Chapter 6

Photometry

The original photometric system is the UBV (ultraviolet, blue, visual) system introduced around 1950 by Johnson and later extended with the R and I (red and infrared) bands. Classical photoelectric photometers employed photomultiplier tubes. Many different photometric systems were introduced later, particularly important was the extension to the near-IR and mid-IR bands with infrared detectors, and the introduction of radio flux measurements. Numerous new photometric systems were then introduced by the satellites covering the wavelength regime from the far-IR to the hard γ-rays.

6.1   Science considerations

The photometry, or the measurement of the spectral irradiance, is often a most important measurement for the characterization of an astrophysical target. The following parameters and deduced quantities can be derived from photometry:

– the detection proves the presence of a source,
– the apparent brightness of a source can be used for determining its luminosity,
– the morphology of the sources characterizes the type of object (extended / point like object; symmetric / asymmetric source, etc.)
– the spectral energy distribution (SED) yields the total apparent luminosity of the source and allows a characterization of all important radiation components in a system,
– the color of a system can already provide a good characterization of the system (e.g. temperature of a star, stellar population in a galaxy),
– the temporal variability of the source can be investigated with repeated observations.

Photometry measures a lot of the observable parameters provided by the electromagnetic radiation $\mathbf{I}(x, y, \lambda, t)$ from a target.

6.2   Photometric signal extraction

The first step in the photometric measurement is the extraction of the detector signal. We consider two methods: aperture photometry and PSF fitting.

6.2.1   Aperture photometry

Aperture photometry measures the light from a sources contained within an aperture in the focal plane. The aperture is usually circular and has a certain angular diameter.

With **photoelectric aperture photometers** the aperture was a hardware mask with a hole in the focal plane of the telescope. The photometric measurement consists then of:

– measurements of the flux for the target and the sky background $S_t + S_b$
– measurements of the sky background S_b only.

Subtraction of the sky measurement from the target plus sky measurement yields then the target signal:
$$S_t = (S_t + S_b) - S_b$$
This measurements for target and sky can be taken consecutively or simultaneously using multiple aperture instruments.

With **imaging detectors** one can select software apertures for the target and the sky. Usually a round aperture is chosen for the target with an annular ring just outside for the background. Software apertures can be optimized in various ways for improving the photometric measurements:

– accurate centering on the target,
– the size and the shape of the aperture can be adapted to each individual object,
– the aperture size can be reduced in order to reduce the disturbing background,
– for background subtraction a clean (object free) sky region can be used, which represents best the background at the position of the target,
– the impact of the selected apertures (target and background) on the photometric measurement can be investigated by varying the aperture geometry,
– possible uncertainties due to other sources or instrumental effects can be recognized in the image and considered in the analysis.

All these possibilities offered by imaging detectors should be considered in the signal extraction procedure in order to optimize the results.

6.2.2   PSF fitting

Point spread function (PSF) fitting or profile fitting uses model signals and fits them to the data. Usually the PSF has the shape of point sources, e.g. stars, in the analyzed image. The source model is varied until a good match is obtained for a source, or for all sources in the image. Software packages, e.g. DAOPHOT, ROMAPHOT, and others are available for this procedure. The flux of a target is then defined by the fitted model curve. The stellar images are usually fitted with a radial Gaussian intensity profile

$$I(r) = I_0 e^{-r^2/\sigma^2} , \tag{6.1}$$

where I_0 is the peak intensity, and r the radial distance from the center of the profile. The quantity σ measures the width of the flux distribution:

– $\pm 1\sigma$, a circle with $r = \sigma$, contains 68 % of the signal,
– $\pm 2.5\sigma$ contains 98.7 % of the signal,
– 1.665 σ corresponds to the full width at half maximum (FWHM) of the Gaussian peak.

The fitted PSF can be subtracted from the image. If significant residuals remain then there might be fainter stars close to the fitted source.
Double or multiple stars can be disentangled with a multi-PSF fitting to the blended sources. In this way the signal of all sources in a blend can be obtained.
Extended sources, like galaxies, can be fitted with more complicated flux distribution models. Such an approach provides then the flux contributions of different morphological components, like bulge, bar, disk, halo, etc.

6.3 Calibration of photometric data

Photometric calibration is the transformation of the reduced detector signal (number of photo-electrons) into an irradiance (or radiation flux) from the source outside of Earth's atmosphere. This procedure requires the determination of

- the instrument efficiency and wavelength dependence in the passband,
- the atmospheric transmission for ground-based observations.

The normal procedure is that one measures the signal of a target and of a well known photometric standard object with exactly the same equipment. The comparison of the two signals yields then the photometric flux of the target.

