

Introduction to FMOS Image Simulator

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ABSTRACT

This document introduces FMOS Image Simulator (FIS) (version 1.1, as of 20040320). The simulation software makes simulated FMOS FITS images, using the expected performance of the FMOS spectrograph. With the simulated images, reduction methods, detection sensitivity, and survey limitations can be evaluated. Reduced sample images and sample reduction procedure with IRAF are also provided in the package.

Keywords: image, simulation, spectrograph

1. PURPOSE OF THE IMAGE SIMULATOR

The purposes of the FIS software are as follows,

1.1. Provide baseline data for software developments

The first purpose of the software is sharing the concept of the data format between data-reduction and data-readout software developers in practical ways. The simulator parameters will be revised following the initial test results of the FMOS spectrographs in order to reflect the real spectrograph. In parallel, the data reduction software can be tested with the simulated images from the software. Moreover, the information about each target will be included in the ASCII header of FITS file. The information have to be added by the data-readout software and handled appropriately during the data reduction processes.

1.2. Simulate observational bias with the FMOS instrument

The second purpose is to evaluate the observational biases with the FMOS instrument. Because of the strong OH-airglow lines and OH-suppression masks, the detection limit of the instrument vary with wavelength. Thus, it is important to estimate the sensitivity as a function of wavelength, and evaluate the bias in the redshift determination, etc.

On the contrary, the obtained results can be feedbacked to the specifications of tolerances of optical elements. Additionally, based on the simulation, we can evaluate the observational procedure, such as “double-beam swithing” and so on.

1.3. Share experience of the fibre and OHS data handling

Finally, we can share the difficulty of fibre and OHS spectroscopic data handling by putting as much experience obtained from the 2dF/AAT and OHS/Subaru observations as possible into the software.

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2. PREPARATION : REQUIRED INPUT PARAMETERS

In order to make a image, you need to prepare a input parameter file for each image with the entries like below.

```
SEEING      0.5                /* Seeing FWHM (arcsec) */
AIRMASS     1.0                /* Airmass in sec(z)   */
EXPT        10.0              /* Exposure time in (s) */
MODE        LOW               /* Spectroscopy mode HIGH or LOW */
WAVEMIN     9000.0            /* Minimum wavelength coverage */
SPECLIST    sample/fibre_obj.list /* Spectral template list file */
ATMABS      datafiles/MK_atm_abs.dat /* Atmospheric absorption data at sec(z)=1 */
FLATIMAGE   datafiles/FMOS_flat_model.fits /* Detector flat-field image */
EFFIFILE    datafiles/FMOS_effi_low.dat /* System efficiency model */
MASKFILE    datafiles/FMOS_mask_model.dat /* OH supression mask model */
FITSNAME    sample/test_image.fits /* Output FITS file name */
```

With the file (for example, name SAMPLE1), you can make a FITS file by

```
FIS SAMPLE1
```

Details of each parameters in the input file is as follows. Words written in capital letters are parameters written in “fmos_model.h”, parameters written in an input parameter file, or file names needed to be specified in the input parameter file. For the parameters written in “fmos_model.h” file, the default values are shown in parenthesis.

(char) SPECLIST

Specify name of the file which contains data for each fibre. The format of the file is,

```
TEMP_FILE SKY_CONT_FILE SKY_LINE_FILE WSHIFT TRANS PROF TARG_NAME TARG_RA TARG_DEC TARG_TYPE
:
:
(NFIBRE=200 lines)
```

Each entry in this file corresponds to one fibre in the final image. The number of lines in the file has to match the number of fibres (NFIBRE=200) in the header file. The first three parameters point the file names for each spectrum. The next two parameters simulate the properties of each fibre. The last four parameters are dummy target data for ASCII header.

Sample SPECLIST files are available in the directory ”sample” with file postfix with ”.list”. For example, ”sample/fibre_flat.list” is the SPECLIST used to make the ”fibre_flat.fits” sample FITS image (Details of each sample files, please see 4. Sample Files., below).

