

Comprehensive data reduction package for the Immersion GRating INfrared Spectrograph: IGRINS

Chae Kyung Sim^a, Huynh Anh Nguyen Le^a, Soojong Pak^{a,*}, Hye-In Lee^a,
Wonseok Kang^b, Moo-Young Chun^c, Ueejeong Jeong^c, In-Soo Yuk^c, Kang-Min Kim^c,
Chan Park^c, Michael D. Pavel^d, Daniel T. Jaffe^{a,d}

^a Kyung Hee University, 1732 Deogyong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 446-701, Republic of Korea

^b National Youth Space Center, 200 Deokheungyangjok-gil, Dongil-myeon, Goheung-gun, Jeollanam-do 548-951, Republic of Korea

^c Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-gu, Daejeon 305-348, Republic of Korea

^d University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712, USA

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Abstract

We present a Python-based data reduction pipeline package (PLP) for the Immersion GRating INfrared Spectrograph (IGRINS), an instrument that covers the complete H- and K-bands in one exposure with a spectral resolving power of 40,000. The reduction steps carried out by the PLP include flat-fielding, background removal, order extraction, distortion correction, wavelength calibration, and telluric correction using spectra of A type standard stars. As the spectrograph has no moving parts, the PLP automatically reduces the data using predefined functions for the processes of order extraction, distortion correction, and wavelength calibration. Before the telluric correction of the target spectra, the intrinsic hydrogen absorption features of the standard A star are removed with a Gaussian fitting algorithm. The final result is the flux of the target as a function of wavelength. Users can customize the predefined functions for the extraction of the spectrum from the echellogram and adjust the parameters for the fitting functions for the spectra of celestial objects, using “fine-tuning” options, as necessary. Presently, the PLP produces the best results for point-source targets.

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1. Introduction

IGRINS (Immersion GRating INfrared Spectrograph) is a cross-dispersed near-infrared spectrograph that uses a silicon immersion echelle grating as its main dispersing element. It covers all of the H- and K-bands in a single exposure with a resolving power of $R = \lambda/\Delta\lambda \sim 40,000$. The H- and K-bands echellograms consist of 23 and 20 orders, respectively (Fig. 1). Since the spectrograph has

no moving parts, the transformation functions for the order extraction, distortion correction, and wavelength calibration vary very little from one exposure to the next. Hence, a deliberately designed pipeline is to provide stable quality of data reduction process with minimal human intervention.

The full IGRINS hardware and software system is described earlier (Yuk et al., 2010). The IGRINS software consists of six packages to be used before, in the middle of, and after the observation. To prepare the observation, one can use the Exposure Time Calculator (ETC) and a finding-chart produced with the Observational Preparation Package (OPP). During the observation, Housekeeping Package

* Corresponding author.

E-mail addresses: cksim@khu.ac.kr (C.K. Sim), soojong@khu.ac.kr (S. Pak).

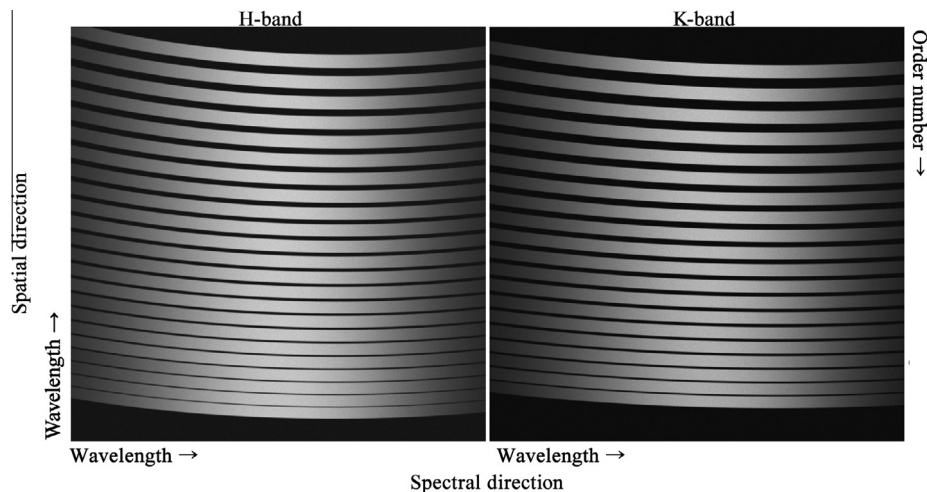


Fig. 1. Simulated IGRINS H- and K-bands flat echellogram. Echelle order number increases from top to bottom; wavelength increases from bottom to top and left to right. In each order, the spectral (dispersion) direction is along the horizontal axis, while the spatial direction is along the vertical axis.

