Observational Astronomy: Introduction

P. D. Lynam

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> Observing at a telescope, even under the best conditions is tedious. Under the worst, it can be [...] miserable.
>
> — Allan Sandage (1926-06-18–2010-11-13), preface to the Hubble Atlas of Galaxies (1961)

> Noooooo [. . .] It was cold, and I hate being cold.
>
> — Virginia Trimble discusses observing in an interview by Sarah Scoles.
> The Woman who Knows Everything About the Universe,
> Wired Magazine, 2018-04-04.
> [https://www.wired.com/story/the-woman-who-knows-everything-about-the-universe/]

Preface

These documents were first prepared to support lectures delivered to the Graduate Student Workshop on Observational Astronomy at Lick Observatory in September/October 2011. The first revision of these documents was undertaken in preparation for the same Workshop from 1 to 5 November 2012. These documents result from a desire to collate information into discrete portable document format (pdf) documents with embedded links. Such documents are desirable, since they provide contingency in the event of network/communications failure or unavailability. A single downloadable document is a convenient aid, since it can be readily viewed on a variety of digital platforms and reproduced as a hard copy which can be annotated and referred to, independent of any infrastructure.

These lectures are ambitious: To give the subjects the full treatment they deserve can, and does, occupy multi-semester courses worldwide. Therefore, these lectures are in no way comprehensive.

The supporting documentation for these lectures is in no way indicative of the amount of attention that should be devoted to each topic. In most cases, the discussion has been reduced to a list of bulleted points to be brought to the attention of the aspiring observer. It is anticipated that these points will be expanded upon in future revisions.

Only the most essential concepts and terminology routinely used when preparing and executing astronomical observations are discussed, for example Hour Angle and Airmass. These terms and concepts will be encountered in practical planning and observing sessions. For those with an astronomical background, this introduction will serve as a review in a practical setting. For others, it will be a valuable introduction.

The approach is deliberately general and practical: the aim is to equip participants with the skills to use *any* observatory safely and successfully. As a result of the Workshops, it is hoped that at a minimum, participants will acquire an introductory level of caution, confidence, knowledge and experience to plan and execute observations safely and efficiently. Ideally, participants will develop some intuitive understanding(s) and behaviours — if there was such a thing as an “Observing License” the Workshops are where participants would earn their qualification!

Notice To All Participants:

Ensure the safety of others.

Ensure the safety of yourself.

Ensure the integrity and safety of resources.

To this end:

- Observe and respect the posted hazard signage.
- Proactively look-out for unsafe situations and inform someone if you believe a situation to be unsafe.
- Know what actions to take and who to contact in the case of an emergency.
- Do not operate any mechanical/electronic function unless you are certain that you understand its complete operation and it is safe to do so. Note that some components that may seem conceptually benign (e.g. switch on/off a calibration lamp) may include a command to a massive movable stage to position an element (e.g. the lamp itself, or a mirror) into the optical path.
- Inform the staff if you begin to feel unwell, so your condition can be monitored and action taken in a timely manner, if your condition deteriorates.
- Comply with the requests and directions of observatory staff. A support engineer's decision to close the telescope is *not negotiable*.

1 Safety

Observatories are special places. Typically located in remote, harsh, hostile environments, it is a fascinating experience to visit an observatory and witness the scale and quality of engineering, technology and manpower deployed, dedicated exclusively to the pursuit of one objective.

To optimize their capabilities, most professional observatories are configurable — fabric and facilities are in a constant state of flux: new facilities are installed, machinery is upgraded, instrumentation is interchanged, interventions are dynamic and on-going. For example, some telescopes, enclosures and auxilary installations are mounted on rails to enable them to be moved.

For the majority of observers, an observatory will *always* remain an unfamiliar place: observers attend observatories as a rarity (a frequent visitor may attend for a handful of occasions per semester) during which the installations will be re-configured multiple times.

Talented staff maintain enclosures, mountings and mechanical functions in optimal condition. Enclosures, telescopes, instruments and their moveable components — sometimes larger than a car — swivel and spin following pre-determined and commonly unsupervised command sequences.

It is an impressive experience to set 2700 tons of heavy metal motion with the single click of a mouse (or even nowadays, with a single SMS message from a cell phone located anywhere in the world).

This ballet happens in virtual silence... in the dark... at altitude... in an unfamiliar location... in a challenging environment... where people are tired from work or changes to their body clock (or both). Awareness and attention span can be detrimentally affected — especially true if physiological effects resulting from high altitude and/or low humidity are also present.

It follows then, that observatories are inherently dangerous places[1]. Unfortunately, people do fall ill and occasionally die at high, dry sites, hours from the nearest medical facilities and despite safeguards, instruments and components have the capaility to kill[2] and serious injury[3] and fatalities[4] are not unheard of.

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[1] It is as a result of safety concerns that groups are not permitted to enter the enclosure of the Automated Planet Finder (APF) on Mt Hamilton.

[2] At the VLT, Chile, the 7 ton VIMOS spectrograph rotates and counter-rotates its angular, unsymmetrical bulk several times while configuring. Anyone in the vicinity of the instrument could easily be dragged into ~2 inch clearance between VIMOS and the floor of the Nasmyth platform. The VLT fibre spectrograph, FLAMES can slice a person in half in the processes of switching between plates.

[3] Limbs have been lost as the result of efforts to prevent instruments slewing into enclosures.

[4] Respected cosmologist Dr Marc Aaronson (1950-08-24–1987-04-30) was crushed to death while observing with the Mayall 4.0 telescope at Kitt Peak National Observatory, AZ.

2 Telescopes At Mount Hamilton

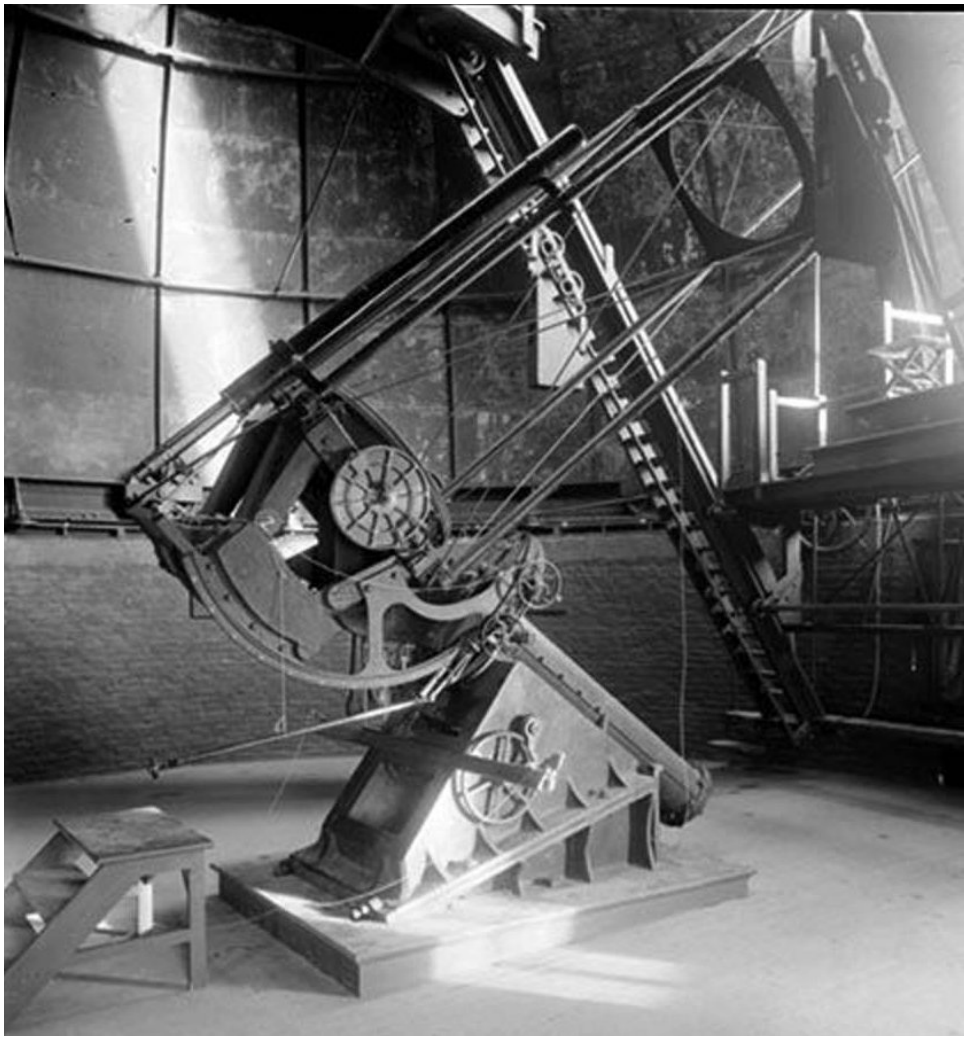

Figure 1: Photograph of the 0.9 m Crossley telescope in its 1895 configuration. (Credit: Mary Lea Shane Archives/UCSC Digital Collections).

Lick Observatory is one of the most important observatories in the history of astronomy. Lick Observatory set standards for all observatories that followed. Since its inception, continuous development and deployment of new technologies at Lick Observatory has opened and made significant contributions to new scientific disciplines (e.g. astrophotography, spectroscopy, astrophysics, cosmology, adaptive optics, exoplanets) — and led to discoveries in arguably every field of astronomy.

Dating from before 1888, Lick Observatory is one of the few observatories in the world for the in-situ inspection of a wide variety of telescope design and vintage.

