Observations using a Bespoke Medium Resolution Fast Spectrograph

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Abstract

Designing and building a medium resolution (R=3000) spectrograph was the relatively easy part. The really challenging part is learning how to use it: learning the characteristics of the spectrograph, choosing the right kind of astronomical problems, learning the best methods of taking data, and figuring out how to analyze the results. I have used several observing projects to "commission" this system, including measuring the doppler shifts in several WUMa type stars. I will briefly describe the spectrograph but discuss in more detail the early experiences of using it.

1. Introduction

After four years of using a low resolution R=100 SBIG DSS7 spectrograph, I am still in awe of what it can do. But in this paper I describe exploratory work with a new bespoke (custom) Fast Spectrograph (FS1) of R=3000—some 30x greater than the DSS7.

The price of high resolution is low signal level! A spectrometer resolution of R=3000 implies roughly a x3000 reduction in s/n at each pixel, so a five minute exposure of say 16 mag now only reaches about 7 mag., and probably only 6 mag with real optical elements!

RGB and similar filter combinations do allow some ability to distinguish among the colors in the light from an astronomical object. RGB filters have a wavelength resolution of about 10 or so—at about 5000A the bandwidth is about 500A, but already we begin to sacrifice s/n for information. But for greater resolution, we move to ever higher resolution spectroscopy: We always want "more more more", whether it is light gathering or resolution, ice cream, or Scotch.

The design and construction of the FS1 is given in detail in a paper on our website (Menke2012) and in a brief poster at this conference. After completing construction and "first light" with the new FS1, I embarked on a series of observations designed to explore the capability of the instrument and to help me learn how to use it. Of course, identifying and conducting useful research opportunities is the real next step.

2. DSS7 Experience

Some may believe that the "low" resolution of the DSS7 prevents useful work. However, in past years, I have used it to learn spectroscopy observational and analytic techniques. Observations included performing coarse stellar classification from the shape of the spectrum, observing a variety of objects including planets, comets, planetary nebula, and novae. The most notable of these were observations of nova UScorpii as reported at SAS in 2010.

In previous papers and on our website, I have detailed some of the limitations of the DSS7 and effective ways to overcome them (Menke2011). One of the limitations of the DSS7 is (as with most spectrometers) that it is designed for an f10 optical system. However, my 18inch Newtonian is f3.5, thus requiring a properly matched Barlow lens. This extends the optical train, and of course, enlarges the stellar image on the slit, thus usually requiring use of a larger slit with reduced resolution and very tight tracking because there is no real time guiding in the DSS7. The second limitation is, of course, the low resolution. .

3. Fast Spectrometer FS1

After several years of using the DSS7-and by no means exhausting its possibilities-I decided to obtain a higher resolution unit in the R=2-6000 range and suitable for my f3.5 Newtonian. A particular attraction of higher resolution is the possibility of measuring astronomical Doppler shifts. While some galactic and nova Doppler shifts can be observed with the DSS7, velocities of planets are in the 10s of

km/s, semidetached binaries are in the low 100s of km/s. 100km/s corresponds to about a Doppler shift of about 1:3000 or 2A at 6000A. To accomplish a 10% precision implies the ability to measure to about 0.2A.

After searching the market, and finding that nearly all units were designed for f7-f10 and had other features I did not like, I decided to "roll my own" (plus I like building things). The design goals included

- Native f3.5 design (but will easily accept slower telescopes)
- Physically compact, and well balanced
- Inexpensive (approx $500)
- Construction requiring only basic machining skills
- Adaptable, easy to modify
- Accept almost any CCD camera (I use an SBIG ST1603)
- R=3000 with possibility to go higher, and with high stability
- Built-in calibration (e.g., neon bulb or other)
- Built-in guiding, including offset guiding (i.e., not using the target) using Starlight Express Lodestar or SBIG SGi

