Basic Observation Training by a Small Telescope (2018)

平成 30 年 11 月 9 日

1 Purpose

This course is to carry out basic astronomical observations by a CCD camera, utilizing the 21cm telescope at IoA. The main goal is to master the basic technique to operate a telescope, to understand the basic concepts of observations under the equitorial coordiate system (RA, Dec), and to master the observation methods using a CCD.

Every year, we attempt to improve the sensitivity by upgrading the CCD camera system and the telescope system , and confirm if it is achived through real observations. Through these processes, we expect you to develop deeper understanding of the concept of "limiting magnitude".

The telescope and the equator mount system is renewed in 2016, and also various new filters are introduced including standard $UBVRI$ as well as narrow-band filers (Hβ, [OIII], Hα, [SII]), however, their performances are not fully verified yet.

Thus, we will work on following items this year ;

Master the operation of the telescope and the equator mount.

Verify the performance of the CCD camera, such as pixel scale and readout noise

Verify the performance of the new filters

Estimate limiting magnitudes

Verify the limiting magnitudes through follow-up observations

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Manuals and documents of the telescope system are available at
`http://www.ioa.s.u-tokyo.ac.jp/~kmotohara/30cm/`

Select 「講義など」→「2018 基礎天文学観測」 in the menubar of
`http://www.ioa.s.u-tokyo.ac.jp/~kmotohara/wiki/` for the website of this course
(Shortened URL :`https://goo.gl/ojMWTu`)

2 Limiting Magnitude

2.1 System Efficiency

System efficiency is defined as

"fraction of photons detected as electrons in the CCD to those entered a telescope aperture".

Number of photons from a target object (s_i (/s)) is

$$s_i = \pi \left(\frac{D}{2}\right)^2 \frac{\Delta\lambda F_\lambda}{h\nu} \tag{1}$$

where

D :aperture of the telescope
F_λ :flux of the object
$\Delta\lambda$:wavelength range of a filter

and number of electrons generated at the CCD (n_i (e^-/s)) is

$$n_i = \frac{N f_{conv}}{t} \tag{2}$$

where

N :counts on an image
f_{conv}:conversion factor
t :integration time.

Therefore, the system efficiency η can be written as

$$\eta = \frac{n_i}{s_i} \tag{3}$$

.

2.2 Limiting magnitude (in case of a single pixel)

To define a limiting magnitude, we introduce a quantity S/N, a signal-to-noise ratio, and if the incoming signal is larger than the noise level by a factor of S/N , we consider the signal to be detected. In the optical-IR imaging, $S/N = 5$ is often used as a threshould.

In our case, S/N can be written as

$$\begin{aligned} S/N &= \frac{n_i t}{N_{\rm noise}} \\ &= \frac{\eta\, s_i t}{N_{\rm noise}} \end{aligned} \tag{4}$$

, where $N_{\rm noise}$ is the noise and t the integration time.

The noise consists of the Poisson noise of the incoming photons and the readout noise of the CCD, and can be written as

$$N_{\mathrm{noise}} = \sqrt{n_i t + n_{\mathrm{sky}} t + n_{\mathrm{dark}} t + N_{\mathrm{read}}^2} \tag{5}$$

, wehre $n_{\mathrm{sky}}(\mathrm{e}^-/\mathrm{s/pix})$ is the deteted background photon count rate per pixel, $n_{\mathrm{dark}}(\mathrm{e}^-/\mathrm{s/pix})$ the dark current electron rate per pixel, and $N_{\mathrm{read}}(\mathrm{e}^-\mathrm{r.m.s./pix})$ the readout noise of the CCD per pixel per readout.

2.3 Limiting magnitude (in case of multiple pixels)

What's going to happen when the stellar image is extended over several pixels of the CCD?

In that case, we have to consider the noises from multiple pixels, and add them statistically, that is, when the stellar image is extend to m pixels, the noise N_{noise} can be written as

$$N_{\mathrm{noise}} = \sqrt{n_i t + m n_{\mathrm{sky}} t + m n_{\mathrm{dark}} t + m N_{\mathrm{read}}^2} \tag{6}$$

3 CCD Camera

3.1 Functional Principle of CCD

- Principle of CCD is available at
  `http://www.kusastro.kyoto-u.ac.jp/~iwamuro/LECTURE/OBS/detector.html`
- For its data reduction, refer to 西浦版『可視光域データ・リダクション法』.