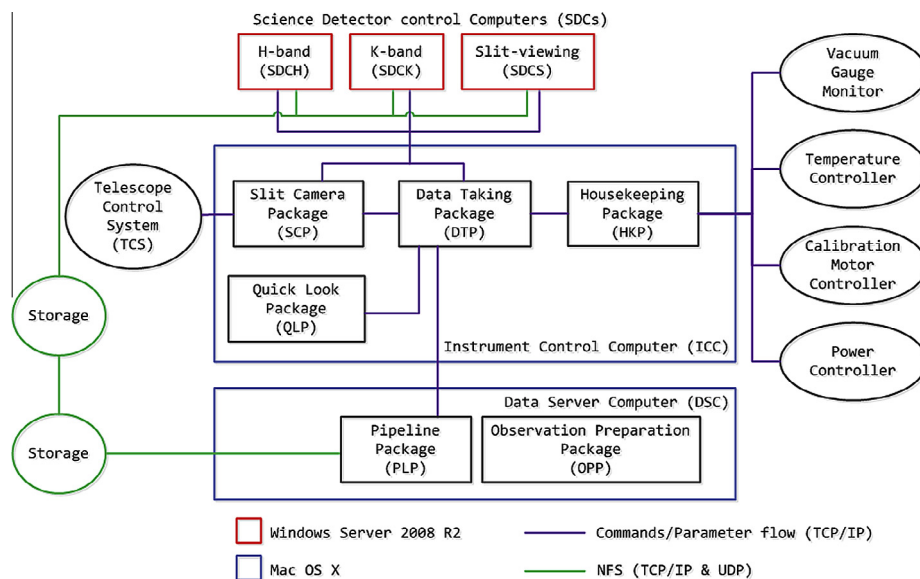


Fig. 2. System architecture diagram of the IGRINS software.

(HKP), Slit Camera Package (SCP), Data Taking Package (DTP), and Quick Look Package (QLP) conduct the observation. Afterwards, the data can be reduced by the Pipeline Package (PLP). This package can also be used during the night to help the observer to decide further observation strategies. A diagram of the overall configuration of the IGRINS system is shown in Fig. 2.

The PLP reduces the IGRINS data following the well-established procedure for reduction of echellogram images: flat-fielding, background removal, order extraction, distortion correction, wavelength calibration, and telluric correction. As the spectrograph has no moving parts, the functions to represent the echellogram mapping are theoretically defined. The reduction processes of order extraction, distortion correction, and wavelength calibration can be run in an automated way using the predefined functions. The functions can then be revised in a “fine-tuning” mode that interacts with the user during the run.

To make use of the PLP, the observer should follow the standard observing sequences which requires assigning reduction group number to each echellogram, observing AOV type standard star, and using “Nod-on-Slit” mode for the stellar objects.

In the following sections, we write about the PLP from the standpoint of its architecture in Section 2, describe the standard observing sequence for IGRINS in Section 3, illustrate the detailed reduction process of the pipeline in Section 4, and summarize in Section 5. The “*pipeline*” hereafter refers to the PLP of the IGRINS software.

2. Architecture of the IGRINS Pipeline

All of the IGRINS software including the *pipeline* is written in Python¹ 2.7, which is freely available for many

¹ <http://www.python.org/>.

platforms including Microsoft Windows, Mac OS, and linux systems. In addition to its straightforward syntax and intuitive graphical user interface, the advantage of python as an astronomical tool lies in its extensibility to many scientific algorithms using the wide variety of available open-source libraries (Greenfield, 2011; Robitaille et al., 2013).

The *pipeline*, developed in the Mac OS 10.8, has been tested in Mac OS 10.7–9, Microsoft Windows XP and 7, CentOS 5.9 and Ubuntu 10.4.4. It makes use of scientific, astronomical, and graphical libraries such as NumPy², SciPy³, PyFits⁴, matplotlib⁵. It also works with NumPy 1.6–8, SciPy 0.12–13, PyFits 3.0–1, and matplotlib 1.1–4. One potential limitation for users running the *pipeline* at their home institutions is the occurrence of memory error in some cases of operation with a 32-bit OS, mainly due to the large size of the IGRINS $2\text{ K} \times 2\text{ K}$ array detector and hence those of FITS files.

During the observing night, raw echellograms are saved as FITS files and an ASCII-formatted observation log is saved to the storage via Data Taking Package (DTP). The *pipeline* makes use of the log to categorize echellograms into dark, flat, arc, standard, and target. At every step of the reduction process, reduced echellograms and spectra are saved as FITS files. The final result is intensity versus wavelength spectrum for each order of the echellogram.

To help users check intermediate stages, additional images displaying the spectra of wavelength calibration and telluric correction processes are saved in the PNG format. Description of each process is displayed in the Python console window and the same content is saved into a reduction log. The current *pipeline* version and system time at the start and the end of the run is also saved into the log file. The reduction history, i.e., metadata, for each FITS file is saved in its header.

The software code, installation guide, and user's manual will be provided via web⁶ in early 2014.

3. Standard observing sequence

To make use of the *pipeline*, the observer should obtain data using the IGRINS standard observing sequence. In short, a star-like point source target and an A-type star as a telluric standard should be observed using “Nod-on-Slit” mode and every frame should have its own “Group ID” assigned.

The rationale for selecting A-type stars as standards is that their H- and K-band spectra contain intrinsic lines that are ignorable or easily removed (Vacca et al., 2003). There are few metal lines whose strengths are only few

percent of the continuum and photospheric hydrogen lines whose spectral profiles are almost Gaussian. As the *pipeline* automatically fits and removes the hydrogen lines from the spectra of standard star frames (see 4.3.1), observing A stars as standard is preferable. Details on the “Nod-on-Slit” mode and “Group ID” are given in the following subsections.

3.1. “Nod-on-Slit” mode observation

The observed data number (DN) is a sum of dark current, telescope and sky background, as well as the target signal. As the background is a significant source of radiation in the near-infrared, *nodding* is one general strategy to effectively remove the backgrounds. When an exposure on the celestial object (**A** frame) is followed by equal time of exposure on the nearby sky background (**B** frame), subtracting the **B** frame from the **A** frame effectively removes the sky background as well as dark current and telescope background (e.g., Cushing et al., 2004).