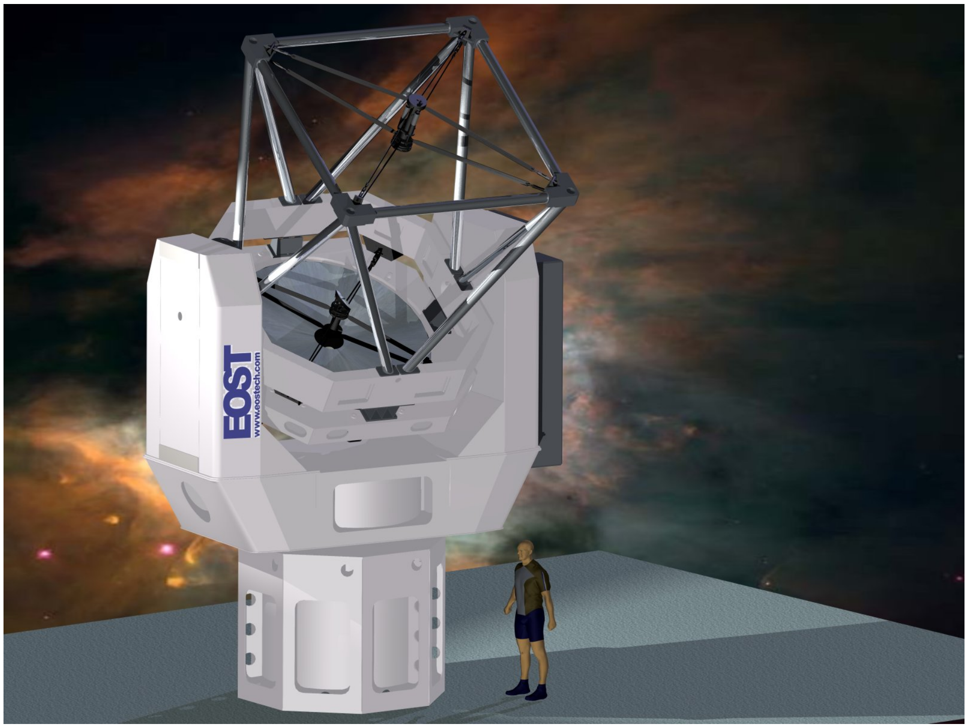

Figure 2: Schematic of the 2.4 m Automated Planet Finder telescope structure. Safety protocols prevent groups entering the enclosure to view the telescope structure directly. (Credit: EOS Tech, Australia).

2.1 General Issues To Consider

When surveying any observatory, try to be pro-active in inspecting the facilities. For each component of location, enclosure, telescope structure, mount, optical elements and optical train/light path:

- Identify advantages and disadvantages and limitations of each design.
- Identify the prime motivators and justifications of each design.
- Identify lacking features or technologies. What modifications could be made to each component to improve performance?
- Consider the purpose of the telescope (common-user, configurable, versatility vs. dedicated science); complexity of instrumentation and mode of operation and observation scheduling (local vs. remote vs. robotic vs. (un)supervised).
- Identify the cardinal compass points.

2.2 Specific Questions To Aid The Tour Of Mt Hamilton Installations

When inspecting specific telescopes/enclosures, consider, compare and contrast the following:

Crossley (1879, 1895) 0.9 m: Vintage? [5] The telescope structure is not original (see figure 2). What was the original telescope structure? How does the original compare with modern structures? Why was the original structure modified? Why is the dome in disrepair? What is the style of mount? Any limitations? Why is this one of the most significant telescopes in the history of astronomy/astrophysics/cosmology?

Nickel (1979) 1.0 m: The enclosure an the telescope are not of the same vintage. What motivated the design?. Limitations of the yolk mount?

SETI (circa 2010–2011) Cams: What are the driving scientific factors of this important observatory compared to other telescopes on Mount Hamilton?

Tauchmann (1937, 1950) 0.55 m: Significance? Instrumentation?

Automated Planet Finder, APF (2011) 2.4 m: Refer to figure 2. Vintage? How many potential instrument stations available? Locations? Advantages and disadvantages of each station? Telescope enclosure vs telescope structure? How does this compare with other telescopes. Why? Advantages, disadvantages, limitations of overall design? Mount and control — why is this design *apparently* so rare?

Carnegie Astrograph (1941, 1962) 0.5 m: Vintage? How does this apparatus differ from other telescopes on Mount Hamilton? Is it possible to achieve/exceed the same science objectives today? How? Where?

DIMM (197X–2011) 0.3 m: Vintage? The optical design of this telescope is unique at Lick. Advantages? Disadvantages? Limitations? Why is this telescope so important to the overall operation of the observatory? What motivates the choice of location/enclosure?

Shane (1959) 3.0 m: How many instrument stations? Advantages and disadvantages of each station? Elongated structure — why? Telescope enclosure vs telescope structure? How does this compare with APF. Why? Pros and Cons of the massive fork mount?

Coude Auxiliary Telescope, CAT (1969) 0.6 m: What type of Mount? What is the form of mirror 1? Advantages of dedcated Coude observations? Limitations?

Katzmann Automatic Imaging Telescope, KAIT (1997) 0.75 m: What type of Mount? Where else has this type of mount been deployed? Advantages? Limitations?

Great Lick Refractor (1888) 0.9 m: Why does this telescope remain superior to every other (larger?) telescope of its type? What instrumentation is available? What science projects can the telescope be applied to?

After touring observatory, reflect on what drives science. Are all the facilities deployed for their original purpose? What disappointed you about the facilities? What surprised you about facilities? What are your expectations compared to other observatories? How does your experience inform those expectations? If your expectations differ from your experience, *why*?

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[5] John McDonald (Machinist); Charles Harkort (Janitor); Chris McGuire (Labourer).

3 The Atmosphere

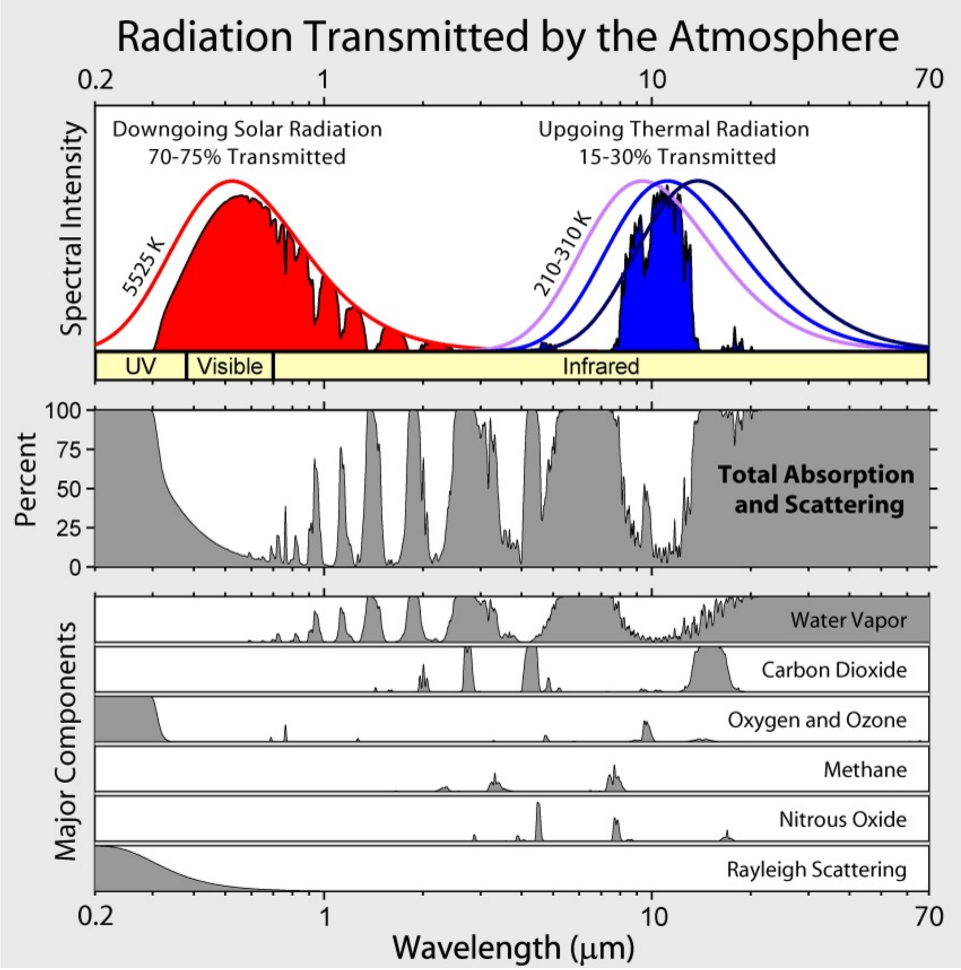

Figure 3: Atmospheric Transmission. Atmospheric absorption bands in the Earth's atmosphere (middle panel) and the effect that this has on both solar radiation and upgoing thermal radiation (top panel). Absorption spectra for individual species plus Rayleigh scattering are shown (lower panel). (Credit: Robert A. Rhode, UCB).

Ground-based observations are tormented by the atmosphere. Early observatories were established close to administrative centres and/or (in order to fulfill their role for the purposes of navigation) by admiralties (and thus at sea-level). However, by observing from high altitude sites, large amounts of the atmosphere can be avoided and undesirable atmospheric effects can be suppressed. Following the demonstrations that observations undertaken at altitude are superior, Lick Observatory became the first observatory permanently established at altitude — and set the standard for every observatory that followed. On-going efforts to overcome atmospheric effects include placing observatories in space (e.g. Hubble Space Telescope; James Webb Space Telescope) and the development of Adaptive Optics technologies (now becoming routine at most major ground-based observatories).

