Gemini Multi-Object Spectrograph

GMOS Overview

Data Reduction:
- Imaging (R. Carrasco)
- Longslit spectroscopy (R. Schiavon)
- MOS spectroscopy (R. Schiavon)
- Nod & Shuffle spectroscopy (R. Schiavon)
- IFU (R. Carrasco)

Rodrigo Carrasco
Gemini Observatory
SGDW, São José dos Campos
27 - 30 October 2011
Winter at Cerro Pachón
Three 2048x4608 E2V chips (6144 x 4608 pixels) with gaps between CCDs - 37 unbinned pixels. Pixel scale: 0.0727 $\mu$m (GMOS-N) and 0.073 $\mu$m (GMOS-S).

GMOS-N will be installed back soon.

New E2V deep depletion devices have been successfully installed.
GMOS Overview

- Broad band: u, g, r, i, z (GMOS-S only)
- Narrow band: Hβ, Hγ, HeII, HeIIC, OIII, OIIIC, SII
- Blocking filters for spectroscopy: GG445, OG515, RG610, RG780, DS920
- Long-slits: 0.5” - 5.0” (fixed size)
- Custom masks (MOS): ≥ 0.5”
- Integral Field Unit (IFU) for 3D spectroscopy
- Nod & Shuffle: long-slits (0.5” – 2.0”), MOS (band and micro-shuffling, IFU (GMOS-S only).
**GMOS Overview**

### Available gratings

<table>
<thead>
<tr>
<th>Grating</th>
<th>Blaze wav. [Ang]</th>
<th>R (0.5” LS)</th>
<th>Coverage [Ang.]</th>
<th>Dispersion [Ang/pix]</th>
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<tbody>
<tr>
<td>B1200</td>
<td>4630</td>
<td>3744</td>
<td>1430</td>
<td>0.23</td>
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<tr>
<td>R831</td>
<td>7570</td>
<td>4396</td>
<td>2070</td>
<td>0.34</td>
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<tr>
<td>R600</td>
<td>9260</td>
<td>3744</td>
<td>2860</td>
<td>0.45</td>
</tr>
<tr>
<td>R400</td>
<td>7640</td>
<td>1918</td>
<td>4160</td>
<td>0.47</td>
</tr>
<tr>
<td>B600</td>
<td>4610</td>
<td>1688</td>
<td>2760</td>
<td>0.67</td>
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<tr>
<td>R150</td>
<td>7170</td>
<td>631</td>
<td>10710</td>
<td>1.74</td>
</tr>
</tbody>
</table>

Grating turret supports only 3 gratings + mirror
GMOS Overview

- GMOS detectors characteristics
  - Good cosmetic, with only few bad pixels
  - Bad pixels masks for imaging – provided by the observatory (1x1 and 2x2) - gmos$data/ directory
- Saturation level: ~64000 ADU and linearity ~60.000 ADU (<1%)
- CCD readouts and gains configurations
  - Slow readout/low gain (science)
  - Fast readout/low gain (bright obj.)
  - Fast readout/high gain
  - Slow readout/high gain (eng. only)
- Readout time (full frame):
  - 1x1 slow/low ~ 140 sec
  - 2x2 slow/low ~ 45 sec