3.2 How to use the FLI CCD camera

3.2.1 Power-on

- Turn on the power by connecting the power cable to the CCD camera.
- Boot toe linux not PC to control the CCD camera
- Login username is `tct2017` (password will be delivered on the first day of the course)
- Wait for ∼10 min for the CCD camera to be cooled down.

3.2.2 Image Acquisition

Open a terminal on the Linux PC and run the following commands:

- `ds9 &` to start the QL viewer,
- `acqfliframe (e or d) (time)` : Exposure(e) or take dark(d) with the integration tim of (time).
- `n_acqfliframe (e or d) (time) (N)` : Exposure(e) or take dark(d) by (N) times with the integration time of (time).

3.3 Filter Exchange

All the filters are housed in the filte wheel, and controlled via USB. The command is ;

```
flifilter (filter name)
```

where the filter can be chosen either by its name (`B, V, R, I, Hb, O3, Ha, S2`) or its slot number(1–8).

Name of the filter is inserted to a header of an acquired image.

3.3.1 Setting Parameters

Parameters such as header information of FITS image frames, directory to which the frames are saved, current filter, and installed filters are all managed by mySQL server of the local machine.

List of keywords and their current values can be referred at

`http://localhost/ccd.php`

, or `statall` command.

To see or change each keyword, use

```
status (Keyword)
status (Keyword) (Value)
```

command.

3.3.2 Important Keywords

Keywords that should be set during observations

- `DATA_DIR_NAME` : data path
- `OBJECT` : object name
- `WEATHER` : weather
- `OBSERVER` : name of observers

Keywords used for FITS header

- `CCD_SERIAL_NUMBER` : frame ID
- `CCD_TEMP_CUR` : current temperature of the CCD chip

4 What to Do before Observation

4.1 今夜の星空のチェック

Use night-sky simulator such as `Stellarium`. (`http://www.stellarium.org/ja/`)

4.2 Select the Star to Observe

4.2.1 For Measurement of System Efficiency

Use `Stellarium`, where magnitudes (at V-band) of stars are displayed.

4.2.2 For Measurement of Limiting Magnitudes

As you need to select stars fainter than 10mag, use online-catalogs, such as aladin sky atlas (`http://aladin.u-strasbg.fr/`) which have GUI interface and is easy to use
As catalog magnitude is not always that of the filter band you are using, so you have to make some estimate in such case.

4.3 Obtain Calibration Data

4.3.1 Bias and Dark Frames

Obtain at least 20 frame for dark and bias. As of dark frames, you have to take them with the exposure time with which you observed.

4.3.2 Flat Frames

Put a white paper in front of the telescope, illuminated by a light, and take images.

4.4 Chek Readout Noise

Take two bias frames, and

- subtract each othe,
- divide by $\sqrt{2}$,
- and get statistics by `imstat nclip=3 (filename)`, then the stddev is the readout noise in ADU unit.

5 Data Reduction

5.1 Computers to Use

Linux machines (ioa09, ioa10, ioa11) are available at the laboratory, but we recommend to use your own PC if you have.

If you use your PC, plase install linux environment and IRAF in it (Ask your tutor how to do it).

5.2 Account Name and Password

Account name is

```
tctcam
```

.

5.2.1 Transfer Frames

To transfer the acquired frames to ioa09, ioa10, and ioa11, you have to copy via network.
If you want to transfer `/home/ccdimages/test.FTS` to the home directory of a user tct2017 at ioa10, execute

```
scp /home/ccdimages/test.FTS tct2017@ioa10:test.fits
```

at command prompot. Another application of this is

- If you want to transfer the directory `/home/ccdimages/hogehoge` to the home directory of a user tct2017 at ioa 10,

  ```
  scp -r /home/ccdimages/hogehoge tct2017@ioa10:
  ```

- If you want to transfer `/home/ccdimages/test.FTS` to the directory `obs` at the home directory of a user tct2017 at ioa 10,

  ```
  scp /home/ccdimages/test.FTS tct2016@ioa10:/obs/
  ```

