Towards the Flux Calibration of Small Telescope Spectra

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Abstract

We present set of reference resources and machine ready spectral data covering optical bands from UVA through 8000+ Angstroms, based on our literature/informatics search of bright spectro-photometric calibration sources suitable for small telescope investigations. These data are made available as ".dat" ASCII whitespace/column data with absolute units of ergs s^{-1} cm^{-2} Å . These catalogs have been translated and augmented for small telescope spectroscopy using additional data from SIMBAD, GAIA and other references to produce a PostgreSQL database. We include generic telluric line table, and files suited to popular planning/operational planetarium programs. We discuss the salient aspects of each library reviewed. We include methodology to acquire spectral measurements of filters and lamp sources common with photometry and spectroscopy. These data and scripts are available through an MIT open source license via GitHUB/Docker and, to the extent possible, are platform agnostic.

ACTION: Filters[1]

1 Introduction

The Next Generation Spectral Library (NGSL) Version 1 (Heap and Lindler, 2007), and NGSL Version 2 (Heap and Lindler, 2010) are published collections of 377 spectra of sources taken with the Hubble Space Telescope's (HST) Space Telescope Imaging Spectrograph (STIS). The reported vacuum wavelengths span 0.2-1.0 μm at an effective resolution R$\sim$1000. These spectra represent the energy distribution as seen from Hubble's orbit, without any Earth based telluric contamination, corrections for radial velocity, line-of-sight extinction or any modeling based adjustments. Wavelength calibrations were done with the star's features and are in the star's rest frame. This calibration approach maximized the satellite's throughput and negates the Earth and satellite's velocities.

We converted the FITS tables to ASCII tabular ".dat" files suitable for both IRAF and for small telescope scientists' tools [1]. To assist with planning and ancillary reduction techniques merged SIMBAD information to the fullest extent possible . We present a technique to develop the spectral profiles of common photometric and other filters that may be used by the community when applying photometric observation technique described by (Bessell, 1983) to estimating overall absolute flux of spectra.

Preliminary tests of this new reference material consists of observing sets of stars and comparing "one-against-the-other". We plan to compare other catalogs popular in the community as well. Poor weather and other conditions prevented completing these test. This paper is an announcement and first report on project. The UV coverage and more exact representation of the flux from these targets are suited to direct observation and use by the Small Telescope community.

Inexpensive spectrographs such as the Lowspec-2 (Rodda et al., 2020) and Lowspec-3 (Gerlach, 2019) provides an excellent response over a 3600-7800Å wavelength range. The newer UVEX 3D/Mechanical

[1] BASS, VSpec, ISIS, Demetra, RSpec, Audine, SpectroCalc etc.

spectrograph (Buil et al., 2019) pushes the lower limit below 3200Å . The UVEX instrument shows promise for research into Earth's physical and aerosol atmospheric characteristics using ground based astrophysical techniques (Pagnutti, 2020).

We have also included a ASCII .dat table of Earth's telluric lines taken from (Ulmer-Moll et al., 2019) to assist with the identification of these features in ST data. The strength of these vary over intervals of just a few minutes and can not be relied upon for energy. They are in the observers rest frame and make for high-reliability wavelength references where they occur. This is very useful with Hydrogen-α observations by small Littorw and echelle instruments in the R$\sim$ 10000-20000 range.

Publication consists of extended electronic appendices at GitHub [2] The documentation is at ReadTheDocs.io[3]. The appendix consists of the raw files, a Dockerfile and other resources needed to reproduce a working copy of the database. The database has been augmented with current SIMBAD information to provide a consistent overview of each target for planning of observations and reduction of data.

This collection is part of a continuing effort to provide complete lower resolution references for faint-magnitude work with SNe and classical novae, and higher resolution work with bright emission stars as well as planetary nebulæwork by (Le Dû et al., 2018).