6.3.1 Magnitude system

The magnitude system is the photometric system used in the ground-based visual and infrared work. By definition the magnitude difference of two objects is:

$$\Delta m = m_1 - m_2 = -2.5 \log_{10} \frac{I_1}{I_2} \,. \tag{6.2}$$

The zero point for the magnitude system is defined by the standard star Vega, which is a 0-mag star in all wavelength bands.

$$\text{Vega}: \quad m_U = m_B = m_V = ... = m_N = 0.0^m$$

This means that also all colors of Vega are zero:

$$\text{Vega}: \quad B - V = m_B - m_V = m_X - m_Y = 0.0^m$$

Standard filters. Widely used standard filters for the measurements of stellar magnitudes are the Johnson filters.

Characteristic values for the Johnson filters are:

band	λ_{central} [nm]	width $\Delta\lambda$ [nm]	photon flux[a] 0^{mag}
U	360	70	$6.0 \cdot 10^7$
B	440	90	$1.5 \cdot 10^8$
V	550	90	$9.6 \cdot 10^7$
R	700	220	$5.5 \cdot 10^7$
I	880	240	$4.0 \cdot 10^7$
J	1250	380	$2.2 \cdot 10^7$
H	1650	310	$9.6 \cdot 10^6$
K	2200	480	$4.5 \cdot 10^6$
L	3400	700	$1.2 \cdot 10^6$
M	4900	300	$5.6 \cdot 10^5$
N	10200	5000	$5.7 \cdot 10^4$
Q	20000	5000	$7.3 \cdot 10^3$

[a]: photons $\text{s}^{-1}\text{m}^{-2}\text{nm}^{-1}$

There are many different types of photometric filter systems and the transformation of magnitudes from one system to another requires careful considerations. The problem is that even identical filters used in different instruments with a different spectral dependence of the efficiency produce different magnitudes.

Example. Two instruments use the same type of B-band filters with central wavelength 450 nm and a width of 80 nm, but instrument A has a blue sensitive CCD with essentially a constant quantum efficiency over the filter pass band, while instrument B has a red-sensitive CCD for which the quantum efficiency QE behaves like QE $\propto \lambda$ (40 % at 400 nm and 60 % at 500 nm) in this wavelength range. A red star will then have a higher flux (lower magnitude) when measured with instrument B.

Due to the dependence of the measured magnitudes on the instrument efficiency it is very helpful to use filters and aim for instrument efficiency curves which are similar or equal to a widely used standard photometric system. In this way one can use the existing magnitude measurements and color indices for the objects without the need to determine a new set of photometric standard stars or to define the correction values for the conversion of magnitudes of objects between the own system and a standard photometric system. This magnitude conversion depends essentially on the color of the measured objects.

6.3.2   Standard stars

Vega is far too bright to serve as calibration star for instruments built for galaxies and other faint objects. For this reason there exist many lists of faint photometric standard stars for visual and near-IR observations. For the mid-IR one uses bright red giants for the calibration because of the strong sky background at these wavelengths. Good photometric standard stars have the following properties:

  – photometrically constant object at the 0.1 % to 1.0 % level as proven by long term monitoring,
  – object with a normal continuum spectrum, in particular without narrow spectro-scopic features like strong emission lines,
  – single source without potentially disturbing other sources nearby.

A popular standard star list is given in: Landold A.U., 1992, Astronomical Journal Vol. 104, page 304.

6.3.3   Atmospheric transmission

In ground-based observations the flux from a source is attenuated by the Earth atmosphere. Even for clear atmospheric "windows" the atmospheric extinction is about 10 % and often significantly higher. For this reason the atmospheric transmission must be taken into account for photometric work. Various effects of the atmosphere have to be considered:

  – strongly variable transmission due to clouds,
  – airmass,
  – attenuation per unit airmass,
  – photometric scintillation due to atmospheric turbulence.

Clouds.   Clouds are very harmful for photometric measurements. Even a very thin, hardly recognizable layer of cirrus clouds can easily introduce transmission variations at a level of 20 % or more. For this reason one has to monitor carefully the clear sky conditions during the night and one should only use data taken under good ("photometric") atmospheric conditions. Nights with some signs of clouds should not be used for photometric work since it is often hard to clarify afterwards in the data reduction process whether unexpected and therefore particularly interesting measurements are real or just due to passing clouds. For this reason one should plan absolutely calibrated photometric

measurements preferentially for sites where the atmospheric conditions are often stable and reliable. Zurich is certainly not such a site.