Col 1: (char) TEMP_FILE

Specify name of a spectral data file of target object (like, model galaxies, average QSO spectrum and so on). The format of the file is

```
WAVELENGTH(angstrom) FLUX DENSITY(erg/s/cm2/A)
:
```

You can find sample template files in ”template” directory.

Col 2: (char) SKY_CONT_FILE (MK_sky_cont.dat)

Specify name of a spectrum file of continuum emission from night sky. The format of the file is

WAVELENGTH(angstrom) FLUX DENSITY(erg/s/cm2/A/arcsec2)

:

The sample "datafiles/MK_sky_cont.dat" file is made assuming 300 (photons/s/m²/μm/arcsec²) in the J-band. The value are based on Tokunaga 2000 ("Astrophysical Quantities, Infrared Astronomy") and Massay et al. 1997 ("Low-to-Moderate Resolution Optical Spectroscopy Manual for Kitt Peak").

Col 3: (char) SKY_LINE_FILE (MK_sky_line.dat)

Specify name of a night sky line list. It describes the wavelength and the strength of each OH night sky line. The format of the file is

WAVELENGTH(angstrom) FLUX(!!photons!!/s/!!m2!!/A/arcsec2)

:

The sample "datafiles/MK_sky_line.dat" file is made based on Maihara et al. 1993 (PASP, 105, 940), Osterbrock et al. 1997 (PASP, 109, 614), Osterbrock and Martel 1992 (PASP, 104, 76), and <http://www.ucolick.org/jfulb/OH.html>.

(You can use different SKY_CONT_FILE and SKY_LINE_FILE for different fibre (for example to simulate spacial variation of sky lines). In this case, you need to prepare sets of SKY_CONT_FILE and SKY_LINE_FILE for each fibre by yourself.)

Col 4: (float) WSHIFT (angstrom)

It is set to simulate the offset of each fibre in the slit. The shift is at the detector in unit of angstrom, i.e. 20 μm shift at the fibre slit means 6.3 μm shift on the detector and that corresponds to 0.3 and 1.3 Å shift in high- and low-resolutoin mode, respectively.

Col 5: (float) TRANS (max=1, min=0)

It is the transmittance of each fibre (max=1 min=0). You can simulate the fibre to fibre variation of the

In the sample ".list" files, WSHIFT and TRANS are calculated with "add_fibre_data.awk" script. See "add_fibre_data.sh" to check how to use the script.

Col 6: (char) PROF (GAU, M23, M24)

Specify type of profile of the model object. GAU : Gaussian, M23 : Median profile of V=23mag galaxies, M24 : Median profile of V=24mag galaxies. The profile will be used to calculate loss at aperture entrance.

Col 7: (char) TARG_NAME

Dummy data for ASCII header.

Col 8: (char) TARG_RA

Dummy data for ASCII header.

Col 9: (char) TARG_DEC

Dummy data for ASCII header.

Col 10: (char) TARG_TYPE

Dummy data for ASCII header.

(char) FLATIMAGE (FMOS_flat_model.fits)

Specify name of the flat-field (reflect pixel to pixel sensitivity difference of the detector) image of FMOS. The sample flat-field image "datafiles/FMOS_flat_model.fits" is made from a CISCO H-band flat-field image "flat_OPNS_H.011103.fits". In order to make 2048 × 2048 image, the CISCO 1024 × 1024 image is 2 × 2 tiled with "imtile" command in IRAF.

It should be noted that with FMOS we can not take an imaging flat-field image during normal operation. We can only take a fibre flat-field image.

(char) ATMABS (MK_atm_abs.dat)

Specify name of the file which contains data of atmospheric transmittance at airmass of 1.0. The format of the file is

```
WAVELENGTH(angstrom) TRANSMITTANCE(max:1,min:0)
:
```

The transmittance is adjusted to input airmass value in the software. The sample "datafiles/MK_atm_abs.dat" is made based on <http://www.ast.cam.ac.uk/science/mkmodels>, <http://www.jach.hawaii.edu/UKIRT.new/astronomy/ext> and Stevenson 1994 (MNRAS, 267, 904).