Accurate spectro-photometric references are critical when producing an instrumental correction curve. Small telescope spectroscopy takes place at lower altitudes than professional observations under more polluted skies. Since these observations are attracting attention from the Earth aeronomic and atmospheric scientists, extended records of the meteorological information in FITS headers is recommended.

2 Methods

Currently we are working with only the NGSL catalog. Others are in progress and issues there inform our general approach. PostgreSQL treats each database as an isolated entity. Inter-database communications is very complicated. However, PostgreSQL schema partition a single database into well managed sub-datasets. Each catalog is maintained in its own schema.

The FITS spectra archives are located, downloaded and the FITS file headers are captured into a master 'raw' database table using the provided "fits2psqlraw" Python3 using Astropy (Astropy Collaboration et al., 2013, 2018) based capture program. Multiple FITS HDU headers are preserved verbatim as a single PostgreSQL JSONB field type, very basic additional data is gleamed and preserved using fits2psqlraw's switches.

PostgreSQL "Materialized Views" and other stored procedures are used to isolate complicated logic and join expressions to facilitate general use. Both the name of a star and its position are not sufficient to find a star's data within the database. Target synonyms, misspellings, abbreviations, truncations of star names, different epochs and small errors in reporting complicate tying a spectra to an exact star.

These data represent a broad survey of stars of interest to the modeling community and do not serve as great photometric reference stars. It is important to remove stars that have their own issues. We have found double stars may not be a problem provided the offending companion can be kept away from the slit to prevent significant signal contamination. Variable stars are identified in SIMBAD's alltypes table group in roughly 28 different ways. SIMBAD's spectral types are of average to poor quality but sufficient to rule out 'complicated stars', such as emission stars and cool giants as not suited for use as reference stars.

[2] `https://github.com/The-SMTSci/NGSL_SAS`
[3] https://ngsl.readthedocs.io/en/latest/

