

# Spectroscopic Data Reduction Pipeline for the Goodman High Throughput Spectrograph

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**Abstract.** The Goodman High Throughput Spectrograph (Goodman Spectrograph) is a highly versatile instrument in operation at the SOAR Telescope on Cerro Pachón, Chile. It is capable of doing low to mid-resolution spectroscopy in a range from 3200 Å to 9000 Å. The data reduction pipeline is conceived as an easy-to-run software, that can process an entire night worth of data by execution of a simple command, with some arguments, from a terminal window. It is written almost entirely in Python, following several Python standard conventions. We aim towards using exclusively standard Python packages, such as Astropy and Astropy-affiliated packages, while at the same time allowing for fast and efficient computing. In its present form the pipeline produces fully reduced, wavelength-calibrated spectra. Flux calibration will be an add-on option for a later release.

## 1. Introduction

The Goodman Spectrograph (Clemens et al. 2004) is a highly customizable spectrograph in operation at the 4-meter SOAR Telescope on Cerro Pachón, northern Chile. It is capable of delivering spectra in a wavelength range from 3200 Å to 9000 Å with resolving power ( $R = \lambda/\Delta\lambda$ ) ranging from 800 to 14,000 depending on the configuration. The Goodman Spectrograph is the workhorse instrument of the SOAR Telescope, with about 65% of the available time on the sky. Hence the need of a dedicated pipeline. Moreover, because SOAR is on a path toward increased automation, looking forward to be an efficient follow up facility in the LSST era, an automated pipeline becomes a critical requirement.

Although IRAF is considered by many the standard tool in data reduction, its scope is to provide data reduction and processing capabilities to a rather wide variety of cases, thus is a bit hard to implement as an automatic pipeline. We chose Python because of its versatility, completeness and because it allows for fast development and robust products. The existence and maturity of Astropy and its affiliated packages was also a big motivation to choose Python.

The Goodman Spectroscopic Pipeline will provide clear advantages to users of the Goodman Spectrograph compared to other tools for data reduction by allowing them

to run full processing of their spectra with one-line command while producing science-quality data.

There have been other efforts to develop a data reduction pipeline for Goodman Spectrograph. However, this is the first one developed not as a solution for one specific project, but rather as a community tool. It has been conceived to be simple to use and very well documented, so users can clearly understand each processing step, and even further develop and modify the software. The project is hosted on GitHub therefore is freely available.

## 2. Pipeline Concept & Structure

In the current stable version (1.0b1) the pipeline is structured as two packages with two scripts that act as the user interface through a console or terminal. The motivation for having two packages is to avoid duplicate work, since the Goodman Spectrograph is actually an *imaging spectrograph* the idea is that one of the packages contain tools for processing *Imaging* data and the 2D part of the *Spectroscopic* data, and the other will continue with the specific steps for spectroscopy only.

For the next release (1.0b2) we are developing a single-package structure that will contain sub-packages including the current two as well as new features, such as a telemetry package that can be used to monitor the instrument performance by comparing wavelength calibration parameters. The split-process idea remains but the code's static structure is better.

## 3. Pipeline Use

The Goodman Pipeline has been developed to be easy to use. There are two scripts or commands that you have to run in order to get fully processed data: `redccd` and `redspec`. `redccd` is for the initial image processing, such as bias subtraction and flat correction and `redspec` is for the spectroscopic part; identification, trace, extraction and wavelength calibration. Both scripts can be called with no arguments and should work well for most general use cases and well behaved data, but there is also the possibility of customizing the behavior up to a certain level. Cosmic Ray rejection is done with the DCR program, written in C (Pych 2004). Though our initial plan was to implement a Python-only project, the Python LaCosmic library (van Dokkum 2001) did not provide entirely satisfactory results for our spectroscopic data. Still, and though the default cosmic ray rejection is DCR, we have left LaCosmic implemented in the pipeline, and it can be selected by the user as a command line argument. Although the execution sequence of DCR was gracefully integrated into the pipeline's workflow there is a rigidity regarding parameter variation, because it uses a parameter file with a specific name and at a specific location.

### 3.1. `redspec`

Perhaps one of the most interesting parts of the code is the interactive and automatic wavelength calibration. It relies on a library of previously calibrated lamps, which makes things extremely easy compared to other methods, like `identify` in IRAF. The interactive mode was developed as a way around the complications that the automatic

wavelength calibration meant at that early stage of development. It allowed us to understand how the data behaved in the wavelength regime. Also, and more importantly, it gave us useful insight that allowed us to later implement the automatic wavelength solution. In order to obtain a wavelength solution in interactive mode, the user has to click-identify the lines in two plots, one with a reference lamp plus reference line values and another with the new lamp and the detected lines marked. The clicks are stored in two lists that later are used to calculate the fit of a low order Chebyshev polynomial. In Python this results in a callable object to which you can assign a pixel axis as argument and will return an axis in Angstrom. The use of the reference lamp is only for *visual reference*.