(char) EFFIFILE (FMOS_effi_model.dat)

Specify name of the file which contains data for FMOS instrument efficiency (w/o aperture loss, atmospheric absorption). The format of the file is,

```
WAVELENGTH(angstrom) EFFICIENCY(max=1; min=0)
:
```

The sample data is based on the efficiency estimate made by Ian Lewis. The original file is available in datafiles/FMOSthroughput2.xls (Excel file)

(char) MASKFILE (FMOS_mask_model.dat)

Specify name of the file which contains data for masked wavelength range. The format of the file is,

```
WAVELENGTH_STR(angstrom) WAVELENGTH_END(angstrom)
:
```

The sample file will mask $\pm 3.7\text{\AA}$ of strong night sky lines.

(char) MODE (HIGH or LOW)

Specify mode of spectroscopic observation. LOW resolution mode is with $R=500$ and $4\text{\AA}/\text{pixel}$ and HIGH resolution mode is with $R=2200$ and $1\text{\AA}/\text{pixel}$.

(float) EXPT, ARIMASS, SEEING, WAVEMIN

Exposure time (in s), airmass (in $\sec(z)$), seeing (FWHM in arcsec), and short edge of wavelength range (in \AA) of the simulation.

(char) FITSNAME

Output FITS file name.

3. INSIDE FIS

In the following subsections, the image simulation steps are shown. Words written in capital letters are parameters written in "fmos_model.h", parameters written in an input parameter file, or file names needed to be specified in the input parameter file. For the parameters written in "fmos_model.h" file, the default values are shown in parenthesis.

3.1. Make array of NFIBRE fibre spectra reading SPECLIST file

At first, an array of NFIBRE(=200) fibre spectra is made based on the SPECLIST file. The SPECLIST file contains object spectrum filename (TEMP_FILE), sky continuum spectrum filename (SKY_CONT_FILE), and sky OH-line spectrum filename (SKY_LINE_FILE) and so on for each fibre. Spectrum data of a model object is read from TEMP_FILE. The spectrum data is resampled into DLAMBDA(=1.0Å) bin from WAVEMIN to NBIN(=11000) bins, i.e., if WAVEMIN=9000Å, 9000Å-20000Å wavelength range will be covered in the initial spectrum. The spectrum data of a model sky continuum is also read from SKY_CONT_FILE and resampled into the same binning as that of object spectrum.

The object and sky continuum spectra data and the OH sky line strengths which are read from SKY_LINE_FILE are multiplied by atmospheric absorption (ATMABS file) normalized to specified airmass value (AIRMASS) and FMOS system efficiency model (EFFIFILE).

To simulate the resolution at the OH suppression mask, the object and sky continuum spectra are convolved by Gaussian with SIGMA_OHS(=0.5Å) +Top-hat with DIA_IMAGE(=4.8Å). It is assumed that all the fibres have the same PSF in the dispersion direction. OH lines with the same profiles are added to sky continuum spectrum.

Next OH line rejection is simulated. The information on the wavelength range masked is provided in MASKFILE. The wavelength range described in the file is masked. It is assumed that in the wavelength range only OHSUP_FRACTION(=0.0001) of light will transmit to the next step.

Finally, for the low-resolution mode, the spectra are convolved with Gaussian with SIGMA_SPE(=11.3Å) representing the resolution on the detector (i.e., after VPH-grating).

Re-sampled based on sampling rate on detector, DPIXEL(=4.5Å/pixel in low-resolution mode, 1.0Å/pixel in high-resolution mode).

3.2. Make 2048×2048 ideal image of fibre spectra based on the array

2048×2048 image is made from the array of the 200 spectra made in the first step. Each fibre spectrum is not a straight line, but curved with bending. This bend is assumed to follow the 2nd-order polynomial ($ax^2 + bx + c$, x is in wavelength direction) shape. The spectra are parallel at $x = 0$ (left edge in Figure 1~5). The separation of fibres at $x = 0$ is FIB_SEP(= 10.0 pixel). The amount of bend is linear function of fibre number: the central fibre (Number 100, i.e. NFIBRE/2) has straight spectrum, bend=0, and fibres at edge (fibre numbers 0 and 200 = NFIBRE) have bend of BEND_EDGE(=26.0pixel) at the other edge, i.e. $x = 2048$ (right edge in Figure 1~5). The amount of bend increases linearly from the centre to the edge.