The Data Taking Package (DTP), the control software for the spectrograph and calibration system of IGRINS, provides the observing modes for a celestial object. One is “Stare” mode that keeps the star at the center of the slit. It will be used to confirm whether the telescope is properly pointing the target and to determine the object's position inside the slit. Another one is “Nod-on-Slit” mode that nods the telescope so that the star is at right and left by turns inside the slit. “Nod-off-Slit” mode also nods the telescope but keeps star and nearby blank sky at the center of the slit in rotation. Among them, “Nod-on-Slit” mode is most likely to be preferred because it reduces the total observing time and averaging **A** and **B** frames increases the signal-to-noise ratio of the spectrum when the target is a point source. When observing extended sources such as planets, interstellar clouds, and galaxies whose angular size is comparable to or larger than the slit length, “Nod-off-Slit” mode is a good alternative.

Reduction processes for extended sources cannot be easily generalized into a single sequence since the reduction procedure varies of the object, its size relative to that of the slit, observing mode (staring or scanning), and the method to remove the background sky feature. In its automated mode, the *pipeline* only deals with IGRINS data obtained in “Nod-on-Slit” mode.

To be compatible with **A** and **B** frames for celestial objects, halogen lamp data should be obtained as a pair of **ON** and **OFF** frames. Subtracting the **OFF** frame from the **ON** frame removes dark current and telescope backgrounds as the nod-and-subtract strategy does.

3.2. Assignment of the “Reduction Group”

For those who observe many point source targets in a single night using on-slit nodding, the *pipeline* categorizes the obtained frames by “Group ID”. The observer designates the “Group ID” for each frame using the DTP.

² <http://www.numpy.org>.

³ <http://www.scipy.org/>.

⁴ http://www.stsci.edu/institute/software_hardware/pyfits.

⁵ <http://www.matplotlib.org>.

⁶ <http://irlab.khu.ac.kr/~igrins/>.

Table 1
Example of the standard observing sequence for “Nod-on-Slit” mode using “Group ID”.

Frame type	Group ID	Reduction process 1	Reduction process 2
Calibration lamp	1, 1	○	
Standard star 1	1, 1	○	
Target star 1	1, 1	○	
Target star 2	1, 1	○	
Calibration lamp	1, 1	○	
Target star 3	1, 1	○	
Target star 4	1, 1	○	
Standard star 2	1, 2	○	○
Calibration lamp	1, 2	○	○
Target star 5	2, 2		○
Target star 6	2, 2		○
Standard star 3	2, 2		○
Calibration lamp	2, 2		○
⋮			

Consecutive frames with the same “Group ID” are regarded as a group and the *pipeline* carries out the reduction separately for each group. Frames in one group share the same calibration data. A standard star needs to be at similar air-mass as the target. In general, each group may last for 1–3 hours of the observing night.

“Group ID” consists of two numbers. A frame that is to be used in only one reduction group ought to have two identical numbers (e.g., 1 and 1) as its “Group ID”. In case of a calibration frame that is to be used for both of the two sequential groups, observer can assign two different numbers (e.g., 1 and 2). Then the *pipeline* uses those frames for reductions of both groups. An example of the standard observing sequence using “Nod-on-Slit” mode is shown in Table 1.

4. Reduction process

The *pipeline* serves to transform the raw IGRINS echellograms of astronomical targets and their associated calibration frames into spectra of relative intensity versus wavelength on the basis of the observational log (written by Data Taking Package (DTP)). In terms of its functional aspects as well as the running-time, the *pipeline* serves in two modes:

- *fast mode*– works within a few minutes to give the observer at the telescope an idea of the science quality of the data, to be used in the observation night;
- *fine-tuning mode*– interacts with the user to review the intermediate results and to fine-tune the reduction processes.

Though several options for the fine-tuning mode are separated in the detailed process inside the *pipeline*, they are blended from the user’s point of view. In the graphical user interface (Fig. 3), the *pipeline* is divided into three parts as follows:

- *Preparations* – Selection and categorization of the frames to be reduced making use of observing log.
- *Calibration data reduction* – Pre-processing of the frames of dark current, halogen lamps, arc lamps, and derivation of the transformation functions for order extraction, distortion correction, and wavelength calibration.
- *Object data reduction* – Pre-processing, order extraction, distortion correction, wavelength calibration of the frames of standard stars and target objects, hydrogen line removal from the standards, and telluric correction of the targets.

We describe each part of the process in Sections 4.1, 4.2, 4.3. To discriminate observation data, we adopt a few notations; [*ttt*] stands for the exposure time, [*ii*] for the sequential number under the fixed observation parameters, and [*jj*] for the order number of the extracted strips from the echellogram. If the observer has assigned two or more Group IDs (see Section 3.2), the *pipeline* repeats the entire processing for each reduction group. The process of one group is illustrated in Fig. 4.

The basic algorithms that are shared for two or more different types of frames appears only once. The methods to correct bad pixels and to combine echellograms are presented in Section 4.2.1. Cosmic-ray correction is described in Section 4.3.1.

4.1. Preparation of frames for reduction

Making use of the observation log written by the DTP during the observation, the *pipeline* reads the file list and automatically categorizes the data files by their type, i.e., dark current, flat field, arc, standard, and target. The names of the classified files appear in a listbox. When the user marks some files in a listbox, only those files are reduced. Files should be marked as a pair of **ON** and **OFF** or **A** and **B** files for calibration or object data, respectively.

4.2. Calibration data reduction

4.2.1. Dark

Dark frames that are observed and corrected for the bad-pixels (if requested) with several different exposure times [*ttt*], dark[*ttt*]_[*ii*], are combined to make DARK[*ttt*] and saved. The number of saved DARK files is determined by the number of different exposure times.