- Transfer all the files starting with "test" such as `/home/ccdimages/test1.FTS`, ... `/home/ccdimages/test100` to the directory `obs` at the home directory of a user tct2017 at ioa 10,

  ```
  scp /home/ccdimages/test*.FTS tct2016@vw:/obs/
  ```

5.3 Tips for UNIX commands

5.3.1 Operations Related to Directories

- Current directory is expressed as:
  `.`
- Upper directory is expressed as:
  `..`
- Thus, two-levels upper directory is expressed as:
  `../..`
- Home directory is expressed as:
  `~/`

If you want to know the current directory, execute the command
`pwd`
.

In general, overall directory of UNIX/Linux system is like the following;

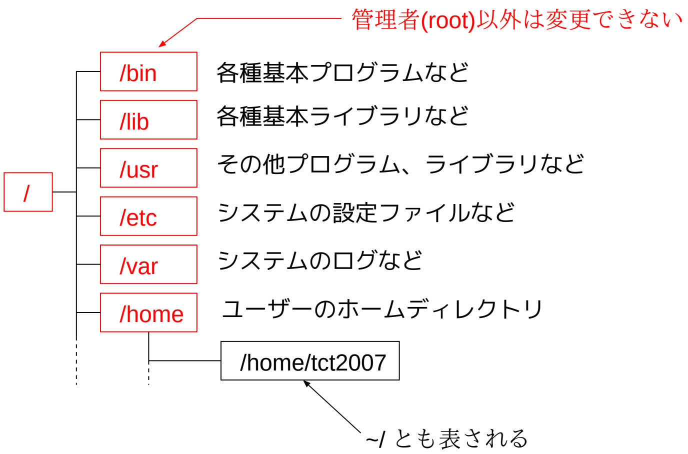

図 1: An example of directory structure of a UNIX-OS system.

5.3.2 Regular Expression

文字列の集合を表現する約束ごと。いろいろあるが、とりあえず役に立ちそうなものを以下に示す。

- `*` ：任意の文字集合
  たとえば、あるディレクトリで `tmp` で始まるファイルだけを表示したい場合は

  ```
  ls tmp*
  ```

とする。あるいは、.FTS という拡張子をもつものだったら

```
ls *.FTS
```

とする。

- ？ ：任意の一文字
  *が複数文字を代用するのに対して、一文字だけを表す。
  たとえば、拡張子が 2 文字のファイルだけを表示する場合は

  ```
  ls *.??
  ```

  とする。`ls *.*` とすると . が入っているファイルすべてが表示されてしまう。

- [ ] ：括弧内に含まれる一文字
  たとえば、test のあとに数字一文字がついた.FTS をホームディレクトリにコピーしたい場合は

  ```
  cp  test[0123456789].FTS ~/
  ```

  とする。これは代わりに

  ```
  cp  test[0-9].FTS ~/
  ```

  と書くことも可能。
  二桁の数字がつくファイルの場合には

  ```
  cp  test[0-9][0-9].FTS ~/
  ```

  とすればいい。

5.3.3 ssh/scp

他のワークステーションにログインする。コピーする

- foo.ioa.s.u-tokyo.ac.jp に bar というユーザー名でログインしたいときは
  `ssh foo.ioa.s.u-tokyo.ac.jp -l bar`
- foo.ioa.s.u-tokyo.ac.jp に bar というユーザー名のホーム下にある aho.txt というファイルをカレントディレクトリにコピーしたいとき
  `scp bar@foo.ioa.s.u-tokyo.ac.jp:aho.txt .`

5.3.4 less, more, cat

ファイルの中身を見たいときに使う。less, more は端末に出せるところまで表示して、続きはスペースキーなどで見ていくことが可能。cat はファイル全部を一気に端末に流し出す。

5.3.5　テキストファイルの編集

テキストファイルの編集をおこなうメジャーなものは vi と emacs が挙げられる。他にも色々あるが。
`emacs aho.txt` のように編集したいファイルを指定して起動。
基本的にマウスではなく、いろんなキー操作で編集するので、詳しいことはマニュアル本を見よ。