Transmission of the "clear" atmosphere. The transmission T or attenuation $1 - T$ of the clear (cloud free) atmosphere depends on the wavelength dependent vertical optical depth $\tau(\lambda)$ of the atmosphere and the airmass.

$$T = \frac{I}{I_0} = e^{-\text{airmass} \cdot \tau(\lambda)} \tag{6.3}$$

The airmass accounts essentially for the zenith angle z dependent path length of the light through the atmosphere:

$$\text{airmass} = \frac{1}{\cos z} \quad (= \sec z) . \tag{6.4}$$

For large zenith angles $z > 60°$ one should use a more accurate formula. However, photometric measurements for large zenith angles are difficult and should be avoided.

The extinction $\tau(\lambda)$ is mainly determined by three principle atmospheric components:

– Rayleigh scattering by molecules
– aerosol particles
– molecular absorptions

Rayleigh scattering. Rayleigh scattering by molecules such as N_2 and O_2 depends on wavelength like $\tau \propto \lambda^{-4}$. It is very strong ($20 - 60$ %) in the blue / near-UV spectral region. Of course the Rayleigh scattering decreases with altitude like the air pressure.

Aerosol particles. Aerosols consists of fine dust, water droplets, ice crystals, and pollution. Aerosols are mainly a problem at low sites and much reduced at high mountain sites. The extinction by aerosols is rather weak, 5-10 % in the visual, and grey, like $\tau \propto \lambda^{-1}$.

Molecular absorption. Molecules produce discrete absorption lines and bands. The most important absorbers are ozone, water vapor, and oxygen.

– *Ozone:* O_3 is responsible for the UV transmission cutoff at 320 nm and a broad shallow extinction of 5 % between 500-700 nm.
– *Water vapor:* H_2O produces very strong line absorption bands in the infrared spectral region, which block at certain wavelengths essentially all the incoming light. The IR photometric bands are just located in the spectral bands between the strongly absorbing H_2O bands. Water vapor absorptions are also strongly attenuating the sub-mm to mm wavelength band in the radio domain. The mm-radio telescopes are therefore located at dry, high altitude sites like Mauna Kea on Hawaii (4000m) or Chajnantor in Chile (5000m).
– *Oxygen:* Molecular oxygen O_2 produces absorption bands in the visual, e.g. at 762 nm (A-band), 687 nm (B-band), and at 628 nm. These are narrow bands and their impact on photometric measurements can usually be neglected. A strong O_2 band is also present at 60 GHz in the radio range.

Photometric scintillation. The atmospheric turbulence cells with typical diameter of about 20 cm produce a time dependent focussing and defocusing of the incoming wavefronts resulting in a photometric scintillation for point sources: the stars twinkle. Planets twinkle much less because they are extended and therefore the small scale phenomenon

(coherence angle $\approx$ 5 arcsec) is averaged out. The flux variations are at a level of 10 %, on timescales of less than 10 ms, and for telescope apertures less than 10 cm.

The effect is strongly reduced for telescopes with large apertures $\gg$ 10 cm and long integration times $\gg$ 10 ms. On a 1 m telescope with integrations of $>$ 1 s the photometric scintillation is below 0.1 %.

At the level of $1.0 - 0.1$ % other instrumental effects become important. For example for imaging detectors the jitter of the star image on the detector pixels is an important source of error because the efficiency of the pixels needs to be calibrated with very high precision for an accurate measurement.

6.3.4   Summary on photometric calibration

For the photometric measurement one needs the following steps:

- a flux measurement for the target,
- flux measurement for photometric standard stars with the same instrument,
- correction for the atmospheric extinction for the target star and photometric standard star,
- flux ratio conversion into a magnitude difference,
- calculation of the magnitude of the target, using the magnitude of the standard star and the derived magnitude difference,
- consideration of possible color effects due to deviations of the instrument efficiency from the standard filter pass band.

The atmospheric extinction correction is not necessary if the target is measured in the same image (simultaneously) with the calibration source.

6.3.5   Relative photometry

The attenuation by clouds is roughly grey. For this reason one can still carry out "relative" photometric imaging when the sky conditions are not perfect. In this case one can measure the brightness of targets with respect to other objects in the same image, preferentially objects with known brightness. Different types of such science programs are possible, for example:

- measurements of the object magnitude on a relative scale, preferentially with respect to a well calibrated source in the field,
- measurements of the colors of an object, again relative to known sources in the field,
- search of objects with special colors or strong spectral features which can be recognized with special filters (e.g. Hα line filter),
- monitoring of the brightness variability with respect to non-variable objects in the field.

When planing "absolute" photometry then one should always consider a backup program for "relative" photometry, which can be carried out under non-photometric atmospheric conditions. Relative photometry can always be "upgraded" to an absolutely calibrated measurement with later "absolute" calibrations of the brightest, non-variable targets in the image.

