5 Telescopes

5.1 Telescope design considerations

5.2 Large mirror types

One real-world issue for large telescopes is the technology of how to build a large mirror which will not be so heavy that it will sag under its own weight. Additionally, since it has been recognized that good image quality requires that the mirrors be at the same temperature as the outside air, the mirror technology must be such that the mirror has a short thermal time constant, or, in other words, it must be able to change temperature to match the outside air fairly quickly. If necessary, one can consider thermally controlling the mirror, e.g., with heating or air conditioning.

In the large mirror regime, there are currently three leading technologies. The first is the construction of a single large mirror (monolithic) made from borosilicate glass, but having large hollowed out regions to keep the weight down. This borosilicate honeycomb design has been pioneered by Roger Angel at the Mirror Lab of the University of Arizona. This type of mirror has been successfully cast in a 3.5m size (used in the ARC 3.5m (APO), WIYN 3.5m (KPNO), and the Starfire Optical Range Telescope near Albuquerque), and in a 6.5m format for the MMT conversion (Mt. Hopkins, AZ) and the Magellan (Las Campanas Observatory, Chile) telescopes; they have also been made in an 8m format (x2) for the Large Binocular Telescope (Mt. Graham, AZ). The second design is also monolithic but has a mirror which is significantly thinner than the borosilicate mirror. These thin mirrors are being built primarily by two companies, Corning (USA) and Schott (Germany). They use materials with good thermal properties, ULE (Corning) and Zerodur (Schott). Thin mirrors are being used in ESO’s 3.5m New Technology Telescope (La Silla, Chile), Japan’s 8m Subaru telescope (Mauna Kea, Hawaii), the two 8m Gemini telescopes (Mauna Kea and Cerro Pachon, Chile), and ESO’s Very Large Telescopes (4 8m’s on Cerro Paranal). Finally, the third design make use of segmented mirrors, in which a large mirror is made by combining many small mirrors. This design is currently operational in the 10m Keck telescope (Mauna Kea), the 11m Hobby-Eberly Telescope, the 11m SALT telescope, and the 10m Gran Telescopio de las Canarias. Future 30m class telescopes: TMT, GMT, and E-ELT.


The borosilicate mirrors have the advantage that they are stiffer than the other designs, so the mirror support is less complicated. For thin mirrors, the support system must be activated to allow for changing shape as a function of telescope pointing. For segmented mirrors, each segment must be controlled to make sure the entire surface is smooth. The thick mirror is also less susceptible to wind shake,
which can adversely affect image quality. The thin and segmented mirrors have the advantage of better thermal properties since they contain less total material.

The choice of a primary mirror technology can be complicated. In designing a large telescope, one generally first decides on an optical prescription which is chosen considering the main scientific goals for the project (e.g., large field, IR, good image quality, etc.). The primary mirror choice is made considering the choice of site (e.g., are there large temperature changes, lots of wind, etc.), availability, issues of engineering complexity, and, especially, cost (and politics). The choice of a mount and control system to use is basically a cost and operations issue.

5.3 Mirror coatings

Aluminum, silver, gold (JWST) most commonly used. See, e.g. [http://www.optiforms.com/metallic.htm](http://www.optiforms.com/metallic.htm) for relative reflectances as a function of wavelength, also here. Curves like these can be incorporated into an exposure time calculator to account for the efficiency of the telescope as a function of wavelength. Note the effect of multiple mirrors: if you have three mirrors with 90% reflectance, you will have a total loss of almost 30% of the light!

Issues with mirror cleaning and recoating; coatings get dirty and also degrade over time. The degradation depends on the exposure, hence observatories often have constraints on humidity and dust levels, for example.

5.4 Telescope mounts

We’ve talked about the optics that go into telescopes. However, it’s clear that these optics need to be supported in some structure and kept in alignment with each other. The support structures needed are really an engineering issue (and a challenging one for large telescopes), and we won’t discuss it here. In addition to supporting the optics, the structure also needs to be capable of tracking astronomical objects as they move across the sky because of the rotation of the earth.