3.1 Atmospheric Effects

Besides the obvious effects of weather, the atmosphere can also create more subtle effects that can threaten observations and may need to be carefully quantified. Sometimes the dangers are difficult to discern:

Transparency: Thick Cloud / Thin Cloud / Clear vs. Photometric — demands multiple observations of standard stars and an accompanying quotation of tolerance.

Precipitation and Humdity: **Rain** and **Fog** can easily foreshorten observations. **Humidity** can condensation on the most unexpected cold surfaces of a telescope/observatory structure. **Snow** can force an enclosure to close *and remain closed for many nights after the snowfall.*

Winds: The effect of wind can depend on telescope-enclosure design. High-altitude winds (e.g. jet-streams) introduce a significant contribution to *seeing* (see below).

Particles: Relatively large particles (**Desert dusts**, **Volcanic clouds**, **Smoke**, **Ash** have the potential to degrade optical surfaces if deposited and cause extinction and sometimes reddening effects.

Refraction: Particularly important in spectroscopy. During the course of an observation, the line of sight through the atmosphere (airmass) will change. The amount of atmospheric refraction will correspondingly change and the apparent position of a source migrate. This effect can be dealt with by using arrangement of prisms (Atmospheric Dispersion Compensators, ADCs) to compensate for the diffraction effect and/or pre-aligning spectrograph slits to a **parallactic angle** — perpendicular to the horizon, which arranges for refraction effects to be displaced along the slit length. Also **differential refraction** which becomes important when aligning/guiding in one wavelength range (e.g. visible), while observing in another (e.g. infra red).

3.2 Atmospheric Transmission

Figure 3 shows atmospheric transmission in the spectral range 0.2 to 70.0 μm, encomapssing the ultra violet (UV), visible, near infra red (NIR) and mid/thermal infra red (MIR) regimes. The middle panel shows the the overall transmission. It is possible to identify 'windows' of transmission, throughout the visible and at several wavelength intervals in the infra red. The lower panel illustrates the relative contribution of different effects and chemical species to defining these atmospheric windows. While it appears that $> 20\mu$m transmission $\rightarrow 0$. It should be noted that at longer (radio) wavelengths ($\lambda \sim fewcm \rightarrow 10m$) more atmospheric windows are available.

UV observations are limited by **wavelength-dependent** (λ^{-4}) **Rayleigh scattering** processes from airbourne aerosol particles and **molecular absorption** by Oxygen and Ozone.

Again, **Molecular absorption**, in this case from water vapour in various wavebands dominates the atmospheric transmission in the infra red, with significant additional contributions from Carbon Dioxide. Standardized infra red filters (e.g. J, H, K) are designed to take advantage of these windows in atmospheric transmission.

Careful selection of an observing site can suppress some contributions from these effects: *high* altitude can avoid observing through excessively large column densities of Oxygen, Water vapour and Carbon Dioxide, permitting limited exploration of the UV regime and accessing some infra red windows. Transmission in the infra red depends sensitively upon the Precipitable Water Vapour (PWV)[6] in a non-linear way, providing a motivation to select *dry* sites.

3.2.1 Zenith Distance, z and Airmass

While there are complicating factors (e.g. humidity and phase), in general, the scale of undesirable atmospheric effects are correlated with the line-of-sight through the atmosphere. With carefully planned calibrations and/or reliable atmospheric modelling, many of these effects can be mitigated.

Observations of a source directly overhead (at **zenith**) traverse the shortest column of atmosphere and are therefore least affected. As we make observations further away from the overhead point (or at greater **zenith distance**, z) the line-of-sight traverses larger columns of atmosphere and undesirable effects are more evident.

Quantitatively, we use the term **airmass** to indicate the path length relative to zenith that our line-of-sight takes through the atmosphere. If we define observations take at the overhead point ($z = 0°$) to be at an airmass ~ 1.0, then observations of a source on the horizon ($z \sim 90°$) have airmass ~ 38 (i.e. the line of sight traverses a path length through the atmosphere ~ 38 times greater than the zenith observations).

It follows that, ideally, in order to minimize atmospheric effects we would like to make observations as close to zenith (airmass = 1.0) as possible. However, this may not be practically possible (most modern Altitude-Azimuth telescopes have a *zenith blind spot*; some telescope enclosures obscure the zenith; sidereal motion means that during a finite time, the object will traverse a range of airmass).

Airmass values increase slowly as observations depart from close to zenith, but increase rapidly as z exceeds $80 - - - 85°$. There are several complicated emprical functions that describe airmass as a function of z at these values (e.g. Young 1994, ApOpt, 33, 1108).

Again, in practice, it is unlikely that telescopic observations are performed at such extreme values: Telescopes are often mechanically limited (horseshoe mounts, lower limit of enclosure, component integrity). For those telescopes with the capability to observe close to horizon, such observations are probably only justifiable for rare/transient objects and may require special advance authorization by the directorship.

Therefore, in a practical range ($z \sim 0.0° \rightarrow 65.0°$) the following expression assuming a homogeneous plane parallel atmosphere is a reliable approximation:

$$Airmass = sec(z) \tag{1}$$

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[6] The phase of water vapour is also important. Some windows may be more transparent if the water vapour is in the form of high-altitude ice crystals

3.3 Stability: Speckle, Seeing/Image Quality

Masses of air at different temperatures will have different refractive indices. Mixing of such masses masses of can induce turbulence and instabilities in the atmosphere which in turn introduce purturbations to wavefronts propagating through the atmosphere and degrade the quality of observations.

Seeing sometimes referred to as **Image Quality** (typically reported in units of arcseconds) is the integrated effect of atmospheric turbulence along the line of sight. Instantaneous effects cause speckles between out-of-phase sections of corrugated wavefront. When integrated over time (as in a typical astronomical exposure) the speckles superpose to produce a seeing disk.

- Measured by observation of the intgrated effect on assumed point sources — not directly applicable on extended sources (e.g. galaxies)
- Measure FWHM of an assumed Guassian seeing disk.
- Access instantaneous measurement via guide camera — careful when guiding in one regime (e.g. visible) and observing in another (e.g. infra red). Measured seeing may be significantly different.
- On-axis in imaging data (most representative).
- Differential Image Motion Monitors (DIMMs).
- FWHM of continuum in resulting spectra.

There are several contributions to the overall integrated seeing. So-called *dome seeing* results from temperature differences immediately between the telescope-enclosure and the ambient air. Efforts to combat dome seeing can include maintaining the telescope-enclosure at night time temperature by refridgerating enclosures and constantly drawing a laminar flow of air through the enclosure and over the telescope. *Ground layer* seeing can result from thermal and other instabilities in the near environment of the telescope. Ground layer seeing is a significant contribution to overall seeing, even though it occurs $\sim$ 10s of metres above the ground. Methods to combat ground layer seeing include removal of peripheral structures, placing telescopes on high towers and moderating the thermal properties of the environment. *Sheer winds* (such as jet streams) also contribute significant components to overall seeing.

Seeing can be combated using Adaptive Optics (which shall be discussed elsewhere) in which concepts such as *Coherence*, *Freid parameter* and *Strehl ratio* are introduced.

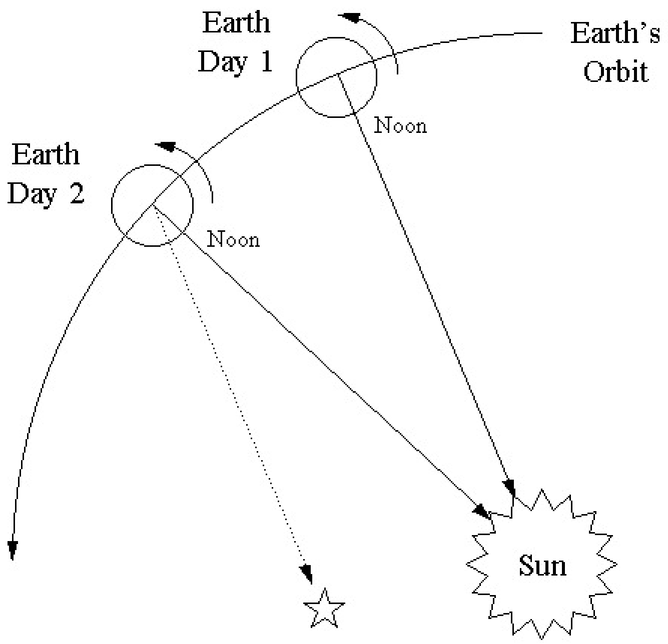

Figure 4: Solar v. Sidereal Time (Credit: Celestrak.com).

4 Position And Time

This section deals with the fundamentals of observational astronomy and introduces some essential terms requried for an understanding of the night sky and coordinate systems/reference frames. One of the great advantages of participants attending the workshop is the opportunity to have a guided tour of the night sky and be able to identify many of the devices used. A Practical Observing Checklist is provided (§ 5) to assist the night sky tour.

Many Resources can be sought to support the material discussed here. Most popular astronomy texts will include an introduction to position and time. A perennial classic, widely available, is 'the most famous astronomical reference in the world': *Norton's Star Atlas and Reference Handbook* first published in 1910. A valuable and freely available Resources to accompany the material discussed here is *Bowditch's The American Practical Navigator, APN* a publication dating from 1802. Explanatory diagrams of the celestial sphere have been selected from APN for use in these notes. Since APN is primarily published as a reference for maritime operations, there are some important differences in devices/terminology used (e.g. Sidereal Hour Angle, measured in degrees West along the celestial equator from the Vernal Equinox is the *expliment* of Right Ascension, measured in hours, minutes and seconds East of the Vernal Equinox). Participants are encouraged to review APN chapter 15 (Navigational Astronomy) — which includes some useful star charts from the Nautical Almanac — and APN chapter 18 (Time). A modern **dictionary of astronomy** is also a useful resource in order to verify explicit definitions.