6.4 Detection of faint sources

For the detection of faint sources one has to push the S/N ratio by enhancing the signal as much as possible and reducing the noise as much as possible. The accurate calibration of the data is not such an issue since the detection will have a low S/N, say S/N $\approx 5-10$ and the calibration must then also be only at this level.

Important points to be considered for an optimization of a detection are:

- optimization of the sky transmission,
- reduction of the sky emission,
- optimization of the instrument efficiency,
- the dependence on seeing.

Sky transmission. The sky transmission was discussed in detail in the previous section. The sky transmission can be optimized by observations near the meridian (minimum air mass for given telescope latitude and object declination). This is particularly important for wavelength regions where the atmospheric absorption is significant. For example when asking for ESO service time, one can specify conditions for the airmass.

For wavelength bands where absorption by water vapor is important one should try to carry out the observations during "dry" nights, if possible.

6.4.1 Sky emission

A dark sky is an important precondition for the detection of faint sources. There are several components which can contribute to the sky emission:

- artificial lights,
- twilight,
- moon light,
- scattered light from interplanetary dust,
- airglow and auroral emission,
- thermal emission from the atmosphere and the telescope.

Artificial lights. The modern civilization produces a lot of artificial light which is very harmful for astronomical observations from the ground. For this reason it is important to protect observatories from disturbing light sources. Faint sources (galaxies) cannot be studied at sites with significant light pollution.

We should also reduce the "light pollution" in populated areas in order to protect good dark sky view to the stars and the Milky Way for the general public.

Twilight. The average time from sunset to sunrise is 12 hours. However there is quite some time after sunset and before sunrise where the sky brightness is still very high due to the twilight. Different phases of twilight are distinguished depending on the angle θ_s of the sun below the astronomical horizon.

- civil twilight: $\theta_s = 0°$ to $-6°$,
- nautical twilight: $\theta_s = -6°$ to $-12°$,
- astronomical twilight: $\theta_s = -12°$ to $-18°$.

For observations of faint sources in the visual region one should avoid astronomical twilight. For near-IR work and bright targets (standard stars) one can use also observations taken during nautical twilight while mid-IR observations are not much affected by the twilight. The sun position moves 15° per hour so that the duration for astronomical observations during one night is roughly the time between astronomical sunset and sunrise minus about 2 hours.

Moon light.   Solar light, reflected from the moon is scattered in the Earth atmosphere and contributes to the sky emission. The dominant process is Rayleigh scattering with some contributions due to scattering by aerosols and clouds. Moon light is particularly strong in the near-UV and blue (Rayleigh scattering) and decreases towards longer wavelengths. The effect of the moon light can be neglected in the near-IR and mid-IR.

The scattered moon light depends strongly on the moon phase and changes the sky brightness dramatically (more than a factor of 30) in the visual. For this reason the moon phase is an important constraint for observations of faint sources. Observatories distinguish for their observing time scheduling between:

  – dark time: new moon phase ± 3-4 days,
  – grey time: half moon phase ± 3-4 days,
  – bright time: full moon ± 3-4 days,

The following table gives an overview of the sky brightness in mag arcsec^{-2} as function of the moon phase.

days from new moon	U	B	V	R	I	z
14	17.0	19.5	20.0	19.9	19.2	18.1
10	18.5	20.7	20.7	20.3	19.5	18.3
7	19.9	21.6	21.4	20.6	19.7	18.6
0	22.0	22.7	21.8	20.9	19.9	18.8
sky brightness for new moon without atmospheric emission lines						
0	22.0	22.7	22.0	21.0	20.5	20.5

Airglow and auroral lines.   The whole red and near-IR region is strongly contaminated by numerous narrow (line width < 0.05 nm) emission lines due to the OH molecules. These lines are a major problem for the detection of faint sources. For example, for high redshift objects the Lyα cutoff is at $(z + 1) \cdot 121$ nm, or at 847 nm for $z \approx 6$. This means that the emission of high redshift objects has to be searched in the spectral region where the OH emission dominates (and which is also affected by H_2O absorption lines). The OH emission is induced in a thin layer at an altitude of 90 km by solar UV radiation. The strength of the emission can vary by a factor of 2 or more within one hour due to large scale wave motions near the mesopause.
The OH lines are blended for small spectral resolution of $R < 500$. For a higher resolution one can investigate the region between the lines and search for faint sources. This possibility is exploited with massive 3-D spectrometers with spectral resolution > 1000.

In the visual regions there are only a few strong auroral lines, for example due to atomic oxygen; O I at 556 nm, 630nm and 636 nm. They are strongly variable in time and from location to location.

Scattered light from interplanetary dust. The reflection of solar light by interplanetary dust produces the zodiacal light and the gegenschein. These two components dominate the sky emission in the 350-750 nm region at a dark site (without moon). The gegenschein is a feature due to the enhanced back-scattering of dust particles and it is therefore located around the "anti-sun" direction.

