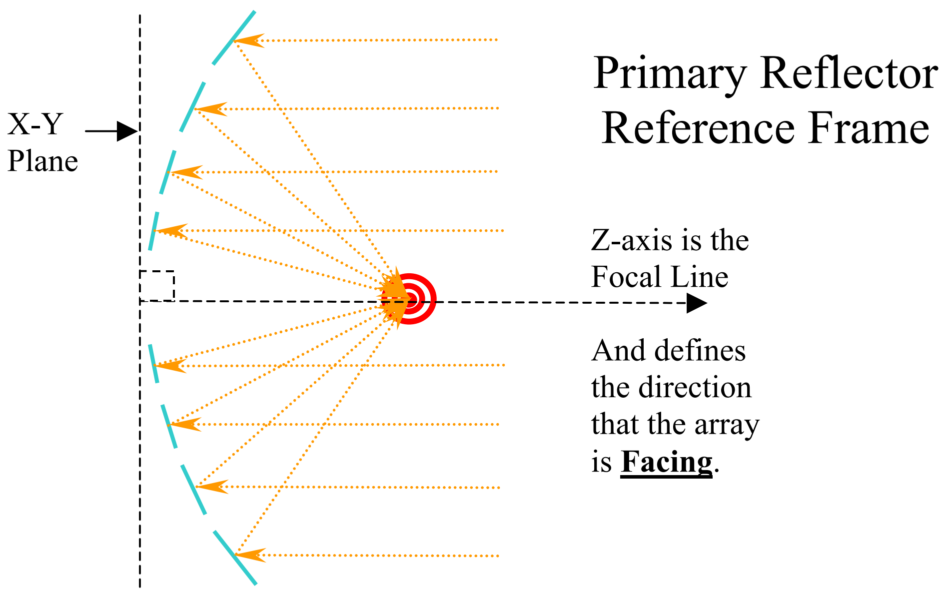
The elevation position is depicted as a moving directional vector (red arrow) that remains in the Y-Z Plane of the elevation axis reference frame as it rotates through the azimuth range of motion. Depending on the context, this directional vector is what is being referred to by the phrases ‘pointing at’, ‘array is facing’ or ‘tracking surface’. In each case the receiver aperture (the opening or surface which absorbs or reflects the sunlight) is actually perpendicular or **normal** to this vector. If the sunlight rays are parallel to this vector it is said to be **direct-normal insolation**. Insolation is a word for the energy received from the Sun. Any amount of angle off of this vector is called the **angle of incidence**. A non-zero angle of incidence reduces the amount of energy absorbed by the receiver, known as losses and commonly referred to as ‘cosine losses’ because they follow the cosine of the angle of incidence.

Tracking Pointer Reference Frame

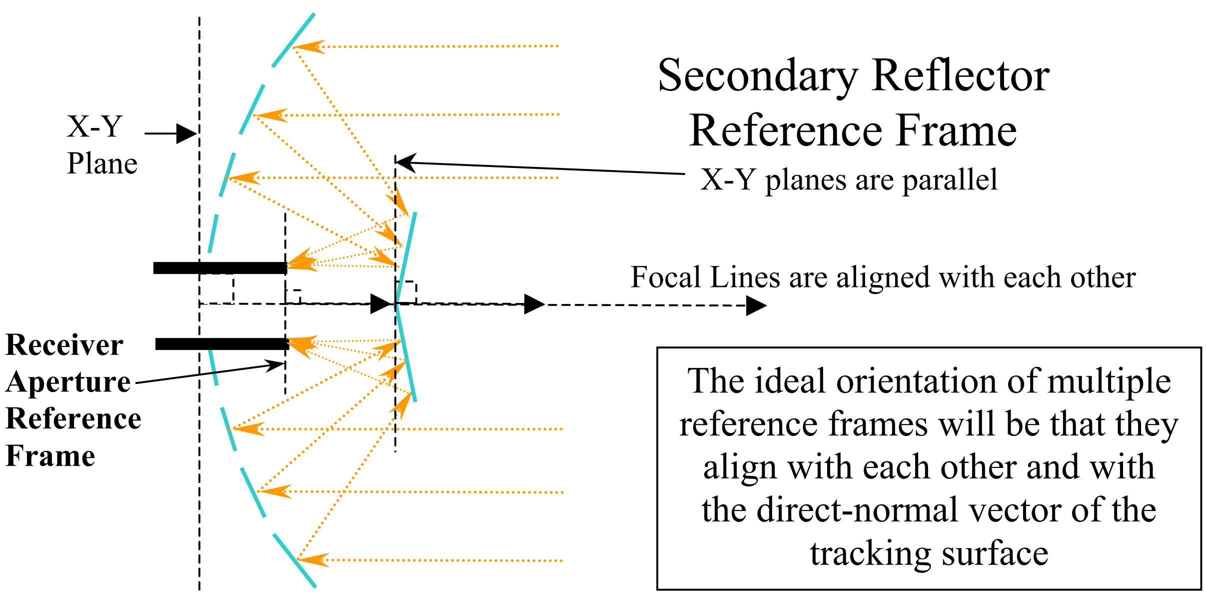
The tracking pointer used for establishing and calibrating proper tracking operation must coincide exactly with (be parallel to) the direct-normal vector and must remain fixed to the <u>mathematical</u> tracking surface (which is defined by the elevation axis of rotation) independent of any adjustments to the receiver assembly.