Bad pixel correction is done when requested. The bad-pixel positions in the observed echellogram image are designated by using a pre-defined mask image. Bad pixels are replaced using a linear interpolation of the two nearest-neighbor good pixels (in lines or columns).

Combining algorithm computes either median or average value of echellograms on a pixel-by-pixel basis. Sigma clipping is one option that ignores pixel values that deviate more than the input value on GUI multiplied by the standard deviation.

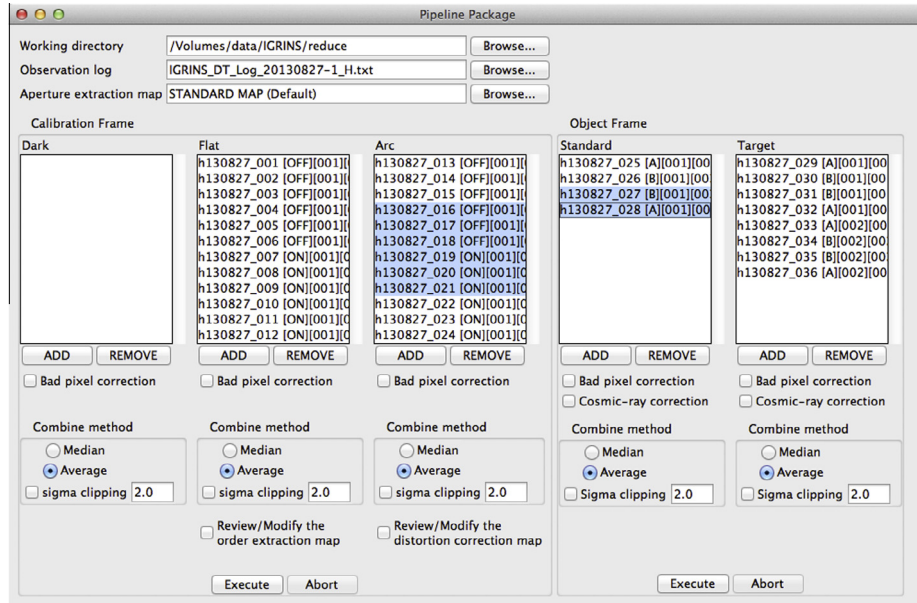


Fig. 3. The main GUI of the IGRINS pipeline.

4.2.2. Flat and order extraction map

It is required to take exposures with the halogen lamp on and off as a set. The observed (and corrected for bad-pixels as described in Section 4.2.1, when requested) `flat_on[ii]` and `flat_off[ii]` images are combined to make `flat_on` and `flat_off`, respectively. Subtracting the `flat_off` from the `flat_on` on a pixel-by-pixel basis makes the difference frame, `flat_onoff`.

The *pipeline* scales the pixel values of `flat_onoff` so as to set the median value to unity to facilitate the estimation of the signal-to-noise ratio (S/N) of the spectra of celestial objects afterwards. The normalized flat image is saved as `FLAT`.

In addition to its use in flat-fielding, the high S/N flat image is essential for the determination of the position of the echellogram orders (Cushing et al., 2004). The *pipeline* makes use of an *edge detection* algorithm to find the order locations. At the center column of the echellogram (center of the spectral direction axis), the gradient of the cross-cut flux f along the spatial direction is the first order numerical derivative (Starck and Murtagh, 2006; González and Woods, 2002; Jain, 1989):

$$f_y = \frac{\partial f}{\partial y}, \quad (1)$$

where y is the pixel positions along the spatial direction.

The pixel positions where the derivatives have positive and negative peaks are the upper and lower edges, respectively, of orders in the echellogram (Fig. 5). The *pipeline* repeats the *edge detection* for columns of every 40 other pixels along the abscissa and fits the edge positions of each order with a septic function:

$$y = a_0 + a_1x + a_2x^2 + \dots + a_7x^7, \quad (2)$$

where x is the pixel position along the spectral direction.

An *order extraction map* refers to an ASCII file that contains the coefficients table for all orders. It is saved to a designated folder in storage for the spectral extraction process afterwards. Once saved, the map can be used whenever needed and thus saves computing time. For this purpose, the “Standard Transformation Functions”, predefined order extraction map and distortion correction functions (see Section 4.2.3), will be distributed along with the software. The *fast mode* (see Section 4) of the *pipeline* as well as the Quick Look Package (QLP) utilizes the “Standard Transformation Functions”. The fine-tuning process, i.e., reviewing of the extraction result and/or customizing the map or switching it to another one previously customized, can be done upon request in the GUI.

In the fine-tuning mode, the *pipeline* displays the differences between the *current* extraction map and that derived by the *edge detection* algorithm. Fig. 7 shows one example; residuals of pixel positions in the upper and lower edges when the standard map is used. When closing the residual display, the user is asked to decide whether to update the extraction map.

From the Flat image, orders are extracted using the extraction map defined above. When rectifying the curved orders, the pixels move only along the ordinate (spatial direction axis) by an integer-number of pixels to preserve the observed data number (DN) without interpolation. Extracted strips are saved to storage as `FLAT[jj]`.