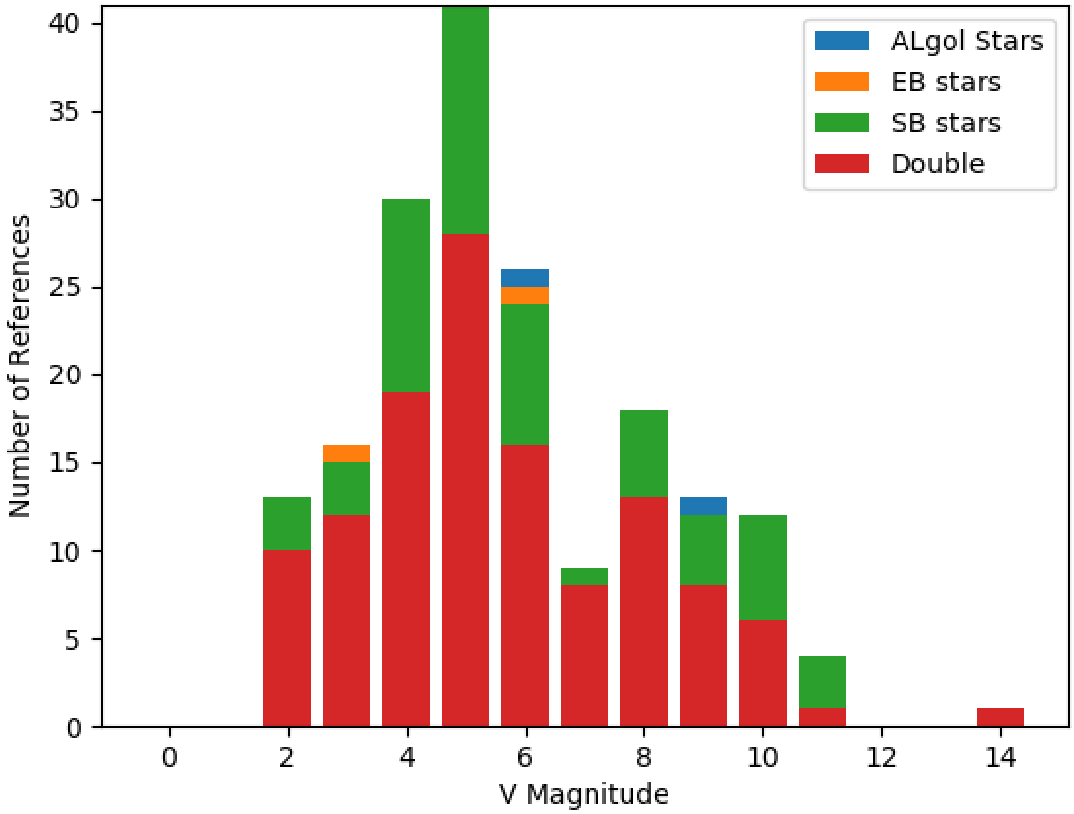


Figure 2-1: Magnitude Distribution out of 377 total stars of questionable NGSL Reference Candidates. Created with complex logic within PostgreSQL and Python/Matplotlib. One T-Tauri star omitted.

Currently, the Washington Double Star Catalog (Mason et al., 2001), as retained in SIMBAD and therefore directly accessible via TOPCAT by the broad community, is downloaded and maintained in its own PostgreSQL schema.

A double star example: SIMBAD has a synonym for WDS J04076+3804AB, where the WDS catalog itself omits both the "WDS", the "J" and the "AB". The WDS to SIMBAD name translation is achieved through SQL by concat('WDS J',wds.coord,wds.comp). It is often the case with FITS header's OBJECT names that the approach to abbreviations differ within the same collection of files. Since the number of FITS files are small, this requires a bit of manual editing to make a consistent database. This paper presents tricks for manual editing in the electronic appendix.

Discordance between FITS headers and SIMBAD's collection includes conditions like:

1. Correct Names (we prefer SIMBAD's main_id name).
2. On average, 30 synonyms as popular name are often more widely used by the community.
3. All SIMBAD Fluxes aid in estimating the overall blackbody and for first-order flux calibration. In particular missing fluxes factor into our confidences.
4. Position in crowded fields, together with the magnitude offer strategies to choose references. Some NGSL stars are in clusters.

5. Spectral classification helps to match reference star to target stars
6. Combining an instrument's response curve and spectral classification together with fluxes helps to predict overall exposure times to match SNR requirements.
7. Reference stars with companions or background contamination unknown at the time the FITS files were produced. The WDS catalog (separation, pa, etc) with 150,803 stars is included. Our extended release will include background stars from GAIA data:
   (a) resolved - wide pairs are fine,
   (b) unresolved - close pairs with close magnitudes are an issue,
   (c) the Vizier ID for WDS is "B/wds/wds".
8. Variable stars - the SIMBAD nomenclature for variability has numerous types that require a complex test.
9. Luminosity class – Hotter stars with small features are preferred for reference stars.
10. Other peculiar aspects of the star. emission, nebula lines, peculiar nebula, etc.

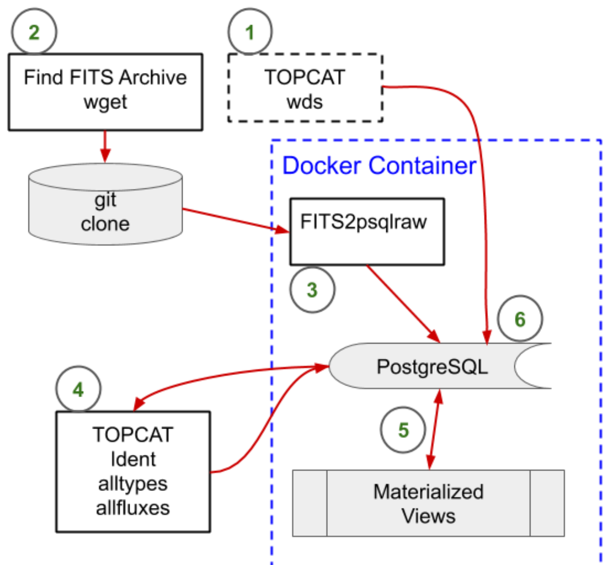


Figure 2-2: NGSL Basic Workflow: 1) Get the WDS catalog once; 2) Find and download the FITS archive; 3) Export 'raw' file with single/multiple HDUs into database schema; 4) Use TOPCAT to create raw tables of with SIMBAD/Other data; 5) Materialized Views and external routines to create the working tables; 6) Export database, save to clone, prepare working information.