Receiver/Collector Reference Frames

In the following discussion of sun rays and their reflections, it may be assumed that when two otherwise independent reference frames are struck by parallel or nearly parallel (columnar) rays as are emitted by the Sun, they may be assumed, for strictly mathematical purposes, to be effectively coincident. When non-parallel rays are involved that assumption is invalid.



The primary reflector reference frame is but one of several that must work in mathematical concert with each other.



Secondary Reference Frame shown effectively coincident with
Primary Reference Frame at zero relative rotation

Discussion of Non-Geometric Problems

Backlash

As mentioned before, in a mathematically-based control system it is absolutely essential that the reported position be exactly the same each time the unit passes through any specific three-dimensional orientation with respect to the Earth and that must include motion from any direction.

As one might assume from the previous discussion, most of the problems that can arise in the successful implementation of this type of controller are rooted in geometric inconsistencies or non-linearities that produce non-quantifiable motion but there is still the issue of non-repeatable position sensing due to inconsistencies or non-linearities in the feedback pulse generation system.

Backlash is a term liberally used to indicate looseness in gear or chain drive trains where one end of the train can move without moving the other. There are, in this mathematical context, two types of backlash:

1. Looseness in the geardrive where motion can occur in the gear train without producing motion at the axis of rotation or where motion can occur at the axis of rotation without back-driving the gear train.

2. Looseness such that pulses are generated without motion at the axis of rotation and motion at the axis of rotation that does not result in the generation of pulses.

It is the primary goal in the design and installation of a feedback pulse generator to preclude the possibility of the second form of backlash. It is generally neither possible nor wise (due to required mechanical tolerances) to preclude the first.

When installing an electronic feedback pulse generator onto a mechanical device, there is often the temptation to place the unit in the most convenient (spelled cheapest or easiest) position, rather than the most functional, although when retrofitting a feedback device to a mechanism not designed for it, there may actually be some attachment point limitations. Any unnecessary savings in this area will come back to haunt you in the long run and should be avoided.

A popular type of feedback pulse generation consists of a rotating magnet and a magnetic reed switch or Hall-effect sensor or else an optical interruptor setup like an LED/Photodetector pair mounted on a gear or a more sophisticated optical encoder device. The rotating part can be placed in a variety of positions in the drivetrain of the mechanism depending on accessible points and the resolution of angular motion sensing that is required.

Keeping in mind that the actual piece of information that this feedback device is supposed to provide is the angular position at the axis of rotation, the farther from that axis the device is located, the more error that can build up between the actual position of the array and the current number of feedback pulses (counts) that have been reported.

The ideal location of such a device, provided it has a high enough resolution, is precisely on the axis of rotation. Barring that option, the closer the better.

It is possible to allow the appropriate mechanical tolerances without sacrificing the position reportability such that there can be wavering around in the position of the array due to looseness but the controller knows exactly where the array is at any given moment. Still, there are some very important reasons to limit the mechanical looseness as much as possible.

Mechanical backlash is considered an ‘un-damped’ motion. Forces such as friction or fluid viscosity produce damping. Either may be present to some degree in a mechanical gear train but are usually low compared to external forces when the effect is great enough to be considered backlash. ‘Un-damped’ motion is when something can move essentially without resistance until it hits something. Once it hits, it will bounce freely back the way it came.

It is an implicit fact that these solar arrays are installed outside where they will be exposed to wind. Although we may often think of wind as a fairly steady force given that when we walk through it there does not seem to be much fluctuation, its effect on a solar array with very much backlash in the mechanical system can approximate a slow motion version of the flutter seen in window shades when the wind is blowing hard through them.