4.1 Time and Meridian

Probably, the most important instrument at any observatory is the clock. While time services today are currently defined via atomic clocks, for many centuries the apparent movement of celestial bodies dictated our measurement of time and astronomers where known as ‘the keepers of time’. Since the position of celestial bodies helped contain our measurement of time, then conversely, given a measurement of time we are able to locate celestial bodies. One of the priorities of the observer is to regularly verify that the clocks are working. With simply a well-understood clock and knowledge of geographic location, all other necessary information can in principle be determined. Clocks do not necessarily need to faithfully reflect exactly the correct time — it is more important that clocks lose time in an understood and predictable way.

A commonly-used concept used to measure the passage of the heavens is that of transiting the **celestial meridian** — a great circle passing through the North Pole, South Pole and the zenith. The Earth’s rotation causes (non-circumpolar)[7] points on the celestial sphere to appear to rise in the East, set in the West and achieve their highest altitude/elevation as they transit the celestial meridian (also called upper **culmination**).

4.2 Solar Time and Sidereal Time

Solar time is measured with reference to the motion of the Sun. One solar day is the interval between two successive noons. There are distinctions between **apparent solar time** and **mean solar time** since the Earth’s orbit is non-circular.

Sidereal time is a time scale based on the Earth’s rate of rotation measured relative to the ‘fixed’ stars and differs from solar time due to the additional length of time/rotation angle required for the Sun to return to the same point from noon-to-noon as the Earth orbits the Sun (see figure 4). Thus a sidereal day is somewhat shorter than a solar day.

4.3 Universal Time, Julian Date, Modified Julian Date

Conceptually, **Universal Time, UT** can be described as the mean solar time on the Greenwich **meridian**, measured in 24 mean solar hours, beginning at midnight. As such, Universal Time is equivalent to Greenwich Mean Time, GMT.

The *details* can potentially introduce pitfalls — especially for high time resolution studies. It is important to know that different methods for determining/reporting a measure of Universal Time (UT0, UT1, UT2) have very specific definitions and/or corrections applied that may differ by $\sim$ few seconds from each other, Coordinated Universal Time (UTC) and International Atomic Time (TAI). Thus, it is necessary to pay attention to which definition is used and to be aware that;

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[7] Circumpolar objects never rise or set and transit the celestial meridian twice: Upper culmination (from East to West) and Lower culmination (from West to East)

$$UT0 \not\equiv UT1 \not\equiv UT2 \not\equiv UTC \; (\propto TAI) \tag{2}$$

Julian Date, JD is the number of days elapsed since noon UT on 1 January 4713, plus the decimal fraction of that day that has elapsed since the preceding noon. It is a convenient device independent of the length of month or year to allow consecutive numbering and the identification of a specific moment in history using a single real number. Useful for studying periodic phenomena.

Modified Julian Date, MJD is a further convenience:

$$MJD = JD - 2400000.5 \tag{3}$$

For example, 2011-03-01UT12:00 = JD 2451605.0 = MJD 51604.5.

4.4 Vernal Equinox and Coordinate Systems

Astronomers use Sidereal Time as a foundation for their **equatorial** and **ecliptic** (and by extension, Galactic and Supergalactic) coordinate systems.

The zero point of Sidereal Time is defined to be the Vernal Equinox:

Vernal (Spring) Equinox (a.k.a. First Point of Aries), ♈: The point on the celestial sphere at which the Sun in its annual motion crosses from South to North of the equator.

Due to the phenomena of **precession** and **nutation** of Earth's axes, the position of the vernal (and autumnal) equinoxes is known to change. Hence, coordinates require an associated **equinox** to be quoted to incorporate these effects.

- Sidereal Time, usually measured from 0 to 24 hours in units of hours, minutes and seconds indicates the position of a nominated meridian East of the vernal equinox. **Local Sidereal Time, LST** indicates the position of an observer's local meridian East of the vernal equinox.
- **Hour Angle, HA** indicates the position of a nominated point on the celestial sphere West of a meridian. Thus, Hour Angle is negative East of the meridian (object rising) and positive West of the local meridian (object setting). Hour Angle is expressed in the same units as, *but in the opposite direction to*, Sidereal Time and Right Ascension.
- **Right Ascension, R.A.** indicates the position of a nominated point on the celestial sphere East of the vernal equinox.
- **Declination, Dec** indicates the poistion of a point on the celestial sphere North or South of the vernal equinox.

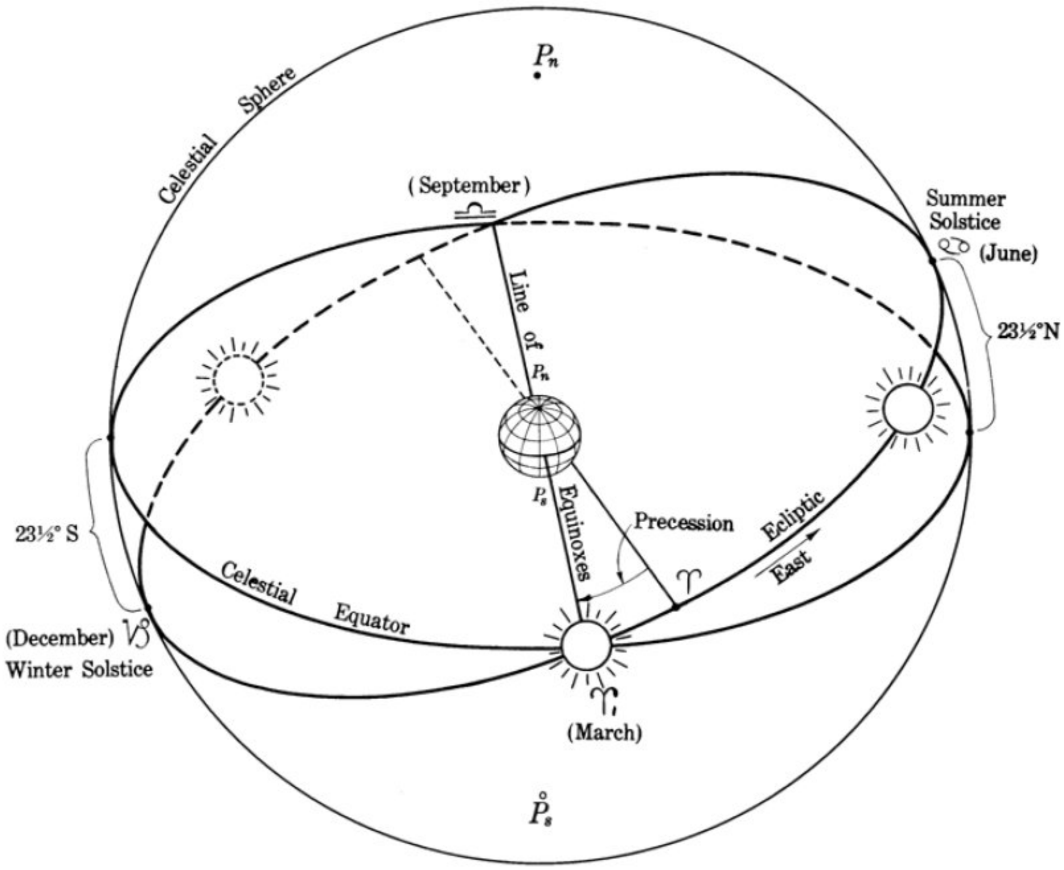

Figure 5: Elements of the Celestial Sphere defining the equinoxes, solstices and indicating the effect of precession (nutation is an additional smaller effect). (Credit: Bowditch's American Practical Navigator).