5.3.6　gawk

gawk はファイルテーブルの操作や、様々な計算が簡単にできる。

- たとえば
  ```
  1 4   20.31
  2 50  40.1
  3 5   60.3
  ```
  というテーブルが aho.txt という形であって、各行で 2 番目と 3 番目の要素を足し合わせて多テーブルに変換したい場合
  `gawk '{print($1,$2+$3)}' aho.txt`
  とすればいい。さらに、その結果を boke.txt に書き込みたいのなら
  `gawk '{print($1,$2+$3)}' aho.txt > boke.txt`
  とする。

- 電卓のようにしても使える。
  $$10 \times 2 \times \frac{5}{2 \times \sin(5)} \times \exp(10.4/300)$$
  だと
  `gawk 'BEGIN{print(10*2*5/(2*sin(5))*exp(10.4/300))}'`
  とすればいい。

  変数を定義して使うこともできる。$a = 10\sqrt{5}$, $c = 3 \times 10^{10}$ として
  $$100 * a/c$$
  を計算したいのであれば、
  `gawk 'BEGIN{a=10*sqrt(5);c=3e10;print(100*a/c)}'`
  とする。

  常用対数関数がないので要注意である。
  `gawk 'BEGIN{print(log(100))}'`
  は ln(100) を表示する。

他にもいろんなことができる。詳しくはマニュアルとかを見よ。

5.3.7 リダイレクト、パイプ

あるコマンドの出力を、ファイルに流し込みたいときはリダイレクト。" > "を使う。さっきの
`gawk '{print($1,$2+$3)}' aho.txt > boke.txt`
とか。

さらにその出力をべつのコマンドに流し込みたいときはパイプ " | "を使う。さっきの
`gawk '{print($1,$2+$3)}' aho.txt | gawk '{print($2-$1)}'`
のようにする。

5.4 How to Use IRAF

- Before you start, execute
  `mkiraf`
  at the directory you work in. It will then ask you the terminal type, so answer xterm, or if you are using xgterm, xgterm.

- Execute
  `xterm &`
  to run a terminal.

- Execute
  `ds9 &`
  to run image viewer.

- Execute
  `cl`
  in the terminal.

  Below is various command of iRAF. Arguments shown with `()` is mandatory, and with `[]` optional.

  For more detailed information, use

  `epar (command)` to get a help for arguments,
  `help (command)` to get a help of the command.

  - `display (filename) (frame) [fi+] [zr-] [zs-] [z1=xxxxx] [z2=xxxxx]`
    Display image to frame number `(frame)` of ds9

    use `fi+` to display full-frame,

    use `zr- zs-` to turn off automatic scaling, so you have to specify the display scale using arguments`z1=xxxx z2=xxxx`.

  - `imstat (filename)`
    Get statistical information of the image.

- `imhead (filename)`
  Show major header information of the image.
  To show all the header, use
  `imhead (filename) longhea+`
  .

- `imcombine (filelist) (output)`
  Average (or coadd by changing an option)) all the images specified by `(filelist)`.
  `(filelist)` can be written either as

  * `filename1,filename2,filename3,...`
    or
  * `@filename.list`
    where filename.list is a text file listing all the files.

- `imarith (filename1) (+-*/) (filename2) (output)`
  Arithmetic calculation`(+-*/)` between `(filename1)` and `(filename2)`.

- `imexam [filename]`
  Get properties of pixels in `(filename)` interactively. Point to the pixels on ds9 and executle a keyboard action there.
  For example,

  * `a` : Get statistical information of a peak near the pointer position, such as FWHM, flux and background level.
  * `e` Draw a contour around the pointer position.
  * `z` Print a list of the pixel values around the pointer.
  * `m` Calculate statisitical values of the pixels around the pointer.
  * `q` Quit the command.

- Photometry
  Use apphot package. In the IRAF shell, type

  ```
  noao
  digi
  apphot
  ```

  and you are in the apphot package.
  Next, setup parameters by;

  - Execute `epar phot`

  - Move to `photpar` and type `:e`.
    * Set appropriate value for `apertur` (more than FWHM of a star).
    * Set `zmag` if you have zero-magnitude information (otherwise, leave it).
    * When finished, type `:q`.