<table>
<thead>
<tr>
<th>SDSU Gain number</th>
<th>1 (High)</th>
<th>2 (Low)</th>
<th>3 (High)</th>
<th>4 (Low)</th>
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<tbody>
<tr>
<td></td>
<td>CCD</td>
<td>Rate</td>
<td>Amp</td>
<td>Gain Noise</td>
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<tr>
<td>1 F L</td>
<td>5.054</td>
<td>6.84</td>
<td>2.408</td>
<td>4.49</td>
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<tr>
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<td>5.253</td>
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<td>2.561</td>
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<tr>
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<td>3.98</td>
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<td>5.19</td>
<td>2.403</td>
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<td>2.295</td>
<td>4.42</td>
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<td>2.076</td>
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<tr>
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<td>2.134</td>
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<td>8.56</td>
<td>2.264</td>
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<tr>
<td>3 F R</td>
<td>4.833</td>
<td>7.88</td>
<td>2.260</td>
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<td>3 S L</td>
<td>4.381</td>
<td>4.81</td>
<td>2.056</td>
<td>3.27</td>
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<tr>
<td>3 S R</td>
<td>4.411</td>
<td>4.34</td>
<td>2.097</td>
<td>3.16</td>
</tr>
<tr>
<td>Ave F</td>
<td>5.002</td>
<td>8.09</td>
<td>2.344</td>
<td>4.622</td>
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<tr>
<td>Ave S</td>
<td>4.622</td>
<td>4.968</td>
<td>2.189</td>
<td>3.683</td>
</tr>
</tbody>
</table>
Grating turret
Filter wheels

Mask assembly with cassettes and masks
to the detector
Integral Field Unit Cassette # 1

OIWFS and patrol field area
GMOS Images: Data Reduction
General guidelines and suggestions

- Fetch your program using the Observing Tool
- Check the notes added by the observer(s) and/or the Queue Coordinator(s) regarding your observations
- Check the observing log (you can use the OT)

**Program Note**
Enter notes for the operator/astronomer here.

<table>
<thead>
<tr>
<th>Title</th>
<th>QC note, 2005 sep 09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Note</td>
<td>IQ = 1.38 at X=1.39 for the g filter - usable</td>
</tr>
<tr>
<td></td>
<td>IQ = 1.12 at X=1.27 for the i filter, but too many clouds - usable</td>
</tr>
<tr>
<td></td>
<td>Repeat both sequences</td>
</tr>
</tbody>
</table>
GMOS Images: Data Reduction

Arranging your files: suggestion

Raw data:
- calibrations/ - all baseline daytime calibration raw images
- science/ - all science data
- standards/ - photometric standard stars (nighttime calibrations)

Reductions:
- reductions/ - all reductions
  - calibrations/ - reductions of daytime calibrations
  - Obj1/ - reduction of the first science object
    - combined/ - combined images
    - photstd/ - reductions of phot. Std.
  - Obj2/ - reduction of the second science object
GMOS Images: Data Reduction
General guidelines and suggestions

- Inspect all images (bias, twilight flats, science images) using your favorite tools: imstatistic, implot, etc in IRAF, IDL routines, etc.
GMOS Images: Data Reduction

Typical GMOS imaging observations

- Science Observations
  - A sequence of exposure using one or more filters.
  - The sequence normally has offsets to avoid the gaps between CCDs.

- Daytime calibrations (Baseline) – GN(GS)-CALYYYYYMMDD
  - Routine Bias for all binning (slow/fast readout, low gain).
  - Routine twilight flats for 2x2 binning (all filters).
  - Processed bias and twilight flats are in the GSA, but not over-scan subtracted

- Nighttime calibrations (Baseline) – GN(GS)-CALYYYYYMMDD
  - Photometric standard stars – zero point calibrations
  - Blank fields – fringe correction (i' and z' filter only)
GMOS Images: Data Reduction

- Basic IRAF data reduction information in the web.
- Good starting point to reduce your data
- [http://www.gemini.edu/sciops/data/IRAFdoc/gmosinfoimag.html](http://www.gemini.edu/sciops/data/IRAFdoc/gmosinfoimag.html)

**Dataset**
- SV data on Hickson Compact Group 87 from 2003
- Observations with g’, r’ and i’ filters, 1 x 1 (no binning)
- Offsets between exposures to avoid gaps