The automated wavelength calibration instead detects emission lines in the comparison lamps and then splits the spectrum in an even number of parts according to the number of lines detected. The reference lamp is also split. Equivalent portions are then cross-correlated, producing an offset value for the corresponding center value, still in pixels, of the lines detected in the new comparison lamp. Using the mathematical model of the reference lamp's wavelength-solution the equivalent line center in angstrom is obtained using the equation  $\lambda_A = model(pixel + offset)$

As a first order filter for mismatched lines the cross-correlation values, which are stored separated, will be sigma-clipped using 2-sigmas and one-iteration only. This eliminates the most obvious mismatched lines. The rejected values also reject their pixel and angstrom equivalents, producing a cleaner new wavelength solution.

Using the Angstrom values previously found and the detected lines plus the newly calculated solution, the differences in angstrom are calculated, and a new sigma-clipping is applied, since the distributions are not necessarily normal distributions.

Once these values are cleaned of rejected values the final solution is calculated using a low order Chebyshev polynomial.

#### 4. Results

The pipeline has met our expectation of being an efficient and fast spectroscopic data processing tool. Although its scientific usefulness has not been validated yet, we believe we are close because the results are repeatable and consistent. Since there is no other production-ready pipeline available for the Goodman Spectrograph data, at the moment we can only compare it to IRAF. Figure 1 contains the result obtained for the same spectrum using the pipeline in automatic mode versus IRAF, by two different users. The good match is evident even when zooming in. We find that, using the 400 l/mm grating with the 1'' slit, which yields a resolution  $R \sim 800$  (FWHM  $\sim 6\text{\AA}$ ), the pipeline produces an automated wavelength solution with  $RMS \sim 0.3\text{\AA}$ . This is roughly the same RMS obtained with IRAF.

#### 5. Future Work

At the moment of writing, the pipeline is in its first beta version and as expected there are some features still missing. They should appear in future releases. Examples are flux calibration, and a complete implementation of fractional pixel extraction and optimal extraction (Marsh 1989) and (Horne 1986). We also want to change the Matplotlib UI by Qt UIs. An important development looking forward will be the implementation

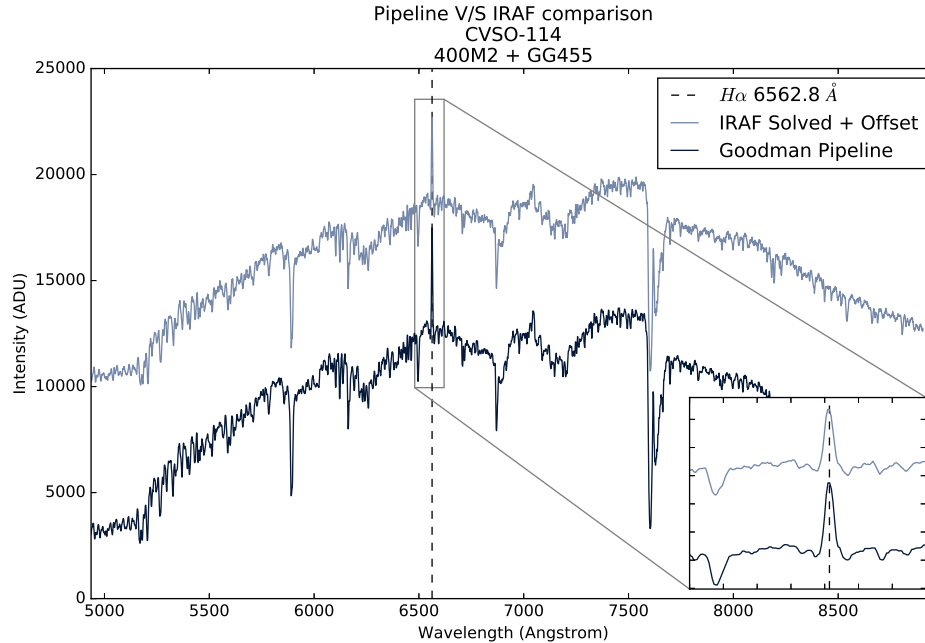


Figure 1. Results obtained using the Goodman Pipeline compared to IRAF. There is an arbitrary vertical offset to clearly set apart both results. The zoomed portion focuses on  $H\alpha$ , in emission, also allowing to view nearby features.

of an online version of the pipeline, that can output reduced, wavelength calibrated 1-D spectra just seconds after the shutter has closed and the raw data saved to disk.

Other planned changes are: to modify the overall architecture of the pipeline, since it started as two separated projects and evolved into a single one, there is a development version that integrates everything as a single package.

Talking about Astropy, there should be a replacement of tasks that are becoming available in Astropy and Astropy Affiliated Packages as they mature, wavelength solution storage for instance.

On the coding side itself we must implement test code and in fact we might switch to a *test driven development* philosophy.

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