In the spatial direction, each fibre spectrum has profile of Top-hat profile with DIA_FIMA_PIX(=4.9pixel) convolved with Gaussian profile with a sigma. The sigma value depends on fibre number: the central fibre has SIGMA_FIB_CEN(=0.4pixel) and fibres at edge have SIGMA_FIB_EDGE(=0.8pixel). The size of the sigma increases linearly from the centre to the edges.

3.3. Simulate pixel-to-pixel sensitivity difference with a flat image

The simulated image is multiplied by the simulated flat image, FLATIMAGE. In the current simulator 2×2 tiled flat images of CISCO is used.

3.4. Add noise on the ideal image

Thermal background is added to the ideal image. The countrate of the background is assumed to be BACKGROUND(=0.05 photons/s/pixel). After that poisson and read out noises are added on the ideal image. The noises are assumed to follow Gaussian distribution. The read out noise is READ_DN(=10.0 e^-).

3.5. Simulate detector linearity limit and GAIN correction

The calculations so far made in float. The noise-added (float) image is divided by GAIN(=3.5) and all the values are made to short integer value. The linearity of the detector is also considered. The counts (CTS) above LIN_LIMIT(=20000) follows the equation below,

$$(\text{CORRECTEDCTS}) = (\text{LIN_LIMIT}) + ((\text{CTS}) - (\text{LIN_LIMIT}))^{\text{POW_LIMIT}} \quad (1)$$

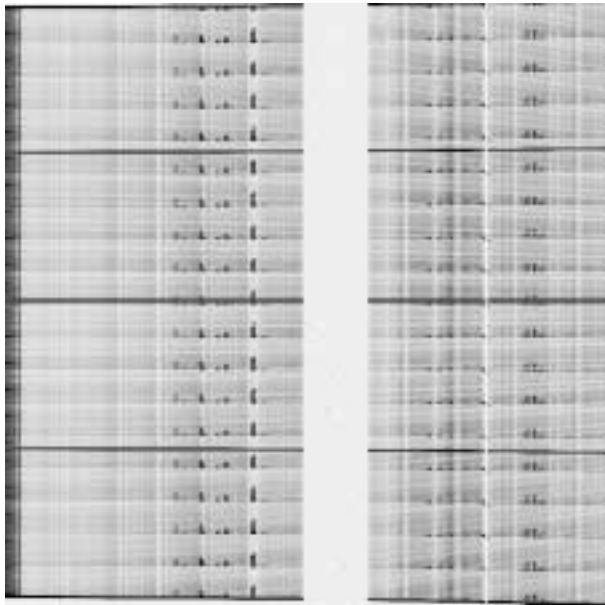


Figure 1. Simulated target (200 H=20 mag QSOs with 1800s integration) spectrum in the low-resolution mode. The spectra are dominated by night sky component, thus looks similar to the night sky spectra in Figure 2.

3.6. Add cosmic rays

Cosmic rays are added at this step. Number of cosmic rays are determined by $\text{NCOSMIC}(=0.5) \times \text{EXPT}$. The counts of cosmicrays are $\text{COS_VALUE}(=30000\text{ADU})$.

3.7. Make FITS file

The image (short) data array is converted to FITS image by cfitsio functions. The final image name is FIT-SNAME.

4. SAMPLE IMAGES

Sample simulated images are shown in the following Figure 1~5.

5. EXAMPLE OF REDUCTION OF THE SAMPLE DATA

Using IRAF, the simulated images can be reduced as follows,

Step 1: Remove Cosmic Rays

Remove cosmicrays on the images with `imred.crutil.cosmicrays`

Step 2: Subtract Sky-frames from target frames

CR-removed sky-data frames are subtracted from CR-removed target frames. Both images should have same integration time.

Step 3: Extract 1D spectra from 2D frames, Flat-fielding, Wavelength calibration

Two hundred 1D spectra are extracted from the sky-subtracted frame using `imred.hydra.dohydra` package. In the package, flat-fielding and wavelength calibration are also done.