The 150,803 stars of the Washington Double Star Catalog was acquired via a TOPCAT query of VizieR's "B/wds/wds". The star "HD 25893" indicated "bad". Using the WDS Nomenclature of "04076+3804" for SIMBAD's synonym of"WDS J04076+3804AB", a query of the WDS shown in Table 2 shows a close companion to the main star and a close companion of a widely separated star. The AB companion case rules this star out as a decent reference star – but the CD case, while close is not related to the A component. Complete consideration of all separations in the hierarchial structure of the target star is necessary.

Double Stars (separation, pa, etc) 150,803 stars. resolve unresolved The catalog is "B/wds/wds"

Example from our PostgreSQL database:

SIMBAD Name	First Separation	Last Separation	Primary Mag	secondary Mag
WDS J04076+3804AB	3.4	2.9	7.32	9.69
WDS J04076+3804AC	239.8	225.1	7.32	8.81
WDS J04076+3804AE	746.1	746.0	7.32	5.57
WDS J04076+3804CD	1.0	1.2	8.81	10.71

Table 1: Local PostgreSQL Database Results show the tight separation between C and D components are not an issue, as C is well away from the primary. However the separation between A and B is an issue.

2.1 Risk of contamination by a close companion

HD 25893 has two of its components with small separation and relatively same brightness. This star is not suited for spectrographic comparison. Assessing the impact of the background contamination requires a bit of logic. Here HD 25893 A component is the one studied, with a close proximity to the B component. The AC separation is large, and while the CD separation is close – that problem is well away from the main star, and capable of being ignored. The fail for this star is on the AB pair's separation and comparable brightness.

$$m - m_0 = -2.5 \times log_{10}(\Delta flux) \tag{1}$$

$$\frac{7.32 - 9.69}{-2.5} = log_{10}(\Delta flux) \tag{2}$$

$$log_{10}(\Delta flux) = 0.948 \tag{3}$$

$$\Delta flux = 10^{0.948} = 8.87 \text{ times fainter.} \tag{4}$$

$$\frac{1}{8.87} = 11\% \text{ noise contribution.} \tag{5}$$

2.2 Other methods

TOPCAT will return data with the occasional 0x00 bytes. While designated as "NULL" in the ASCII table, PostgreSQL will fail during a TOPCAT upload operation. The TOPCAT data is repaired by saving to a local CSV file, running a Unix command, `< bad.csv sed -e 's/\o000/NULL/g' > good.csv` loading the good.csv file and resuming the upload attempt.

FITS files consist of one or more "Header Data Units". Each HDU consist of three fields (KEYWORD, value, [optional comment]). The new standard provides for continuation cards. Historically, COMMENT and HISTORY cards may be used. The Python/Astropy program "fits2psqlraw" is given a set of FITS files and produces an textual file suitable for directly loading into PostgreSQL. There are times where the older HDUs written are inconsistent consistent with Astropy's wrapped version of cfitsio (Pence, 1999, 2020). While Astropy is forward-looking, there is no easy way to ameliorate the problems.

The database is designed to be extensible to meet local users' needs. Tools like Aladin (Nebot Gomez-Moran et al., 2020) are interoperable with TOPCAT (Taylor, 2020) and SAOImage/ds9 (Joye and Mandel, 2005) to assist with the program development, planning, reduction and publication.

3 Usable stars

The disambiguation of usable stars using SIMBAD data has complicating issues. Testing the database against other resources like Aladin, the WDS catalog, etc shows care must be exercised with each star.