<table>
<thead>
<tr>
<th>#</th>
<th>Reducing HCG87</th>
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</thead>
<tbody>
<tr>
<td>#157-159 HCG87</td>
<td>g - - 300</td>
</tr>
<tr>
<td>#161-163 HCG87</td>
<td>r - - 180</td>
</tr>
<tr>
<td>#164-169 HCG87</td>
<td>i - - 120</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th># Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS-CAL20030525-2 10:37 212-221 Bias - - - - 1 1x1,full/slow/low/low</td>
</tr>
<tr>
<td>GS-CAL20030527-3 22:15 39-48 Twilight g - - 5,5,7,20,35,50 1x1,full,slow,low,best</td>
</tr>
<tr>
<td>GS-CAL20030530-6 22:38 45-47 Twilight r - - 1x1,full,slow,low,best</td>
</tr>
<tr>
<td>GS-CAL20030527-4 22:38 49-52 Twilight i - - 30,80,120,160 1x1,full,slow,low,best</td>
</tr>
<tr>
<td>Blank field - fringing correction</td>
</tr>
<tr>
<td>GS-CAL20030525-10 9:15 173-177 Blank21b i - - 180 1x1,full,slow,low,best</td>
</tr>
</tbody>
</table>
GMOS Images: Data Reduction

Reduction Steps

- Combine bias (trim, overscan)
- Twilight flats: over-scan, bias subtraction, trim and combine the frames
- Science images: bias and over-scan subtraction, trim and flat-field the frames
- Blank fields to construct a combined image for fringing correction (i’-band only)
- Mosaic the images and combine the frames by filter
Be sure to use the correct bias → slow readout/low gain, 1x1 binning

GSA gives you a processed combined bias, but not overscan subtracted. Check also for compatibility (binning, read mode)

Tip: check keyword AMPINTEG in the PHU

AMPINTEG = 5000 – Slow, AMPINTEG = 1000 – fast

Gain -- in the header, CCDSUM (ext)

Bias reduction -- uses gbias @ bias.list bias_out.fits fl_trim + fl_over + rawpath = dir$

Check the final combined bias image

Reducing GMOS Images
Twilight flats are used to flat field the images and remove artifacts caused by variations in the pixel-to-pixel sensitivity of GMOS detectors. 20 to 25 flats per filter per month are observed during twilights under good weather, using a special dithering pattern.

Reducing GMOS Images

Final flat is constructed using `giflat`

```
giflat @flat_g.lst outflat=gflat bias=bias.fits fl_over+ rawpath=dir$
```

The default parameters work ok for most cases.

Over-scan is recommended.

Final flat is normalized.
Reducing GMOS Images

Fringing correction

Significant fringing in i and z bands (worse with GMOS-S)

Blank fields for fringing removal → observed every semester in i and z (2x2 binning, slow readout/low gain).

Best fringing correction - use the same science images

Constructing the fringing frame with gifringe using bias, over-scaned, trimmed and flat-fielded images.

Output = Input - s * F

s = stddev(Inp)/stddev(Out) for fl_statscale=yes

s = exptime(Inp)/exptime(Out) for fl_statscale = no (DEFAULT)
Reducing GMOS Images

Science images

- Reducing the images with `gireduce`
  
  `gireduce`: gprerare, bias, overscan and flatfield the images
  
  `gireduce @obj.lst fl_bias+ fl_trim+ fl_flat+ fl_over+ bias=bias.fits flat1=flatg flat2=flatr flat3=flati rawpath=dir$

- Removing fringing with `girmfringe` (i’ band images only)
- Inspect all images with “`gdisplay`”
- Mosaicing the images with `gmosaic - > gmosaic @redima.lst`
- Combining your images using `imcoadd`
  
  `imcoadd` - search for objects in the images, derive a geometrical trasformation (shift, rotation, scaling), register the objects in the images to a common pixel position, apply the BPM, clean the cosmic ray events and combine the images
Final GMOS image