Fig. 1 shows the FS1, while Fig. 2 shows the Littrow design (in which the light comes back off the grating at the same nominal angle as incoming) that allows for a single collimating lens that is more compact. The many design considerations are detailed in our website paper Menke2012a. Construction and alignment was relatively straightforward using several red lasers to trace rays through the unit and neon bulb and sodium flame sources to measure resolution as described in the reference.
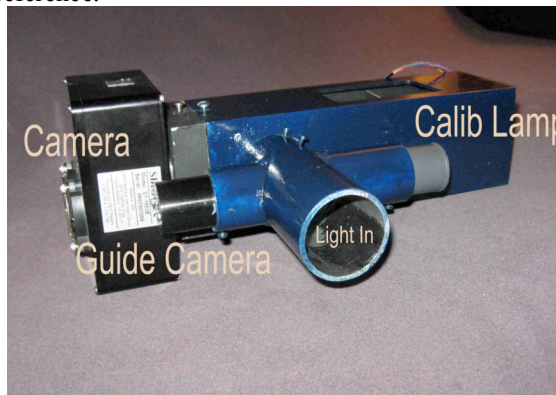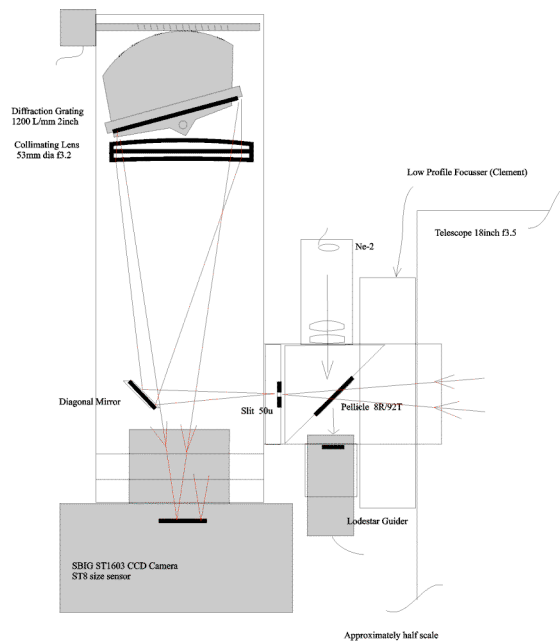

Fig. 1. Picture of FS1 Spectrograph

Fast Spectrometer f3.5 R=3000

Fig. 2. Schematic Diagram of FS1

Once turned on the sky, it was obvious that this was a very different instrument from the DSS7! The integral real time guiding meant that keeping the star on the slit, or even precisely in the middle of the slit, was now easy-no custom software needed. The very first night showed lots of solar lines from the moon, splitting sodium D-lines, and even (incorrectly) seemed to show the rotation of Jupiter. And it showed that the expected mag8 was indeed about the practical limit with good S/N.

After the first night euphoria, the challenges were to measure the characteristics of the FS1 (and making any necessary modifications) while performing "real" observations that would help me learn how to use it and how to interpret the data.

4. Studies of FS1 Performance

The first "real world" task was to determine how well the tracking worked, not only for short data runs, but also for long runs while the telescope shifted in direction. In general, the guider kept the target within the slit to a few tenths of a 8u pixel: guiding was a cinch. Another question was whether there were special demands for the focus of the telescope. Due to a fault in the design of the telescope, its focus shifts when low in the sky, especially toward E/W; however, this did not affect the spectrograph more

than expected and defocus could be easily detected and compensated.

There were many questions about wavelength measurement: resolution, dispersion, stability, repeatability, etc. Measurements quickly using the ST1603 camera (ST8 size chip) showed that the wavelength span is approximately 600A at approximately 0.4A/pixel(9u) dispersion. The remote stepping motor controlled operation of the grating sets the coarse energy scale:. When setting the energy scale using the stepping motor drive, the repeatability is about 10A (corresponding to approximately 1 a-m of grating rotation). While the spectrometer has a resolution of about 2A, it is important that the stability exceed this so that wavelength changes can be accurately followed. Studies discussed below showed that the stability over a data run is normally about 0.2A, thus allowing Doppler shift and related work more than 10x finer than the resolution.

As I expected, it is essential to establish the wavelength scale using either the internal calibrator (usually Neon, fluorescent, or other source) or a spectral feature. One limitation of using the calibrator is that it does require a special exposure, i.e., during long data runs, the sequence must be interrupted either manually or via special software to obtain a calibration image. Calibrating on a feature of the spectrum being taken is often feasible, depending on the wavelength range being used and the object being observed. In some cases sky background can provide a line; however, the most useful for many of my observations in the 6200-6800A band has been use of the O2 absorption at 6283A which I used to measure the wavelength stability of the spectrometer.