For example, HD 28978 with SIMBAD 'otypes' of `X |* |UV |IR`, a spectral classification of A2IV with a confidence level of 'C'. The otypes of NGSL database lists 57 X-Ray sources (otype of X). While SIMBAD offers a XMM observation number of 0143630901, casual use of Aladin's offers of XMM images show no strong evidence of X-rays from this star's position. There is a near-by target: Mrk 1506, a Seyfert 1 Galaxy that is quite bright. Additional follow up is required.

Conclusion: A deeper investigatin of the X-ray reference attached to this star, contained in the associated otypes from SIMBAD is in order.

A second example is a deep-dive into the double star HD 25893, from the database:

SIMBAD Name	From WDS			
	First Separation	Last Separation	Primary Mag	Secondary Mag
WDS J04076+3804AB	3.4	2.9	7.32	9.69
WDS J04076+3804AC	239.8	225.1	7.32	8.81
WDS J04076+3804AE	746.1	746.0	7.32	5.57
WDS J04076+3804CD	1.0	1.2	8.81	10.71

Table 2: Local PostgreSQL database results show the tight separation between C and D components are not an issue, as C is well away from the primary. However the separation between A and B is an issue.

HD 25893 shows the need for a containerized database, accessible from a more traditional programming language like Python 3 or SWI-Prolog. This permits complex logic to be applied through the use of an if-then-else structure or the judicious use of triggering a green-cut operator when the target is too close to a contaminating source.

Summary: We have to rely on larger datasets for raw information related to targets or reference sources. The container offers ease of access without un-necessary impact on the analysist's operating system resources.

3.1 Risk of contamination by a close companion

HD 25893 has two of its components with small separation and relatively same brightness this star is not suited for spectrographic comparison. The impact of the background contamination requires a bit of logic. Here HD 25893 A component is the one studied, with a close proximity to the B component. The AC separation is large, and while the CD separation is close – that problem is well away from the main star, and capable of being ignored. The fail for this star is on the AB pair's separation and comparable brightness.

For this paper, a set of PostgreSQL selection criteria were developed to casually examine set. At least 301 stars require careful step-by-step consideration to be certified as a usable ST spectral reference source.

The NGSL has 377 stars, of which a total of 270 are still viable by current tests – albeit their luminosity classes may not be suitable for most work. Of the 107 flagged candidates:

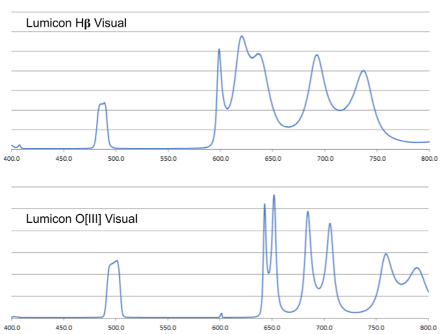
Type	SIMBAD Abbreviation	Count
ALgol Stars	Al*	2
EB stars	EB*	2
SB stars	SB*	57
Double SB	**, not V* or SB*	123
Variable Stars	V*	117
Total:		301

Table 3: Basic Bad Star Distributions

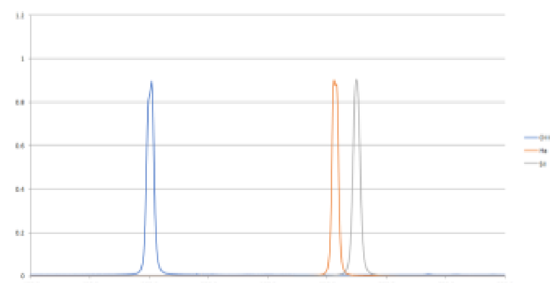
4 Photometric filters

Flux data was added to the NGSL database to assist with rough estimates of exposure times, SNR and for first-order absolute flux calibration. Bessel (Bessell, 1983) describes a technique to use photometric observations of spectrographic targets for a first-order absolute flux calibration fit. In order to use this technique for ST work, it is necessary to have a good understanding of the filter being used. Modern bi-refrengent filters have different response curves. The small telescope scientist that wishes to use this approach may consider measuring their exact filters.