HCG 87
Integral-Field Spectroscopy

→ Obtain a spectrum at every position
Each spectrum gives

Lagos et al. (2009)
IFU Zoo: How to map 3D on 2D

Telescope Focus

Image Slicer

mirrors

Spectrograph Input

1 2 3 4

Slit

Spectrograph Output

1 2 3 4

$\lambda$

GMOS

Final Output

Data Cube

Lens Array + Fibers

fibers

“Spaxel”

Pure Lens Array

lens image

$X$

$\lambda$

$\lambda$
GMOS IFU

- Optical Integral Field Spectrograph
- Lenslet-fiber based design
- Various spectral capabilities
- Two spatial setting
  - “Two slit” mode:
    - 5”x7” (5”x3.5” sky)
    - 3,000 spectral pixels
    - 1500 spectra (500 sky)
  - “One slit” mode:
    - 5”x3.5” (5”x1.75” sky)
    - 6000 spectral pixels
    - 750 spectra (250 sky)
- Spatial sampling of ~0.2” per fiber
- Dedicated sky fibers 60” offset for simultaneous sky
GMOS Example 2 slit mode M32
GMOS Example: 1 slit mode Mrk996
How is the 3D data mapped?
Mask Definition File (MDF) provides sky coordinates of each fibre on CCD.

Together with wavelength calibration, provide translation from CCD (X,Y) to data-cube (RA, DEC, \(\lambda\))

<table>
<thead>
<tr>
<th>Slit mode</th>
<th>GMOS-N</th>
<th>GMOS-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Slit</td>
<td>gnifu_slits_mdf.fits</td>
<td>gsifu_slits_mdf.fits</td>
</tr>
<tr>
<td>1 slit mode (Blue)</td>
<td>gnifu_slitb_mdf.fits</td>
<td>gsifu_slitb_mdf.fits</td>
</tr>
<tr>
<td>1 slit mode (Red)</td>
<td>gnifu_slitr_mdf.fits</td>
<td>gsifu_slitr_mdf.fits</td>
</tr>
<tr>
<td>N &amp; S 2 Slit mode</td>
<td>gsfu_ns__slits_mdf.fits</td>
<td></td>
</tr>
<tr>
<td>N &amp; S 1 slit mode (Blue)</td>
<td>gsfu_ns__slitb_mdf.fits</td>
<td></td>
</tr>
<tr>
<td>N &amp; S 1 slit mode (Red)</td>
<td>gsfu_ns__slitr_mdf.fits</td>
<td></td>
</tr>
</tbody>
</table>
Mask Definition File (MDF) provides sky coordinates of each fibre on CCD

Together with wavelength calibration, provide translation from CCD (X,Y) to data-cube (RA, DEC, λ)
GMOS IFU Reduction
Organizing your files: suggestion

Raw data:
calibrations/ - all baseline daytime calibration raw images
science/ - all science data
standards/ - photometric standard stars (nighttime calibrations)

Reductions:
reductions/ - all reductions
calibrations/ - reductions of daytime calibrations
Obj1/ - reduction of the first science object
Grating1/ - first grating
Grating2/ - second grating
combined/ - combined images
Obj2/ - reduction of the second science object
fluxstandard/ - flux calibration
Typical GMOS IFU observations

Science Observations
- Acquisition
  - Direct image of the field $\rightarrow$ initial offsets
  - Un-dispersed IFU image $\rightarrow$ fine centering
- Observation sequence:
  - Flat (fringing is flexure-dependent)
  - Science Exposure (up to 1 hour)
  - Flat (and CuAr arc if you need good Wavev. Calib.)
- Daytime calibrations (Baseline)
- Bias – GN(GS)-CALYYYYMMDD
- Twilight sky flat and CuAr arcs (inside the program)
- Nighttime calibrations (Baseline) – GN(GS)-CALYYYYMMDD
- Flux standard for relative flux calibration (not – coincident)
GMOS IFU Reduction $\rightarrow$ acquisition

GMOS IFU-2 reconstructed (undispersed) image
GMOS IFU Reduction

Typical GMOS IFU raw data

Science Object

Arc

Flat Lamp

Block of sky fibers

Fiber

Wavelength
Basic IRAF data reduction information in the web.