4.2.3. Arc and distortion correction function

Similarly to the flat frame processing in Section 4.2.2, the observed (and corrected for bad-pixels upon request) echellograms with the arc lamp on and off, `arc_on[ii]` and `arc_off[ii]`, are combined to make `arc_on` and `arc_off`, respectively. Subtracting `arc_off` from

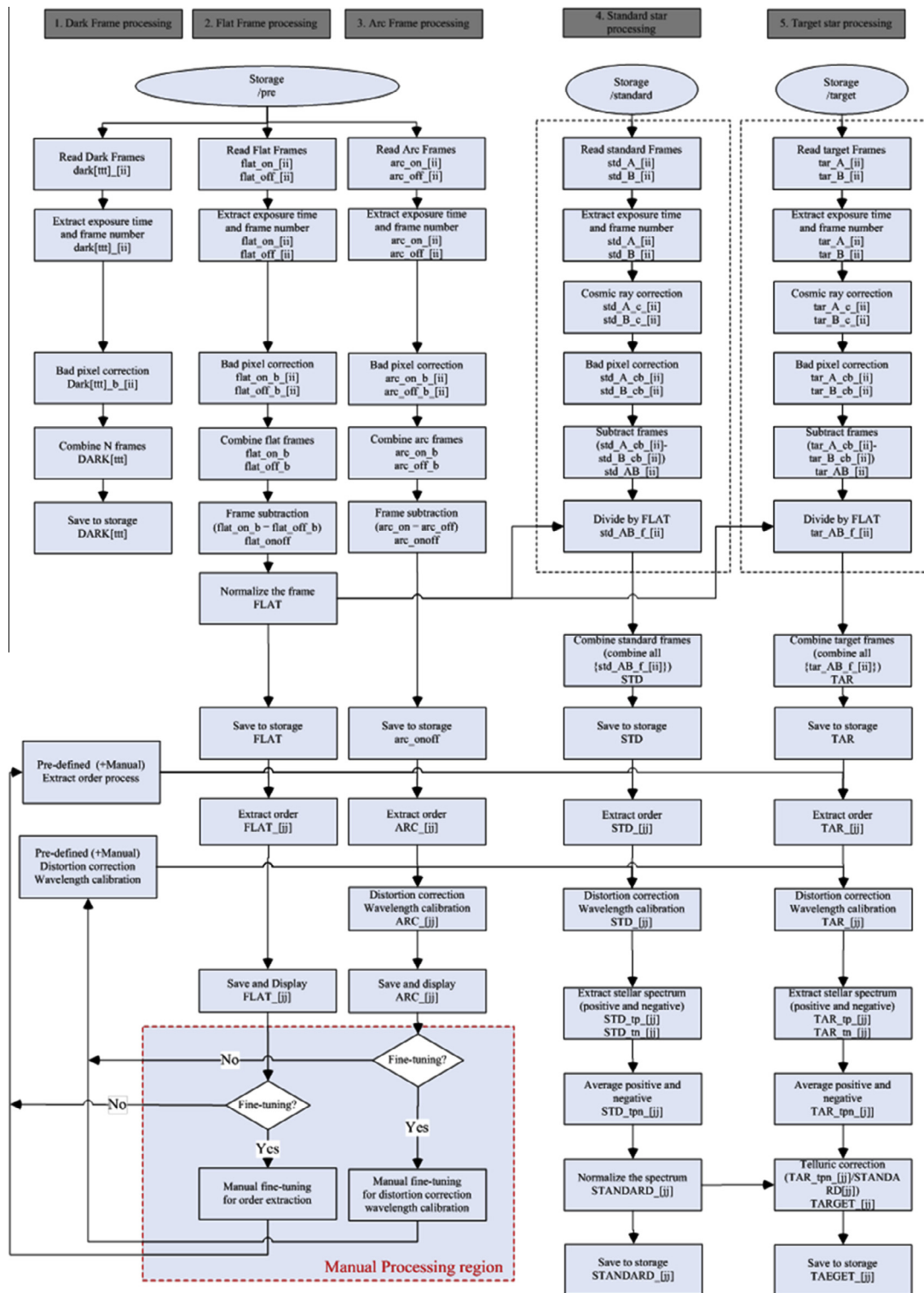


Fig. 4. Pipeline processing procedure. $[ttt]$ stands for the exposure time, $[ii]$ for the sequential number under the fixed observation parameters, and $[jj]$ for the order number of the extracted strips from the echellogram.

arc_on on a pixel-by-pixel basis makes the difference frame, arc_onoff . To extract orders from the arc image, the same extraction map used in the flat frame processing is used. Extracted strips are saved as $ARC_{[jj]}$ in storage.

Arc frames are used to correct the distortion in the spectral direction of the extracted orders. The *pipeline* finds

emission features for several rows along the ordinate (spatial direction axis) and fit the features with a second order polynomial to make the distorted spectral lines straight. The pixel value moves only in abscissa (spectral direction axis) at this time and the observed DN are preserved without interpolations. Comparing the straightened emission