Thermal radiation. The thermal radiation of the atmosphere and telescope starts at about 2.2 μm and it increases strongly towards longer wavelengths.
Since the atmosphere and the telescope optics have a temperature T they emit a thermal blackbody radiation

$$S_\lambda = \epsilon_\lambda \cdot B_\lambda(T)\,, \tag{6.5}$$

with an emissivity of ϵ_λ. According to the Kirchhoff law the emissivity is related to the absorption κ_λ of the atmosphere or an optical component

$$\epsilon_\lambda = 1 - \kappa_\lambda \tag{6.6}$$

Atmosphere: The absorption of the atmosphere is dominated by the water vapor layers and the corresponding temperature is given by the average temperature of these layers. The emissivity is:

- $\epsilon = 1$ at wavelengths where the atmosphere is opaque,
- $\epsilon \approx 0.1$ in good spectral windows with low absorption.

Telescope and instrument: The telescope is typically $\approx 20°$K warmer than the atmosphere (water vapor). Therefore the telescope emission is higher at wavelength $< 13\ \mu$m. A typical telescope mirror reflects $R = 0.95 - 0.99$ of the light and the transmission through a lens is also at the $T = 0.95 - 0.99$ level. Thus the total emissivity of the telescope and instrument is the summed up emissivity contribution of all warm components. In addition one has to consider the opaque dust on the components which emit like blackbodies with $\epsilon = 1$. In particular the primary mirror of astronomical telescopes can be pretty dirty with dust covering several % of the surface. The dust on dirty components can add a dominant contribution to the thermal emission budget. The instrument emission is reduced by putting most components into a cold dewar.

6.4.2 Optimize instrument efficiency

For faint sources it is important to understand well the instrumental limitations on throughput and sensitivity. The goal is to have as much signal as possible and to reduce the noise signal as much as possible.

The design of a telescope or an instrument must be optimized for high throughput. The transmission of an instrument can be enhanced by using a minimum number of optical components with high efficiency, because mirrors do not reflect all light and transmission optics does not transmit all light. In the final efficiency budget the efficiency of each component must be multiplied.

A strongly simplified example for a transmission budget of an imager:
Typically a telescope has two aluminum mirrors which reflect each about 90 % of the light. A collimating lens system and a camera lens system transmit each about 95 %, the transmission of a broad band filter in the passband is about 80 %, and a detector can have a quantum efficiency of 80 %. The total efficiency is then given by:

$$0.90^2 \cdot 0.95^2 \cdot 0.80 \cdot 0.80 = 0.47$$

This simple example shows that a significant fraction of the photons are "lost" in the instrument.

Often one has to work with a given instrument. Despite this one can still optimize the detection efficiency with a good observing strategy.

The signal can be enhanced by selecting an optimum instrument configuration:

– select a pass-band where the signal from the target is strongest,
– use the instrument configuration with the highest quantum efficiency in the selected pass-band,
– enhance as much as possible the width of the pass-band,
– optimize the integration time by reducing overheads.

On the other side one has to reduce as much as possible the noise sources with good choices for the instrument configuration:

– select a passband which minimizes the sky background (the thermal emission),
– select detector modes with the lowest detector noise level,
– optimize the spatial resolution of the detector to the required spatial resolution of the observations. As a rough rule the full width at half maximum of the source (in seeing limited or diffraction limited observations) should match about 2 detector pixels.

Often it is not possible to optimize the throughput without enhancing also the background. Therefore one should carry out a trade-off study and compare the different options.

6.4.3   Dependence on seeing

The spatial resolution is very important for the detection of faint, point-like sources in background noise limited observations. If a point target S_t can be focussed onto a smaller detector area then the S/N is strongly enhanced, because the sampled background signal decreases like the area of the focussed target image.

$$S_b \propto \text{area} \approx \text{seeing}^2 \,.$$

Thus, the S/N-ratio behaves like

$$\frac{\mathbf{S}}{\mathbf{N}} = \frac{S_t}{\sqrt{S_t + S_b}} \stackrel{S_B > S_t}{\approx} \frac{S_t}{\sqrt{S_b}} \propto \frac{1}{\text{seeing}} \,. \tag{6.7}$$

The seeing is therefore a most important parameter for the detection of faint sources. For a good site and for an excellent telescope like the VLT the seeing can be as small as 0.4 arcsec, with a median value of about 0.8 arcsec.

Achieving an enhanced spatial resolution has therefore not only the goal to get sharper images but also a deeper detection limit. This explains the huge efforts made for achieving a better spatial resolution with adaptive optics at ground-based telescopes.