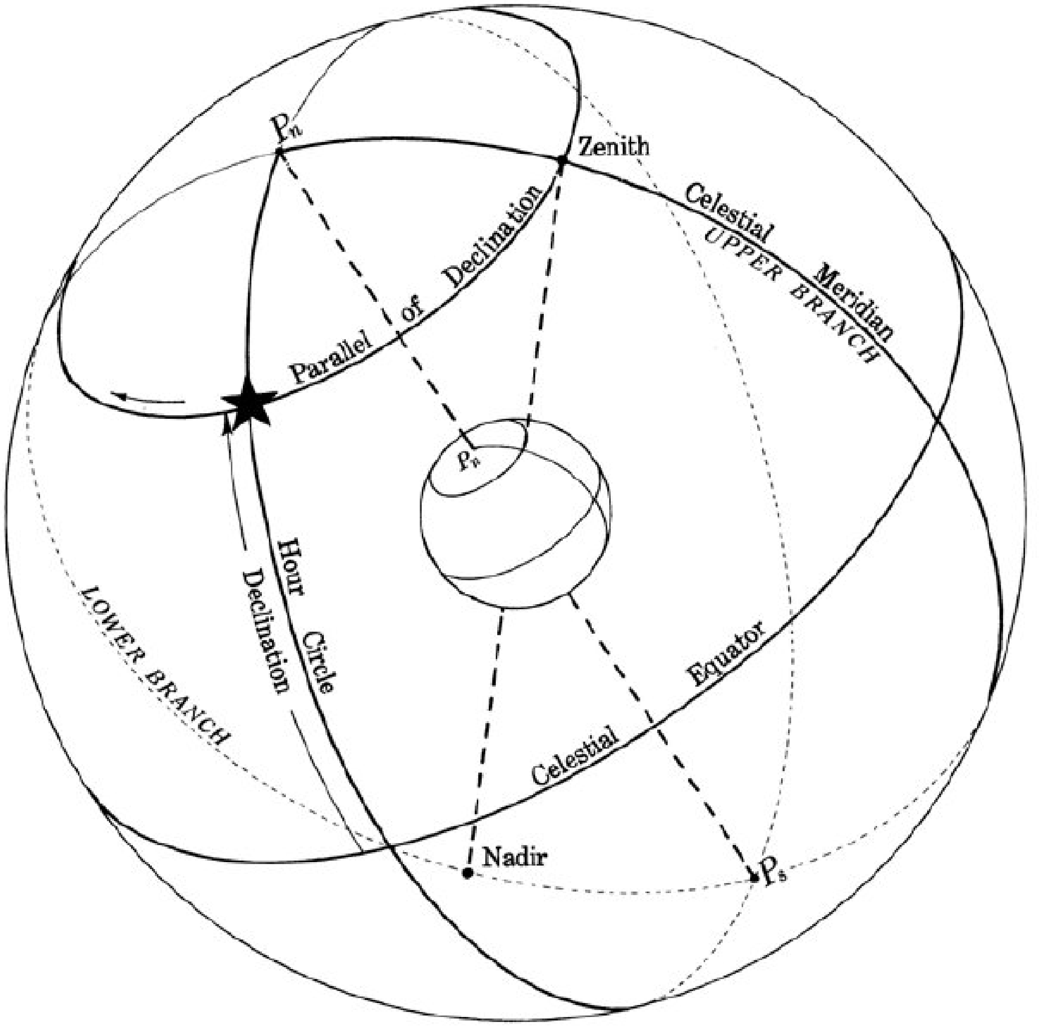

Figure 6: Elements of the Celestial Sphere illustrating the concept of North Celestial Pole, P_n; South Celestial Pole, P_s, Celestial Equator, Zenith, Nadir and Celestial Meridian. (Credit: Bowditch's American Practical Navigator).

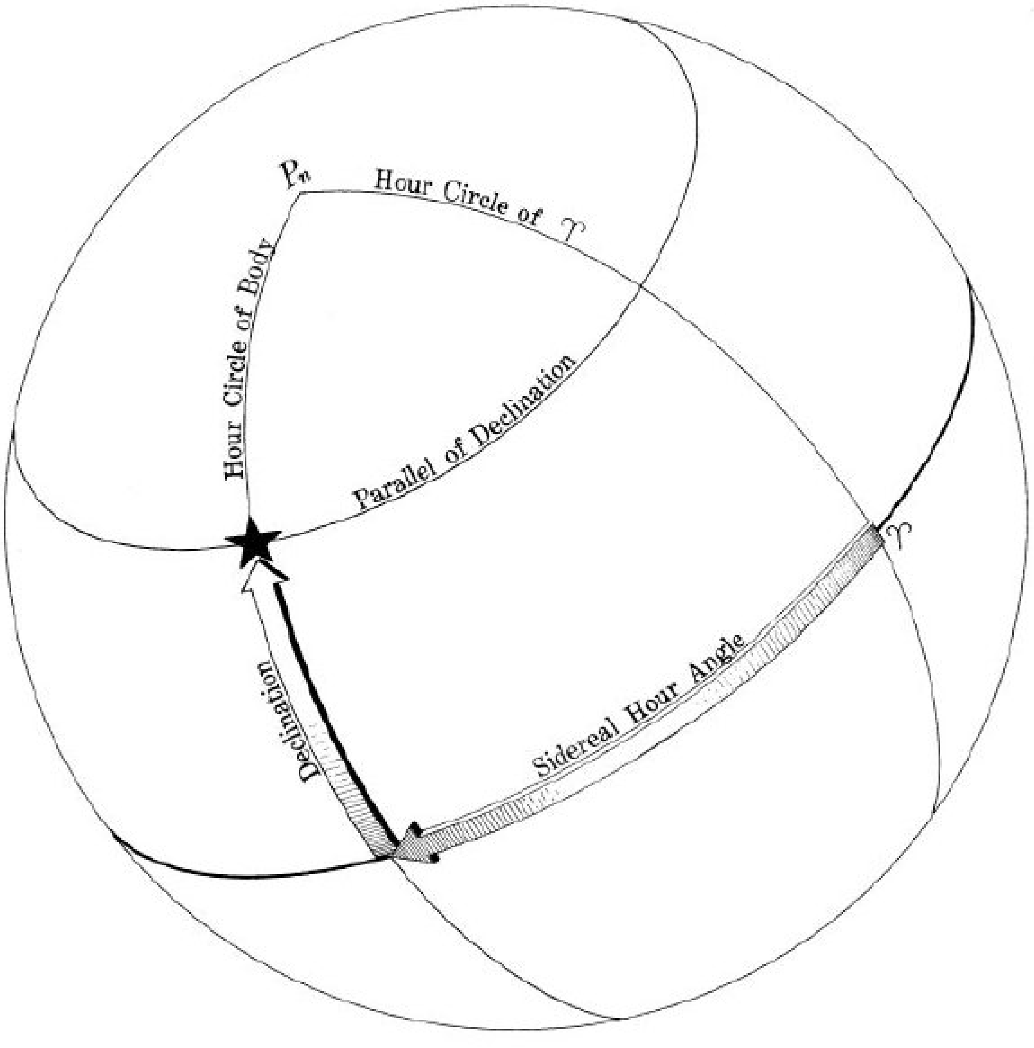

Figure 7: Elements of the Celestial Sphere illustrating the concept of Hour Angle, HA defined as the position of point on the celestial sphere West of a celestial meridian. (Credit: Bowditch's American Practical Navigator).

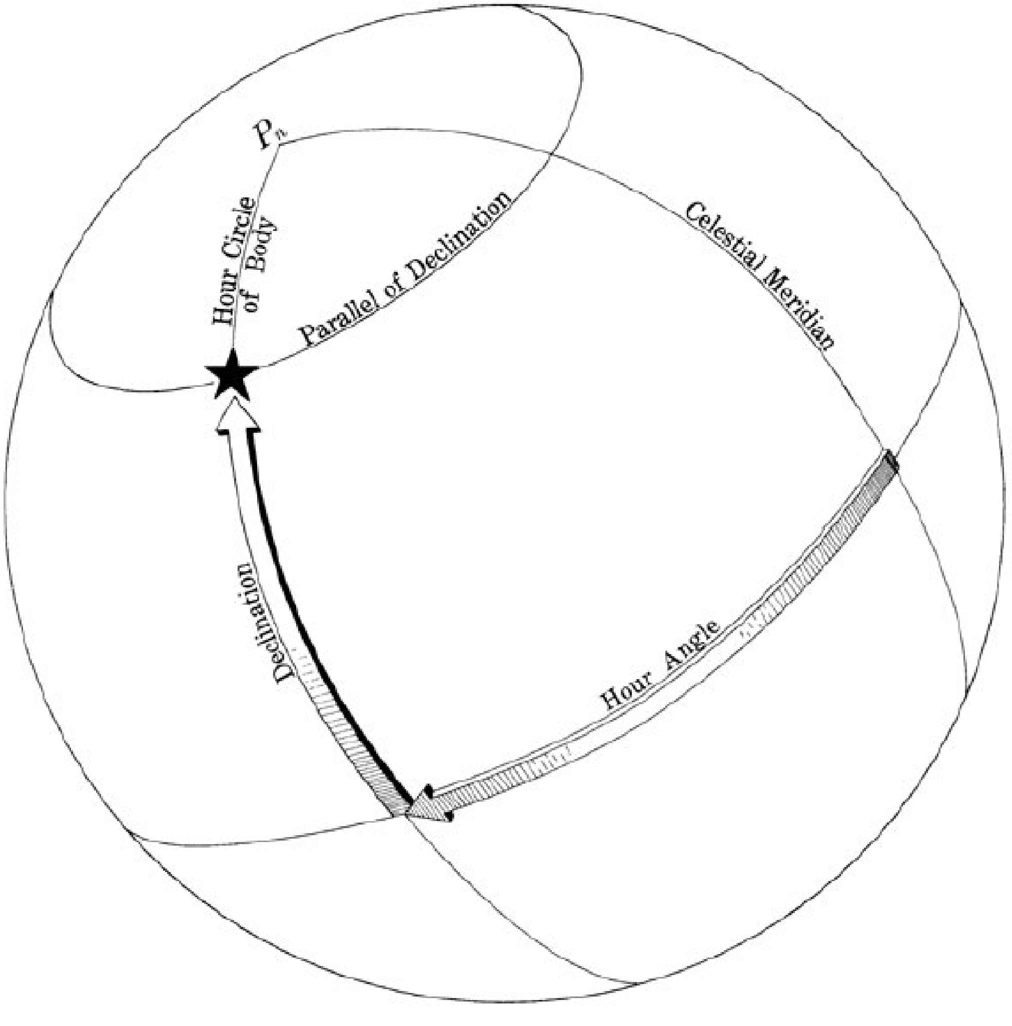

Figure 8: Elements of the Celestial Sphere illustrating the equatorial coordinate system including the concept of Right Ascension, R.A. defined as the position of point on the celestial sphere East of the vernal equinox, ♈. (Note: Right Ascension, R.A. measured in hours, minutes and seconds East of the vernal equinox is the expliment of the mariner's 'Sidereal Hour Angle', measured in degrees West along the celestial equator from the vernal equinox.) (Credit: Bowditch's American Practical Navigator).