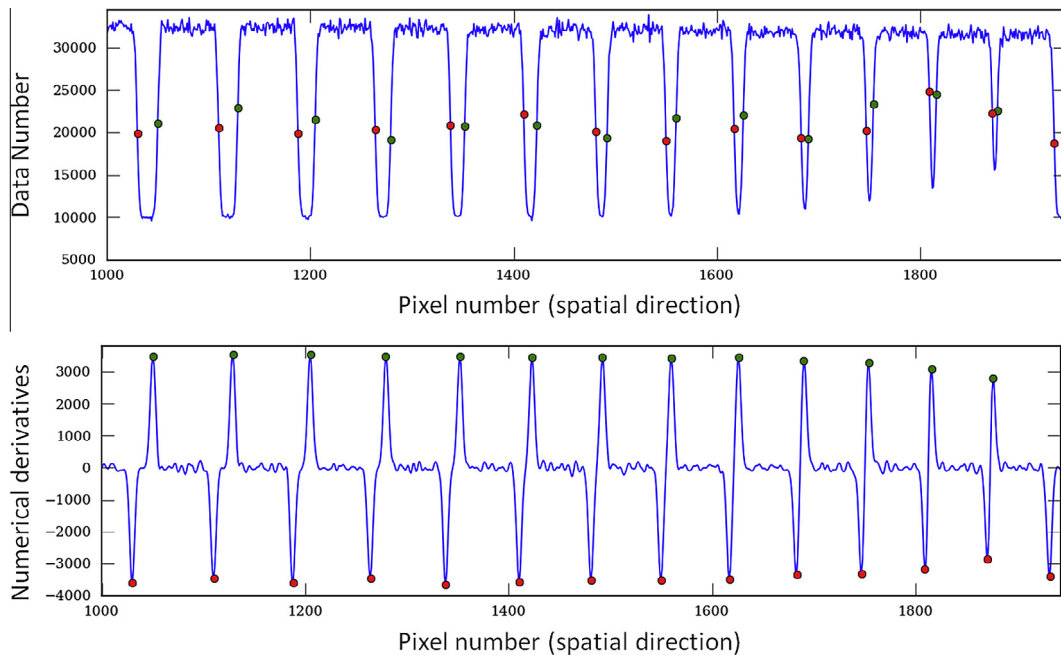


Fig. 5. Spatial direction cross-cut of the FLAT at the center column of the spectral direction (upper panel) and the numerical derivatives of the cross-cut to find the upper and lower edges of each order of the echellogram.

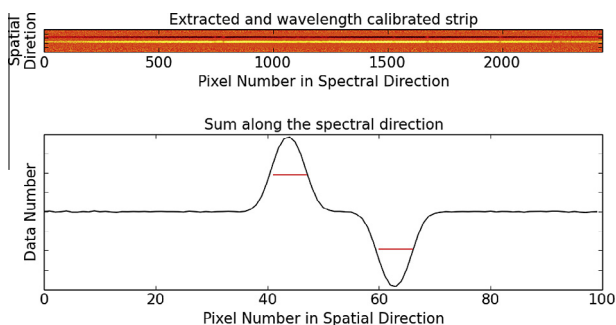


Fig. 6. An extracted strip of the echellogram showing a positive **A** and a negative **B** features (upper panel) and the summation of that strip along the spectral direction (lower panel). The read lines show pixel range corresponding to the FWHM for each signal.

features to the arc line list enveloped in the software, the *pipeline* transform the rectified strip into the wavelength-calibrated one. Fig. 8 shows before and after the transformation.

To ensure the quality of the rectification and wavelength registration, every order should have several spectral lines of the arc lamp and the lines should be widely distributed along the spectral direction in an order, which is not the case of several orders of IGRINS echellogram. One good substitute for the arc lamp is the emission lines of the night sky. For the sake of the OH lines that are bright, numerous, and diversely distributed at most of the orders of H- and K- band (Rousselot et al., 2000). To use OH lines as arc, one is to add the sky frame into the arc list on the GUI. The *pipeline* will select appropriate lines in its enclosed database that consists of ThAr and UNE lamp

lines and OH lines on the basis of the `target name` field in the observation log.

As briefly mentioned in Section 4.2.2, the distortion correction function and the order extraction map makes “Standard Transformation Functions”. As fine-tuning processes, result-viewing of the distortion correction and wavelength calibration and/or correcting or switching the functions can be done upon request in the GUI.

4.3. Object data reduction

Here we describe the process of the A-type standard star and a star-like point source target that are observed in the “Nod-on-Slit” mode as illustrated in Section 3.

4.3.1. Standard star and telluric correction spectra

The observed `std_A[ii]` and `std_B[ii]` images are corrected for bad-pixels and for cosmic rays upon request in the GUI. The bad-pixel correction method is the same as described earlier in Section 4.2.1.

Cosmic ray correction is done by detecting the pixels with brighter flux than a threshold value of $\text{flux} = 1,000$ in analog–digital units (ADU). When the candidate pixels are marked, the ratio of the median value of the 8 surrounding good pixels (within the window of 3×3) to the marked pixel is computed. If the calculated ratio is lower than the flux-ratio threshold of 0.2, then the value of the marked pixel is replaced by the median value of the 8 surrounding good pixels. We note that the flux-ratio threshold of 0.2 is from heuristics during the development stage and is subject to change when the real observation test is available in the early 2014, before distribution of the *pipeline*.