6.5 High precision photometry

High precision photometry at a level of better than $\Delta m = 0.01^m$ is useful for many applications. Two examples are:

- Search for subtle photometric differences of stars in a star cluster in order to distinguish stellar populations which differ in age (multiple main sequence turn-offs) or metallicity (spread in the main sequence or the red giant branch).
- Search for planetary transits in high precision light curves of stars. The typical signal of a transit from a Jupiter-sized object is about 1 % and of a terrestrial planet 0.01 %.

These two example must achieve two different flavors of photometric precision.

Star cluster photometry. Photometry of rich stellar fields can be carried out as "relative photometry" where the brightness of sources can be determined with respect to other stars in the field. In this application it is important to reach a high fidelity of the relative magnitude measurements over the whole field of view. Two important aspects which must be considered are:

- *Field dependent transmission:* For many telescopes and instruments the transmission can be slightly lower for off-axis regions when compared to on-axis regions. Such a radial gradient in the transmission may be introduced by vignetting or an incident angle dependent transmission of strongly curved lenses. Such effects may be recognized and corrected with sky flatfields.
- Field dependent PSF: Coma or other aberrations may produce less well focussed stellar images in the outer regions of the field of view. The extraction aperture should take the field dependent PSF of stars into account in order to avoid a spurious radial dependence of the flux measurement.

High precision light curves. Photometry of single targets at a level of $\Delta m = 0.01^m$ is a real challenge for ground based instruments, because atmospheric transmission variations and instrument drift can produce disturbing signals which are hard to disentangle from real variations of the target. Possible ways to solve the problem are:

- Simultaneous, multiple-site observations are a powerful way to disentangle local atmospheric effects and telescope specific features from real variations,
- relative photometry using targets in the same field of view as reference is an easy solution. However, for bright targets this is often not possible, since usually the other stars in the field are too faint for an accurate calibration of the primary target. A wide field system providing simultaneous observations of several bright stars can solve this problem.
- space observations do not suffer from atmospheric transmission variation and therefore provide a much higher photometric precision for light curves than ground-based observations.

6.6   Thermal infrared

We compare the sky surface brightness at different wavelengths in order to illustrate the brightness of the thermal radiation in the IR.

– blue at 0.45 μm: m = 22 mag/arcsec^2 (no moon)
– near-infrared at 2.2 μm: m = 13.5 mag/arcsec^2
– mid-infrared at 10 μm: m = -3 mag/arcsec^2

(Exercise: calculate the number of photons per sec and m^2 in the corresponding broad band filters B, K and N).

Thus, typically the sky is much brighter than the target in the mid-IR. An additional problem is that the thermal emission is strongly variable in time with gradients over the sky. Therefore one has to apply accurate procedures for the sky subtraction.

Chopping and nodding.   One technique for an accurate subtraction of the sky emission is chopping. The infrared beam is rapidly switched between the source position and a nearby sky reference position by a wobbling secondary mirror in the telescope (or an intermediate pupil mirror in the instrument). Typical chopping frequencies are 10 - 20 Hz. The subtraction of the sky observation from the target observations then yields the target signal. With this procedure only half of the telescope time is used for on target integrations. The sky frame serves not only for background subtraction but also for bad pixel identification and flatfielding.

In addition it is usually necessary to move the entire telescope (to nod the telescope) every minute or so to measure the sky background on the other side of the target to eliminate a possible large scale gradient in the sky emission or the instrument. Nodding requires some overhead time because the telescope has to be moved.

If small sources are observed with mid-IR detector arrays providing sufficient field of view, then the chopping and nodding can be performed with the target always in the field of view of the detector. The target is then observed at two or more "dithering" positions.

Subtraction of two images taken with some spatial offset then yields the sky corrected target signal, once as positive signal and once as negative signal. Both signals can be added up. Again the pure sky area present in both frames is useful for detector pixel calibration.

Image dithering.   When defining a dithering pattern for imaging one should avoid periodic offsets. If the dithering pattern uses a regular grid with redundant offsets values $n \cdot \Delta x$ and $n \cdot \Delta y$, then non-related sources located at a separation near to Δx or/and Δy from the main target will disturb the sky subtraction for many frame combinations.

6.7 Narrow band photometry

Narrow band imaging provides the opportunity to measure emission line intensities of astrophysical emission nebulae over an extended field of view. Emission nebulae are an important class of extended astronomical objects which emit strong emission lines. Narrow band imaging and photometry of emission lines is an obvious technique since it reduces strongly the background but hardly the signal. The background is roughly proportional to the filter width $S_b \propto \Delta\lambda$ and therefore S_b is much reduced for a filter width of $\Delta\lambda = 5$ nm when compared to a broad band filter with $\Delta\lambda = 100$ nm.