There are then two potential problems with mechanical backlash even when the controller has accurate position data:

1. A resonance can occur with such intensity that the array shakes itself apart.

2. The controller senses the change in position and tries to compensate but only chases the problem rather than successfully correcting it due to the time lag in sensor reporting and controller reaction.

A mitigating mechanical factor in the character of backlash is that there is often a ‘favorite spot’ or ‘resting point’ that the mechanism will settle in when not under external or motivational forces. This spot is, more often than not, the effect of mechanical wear, relative deformation or gravity. Although potentially predictable it is possible, if not probable, that a lack of due concern for this phenomenon will cause problems when trying to minimize or calibrate out errors.

Gravity Effects

Gravity plays a distinct role in all of this as well. The elevation axis of an azimuth-elevation system geometry is often designed such that the weight distribution, on the tower as well as the drive components, changes as the elevation angle changes. Such a circumstance is actually quite difficult to avoid.

There are two significant effects that gravity can have on the actual orientation of an array during normal operation through the full range of motion:

1. As the array crosses the weight balance point, the drive train ‘resting point’ will shift from one end of the backlash to the other.

2. The structure deforms (bends) under the sheer weight according to the current distribution and coupled effects of all involved support sections.

Although the first of these two can be counteracted with a final stage (axis of rotation) encoder, the latter affects the structure in a very non-linear fashion and requires a substantially complex formula to characterize the effect on the orientation of the array at any given moment especially since the effect may occur both in the primary tower and any additional cantilever-style support mechanisms which may very well have radically different section properties.

If the forces applied to the mass of the array are not properly centered to maintain balance where possible, the array can twist in a non-linear fashion that produces coupled errors in both elevation and azimuth.

Deformation and Resonance due to High Weight to Stiffness Ratio

Even without un-damped motion, the mechanical response of a springy structure (all structures are springy or more precisely, elastic) can be one of repetitive oscillation which could be referred to as the 'stop sign effect' where a steady wind on a stop sign produces 'back and forth' motion at a frequency depending both upon the speed of the wind and the stiffness of the sign post. This type motion is called a resonance and has the potential to occur any time an elastic structure is subjected to a dynamic force.

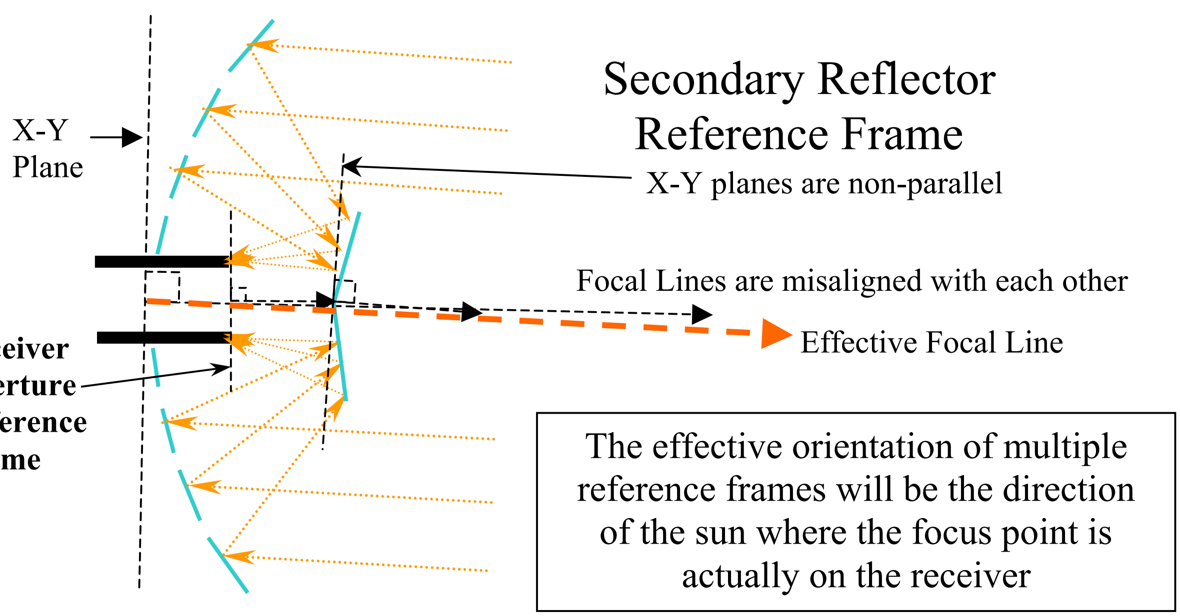
When the weight of an array exceeds some critical level such that the stiffness of the structural system is low by comparison, it is possible to have destructive resonance without any undamped motion such as backlash. The wind forces will drive a system at somewhat low frequencies and if the weight to stiffness ratio climbs too high, the resonant frequency of the system will potentially drop into the range of the forcing function, which is where large deformations due to resonance come from.