There are two main different sorts of telescope mounts found in observatories: the equatorial mount and the altitude-azimuth (alt-az) mount. The equatorial mount is by far the most common for older telescopes, but the alt-az design is being used more frequently for newer, especially larger, telescopes. In the equatorial design, the telescope move along axes which are parallel and perpendicular to the polar axis, which is the direction parallel to the earth’s rotation axis. In such a mount, tracking the earth’s rotation only requires motion along one axis, the one perpendicular to the polar axis, and the tracking motion is at a uniform rate. In the alt-az mount, the telescope moves along axes which are perpendicular and parallel to the local vertical axis. With this mount, however, tracking of celestial objects requires motions of
variable speed along both axes. An additional complication of an alt-az mount is the
fact that, for a detector which is fixed to the back of the telescope, the image field
rotates as the telescope tracks an object. Note, however, that the telescope pupil
does not rotate with the object.

An equatorial mount is much easier to control for pointing and tracking. However,
from an engineering point of view, it is much more demanding to construct, especially
for large telescopes which have significant weight. The engineering complications
generally result in a significantly larger cost (for large telescopes) than for an alt-
az design. An alt-az telescope, however, has a significantly more complex control
system, and must have an image rotator for the instruments. Given the advances in
digital motor control and computing, the control system usually no longer poses a
very significant challenge.

Regardless of mount type, the mount is never built absolutely perfectly, i.e. with
axes exactly perpendicular, exactly aligned as they should be, totally round surfaces,
optics aligned with mechanics, etc. As a result, a telescope does not generally point
perfectly. However, many effects of an imperfect telescope are quite repeatable, so
they can be corrected for. This correction is done by something called a pointing
model, which records the difference in true position from prediction position over
the sky, and, once derived, the pointing model can be implemented to significantly
improve pointing. A good telescope points to within a few arcseconds after imple-
mentation of a good pointing model.

Related to pointing is tracking performance. The issue here is how long the
telescope can stay pointed at a given target. You can consider this question as how
well the telescope can point over the area of the sky through which your object
will drift. Since your required pointing stability should be significantly less than
one arcsec, so that tracking does not degrade the image quality significantly, almost
no telescopes have sufficiently good pointing to track to within an arcsecond for an
arbitrarily long time. Most telescopes can track successfully for several minutes, but
will give significant image degradation for exposures longer than this. Consequently,
most telescopes/instruments are equipped with guide cameras, which are used to
continually correct the pointing by observing an object somewhere in the field of
view of the telescope (possibly the object you are interested in, but usually not, since
that’s where your detector is looking). These days, most guiders are autoguiders,
meaning that they automatically find the position of the guide object, compute the
pointing offsets needed to keep this object in one position, and send these offsets as
commands to the telescope. The observer generally just has to choose a guide object
for the autoguider to use, though they also may have to adjust the guide camera
sensitivity or gain to insure that the guide star has a strong signal. These days, many
autoguiders can automatically find guide stars in the field or from some on-line catalog
(e.g., the HST Guide Star Catalog, which catalogs stars down to V 14). However,
if one is taking long exposures and knows that they’ll need to use guide stars, make
sure to find out whether such a facility is available; if not, it may still be possible
to find guide stars in advance of your observing run, e.g., from the sky survey. If so,
you should seriously consider doing so, as it can take a frustratingly long amount of
time to search for a guide star at the telescope in real time. Since telescope time is
heavily oversubscribed at most facilities, you really want to maximize your efficiency,
and doing so is a large part of what will make you a “expert” observer.

Note guiding in spectrographs is often done off of the slit with a slit-viewing
camera.

5.5 Using telescopes

Generally it is usually fairly straightforward to use an astronomical telescope. Most
of the time after arrival at an observatory can be spent checking the instrument and
detector performance rather than checking the telescope performance. You should
carefully consider, however, how to maximize your efficiency at the telescope; tele-
scope time is expensive and hard to come by.

Before going to a telescope, you might consider the following checklist of things
to do:

- Learn how the telescope is commanded. In particular, you may wish to find out
  whether scripts can be written (or are already available) to do routine motions
  on the sky (e.g. dither back and forth between positions, especially important
  for IR observing)

- Find out whether user object catalogs can be used, and if so, find out the
  format and prepare files. It can save a lot of time and headaches to have your
  coordinates preloaded in a file and save the agony of typing numbers in the
  middle of the night and getting them wrong.

