DFM Engineering, Inc.
1035 Delaware Avenue, Unit D
Longmont, Colorado 80501
Phone: 303-678-8143
Fax: 303-772-9411
Web: www.dfmengineering.com

SATELLITE TRACKING TELESCOPES

Tracking artificial satellites places particular demands upon a telescope. This article investigates the configuration, mechanical, and servo drive considerations.

Mount Configurations:
Two axes of rotation are required to track an object across the sky. If the two axes are orthogonal, then the tracking is simplified. There are basically three configurations of tracking mounts: The Altitude over Azimuth (Alt-Az), The Altitude over Altitude (Alt-Alt), and the equatorial configuration.

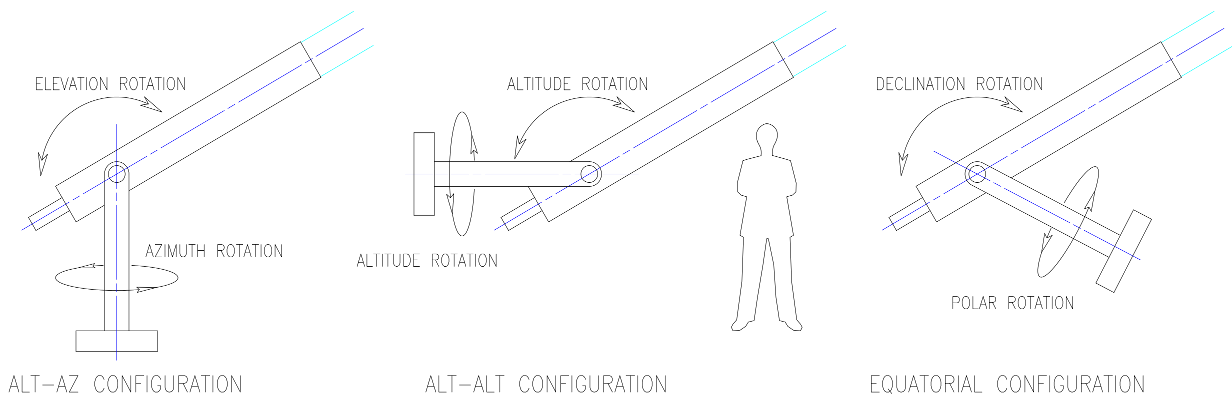

Figure 1 Alt-Az, Alt-Alt, and Equatorial Mount Configurations

Essentially, all three configurations are identical. Only the orientation of the first axis (the rotational axis closest to the ground) is rotated in space. The Alt-Az mount places the first axis perpendicular to the Earth's surface. The Alt-Alt mount places the first axis parallel to the Earth's local surface. The equatorial mount places the first axis at a particular angle to the Earth where the angle is equal to the latitude of the telescope site and at an azimuth rotation so this axis is parallel to the Earth's rotational axis (pointed to Celestial North).

The equatorial configuration allows tracking stars by rotating in a single axis-the axis closest to the Earth's surface. The other configurations require simultaneous tracking in two axes plus there is field rotation requiring a third axis of tracking where the camera is rotated about the optical axis.

There is some additional discussion of mount configurations located on our web site at:
http://www.dfmengineering.com/optical_config_summary.html

This article also defines the names of the various axes of rotation, for example, Az axis and Altitude axis for the Alt-Az; Major axis and Minor axis for the Alt-Alt, Polar axis and Declination axis for the equatorial mount.

Instrumental Pole:
The telescope mount configurations have what is called an "Instrumental Pole". This is the point in space that the first axis rotates about. From Figure 1, one can see that the instrumental pole for

the Alt-Az is located at the zenith. For the Alt-Alt the instrumental pole is located at the horizon, and for the equatorial mount, the instrumental pole is located at an angle to the horizon equal to the site latitude and in azimuth oriented to celestial north (or celestial south for the southern hemisphere).

The telescope mount cannot track an object that passes through the instrumental pole because the rotational velocity becomes infinite. In practice, the area around the instrumental pole that does not allow tracking can be made to be a degree or so depending upon the velocity and acceleration capabilities of the telescope mount and the velocity of the object.

When we track a satellite or a celestial object from the Earth's surface we are looking through a lot of atmospheric optical turbulence (Seeing). When looking near the horizon, we see slantwise through the atmosphere increasing the air mass of the atmosphere to values exceeding 3 times the air mass when looking at the zenith. The atmosphere also has differential refraction where red and blue light is bent (refracted) in different amounts further blurring the image. The differential refraction can be corrected by inserting prisms. The seeing can be partially corrected by adaptive optics, however, adaptive optics can only correct a very narrow Field Of View (FOV) and the cost is very high.

So the best part of the sky to observe an object is at the zenith which is where the Alt-Az mount has its instrumental pole. The Alt-Alt mount has its instrumental pole at the horizon where the imaging conditions are the poorest. The equatorial mount has its instrumental pole somewhere between the horizon and the zenith so is a compromise. The equatorial mount tracks stars nicely which has some distinct advantages for pointing model calibrations using star positions and for tracking some categories of space debris.

The best configuration for tracking artificial satellites is the Alt-Alt. The equatorial configuration is a compromise and the Alt-Az configuration can't use the best part of the sky.

Mechanical Considerations:
When a telescope is tracking a satellite, the tracking rates in both axes are constantly changing. The telescope dynamic response is very important. The dynamic response can be described as the time required for the telescope to respond to a change in position or velocity and the fidelity of the tracking (i.e. how well does the telescope follow the commanded trajectory of the satellite). In order to accurately track a satellite, the telescope needs to have a high resonant frequency. The natural resonant frequency of a simple spring mass lightly damped system can be expressed as: $\Omega = \sqrt{K/J}$ Where J is the polar moment of inertia and K is the stiffness of the spring. From this we can see that the polar moment of inertia wants to be small and the stiffness wants to be high.