Step 4: Atmospheric absorption line correction and flux calibration

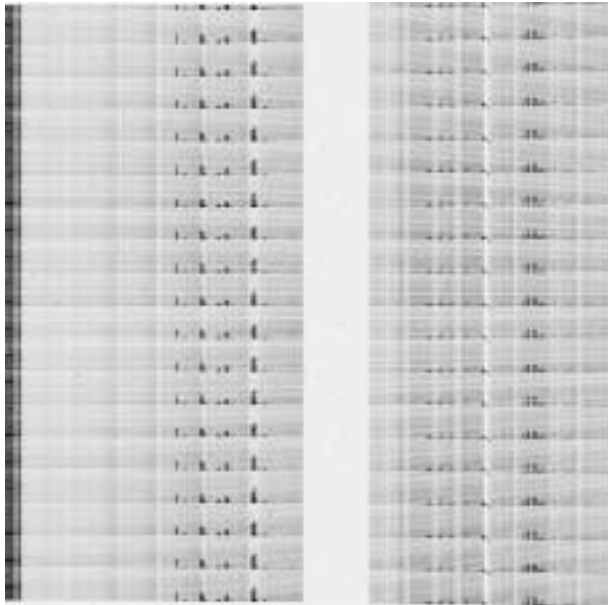


Figure 2. Simulated night-sky spectrum (1800s integration) in the low-resolution mode. The black spots in each fibre spectrum are residual night sky lines due to fibre mis-alignment at slit (in this simulation, the shift corresponds to $40 \mu\text{m}$ shift at most at the fibre slit).

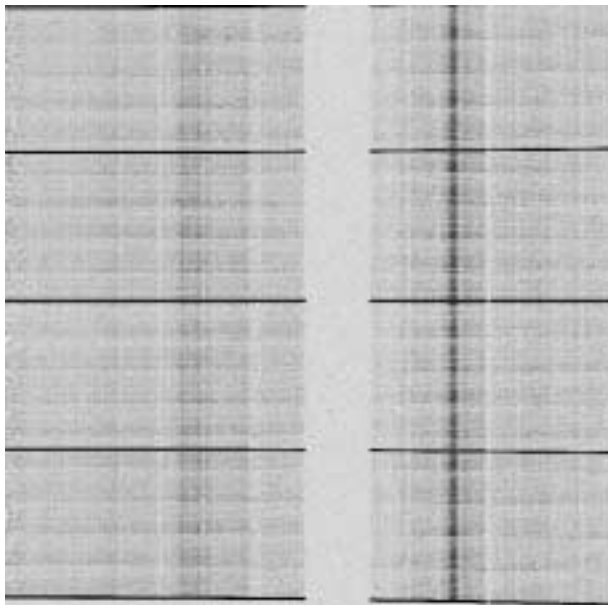


Figure 3. Target frame after sky subtraction (Figure 2 subtracted from Figure 1). The dark feature in the H band spectra is broad $\text{H}\alpha$ emission line at $z=1.4$. Five bright spectra in the frame are spectra of bright blue stars for atmospheric absorption correction and flux calibration.

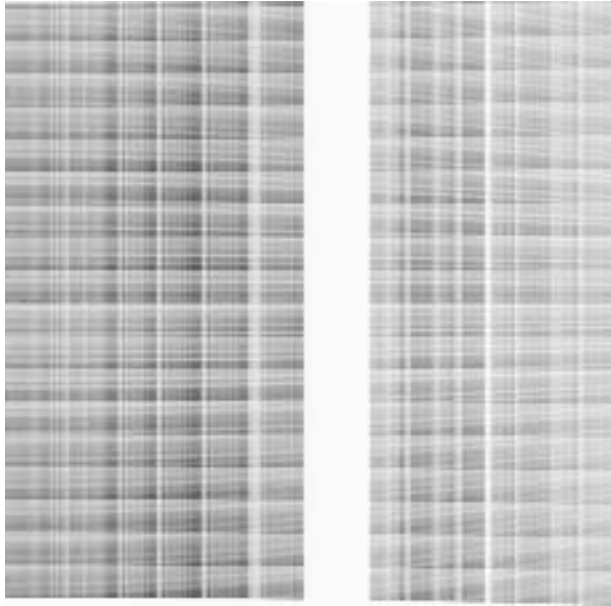


Figure 4. Fibre flat frame. It should be noted that we cannot take the fibre flat image without closing the dome.