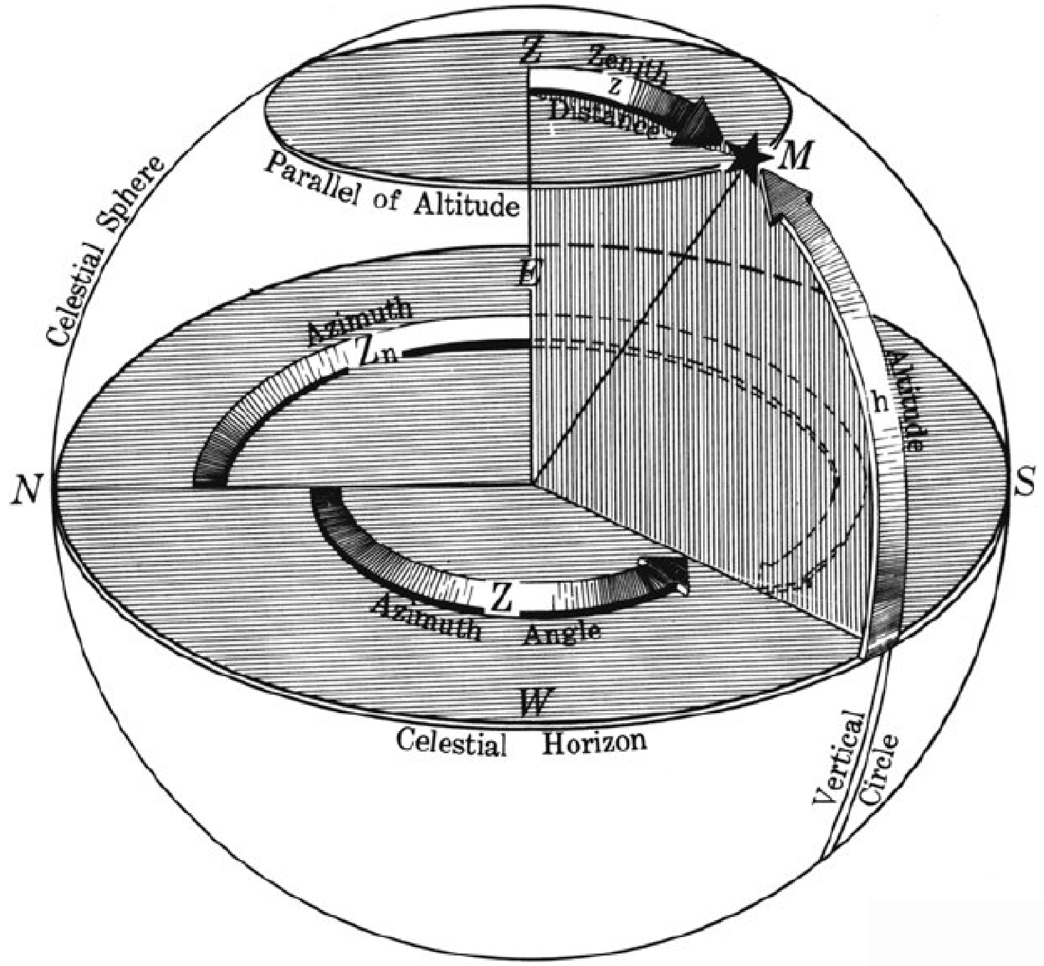

Figure 9: Elements of the Celestial Sphere illustrating an Altitude-Azimuth (Horizon) coordinate system including zenith distance. Note the definitions of the explimentary **Azimuth,** Z_n and **Azimuth Angle,** Z and the potential for confusion. (Credit: Bowditch's American Practical Navigator).

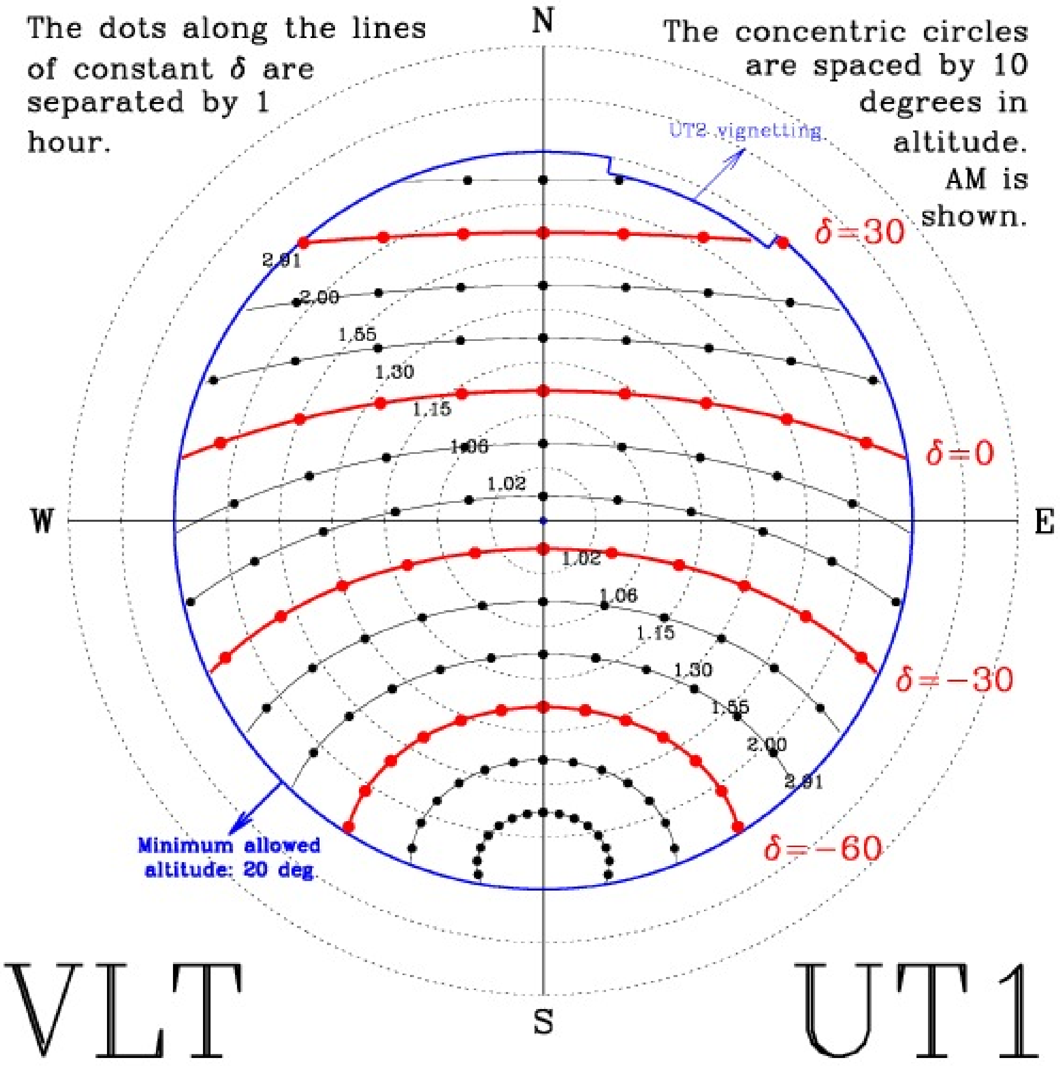

Figure 10: A useful visualization tool: A pointing plot for Unit Telescope 1 (UT1) of the European Southern Observatory (ESO) Very Large Telescope (VLT) at Cerro Paranal, Chile. The plot shows **Hour Angle, HA** in 1 hour intervals for sources with **declination** between approximately +40° N and the South Celestial Pole in intervals of 10°. Pointing limits (**altitude** +20° and vignetting by adjacent structures) are illustrated. Concentric circles in steps of 10° of **zenith distance** labelled with their corresponding **airmass** values. (Credit: M. Romaniello, ESO).

5 Practical Observing Checklist

Question: Why does a clock move clockwise? ☐

Question: Why are astronomical sources *never* at their published coordinates (with the exception of a specific, unique instant in time)? ☐

Horizon: Nadir ☐

Horizon: Zenith ☐

Horizon: Zenith Distance, Airmass, (Zenith Angle) ☐

Horizon: Altitude (Elevation) ☐

Horizon: North Celestial Pole (UMi), South Celestial Pole (Oct), East, West ☐

Horizon: Azimuth ☐

Horizon/Equatorial: Meridian (Local, Prime; Culmination/Transit) ☐

Equatorial: Latitude ☐

Equatorial: Celestial Equator ☐

Equatorial: Declination, Declination Limit (90° − *Latitude*) ☐

Equatorial: Circumpolarity ☐

Equatorial/Ecliptic: Vernal Equinox (Psc) ☐

Equatorial/Ecliptic: Precession (Ari, Psc, Aqu; Lib, Vir); Nutation ☐

Equatorial/Ecliptic: Equinox (Precession, Nutation) ☐

Equatorial/Ecliptic: Epoch (Proper motion, Parallax, Orbital Elements) ☐

Equatorial: Right Ascension ☐

Equatorial: Hour Angle ☐

Ecliptic: Ecliptic Plane ☐

Galactic: Galactic Equator ☐

Galactic: Galactic Center (Sgr) ☐

Galactic: North Galactic Pole (Com) ☐

Galactic: South Galactic Pole (Scl) ☐

Galactic/Supergalactic: (Scl, And 31, Tri 33, Men, Tuc) ☐

Supergalactic: (Vir, Per-Psc, GA: Hyd-Cen) ☐

6 Techniques, Modes, Utilities

> The life [...] of the experimental research worker is controlled by [...] subtle factors and especially by the nature of the equipment with which he works.
>
> — Prof. Sir Bernard Lovell (1913-08-31–2012-08-06), Astronomer by Chance (1990)

6.1 Imaging

- Filter Systems: Bessel, Stromgren, Johnson-Kron-Cousins, AB, HST, Sloan (Fukugita et al. (1996), AJ, 111, 1748)...
- Direct
- Astrometry
- Photometry Hipparchus, Podgson, . . .