The polar moment of inertia is the rotational equivalent of an objects mass in translational motions. It is formed by summing the mass of each element times its radius from the axis of rotation squared:
$J \approx \sum m\, r^2$ or $J = \int m\, r^2$ Where m is the mass of each element and r is the distance from the center of mass of the element to the rotational axis.

In order to minimize the polar moment of inertia, the telescope wants to have minimum mass and wants to have the various masses located as close as possible to the rotational axes. This speaks for a symmetrical mount such as a fork mount or a yoke mount and argues against an off axis mount such as the German Equatorial Mount (GEM) or the English off axis mount.

For example, if the OTA is mounted off axis (e.g. for a German Equatorial Mount) then the polar moment of inertia about the polar axle will be approximately the sum of all of the OTA component masses times their individual distances squared from the Declination axis plus the mass of the entire OTA times the distance squared from the center of mass of the OTA to the center of rotation of the polar axle. The OTA also needs to be balanced about the polar axle requiring a counterweight. Typically the counterweight is located 2X or 3X the offset distance of the OTA away from the polar axle center of rotation so it will weigh ½ or ⅓ of the weight of the OTA. The polar inertia of the counterweigh itself will be much lower than that of the OTA, But the weight is located far from the polar axis. The polar inertia of the counterweight can be about 1X or 2X the polar inertia of the OTA.

For a given drive stiffness, the GEM will have a natural resonant frequency of about 50% to perhaps 70% compared to a symmetrical mount. This is undesirable. Many of the large telescopes built during the mid 1960s have a natural resonant frequency in the 1 to 2 Hz range. A modern satellite tracking telescope should have a natural resonant frequency > 5 Hz.

Off axis mounts like the GEM have mechanical problems tracking through the meridian and require a re-configuration of the mount because the OTA will not clear the polar axle structure. This requires a time consuming "reversal" of the OTA to the other side of the polar axle structure (or pier). Often the pointing model is different on the other side of the pier making re acquisition of the satellite difficult.

There is additional information on telescope structure and material selection on our web site at:
http://www.dfmengineering.com/news_eng_article_1.html
http://www.dfmengineering.com/news_eng_article_2.html
http://www.dfmengineering.com/news_eng_article_3.html

Drive Stiffness:
Typically the telescope structure is stiffer than the drives so the drives become the spring in the system. In order to achieve a high natural resonant frequency, we want a stiff spring. Most forms of gearing require lubrication. The oil or grease film significantly reduces the stiffness. The friction drive consisting of a large diameter disk and a small diameter drive roller provides the stiffest form of gearing.

Seven types of telescope drives are discussed on our web site at:
http://www.dfmengineering.com/news_telescope_gearing.html

Fast dynamic response requires a drive system with sufficient efficiency that the gearing will back drive (where the telescope motion can drive the unpowered drive motor) This allows removing kinetic energy from the telescope by driving the motor in opposition to the motion of the telescope. Telescope worm gear drives do not back drive so they are unsuitable for the fast dynamic response needed for tracking all but geosynchronous satellites.

The effective drive stiffness may be increased by closing a servo loop around the telescope. Little or no improvement can be achieved with a worm gear drive telescope mount.This is discussed further below.

Structural Stiffness:

In general, the structural stiffness can be increased by adding more metal. However, more metal means more inertia and the resulting resonant frequency may not be improved. The geometric shape of the component can increase the stiffness to weight ratio. In general, a closed box (or tubular) shapes which encloses a large area with a thin wall thickness produces a high stiffness to weight ratio which leads to a high resonant frequency. An example of this effect is discussed on our web site at:
http://www.dfmengineering.com/news_eng_article_2.html

The choice of material to use for the structure depends more upon the cost to fabricate the material rather than the density of the material as most metals have nearly the same stiffness to weight ratio. The use of carbon fiber reinforced plastic (composite material) can be justified for aircraft and race cars, but is hard to justify for a ground based telescope.

This is discussed on our web site at:
http://www.dfmengineering.com/news_eng_article_1.html

Servo System:
An astronomical or satellite tracking telescope operates through a very wide dynamic velocity range. If one considers the slowest tracking rate to be 0.1 arc second per second, and a slew speed of 4 degrees per second, the dynamic velocity range is 144,000 to 1. Most commercial servo drive systems are designed for point to point positioning with a limited velocity resolution and dynamic velocity range. A telescope requires very precise positioning <u>and</u> velocity control because the target is almost always moving.

The servo system can be used to significantly increase the effective stiffness of the telescope by closing a PID (Proportional, Integral, and Derivative) control loop around the telescope. This requires very high resolution encoders mounted on axis to provide the position and velocity feedback for the servo controller. Until recently, encoders with sufficient resolution have been very expensive ($70,000 each) and large (12-inches diameter).

Encoding the worm shaft of a worm gear telescope does not provide accurate information of where the OTA is actually pointing due to dynamic effects, so very little improvement of the telescope stiffness can be provided. Removing energy from the telescope through the worm gear cannot be done quickly further limiting any dynamic improvement of the telescope performance.

Conclusions:
A worm gear driven telescope is a poor choice for a satellite tracking telescope. An off axis (non symmetrical) mount is a poor choice for a satellite tracking telescope. The Alt-Az configuration requires a significant increase in the maximum speed in the azimuth axis to reduce the dead zone at the zenith. The Alt-Alt configuration is the best configuration while a symmetrical (fork) mount is a good compromise.

DFM Engineering has built all three configurations of telescope mounts. We believe the equatorial fork mount to be the best compromise. The equatorial fork mount also simplifies tracking stars and allows pointing modeling and photometric calibrations to be more easily performed.