Such resonance and large deformations can cause permanent deformations when the stresses in the structural system extend into the 'plastic' range due to momentary stress peaks. Such deformations will cause geometric changes that affect tracking accuracy.

Geometric Misalignment Issues

Non-Orthogonality

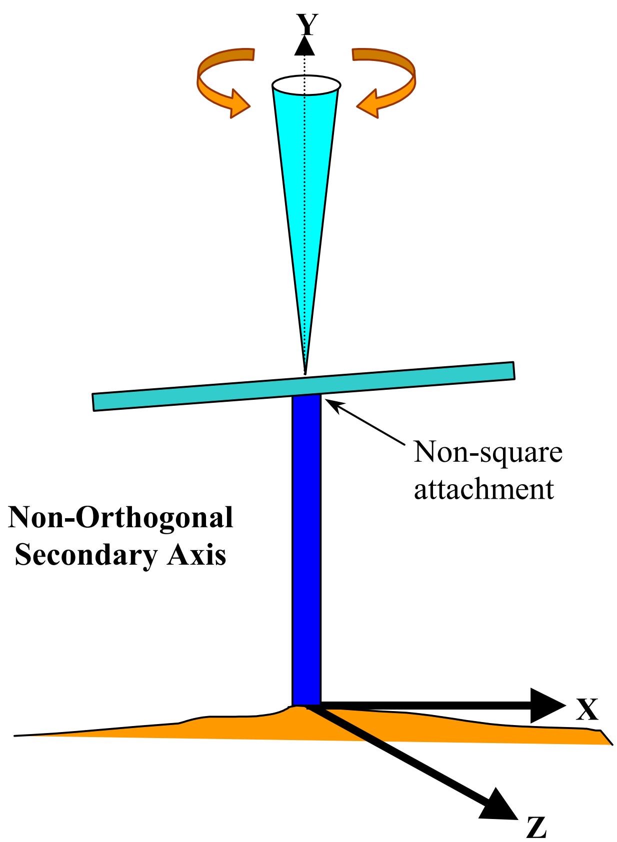
The fastest way to permanently preclude long-term accuracy is to fabricate welded assemblies out of square. Any assembly that cannot be jigged to a perfectly square configuration should be provided with adjustment screws, bolts or shims to allow alignment after the fact. There are some exceptions where several non-orthogonalities can counteract each other but they are only <u>within</u> the receiver assembly. Ultimately the resultant focal line of the receiver must be properly aligned with the tracking mechanism's direct-normal vector. There is one misalignment, the main tower with the Earth, that can be readily measured, quantified and corrected but all others must be adjusted out. It is certainly an option to include more and more error correction equations but the calibration process becomes one of trial and error (pun unavoidable) such that the more units installed, the longer it will take without the hope of a finite installation process or fixed time.



Secondary Reference Frame shown with effective focal line

Secondary Axis Misalignment

The secondary axis of rotation must be perpendicular to the primary. If it is not, there is a cone of mechanically unreachable sky, axially centered on the primary axis of rotation directly above the tracker, which has a spread of twice the misalignment angle. In addition to being unreachable, this misalignment induces an error that follows a complex function not supported by the SolarTrak error correction routines. If the tracker is installed at a latitude within the tropics, there will be times of day that the tracker cannot be made to face the Sun directly due to the mechanical limitations and because of that fact, there is no justification to add such support. The logical remedy is to build the connection properly.