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{I_1}{I_2}\right) \tag{4}$$

$$-0.4\,(m_1 - m_2) = \log_{10}\left(\frac{I_1}{I_2}\right) \tag{5}$$

$$10^{-0.4(m_1 - m_2)} = \left(\frac{I_1}{I_2}\right) \tag{6}$$

  Thus, a difference of 1 magnitude corresponds to a flux difference of 2.512. A source of magnitude 1 is 100 times brighter than a source of magnitude 6.

- Occulting Bars
- Coronography
- Wide-Field

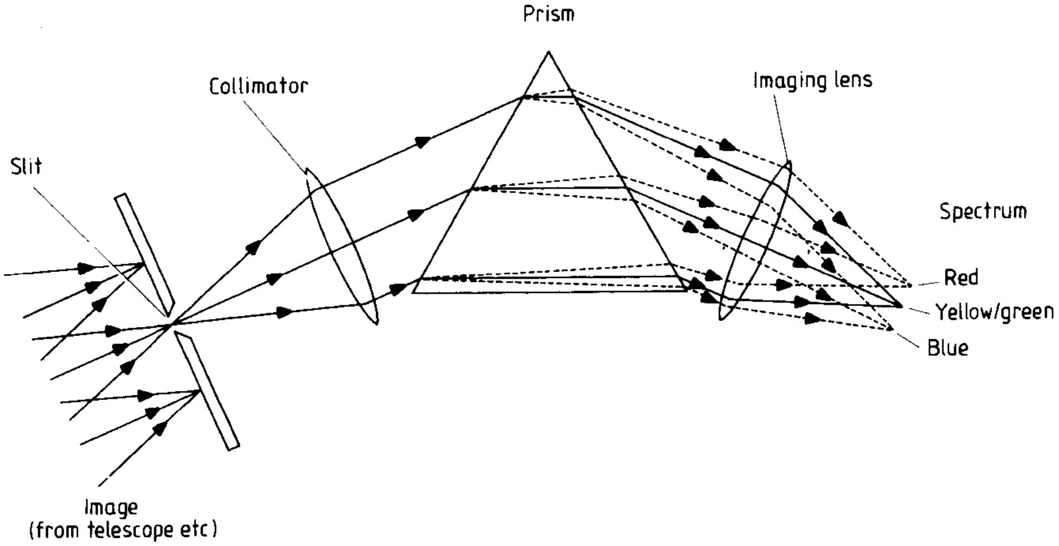

Figure 11: Basic spectroscope (Credit: C. R. Kitchen, *Astrophysical techniques*).

6.2 Spectroscopy

Spectroscopy is one of the most powerful techniques at astronomers' disposal. The technique of probing the light from remote sources provides a wealth of information about the chemistry (e.g. isotopic abundances) and physics (e.g. temperatures, dynamics, magnetic fields) of both remote objects and environments along the intervening line of sight.

The first observation of the dispersion of light when passed through a prism into a spectrum is credited to Isaac Newton (1642-12-25–1727-03-20). Using similar techniques, William Herschel (1738-11-15–1822-08-25) discovered infrared radiation in sunlight. Newton and later, William Wollaston (1766-08-06–1828-12-22) both noted the appearance of dark lines in dispersed sunlight. However, Joseph von Fraunhofer (1787-03-06–1826-06-07) is credited with the invention of the spectroscope and recording a characteristic sequence of several hundred dark 'Fraunhofer absorption lines' in the otherwise continuous spectrum of of the Sun.

In 1860 Robert Bunsen (1811-03-30–1899-08-16) and Gustav Kirchoff (1824-03-12–1887-10-17) used a spectroscope of enhanced design to identify a new element (Caesium, 1860) in the laboratory by spectral analysis (followed in 1861 by Rubidium).

During a Solar eclipse in 1868 Pierre Jules Janssen (1824-02-22–1907-12-23) observed a previously unidentified absorbtion line in the solar spectrum. Independently, Norman Lockyer observed a line at the same position in the and suggested the line was associated with a previously unidentified element. Lockyer proposed the name Helium. Helium was not isolated in a terrestrial setting until 1895 through the work of Per Teodor Cleve (1840-02-10–1905-06-18) and Nils Abraham Langlet (1868-07-09–1936-03-30).

A basic spectroscope (spectrometer / spectrograph) consists of at least five elements:

1. Entrance aperture (e.g. slit)
2. Collimator
3. Dispersion element (e.g. grating/prism/grism)
4. Focussing optics (e.g. camera lens)
5. Detector

Rudimentary (slitless) spectroscopy can be performed by assuming collimated light from a distant source and placing a dispersion element at the objective of the telescope (the entrance aperture) which functions both as entrance aperture and focussing lens. The detector can be an observers eye, or any other form of recording apparatus. Objective prism spectroscopy, where a prism is placed immediately in front of a telescope's primary objective was formerly a common method of performing such slitless spectroscopy. However, the use of refractive prisms as dispersing elements is limited by their relatively poor efficiency (due to absorption losses of light in the refractive medium) and difficulties in reliably manufacturing objective prisms matching increasing telescope apertures.

Today, various designs of plane diffraction grating are almost universally used as the dispersive elements in astronomical spectrographs. As such they are governed by the *grating equation* (equation 7):

$$d \sin(\theta_i + \theta_d) = m\lambda \tag{7}$$

where d is the distance from the center of one slit to the center of an adjacent slit, λ is the wavelength (d and λ expressed in the same units), θ_i is the angle of incidence, θ_d is the angle of refraction and m is an integer corresponding to the order of refraction.

Simple **transmission gratings** are not commonly used in modern astronomical spectrographs. For such gratings, the diffraction envelope has its highest amplitude at the zeroth order ($\theta = 0$) where chromatic dispersion is zero.

It is possible to shift the interference pattern envelope to preferred wavelenghth ranges. Conceptually, this can be achieved by placing a prism at each grating slit. This would have the effect of deviating the beam. However, the dispersive nature of the prisms would be an undesirable complication.

Introduction of a phase delay between successive planar wavefronts also results in a shift of the interference pattern. Practically, this is a achieved using a **reflection grating**, in which the slits of the transmission grating are replaced by tilted, or **blazed**, mirrors resulting from the facets cut into a reflective surface during manufacture and the grating surface is zigurated. The blaze angle determines the amount of envelope shift. Thus, blazed reflection gratings enable more efficient observation at higher orders.

A consequence of observing at high order is the potential for the extreme wavelengths of adjacent orders to overlap the order of interest. In cases where this effect is unwanted, **order sorting filters** can be placed in the beam to exclude these extreme wavelengths.

Echelle gratings take advantage of overlapping many very high order spectra. Coupled with a **cross disperser** — a low resolution dispersive element (grating or prism) with a disperison perpendicular to that of the echelle

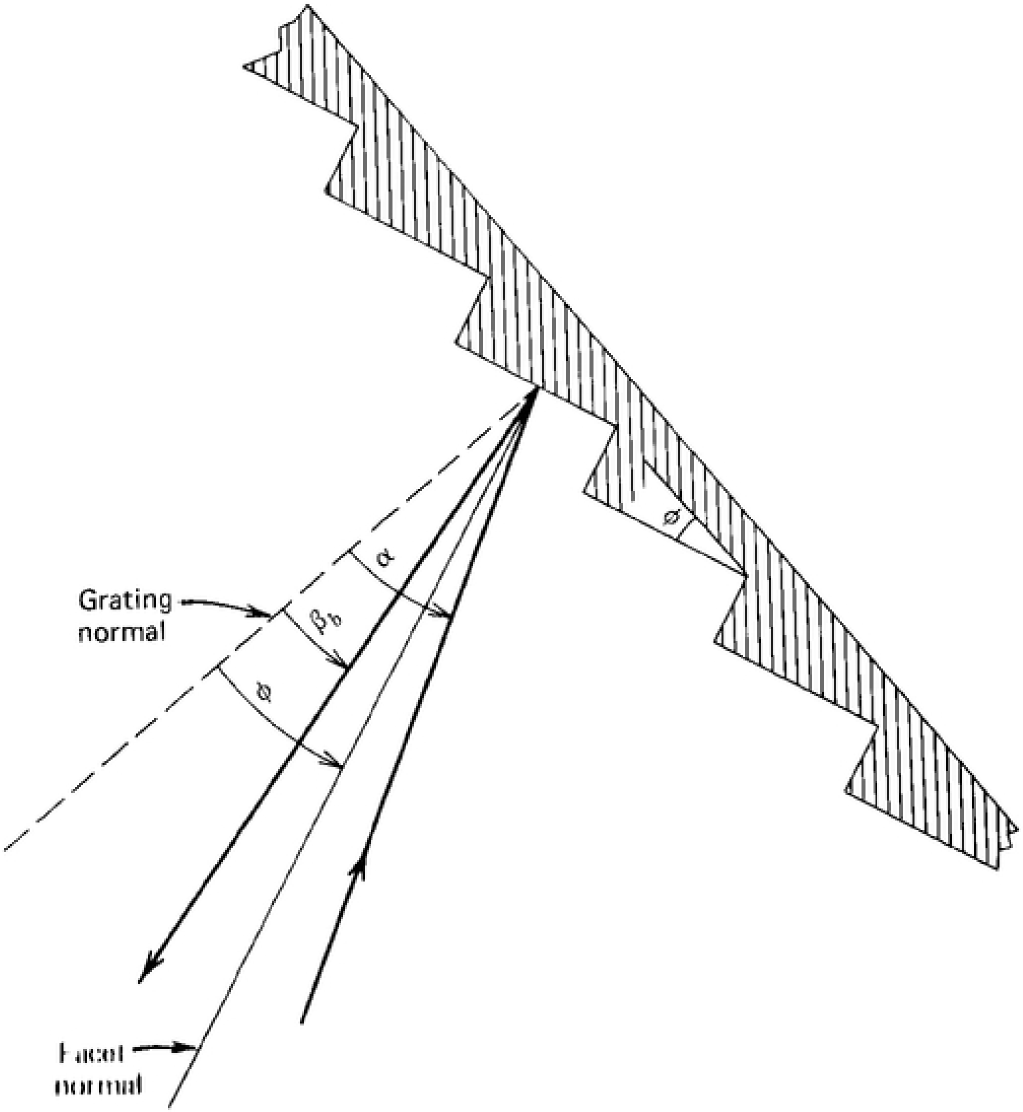

Figure 12: Blazed reflection grating in which β_b is the blaze angle. (Credit: D. F. Gray, *The observation and analysis of stellar photospheres*).