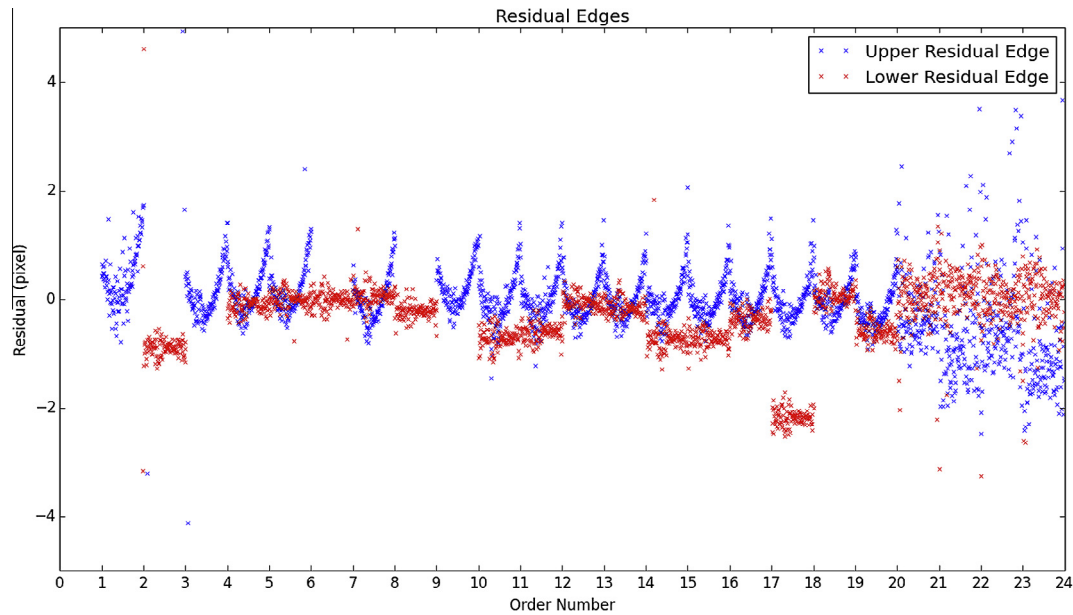


Fig. 7. The residuals of the pixel positions of the upper (blue) and lower (red) edges of extracted strips from a flat frame using the standard map. The numbers in the abscissa refer to the order. Between the order numbers are pixel positions in the ordinate (spectral direction axis) of each extracted strip. Since we deliberately tilted the flat image by 0.1° to test the fine-tuning mode, the residuals in this plot exaggerated relative to those in the real observation. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

For each pair of **A** and **B** frames, subtracting the `std_B[ii]` frames from the corresponding `std_A[ii]` frames in order makes the difference images, `std_AB[ii]`, that are free from dark currents and sky and telescope background. After dividing the difference images by the normalized `FLAT`, the *pipeline* combines the flat-fielded `std_AB[ii]` and save to storage. The number of the combined images are determined by the number of standard stars observed in a “Reduction Group”.

Then the *pipeline* extracts the orders, correct the distortions, and register wavelenthsn to make `STD[jj]` using the “Standard Transformation Functions” or other ones that is determined in the most recent calibration data processing or specified directly in the GUI by the user.

Now each order strip consists of a positive **A** spectral signal and a negative **B** signal (Fig. 6). To extract both of them excluding the background, the *pipeline* uses the sum of the cross-cuts. The rows within the full-width at half-maximum (FWHM) of each stellar feature. Then the

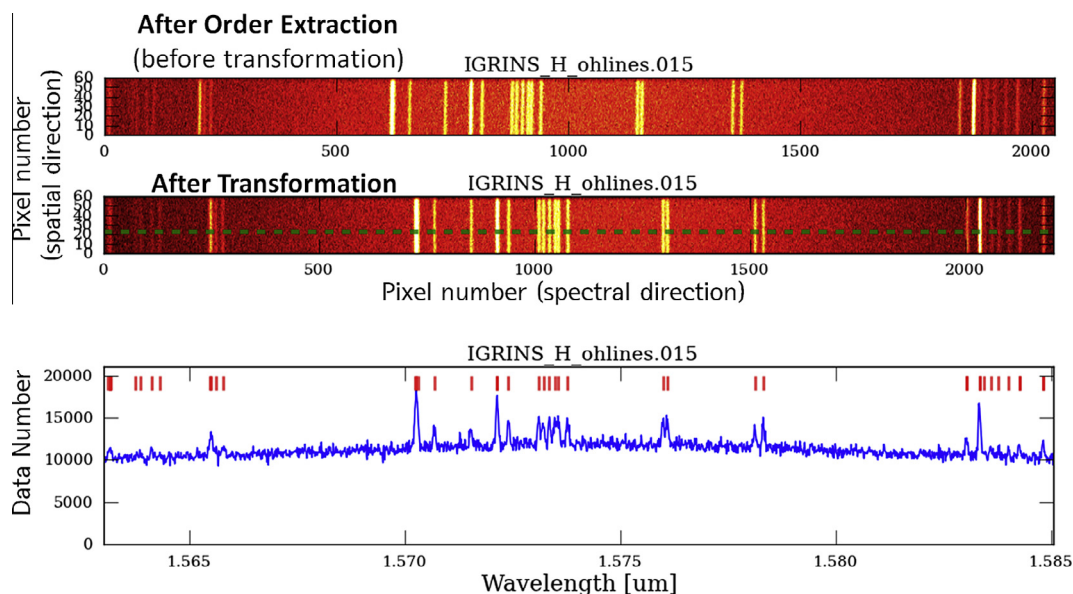


Fig. 8. A strip of IGRINS echellogram before (upper panel) and after (middle panel) the distortion correction and wavelength calibration using night sky OH lines and the resulted spectrum of the strip (lower panel).

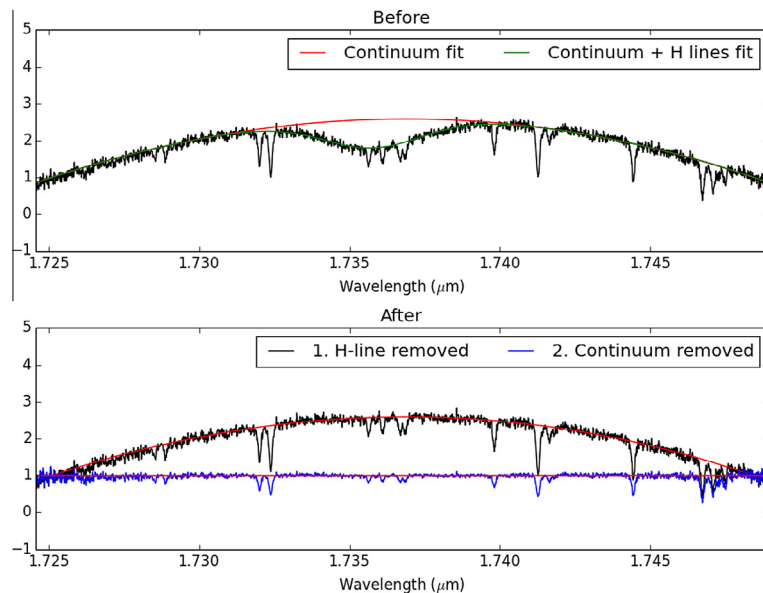


Fig. 9. An example of simulated standard star spectrum of an order Before (upper panel) and After (lower panel) the H lines and continuum removal. Best fits for the continuum (red) and Gaussian mixture to reproduce the hydrogen lines (green) are also shown. Telluric lines are ignored in fitting by sigma clipping. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