A particular concern was to measure the stability of the wavelength calibration, especially over long observing runs. The most obvious potential problem is mechanical shifts are due to orientation changes as the telescope tracks the star, temperature, etc. However, there a more subtle issue is the stability of the target position in the slit.

Depending on the target, the slit of the spectrograph has two major purposes. If the target is a star (point source) focused at the plane where the slit would go, and if the star image is placed and held on precisely that spot, then the spectrum will be formed even though the slit is not present and the wavelength scale will be set and stable. If the star is faint, then the sky background light may contaminate the spectrum, but providing a slit reduces this. If the

target cannot be kept stable in position, the wavelength scale will change but a slit at least limits this change. Of course, a slit also allows a spectrum to be formed from a diffuse target.

The point of this discussion is that good guiding stability allows a stability of the wavelength calibration that can be substantially tighter than the resolution calculated from the slit width, and indeed, tighter even than the FWHM of the target image would indicate.

To test wavelength stability, Fig. 3 shows the result of a long run of taking neon calibrator spectra every ten minutes. The graph shows a variation of nearly 5A, which of course, should not happen. I traced this instability to a minor slop in the grating holder that was cured with a 5cent spring.
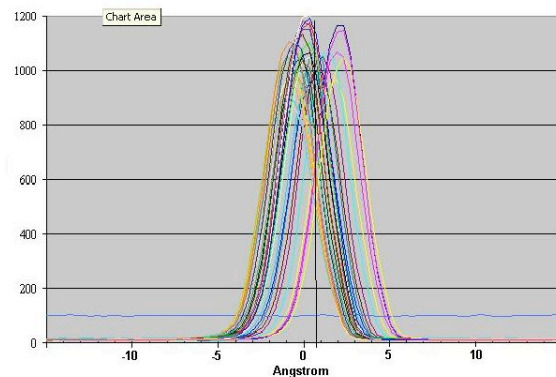

Fig. 3. Wavelength Stability Test (Neon)

Just as challenging as learning how the spectrograph operated was learning how to analyze and interpret the spectral. To accomplish these goals, I undertook two major observational programs as discussed below:

- Measuring the Doppler shift from a pulsating star. The star chosen was Beta Cephei, the namesake of this class. It is bright and hot: 3.3 mag and B spectral class, so there is plenty of light. The pulsations will cause the lines to swing back and forth over a few tenths of Angstrom.

- Measuring the Doppler shift for several semi-detached eclipsing binaries (including WUMa 7.8mag) having Doppler shifts of 1-200km/s (about 2A). With an 8hr period, WUMa would show splitting of the lines every four hours.

5. Data Processing Methods

I will describe the observing and data analysis used for the Beta Cephei project, and later the modifications needed for the WUMa observations.

The FS1 operates with automatic guiding using the internal beam splitter (pellicle) and Starlight Xpress Lodestar guide camera that has an electronic shutter system. In general, guide exposures can be 10 sec or longer if needed, however, this bright target star allowed <1 sec exposures to avoid saturation. The guider easily kept the target on the slit to within the desired 0.1-0.2 pixel rms.

Spectral images were five minutes duration, for Beta Cephei typically reaching about 1/3 of saturation, and were taken using the MaximDL in sequence mode.

Each morning, after a night of automated data collection, the archived images were downloaded from the observatory (about 400ft away). I use Maxim and Visual Basic for the image manipulation and reading the images, then Excel for analysis. This allows me to easily tailor the spreadsheet to perform the analysis I need and the graphic or other outputs I desire. Plus, the spreadsheet itself records all the arithmetical steps so that I can later review and verify what was done. As you will see later in the WUMa analysis, this process also allows easy simulation of data so that one can explore alternative analytic schemes with "known" data.