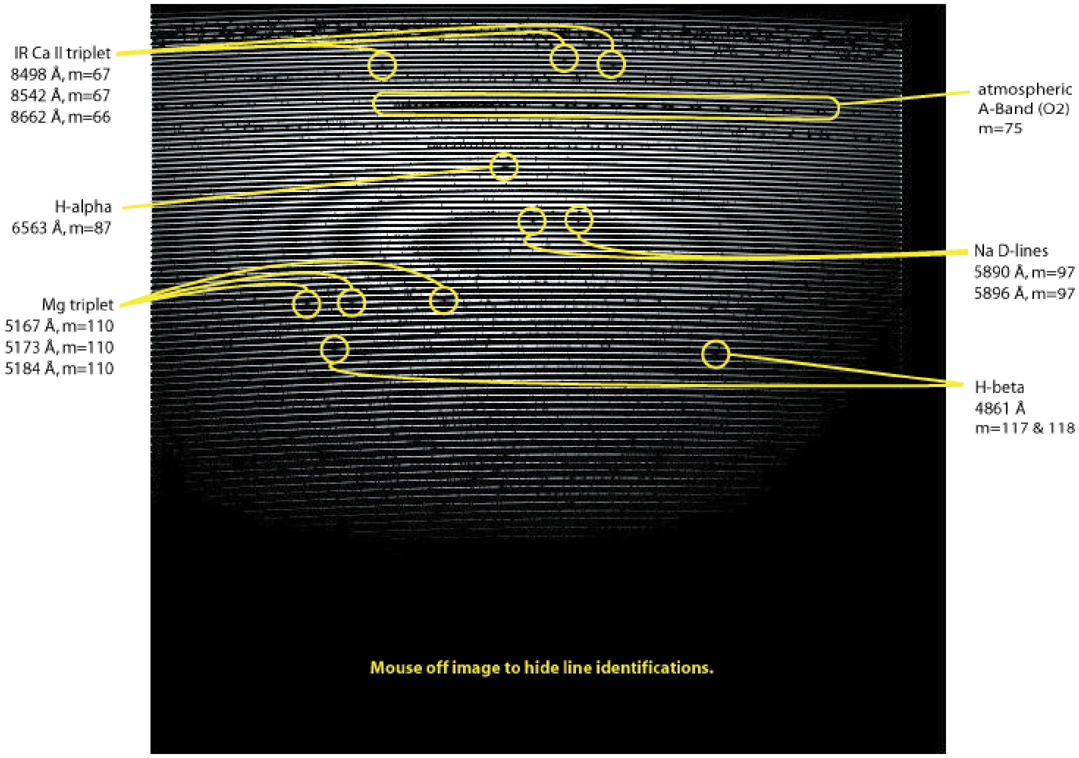

Figure 13: Anotated daytime sky spectrum. Hamilton Echelle Spectrograph. Mount Hamilton. (Credit: UCO/Lick; `http://mthamilton.ucolick.org/techdocs/instruments/hamspec/images/daysky`).

grating — overlapping orders are separated, stacked and recorded on a two-dimensional detector. While Echelle spectroscopy is a powerful high resolution technique, it does have limitations including steep variation in continuum with wavelength compromising accurate line profile measurements, a greater susceptiblity to scattered light, and curved spectra resulting from the cross dispersion optics.

Resolution and Resolving Power, R:

$$R = \frac{\lambda}{\Delta\lambda} \tag{8}$$

$$R = \frac{c}{\Delta v} \tag{9}$$

Grism. A grating and prism combination enabling both spectrosopy and imaging to be performed with the same camera optics.

Spectroscopic Modes

- Dispersion elements: Gratings, Prisms, Grisms; Resolution

- Long-Slit
- Fibre
- Multi-Object Spectroscopy (MOS/MXU)
- Integral Field
- Image Slicing

6.3 Polarimetry

- Imaging Polarimetry
- Spectropolarimetry

6.4 Modes

- Visitor/Local
- Delegated
- Remote
- Eavesdrop
- Queue/Service
- Target of Opportunity
- Rapid Response
- Robotic/Unsupervised

6.5 Utilities

Coordinate Lists ...

Finding Charts ...

Ephemerides & Almanacs ...

Efficiency and Overheads:

- The primary objective is to observe efficiently (i.e. by maximizing open shutter time and ensuring data relevent and useful both to you and potential future archive use — calibration and documentation are important). Despite these efforts overheads exist and should be planned for.

- Calibration, Pointing, Focussing, Slew, Acquisition and Guide, Read(-out), Technical — *Machines Break*.
- Have the next observation and configuration prepared, before the current observation completes. Ideally, plan at least a couple of sources ahead in the program, legislating for a possible change in conditions. Always have a calibration/standard source ready in case of difficulty acquiring a science source.
- **Be patient**: Each Telescope-Instrument combination has a rhythm at which the sum of all its configurable functions work. It takes a while to learn the rhythm of each. After sending a command, wait a moment. Wait a moment more. Force yourself to add another additional half-moment to give the function the opportunity to update.
- **Be patient**. After changing a function, it is wise to allow a couple of duty-cycles for the system to converge and damp onto the new configuration.

Logging …

Back-up Program

- Always have a back-up program(s) available in the event of poor conditions, degraded modes or technical failure.

Serendipity & Collaboration …

Public Outreach

- Do not lose sight of the 'Big Picture' — you may be called upon to discuss any aspect of astronomy. Have a plan.

7 Qualification

Assume poor data. Inspect data. Prove to yourself it is good data.

Monitor Changes: Temperature, Features, Seeing, Continuum, ...

Parallactic Angle: ...

Instrument Flexure: ...

Sky Background: ...

Calibration:

- Bias
- Dome Flat
- Sky Flat
- Super Flat
- Alternative, Narrow Band Flat
- Fringe Map
- Wavelength Calibration (Arc Spectra)
- Median v. Mean!

Calibration: Photometric Standards: Magnitude, Colour, Distribution, Timing

Calibration: Radial Velocity Standards

Calibration: Flux Standards, Slit losses

Calibration: Telluric Standards, Distribution, Timing

Calibration: Polarimetric Standards

Calibration: Linearity, Saturation, Gain, Remenance, QE...

8 What does it take to be an efficient observer?

> Planning. You must arrive with all the materials and all the numbers that you need. It would be very helpful if you had walked mentally through a script of the entire evening or observing run. This usually consists of afternoon calibrations and then twilight calibrations, evening observations and more twilight calibrations. So you had better have thought through exactly what you're going to look at, what the pointings are, what the exposure times are, what the position angle is, all of these parameters that you need for every observation. You should either have written them down or know them so well that you don't need to write them down. So I would say that's the first and foremost thing. Then attention to all the details as the data are coming in, because things go wrong. So you have to be extremely attentive. And this is probably the most wearing part of it, because you have to worry about it.

— Interview of Sandra Faber by Patrick McCray on 31 July 2002.
Niels Bohr Library & Archives,
American Institute of Physics,
College Park, MD USA
[http://www.aip.org/history/ohilist/25489.html]

Oh, I love observing

Oh, I love observing. Observing is addictive. Yeah... I like being alone with the telescope at night. It's almost a mystical experience. You sort of feel special... you're communing with the universe... looking at things that nobody has ever looked at before. I like that feeling. I am the first person in the history of the human race to make this observation... it's very satisfying... to do it well demands total concentration... You forget the rest of the world, because you have to. You have to be completely focused. I like the thought of being super efficient. I sort of look down my nose at observers who come ill-prepared and who waste telescope time.

— Interview of Sandra Faber by Patrick McCray on 31 July 2002.
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American Institute of Physics,
College Park, MD USA
[http://www.aip.org/history/ohilist/25489.html]

The Itinerant, Peripatetic Astronomer

An astronomer must be cosmopolitan, because ignorant statesmen cannot be expected to value their services.

— Tycho Brahe.
in Tycho & Kepler:
The Strange Partnership that Revolutionised Astronomy
by Kitty Ferguson (2002)

9 Resources

American Practical Navigator ('Bowditch', 1802) (National Geospatial-Intelligence Agency)
http://msi.nga.mil/NGAPortal/MSI.portal

The Astronomical Almanac and The Astronomical Almanac Online (HMNAO & USNO)
http://asa.hmnao.com/

Monthly Skymaps (Skymaps.com)
http://www.skymaps.com/

Getting Started in Astronomy (Sky and Telescope, 2003)
http://www.skyandtelescope.com/howto/basics/Getting_Started_in_Astronomy.html

A library of Stellar Spectra
Jacoby et al. 1984, Ap. J. Suppl., **56**, 257.