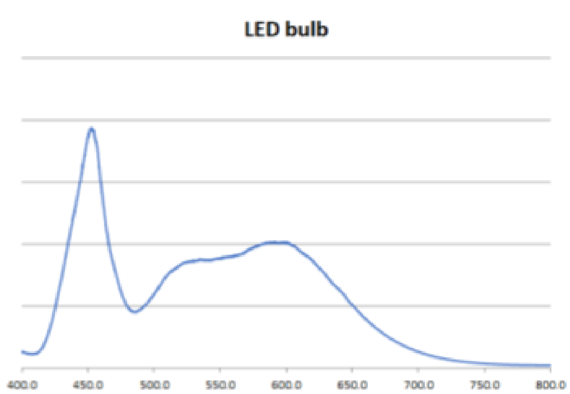
Yeager undertook examining as many filters as we could find with the Lowspec-2 spectrograph with an eye towards 'science-in-the-city'. This was extended to include additional photometric filters. The data were taken in a closed room using a Zwo 16000mm-cooled camera and filter wheel pointed at a tungsten light source. The exposure times were varied and levels of noise were determined for the detector. The exposures were calibrated in the usual manner using a Ne/Ar Relco bulb. Results were published in a presentation made to a local astronomy group.



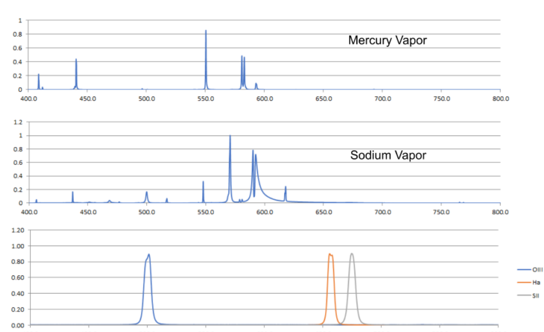
(a) Visual Filters



(b) NarrowBand Filters



(c) Narrow/Pollution



(d) LED Bulb

Figure 4-3: Example of some common filters measured. (a) shows how visual filters are not suited to science observations; (b) measured narrow band filters suited for science work; (c) spectrum of a LED lamp bulb with – brighter in the blue; (d) alignment of narrow band filters shows the O[III] lines up with a city's mercury lamp line.

The critical issues for flux calibration include: 1) the state-of-affairs of the observer's local atmosphere and current solar activity's nightly contributions to telluric lines; 2) engineering aspects including the telescope/spectrograph's combined point-spread-functions, deflection and thermal expansion; 3) operational aspects including planning and scheduling reference star observations and applying parallactic angle for observations; 4) reduction of the data under necessary attendant subjective decisions and 5) and the need to provide a meaningful audit trail of reduction steps. Many of the pressing issues for large professional telescopes are lost in the noise for R$\sim$1000 low-resolution small telescope (ST) community but remain for the R$\sim$10000/20000 spectrographs.

The small telescope community works closely with projects and individual researchers to collect and publish spectra. Each project has its area of emphasis, perspectives and priorities. Every reduced spectra carries inherent noise. This makes it mandatory to retain all images related to spectra that we publish. Today's routine ST patrol image is tomorrows pre-discovery image.

5 Conclusions

The need for flux-calibrated bright stars to support small telescope spectroscopy is needed. All white dwarfs are too faint for practical use. A follow-up program of monitoring the handful of NGSL stars that meet the selection criteria under different conditions and over a period of time can be achieved by simply collecting all attempts together and performing the necessary statistical analysis. The piggy-back observations of the fields will provide a wealth of photons of these bright stars and fews of millimag photometry will be possible. Future work will include refining this technique and applying it to several other catalogs we uncovered during the research for this work.

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