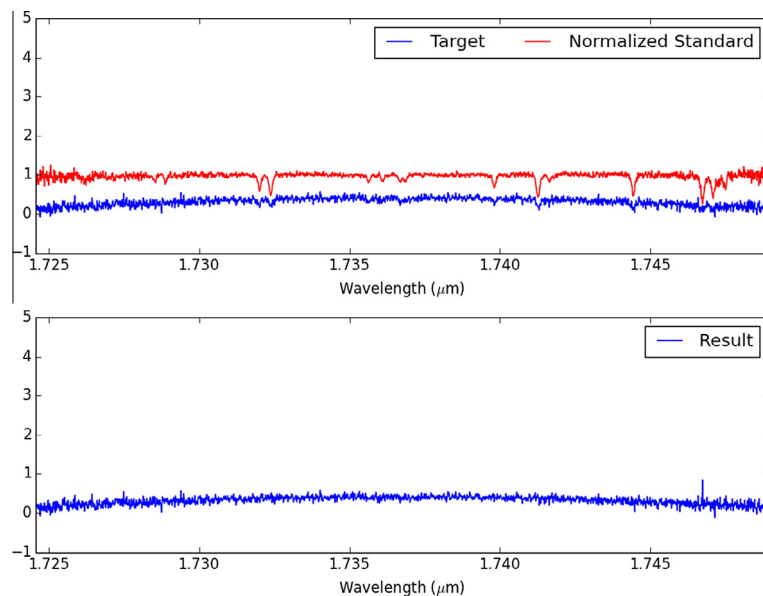


Fig. 10. Example spectra of the final step using simulated echellograms.

pipeline accumulates the the pixel values along the ordinate (spectral direction axis) to make a positive **A** ($\text{STD_tp_}[jj]$) and a negative **B** ($\text{STD_tp_}[jj]$). Averaging $\text{STD_tp_}[jj]$ (**A**) and $-\text{STD_tn_}[jj]$ (**-B**) yields $\text{STD_tpn_}[jj]$, spectra of the standard star with an increased S/N.

Spectra of A-type stars can be used for telluric line correction of the stellar A stars have very few absorption features in the near-infrared (Vacca et al., 2003). The A star spectra, however, have strong hydrogen absorption lines. Brackett series transitions are widely distributed in the H-band and the Br- γ and δ lines appear in the K-band.

Removing hydrogen lines is a straightforward process due to their line shape that is analogous to a Gaussian profile. From the spectra of $\text{STD_tpn_}[jj]$ above, hydrogen lines are fitted with Gaussian profiles. The first guess on the center wavelengths comes from the Rydberg formula. Two or more lines in one order are fitted with the sum of the same number of Gaussians (Gaussian mixture). The continuum of each order is fitted with a third order polynomial and multiplied with the Gaussian mixture to provide a proper baseline. While fitting, telluric lines are excluded by sigma clipping. With iteration, a combination of Gaussian mixture and a polynomial that fits best to spectrum of

each order is attained. Subtracting the Gaussian mixture model from the `STD_tpn_[jj]` makes the intrinsic hydrogen lines to be removed.

The hydrogen-free standard spectra are normalized to make telluric correction spectra. Assuming the similar air-mass condition for each group, the *pipeline* removes the continua of the standard star dividing them with derived polynomials and makes the telluric correction spectrum (Fig. 9). Resulted `STANDARD_[jj]` are saved to storage and to be used for the telluric correction of the target spectra.

4.3.2. Target star

The processing procedure of the target star is same with standard star case; subtraction **B** from **A**, flat-fielding, order extraction, distortion correction, wavelength registration, and average **A** and **A** stellar features. Telluric correction process divides the resulted target spectra `TAR_tpn_[jj]` by `STANDARD_[jj]`, the telluric correction spectra derived previously in Section 4.3.1. That makes the final result, `TARGET_[jj]` (Fig. 10).

5. Summary

We present a Python-based data reduction pipeline for the Immersion GRating INfrared Spectrograph (IGRINS). The software treats the FITS format data obtained with the “Nod-on-Slit” observing mode on the basis of the “Reduction Group” assigned during the observation. The *pipeline* provides high-quality spectra with minimal human intervention and order extraction, distortion correction, and wavelength calibration can be automatically carried out using the predefined functions. The optional fine-tuning mode facilitates reviewing the automated process and modifying the pre-defined transformation functions.

IGRINS will be compatible with telescopes of diameters ranging from 2.7-m (the Harlan J. Smith telescope at McDonald Observatory) to 8–10 m. Commissioning and initial operation of the IGRINS will be on the 2.7-m Harlan J. Smith telescope at McDonald Observatory from early 2014. Since IGRINS is a prototype of GMTNIRS, Giant Magellan Telescope Near-Infrared Spectrometer

(Lee et al., 2010), an extension of this *pipeline* will serve as the basis for the GMTNIRS reduction software.

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