Good starting point to reduce your data and form the base of this tutorial.

Goal → to get a combined data cube with basic calibrations (wavelength, transmission, etc...)

Dataset

• SV data on NGC 1068 from 2001
• 2-slit mode IFU → 5”x7” per pointing
• 2x2 mosaic for field coverage
• B600 grating, targeting H_α and continuum
• Bias is prepared already
• Twilight sky included
• Flux standard also included (not described here)
GMOS IFU Reduction

Step to follow

1. Bias and over-scan subtraction from all images (science spectra, flats, twilight sky, CuAr arcs, etc) – recommended
2. Identify the fibers using a flat image
3. Construct the Flat
   I. Spectral flat field to correct for transmission function → using the GCAL flats
   II. Spatial flat field to correct for illumination function & fiber response → using twilight sky
4. Establish wavelength solution using CuAr arcs
5. Reducing science images
6. Construct Data Cubes
**Step 1: bias subtraction**

- Use **gprepare** on your data (Science, flats, CuAr arcs). The task will add the MDF to the frames.
- Suggestion → copy the MDF file to your local directory in case that you need to edit it → gnifu_slits_mdf.fits

```bash
gprepare @obj.lst rawpath=rawdir$ fl_addmdf+\mdffile="gnifu_slits_mdf.fits" mdfdir="gmos$data/"
```

- Use **gfreduce** for bias and over scan subtraction
- Suggestion: do this interactively

```bash
greduce g//@obj.lst fl_addmdf- fl_inter+ \fl_over+ fl_extract- fl_gsappwave- fl_wavtran- \fl_skysub- fl_fluxcal- fl_gscrrej- slits=both
```
Step 2: identifying the fibers (spectra)

- CRUCIAL step — make sure the spectra can be traced on the detector.
- Use the flat lamp (high S/N) to find the fibers on the detector, and trace them with wavelength.
- Once again, we use `gfreduce` interactively.
- We want to identify and trace the fibers only.
- There are dead fibers — don’t want miss-identification.

```bash
gfreduce reduce 
fl_bias - fl_wavtran - fl_skysub - fl_gscrrej - fl_fluxcal - df - fl_trimm - fl_inter + slits=both
```
Step 2: identifying the fibers (spectra)

Fibers are in groups of 50 – inspect the gaps between groups
Step 2: identifying the fibers (spectra)
Step 2: identifying the fibers (spectra)

Trace of one fiber

Contamination from slit_2?

Jump to CCD2
Step 2: identifying the fibers (spectra)

Trace of one fiber

Jump to CCD2

Contamination from slit_2?
Step 2: identifying the fibers (spectra)

Non-linear component

Rejected points
Step 2: identifying the fibers (spectra)

Jump to CCD2
Step 2: identifying the fibers (spectra)

- Following extraction, data are stored as 2D images in one MEF (one image per slit) → ergN20010908S0105
- This format is VERY useful for inspecting the datacube
Step 3: prepare the flat-field

Flat-fielding has two components:

- **Spectral Flat-field**
  - Correct for instrument spectral transmission response
  - Use black body lamp and divide by fitted smooth function

- **Spatial Flat-field**
  - Correct for illumination function & fiber response
  - Use Twilight sky flat to renormalize the (fit-removed) flat lamp

But first, we have to trace the fibers for twilight sky flat using the processed flat image as reference to trace the fibers

```
gfreduce rgN20010908S0112 fl_bias- fl_over- fl_gscrrej- \ fl_wavtran- fl_skysub- fl_inter+ slits=both trace- recenter+ ref="ergN20010908S0105"
```
Step 3: prepare the flat-field

Make response curves with twilight correction

gfresponse ergN20010908S0105 ergN20010908S0105_resp112
sky=ergN20010908S0112 order=95 fl_inter+ func=spline3
sample="*"