As noted, image manipulation was done in MaximDL. Due to the volume of data, I wrote a VB program (Fig. 4) to control Maxim that would allow processing scores of images at a time using simple checkboxes to set the manipulations needed. In this case, the spectral image manipulation included dark and bias calibration and rotation of the image to align the spectral band. The program measures the vertical center of the spectral band in the image, averages the value at each wavelength interval (horizontal pixel), and subtracts the associated background. The program also automatically averages a specified number of successive images, and has the ability to reject images with poor s/n while maintaining a uniform cadence (timing) of the averaged images. The resulting averaged images (typically 10-30) in the batch are written into a single numerical array. I call the entire array the dataset for the night, while each averaged spectral image is a data subset.
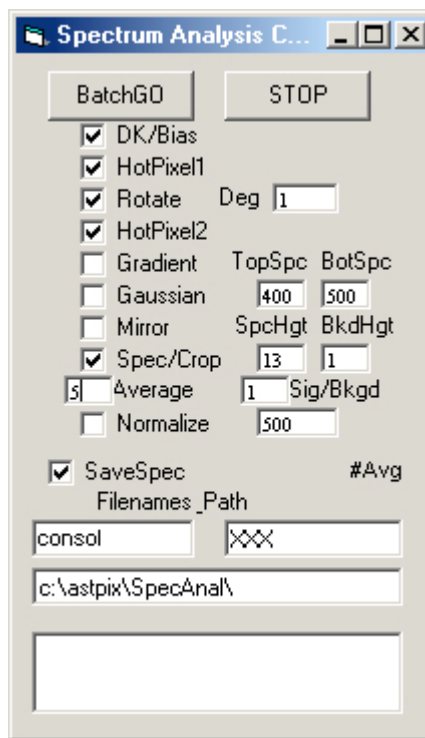

Fig. 4. Spectrum Processing Control Window

Each array is copied into a spreadsheet for that night's run where the array is displayed as "n" spectral image columns. By using a standardized spreadsheet, the data automatically display into the desired graphs. The standard spreadsheet then repeats the array to the right to allow an adjustable wavelength calibration for each data subset. Pasting the data into the sheet takes about 20 sec, and all the results are available immediately. Fig 5 shows a typical result of an observing run, with each data subset vertically offset for easy viewing.
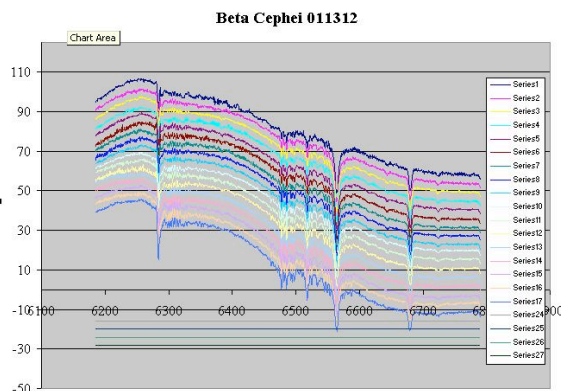

Fig. 5. Typical Spectra Display (Beta Cephei)

6. Beta Cephei Observations

The BCep program data became vital data for verifying FS1 operation and for developing the analytic process.

Beta Cephei pulsates in brightness with a period of 4.57 hr and an amplitude of about 0.02mag. The pulsation is driven by internal processes that result in expansion/contraction of the star's outer surface whose Doppler shifts can be detected. The line of sight velocity of the oscillation is only about 20-30km/s, corresponding to a total wavelength shift of 0.4-0.6A, which is much smaller than the 2A resolution of the spectrometer. The brightness of the star provides plenty of light, however, so that exposures of only five minutes still have sufficient s/n to allow precise determination of the wavelengths of the absorption lines. Thus, if the instrument calibration is stable, or if each exposure can be calibrated, then this instrument would be able to measure the Doppler signal.