- Find out the pointing accuracy of the telescope. You may not necessarily be
  able to count on the telescope pointing exactly at the coordinates that you
tell it to go to. For fainter objects, it is highly recommended that you bring
  finding charts with you to the telescope. Note that it is now fairly easy to
  make finding charts from the Digitized Sky Survey (from Palomar and ESO
  plates). The program getimage is available for your use; this program can
  extract FITS images of arbitrary size from the digitized sky survey, which we
  have on CDROM. Any image processing package should be capable of reading
  these and producing hardcopy pictures. Another easy interface available over
  the WWW can be found at http://skyview.gsfc.nasa.gov.
• Find out the guiding performance of the telescope. For what exposure times is guiding required? If you will be taking exposures which need to be guided, how does one find guide stars? Can time be saved by finding guide stars in advance?

• Plan your observations. You generally want to observe objects at the lowest possible airmass. In combination with your scientific priorities, this will set the order in which you can plan to make observations. You can figure out transit times by considering the sidereal times for your night and the right ascension of your targets using

\[ HA = LST - \alpha \]

You can get observing calendars using the program skycalendar and compute airmass tables, etc., for specific targets using the program skycalc (I’m sure lots of other programs are also available for these tasks). If you are doing spectroscopy, consider whether differential refraction will be important and whether you can mitigate its effects by observing objects around the parallactic angle (which, of course, changes over the course of the night!).

Remember to consider the calibration observations you will need to take (we’ll talk more about this later). Also remember to plan for different possible conditions. For example, if you program requires photometric weather, what will you do if it’s not photometric? What if the seeing is horrible, etc.?

• Be prepared to be able to analyze image quality (e.g., FWHM) and focus the telescope. One of the first things to be done just after dark is focusing the telescope. This generally involves taking images at a range of focus settings and comparing them to determine the best focus. One should be prepared with software for analyzing image quality to make this determination - also, perhaps, software for looking at all images simultaneously. Generally, the focus position is encoded somehow so one gets a quantitative measure of the secondary location. One should be aware, however, of the possibility of slack in the gears controlling the focus mechanism, which can make the focus not repeat even when the readout position is the same; because of this, it is generally wise to always move to a focus position from one direction.

While focussing, one can generally also get an idea of the quality of the seeing of the night. Remember that seeing varies from frame to frame, and because of this, multiple exposures even at the same focus can look very different. To minimize seeing effects, one may wish to choose a focus star on which exposures of several seconds can be made: for a brighter star with very short exposures, seeing changes may confuse you. Clearly, however, one doesn’t want to use a very faint star because one would like to get the focussing procedure over as
quickly as possible so you can get on with your science. Remember, however, the signal-to-noise gains are substantial for a more concentrated image, so it will be worth your while to do a good job: if you rush it, you may regret it later when you have more time to notice how blurred your images are!

You also need to remember that the focus is likely to change throughout the night as the temperature changes. So continue to inspect your images as you take them, and if the quality appears to be degrading, you should redo a focus run. Most likely, the telescope focus will consistently change in one direction (as it gets colder) and you may even be able to get a good estimate of how much it changes as a function of the temperature with experience. Which direction focus goes is a good thing to write down at a telescope, as you can save significant time during mid-night focus changes if you already know which direction you need to go (but always beware of someone coming and rewiring the focus motor/control since the time of your last run!). Determining the correct balance of time spent optimizing (i.e. focussing) vs. taking science data can be tricky, and likely depends on the nature of your program.

One may wish to quickly inspect an out-of-focus image for signs of large aberrations in the system. Almost certainly, nothing will be done about these immediately, but if the image quality is poor enough, it may be possible to have something (e.g., alignment) done the next day, so you still may possibly help your observing run, or certainly, you will help subsequent observers. At least, if something seems strange, you should let someone know so they can judge for themselves if there is really a problem.

Overall, this is a key point; you need to be vigilant to look for peculiarities in your data, and if you see something that hasn’t previously been documented or that you don’t understand, you need to ask someone about it rather than just assume that it is “normal”!

5.6 Planning observing

1. Prepare targets: coordinate files, finding charts, etc

2. Understand S/N requirements per target, and implications for desired number of counts. What exposure times do you expect, and how will you check for each exposure to make sure you are not exposing for too long or too short?

3. Understand calibration requirements, and plan for calibrations exposures