Narrow band interference filters are based on the principle of Fabry-Perot interferometers. Two highly reflecting parallel plates are placed in the beam with a small spacing d. A fraction of the light is reflected back and forth between the plates. The transmission is strongest if a constructive interference takes place, when the half wave criterion is fulfilled:

$$d = \frac{m}{2}\,\lambda\,,$$

where m is an integer number (assuming an air space with refractive index $n = 1$). This indicates that the

- transmission has maxima for the wavelengths $\lambda_m = 2d/m$ where the interferences are constructive. For example for $d = 5$ μm the maxima are e.g. at 500 nm ($m = 20$), 526 nm ($m = 19$), 556 nm ($m = 18$), etc.
- transmission minima occur between the maxima at $\lambda = 2d/(m + 1/2)$.

For plates with reflecting coatings $R > 0.5$ the light can bounce back and forth several times k and create higher orders of interferences. The effective spacing is multiplied by an integer number. If higher orders contribute then the following will happen with the maxima (e.g. $m = 20$):

- constructive interference for light bouncing several times back and forth $\lambda_{20,1} = \lambda_{40,2} = \lambda_{60,3} = ...$, but the interference peaks will become narrower when higher orders are added.
- the different orders have the amplitude T (just transmission), TR^2 (first order), TR^4 (second order), ..., and the higher orders get more weight if the reflectivity of the surfaces increases. The reflecting surfaces should not absorb the light in order to avoid a strong reduction of the throughput. Dielectric layers are essentially non-absorbing and one can write $T = 1 - R$. The peak transmission is then

$$T + TR^2 + TR^4 + ... = (1 - R)(1 + R^2 + R^4 + ...) \approx \frac{1 - R}{1 - R^2} \approx \frac{1}{1 + R}\,. \qquad (6.8)$$

– The finesse F defines the ratio between the full width at half maximum intensity $\Delta\lambda$ of a peak and the separation of the periodic peaks $\delta\lambda$ (for $R > 0.5$)

$$F = \frac{\Delta\lambda}{\delta\lambda} \approx \pi\frac{\sqrt{R}}{1 - R}\,. \tag{6.9}$$

An interference filter must be combined with a bandpass filter in order to select only one transmission peak of the periodic transmission pattern.

Angle dependence. An important issue of interference filters is the angle dependence. For an inclined ray with an angle θ with respect to the paraxial ray the spacing d of the parallel plates is a bit larger

$$d \to \frac{d}{cos\theta}\,.$$

This dependence introduces an angle dependence in the central wavelength of the filter. If such filters are located in the collimated beam then this translates into a radial field dependence. One should consider this problem when planing or analyzing data taken with narrow band interference filters.

Interference fringes. Partially transmitting parallel layers can produce disturbing interference patterns for narrow band imaging. Like in interference filters the light can bounce back and forth and produce an interference for monochromatic light. If layer thickness varies as function of the beam position then the instrument transmission depends on the beam location. This effect is averaged out

– for broad band observations because the interference of different wavelength average out,
– for components away from the focal plane because of spatial averaging.

However, the silicon layer of back-illuminated, thinned (30 μm thickness) CCDs are transparent for $\lambda > 700$ nm and an interference or fringe pattern is produced for monochromatic light which can hardly be avoided. The intensity fringing is hard to calibrate and usually an uncertainty remains because the light from a calibration source differs in the wavelength distribution from the light of a target.

6.8 High speed photometry for lunar occultations

An occultation is the obscuration of a radiation source by an astronomical object. Well known examples are solar eclipses and lunar occultations.

Different types of occultations are summarized in the following table:

occulted object	occulting object	what can be learned
sun	moon	tenuous and faint outer atmosphere and corona of the sun can be studied in great detail, because the glare of the solar photosphere is blocked
distant object	moon	the exact positions of the occulted object can be determined and from the Fresnel diffraction the diameter of the source can be derived
star	asteroid	with multi-site observations the shape of the shadow of the occulting body can be mapped
star or spacecraft	planets and rings	light-curves of the attenuation of the radiation from a star or spacecraft yields information on the structure of the atmosphere or circumplanetary (ring) material. For spacecrafts also the time delay of a timing signal caused by the refraction and deflection in the intervening medium with refractive index $n > 1$ can be studied.

Solar eclipses, asteroid and planet occultations are specific applications providing important results in solar systems research.

Lunar occultations. Lunar occultations have a wide range of applications in astronomy and therefore a description of the effect is given. Lunar occultations are also a very nice example for high speed photometry and Fresnel diffraction (see Sect. 4.1.3).