Likely start of fringing effects

Final flat
Step 4: wavelength calibration

How can we re-sample the data to have linear wavelength axis? → Find dispersion function: relationship between your pixels and absolute wavelength
Step 4: wavelength calibration

Note that the arc in the tutorial has not been observed in the science sequence.
CuAr arcs – over-subtract instead of using the bias since the bias does not apply to fast read and low gain
Using the flat to trace the fibers.

gfreduce N20010908S0108.fits fl_wavtrans fl_inter+
ref=ergN20010908S0105 recenter trace fl_skysub
fl_gscrrej fl_bias fl_over+ order=1 weights=none biasrows

Establishing wavelength calibration

gswavelength ergN20010908S0108 fl_inter+ nlost=10
Step 4: wavelength calibration

First step: Identify lines in your arc frame

Reference list for this lamp from GMOS webpage
Step 4: wavelength calibration

Marked lines in GMOS spectrum, after some tweaking...
Step 4: wavelength calibration

Non-linear component of fit
Step 4: wavelength calibration

- **RMS ~0.1 pix**

- First solution used as starting point for subsequent fibers.
- Usually robust, but should be checked carefully.
- Often best to edit the reference line file (CuAr_GMOS.dat).
- Two slits are treated separately – need to repeat.
Step 4: wavelength calibration

Checking the wavelength calibration

- Testing quality of wavelength calibration is critical
- Not always obvious from your science data
- May not have skylines.
- Detect nonlinearity systematics
- Basic check is to apply the calibration solution to the arc itself, and inspect the 2D image
Step 4: wavelength calibration

Checking the wavelength calibration

- Twilight sky is also an excellent test
- Reduce it like your science data
- Check alignment of science and twilight
- Can also be compared with solar spectrum
- Correlate with solar spectrum to get a "velocity field" of twilight

Slit 1

Slit 2

Wavelength

~1500 Fibers
The effect of fringing from bad flat

Uncorrected Mean Velocity

Twilight Fringe Correction

OASIS
McDermid et al. 2006

SINFONI data on NGC 4486a
Nowak et al.

Such effects would be completely missed in long-slit data....
Step 5: reducing the science data

Now run “gfreduce” on science data to (bias subtraction already done):

- Extract traces using the flat as a reference
- Apply flat-fielding correction (output from “gfresponse”)
- Cleaning cosmic rays using a Laplacian Cosmic Ray Identification routine by P. van Dokkum
- Apply wavelength solution and rectify the spectra
- Sky subtraction

```
gfreduce rgN20010908S0101 slits=both fl_inter- fl_over- fl_bias- fl_wavtran+ fl_flux- refer=ergN20010908S0105 recenter- trace- wavtrant=ergN20010908S0108 response=ergN20010908S0105_resp112 slits=both
```
Step 6: Constructing Data Cube

Data cube is constructed with “gfcube” → Resample extracted IFU spectra onto an x-y-λ datacube

gfcube stergN20010908S0101 sample=0.1 fl_atmdisp=

- `sample=0.1` → spatial sampling rate or pixel size to use in the output datacube.
- `fl_atmdisp=yes` → Compensate for atmospheric dispersion (differential refraction) when resampling the fibre spectra onto the output datacube

Differential atmospheric refraction (DAR) estimated using the atmospheric model from the version of SLALIB distributed with IRAF (v2.3.0 as of gemini v1.10) → “help refro”
Lack of atmospheric dispersion compensator (ADC) in both GMOSs

Atmospheric refraction = image shifts as function of wavelength

- Shifts large at blue wavelength
- Can be corrected during reduction by shifting back each $\lambda$ plane or …
- Use "gfcube" (fl_atmdis=yes). The correction is relatively good.
- OR...

Can use the approach given by Arrivas et al. (1999) for DAR IFU correction.

Differential Atmospheric Refraction