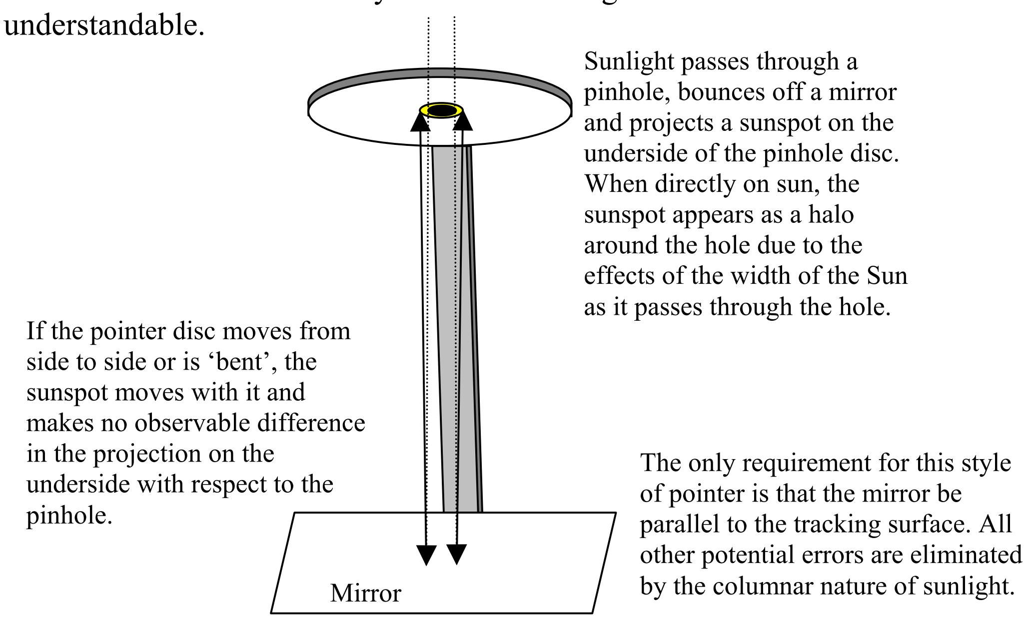
Receiver Assembly Misalignment or 'Bent Pointer'

Once the secondary axis has been verified true, the receiver assembly must be aligned with it. The concept of a 'bent pointer' actually refers to any focal line that is not perpendicular to the secondary axis. Even though the secondary axis may be properly perpendicular to the primary, using a non-perpendicular focal line to point at, and therefore set the reference to, the Sun, will result in the SolarTrak controller having a wrong impression of where South and Vertical are, which will cause imprecise computation of the necessary position that points directly at the Sun.

To avoid the pitfalls of such a circumstance, a stepwise procedure, involving a more dependable pointer device is the established method of coordinating all of the reference frames that must be aligned with each other.

The first step was to fabricate the primary and secondary axes to prevent non-orthogonality. The moving part of the array which rotates horizontally on the primary axis and vertically on the secondary axis must now be fitted with a pointer device to use as a reference for establishing the proper Sun reference offset values (offset from one end of each range of motion) and for subsequent measurement and calibration of the tower tilt misalignment if that is necessary.

The use of a reflector-based pointer where the reflector (a small mirror) can be mounted to a surface known to be parallel with the secondary axis precludes the possibility of a 'bent pointer' because it is based solely on the relative angle of the Sun and cannot show 'on-sun' unless it really is. The following illustration will make this a little more understandable.



With this pointer style implemented, the tracker can be configured and calibrated even before connecting the receiver assembly. This pointer is the tracking reference, not the receiver, and the Sun itself will be used to align the receiver without complex ray-generating equipment. This method also does not require that the primary tower be exactly vertical because it is using the Sun as its reference. An alternate method described below is also acceptable when the system is sufficiently stiff structurally.