We consider Fresnel diffraction at a knife edge for monochromatic radiation λ from a source. The phase difference δ [in radians] between the direct and diffracted light at a point P located at a distance $y = d_2 \tan \theta$ from the nominal (geometric) shadow border is:

$$\delta = \frac{2\pi}{\lambda} \left(d_1 + \sqrt{d_2^2 + (d_2 \tan \theta)^2} - \sqrt{(d_1 + d_2)^2 + (d_2 \tan \theta)^2} \right)$$

The phase differences δ simplifies for small θ ($\tan \theta \approx \theta$) and for stars occulted by the moon ($d_1 \gg d_2$) to

$$\delta \approx \frac{2\pi d_2}{\lambda} \theta^2 \,. \tag{6.10}$$

Depending on the phase difference δ between direct and diffracted light there will be local interference maxima and minima. Interference maxima will occur at $\delta = 2\pi \, m$ or

$$\Delta y = d_2\theta \approx \sqrt{m \, \lambda \, d_2} \qquad (6.11)$$

A typical value for the wavelength $\lambda = 500$ nm is $\Delta y \approx 14$ m for the first maximum $m = 1$ and using a typical Earth-Moon distance of $d_2 = 3.84 \cdot 10^5$ km. The typical frequency for the visual oscillations are about 80 Hz.

From lunar occultations of an astronomical source one can study:

– the exact position of the target; this can be particularly important for wavelength ranges with limited spatial resolution,

– the presence and relative position of a second close component; this is particularly useful if one likes to know the luminosity ratio of unresolved binaries,

– the diameter of extended sources can be measured from the smearing of the fringe pattern; this is a powerful method for the measurement of stellar radii.

The first two cases require "only" an accurate timing for the occultation of the source or the different components of unresolved sources.

For the **source diameter measurement** the fringe pattern has to be resolved and the strength of the oscillations has to be measured. The fringe pattern is strongest for a point source while the pattern is averaged down for extended sources. Thus, one needs to choose a wavelength short enough so that the source is extended with respect to the fringe pattern, as projected onto the sky.

The fringe pattern measurement is demanding since the individual fringes must be resolved what implies the following restrictions:

– a detector system with sufficient temporal resolution,

– the telescope aperture must be smaller than the typical dimension of the fringe pattern Δy,

– the wavelength band must be sufficiently narrow to avoid spectral smearing of the fringes,

– astronomical object must be sufficiently bright for the used equipment for a good S/N-ratio per time interval.

6.9 Advantages of space telescopes for photometry

Space telescopes provide significant advantages because they can observe wavelength ranges which are not accessible by ground-based telescopes. But space telescope are also extremely useful for the visual and IR regions, where observation with large ground-based observations are possible. Examples for space telescopes are:

– The Hubble Space Telescope, HST, is an observatory with a 2.5 m Cassegrain telescope and several imaging and spectrographic instruments for the UV, visual, and near-IR region. It is operational since 1990 and due to its extreme success still a flagship of the current space missions.

– Kepler is a single purposed instrument for exoplanet transit search. It is based on a wide field Schmidt telescope with an aperture of 95 cm and a field of view of about 12° diameter and equipped with 42 CCD to measure the broad band light-curves of more than 100'000 stars brighter than $m_v = 14$ for 3.5 years in a particular sky region in Cygnus. The images are intentionally defocussed to 10 arcsec to improve the photometric precision. The Kepler mission started in 2009 and the main goal is to find transits from Earth-like extra-solar planets.

– The James Webb Space Telescope, JWST, will be launched around 2017. It is a infrared optimized telescope with a primary mirror of 6 m diameter and it will be located behind a huge sun shield near Lagrange point 2 at a distance of $1.5 \cdot 10^6$ km from Earth (4 times further than the moon). Behind its sun shield and protected from the radiation from the sun, the Earth and the moon the telescope will be at a temperature of 50 K. Therefore, the thermal background will be extremely low providing exquisite sensitivity for the infrared spectral region. JWST will be equipped with imagers and low to medium resolution spectrographs covering the wavelength range from 0.6 to 30 μm.

Most important advantages of space telescopes for the measurements of astronomical sources are:

– low sky background, no sky line emission, no scattered light from the moon (HST, Kepler, JWST)

– photometric measurements are not affected by variable sky transmission effects. This allows to reach a photometric stability at a level of 10^{-4} (HST, Kepler, JWST)

– diffraction limited resolution (down to 0.05 arcsec) with a stable point spread function (HST, JWST)

– strongly reduced thermal emission (JWST)

– no atmospheric absorption in the near-IR and mid-IR (HST, JWST)

– no atmospheric absorption in the near-UV and UV (HST)

Considering all these advantages, it is not surprising that the space telescopes are pushing the observational frontiers in astronomy.