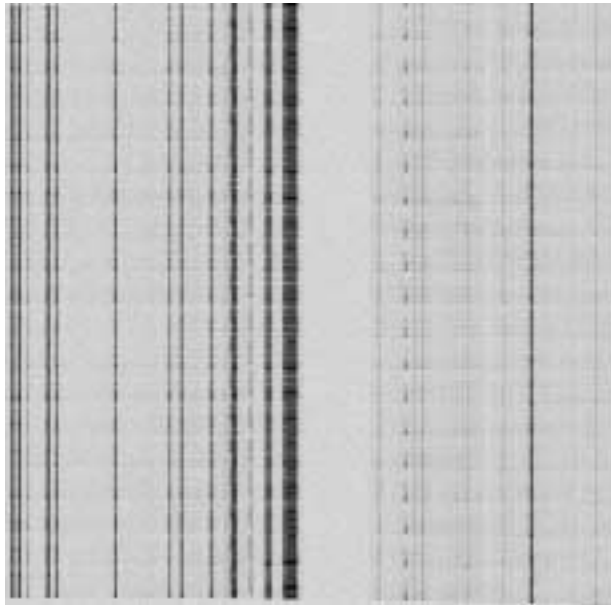


Figure 5. ARC Argon lamp image. The current ARC lamp on the telescope do not illuminate whole FoV of FMOS. It is not considered in this simulation.

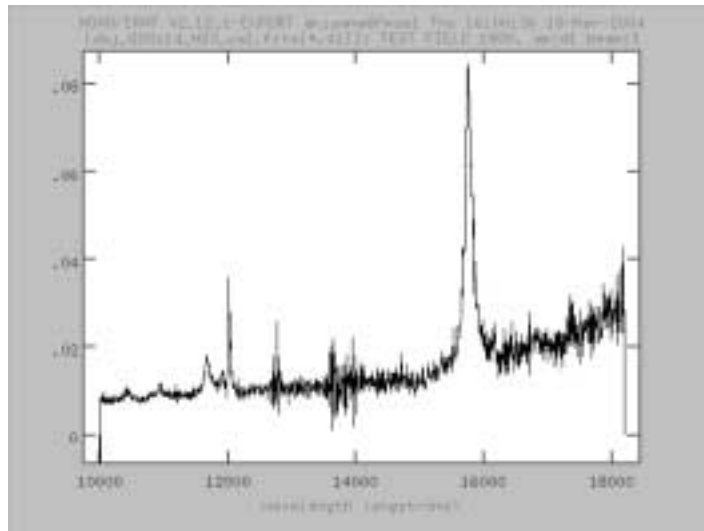


Figure 6. Calibrated spectrum of the model QSO at $z=1.4$.

The flat-fielded target spectra are divided by a flat-fielded standard star spectrum (a bright early-type star in the field). The resulting frame is multiplied by a model spectrum of a standard star. Finally, we obtain the flux-calibrated spectra of targets. An example is shown in Figure 6.

6. WHAT SHOULD BE INCLUDED IN THE FUTURE ?

In the current simulator, wavelength dependence of light loss at fibre entrance due to atmospheric dispersion is not considered. The effect will introduce some difficulties in flux calibration of the target spectrum. The corrector shift mechanism against focal plane will introduce variation of image plane distortion during the integration. The change of the distortion pattern during the integration can cause another loss at the fibre entrance. The current simulator do not include the loss due to the distortion change.

Scattered light inside spectrograph has not been considered. Non-repeatabilities of the movable optical elements, such as slit-unit, VPH-grating, and IR-camera, are not included. These parameters should be included after the initial lab-test of the OH spectrograph.