- Move to `fitskyp` and type `:e`,
    - Set appropriate value for `annulus` (more than twice of FWHM of a star)
    - When finished, type `:q`.
- Move to `datapar` and type `:e`.
    - Set exposure time for `itime`.
    - When finished, type `:q`.
- When finished, type `:q`.

Next, do the aperture photometry by executing;

```
phot (imagefile)
```

Image will be shown in ds9, so move the pointer to the object to be measured an type space key. Multple objects can be measured.
When finished, type `:q`.
Results will be saved in a file `(imagefile).mag.[1-9]`.
Contents of the file are like the following (line starting with `#` are comments).

```
test.fits           2082.000  2449.000  2     nullfile              0      \
   2081.515   2448.083   -0.485  -0.917  0.575   0.777          0    NoError   \
   0.001193246    0.01377304     0.0068786      911    29       0    NoError   \
   1.            INDEF          INDEF                  INDEF                   \
   3.00     4.924091      28.69609   4.88985       23.277 0.491 0    NoError
```

The last line containes the information we need, that are

- (Aperture radius)
- (Total count inside the aperture radius [including background counts])
- (Area size of the apertrue in pixels)
- (Flux inside the aperture, after subtracting the background level)
- (Magitude converted from the total count, using `zmag` set above)
- (Error of the magnitude))

.

5.5 Data Reduction Procedure

Refer to 西浦版『可視光域データ・リダクション法』.

What we have to do is

- Bias subtraction, dark subtraction, and flat-fielding.
- Obtain count from a star by `phot`.
- Convert it to number of electrons n_i.
- Compare with s_i to obtain system efficiency and conversion factor.

6 Tasks to Do

6.1 Evaluate the Properties of the Filters

6.1.1 Download Transmittance Cureve of the Filters

Download the transmittance of the filters from

`http://www.ioa.s.u-tokyo.ac.jp/~kmotohara/30cm/camera/index.html`

and a QE cureve of the CCD camera from

`http://www.ioa.s.u-tokyo.ac.jp/~kmotohara/30cm/camera/mod-ccd-qe.dat`

.

6.1.2 Calculate Effective Transmittance

Plot the effective transmittance curve (combined with the QE of the CCD) of any of the filter, and also calculate

- Central wavelength (λ_{eff})
- FWHM ($\Delta\lambda$)
- Average transmittance (T_{eff})

.
Here, definitions are

$$\lambda_{\mathrm{eff}} = \frac{\int_0^\infty \lambda T(\lambda) d\lambda}{\int_0^\infty T(\lambda) d\lambda}$$

and

$$T_{\mathrm{eff}} = \frac{\int_{\lambda_{\mathrm{eff}}-\Delta\lambda/2}^{\lambda_{\mathrm{eff}}+\Delta\lambda/2} T(\lambda) d\lambda}{\Delta\lambda}$$

where $T(\lambda)$ is the transmittance curve.

6.2 Field of View and Pixel Scale of the Camera

- Calculate the pixel scale (arcsec/pixel) from the focal length of the telescope and pixel size of the camera.
- Observe a binary star or two stars whose separation is known, and estimate the pixel scale from their image.
- Evaluate how these two values match.

6.3 System Effiency

- Observe a star with known magnitude, and measure its total count.
- Calculate the number of photons came in to the telescope from its magnitude.
- Compare the two values and estimage the system efficiency (Equation 3).

6.4 Magnitude Zero Point

Magnitude zero point Z_{mag} defined to be a magnitude of a object which produce 1 count per second for a camera sytem. For example, if 8mag star produces 100 counts with 5 second exposure, the magnitude zero point of this camera is

$$\begin{aligned} Z_{\mathrm{mag}} &= 8 + 2.5 * \log \frac{100}{5} \\ &\sim 11.3 \end{aligned}$$

. Estimate the magnitude zero point of our camera system.

6.5 Sky Background Level

Measure the sky background level in [photons/s/arcsec^2], and in [mag/arcsec^2] .

6.6 Limiting Magnitude

- Observe a faint star (whose magnitude shouldn't be known) and measure its magnitude and its error.
- Calculate S/N ratio of the measurement.
- Calculate the expected S/N ratio using Equation(6).
- Compare the two values, and discuss how they match.