Steps for Final Adjustment and Calibration

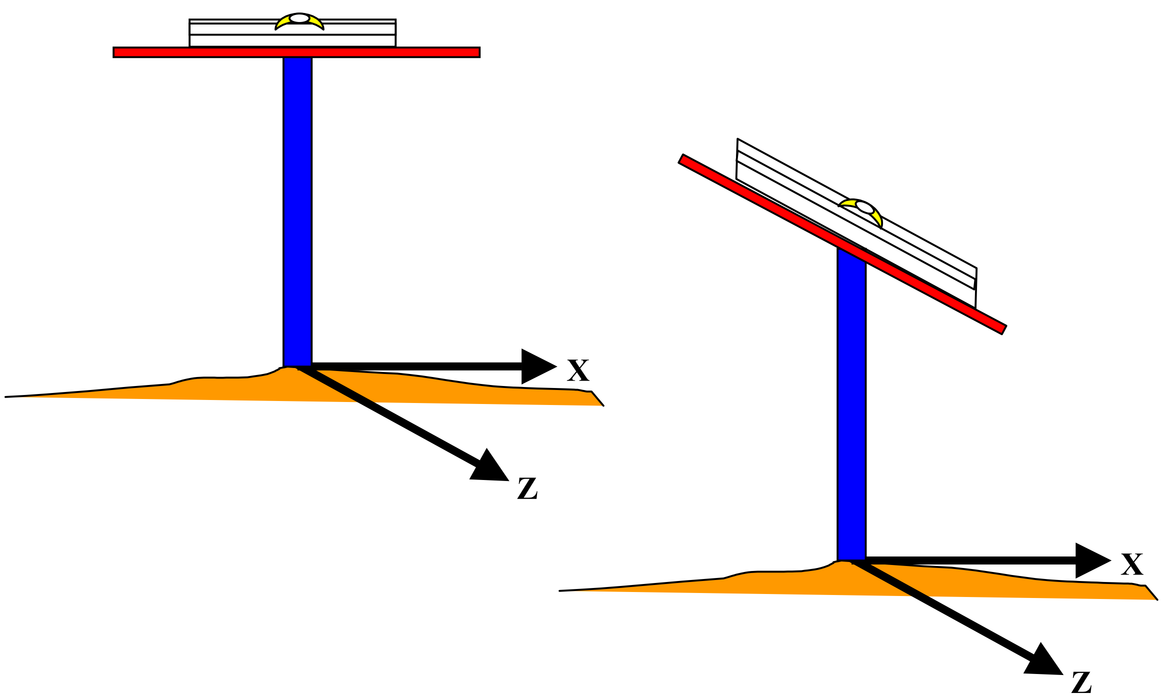
Use of a Leveling Instrument for Mechanical Alignment

It may seem that the quickest way to align everything together is to use a leveling device and that is true as long as the entire system is leveled from the ground up with each successive component adjusted in the correct order. Although the SolarTrak software can incorporate an error function to correct a tower misalignment (tilt), if a level is to be used to align the rest of the system, the tower tilt must actually be corrected first, physically, not mathematically. If the tower (or actually the azimuth axis of rotation) remains physically tilted, all subsequent leveling operations will be mathematically tilted by the same amount, which, although a different way to achieve non-orthogonality, is just as wrong.

Use of this method is actually recommended since it will (if properly done) preclude the need for performing the final calibration step.

Steps to level system:

1. Orient secondary axis parallel to the established X-direction and adjust to level.
2. Orient to the Z-direction (90° - rotation about Y-axis) and level again.
3. Repeat steps 1 & 2 until no adjustment is necessary.
4. Attach and/or check mounting surface used for mirror of reflective pointer in both directions to verify level with secondary and primary axes.
5. All other adjustments should be made while reference pointer is on-sun and the unit is tracking.



Working with Backlash

When operating the tracking unit some care should be taken to minimize the effect of the backlash by taking measurements or setting reference points only after the mechanism has found its ‘resting point’ that it would find under standard tracking conditions. In general, moving the array with the joystick can produce non-standard motions that would not take place if the array was under automated control and the ‘resting point’ is only achieved after the array moves on its own a few times.

The SolarTrak controller uses a reference point that presumably never changes to orient itself. If the backlash in a system is such that the reference point is established a quarter degree off of its intended position, the controller will produce equations that mimic proper tracking at a different latitude and longitude. Some care must be taken to establish a reference point that works.

Conclusions

It is possible to mathematically correct any mechanical misalignments in a digital tracking control system provided that:

1. Accurate data can be collected to quantify the tracking error throughout the year.

2. Error equations exist in the tracking computation algorithm that can accurately characterize all types of mechanical contributions to the error.

3. The range-of-motion limitations do not come in to play.

Presuming the desired result of costly design and development research is to minimize the overall costs of production units including, but not limited to, quick and simple installation using reasonably-priced labor and extended periods of accurate, uninterrupted operation, the preferred method of production will be a combination of accurate manufacturing procedures and the ability to pre-calibrate the finished units prior to final shipment.

Dependence on an on-site labor pool capable of taking scientific measurements and performing visual data analysis will likely result in an ultimate failure in long-term successful operation.

Balanced, low-stress designs that are squat in stature and kept out of strong winds will perform better and be easier to calibrate both mechanically and mathematically. Systems that can be shipped already assembled, ready to attach to the final mounting point without field assembly will be more likely to work sooner and better after final installation. Bigger will not likely be better in precision tracking systems.