Fig. 6 shows the Telluric O2 line at 6283A from a Beta Cephei observing run. One can see that the lines are unchanged in wavelength during the run to better than 0.2A. And as expected, the relative depth of the 6183 line does vary during the run as the light travels through differing thickness of atmosphere, while the lines of astronomical sources do not. The stability results show that long runs with only occasional calibrations with the Neon (or other) calibrator are feasible.
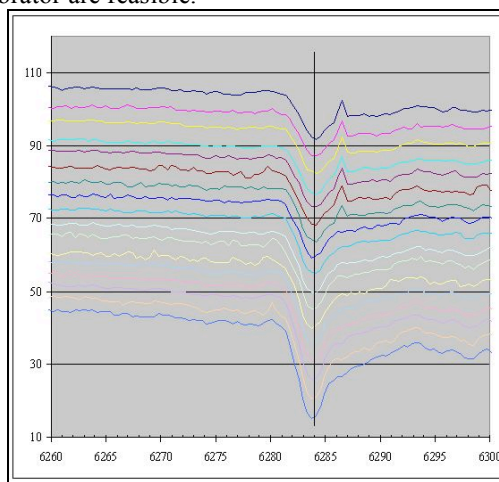

Fig. 6. Stability Verification (Beta Cephei)

So, is the Doppler oscillation of Beta Cephei visible with this spectrograph? Fig 7 and Fig. 8 show the 6563 Ha and 6683 He lines from the same data set. The spectra are vertically offset for easy visibility, and represent 15 minute averages (period

of the pulsation is 4.5 hrs), Clearly, the Ha line shows a wavelength shift during the run of about 0.6A. However, the HeII line at 6283A shows a more complex behavior as both shape and apparent wavelength change hour to hour. Examining the data makes one suspect not only similar wavelength changes as with Ha, but also the strengthening and weakening of nearby absorption lines as the star pulsates. In fact, there are additional HeII lines nearby, at 6678 and 6681, that appear to be varying in strength as the star pulsates.
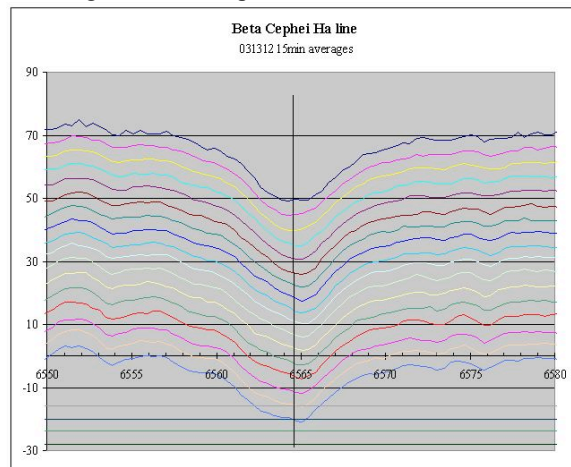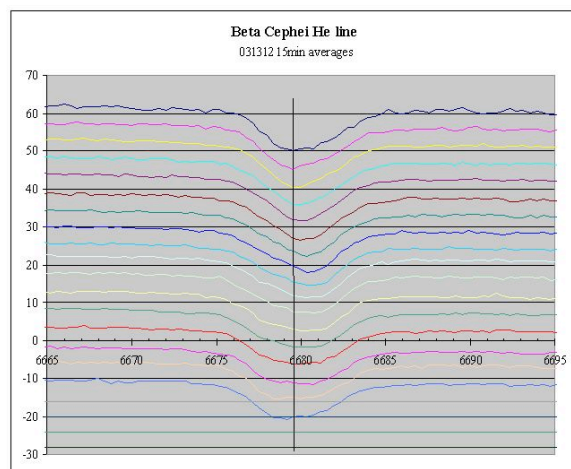

Fig. 7. Beta Cephei Ha Oscillation

Fig. 8. Beta Cephei He Oscillation

These changes in line shapes have been studied since the 1950s as giving insights into the internal process of this class of stars. What is gratifying is that homemade equipment can allow its study by an amateur in 2012! If tracking these or similar variations would be useful to a Pro, this Am would be happy to track this for many nights!

7. WUMa Observations

WUMa is a semi-detached eclipsing binary with an 8.00hr period. The variable nature of the star was discovered in 1903 and its binary nature in 1919 when the first Doppler measurements were published. However, the measurements are surprisingly difficult to make accurately and have been refined ever since.

As the stars orbit one another, they almost totally eclipse one another. During the eclipses, first one, then the second star is the only one seen. At such times, the single star spectrum will show only the system Doppler shift due to the Sun-WUMa relative velocities and the line of sight movement of the front star relative to the system barymetric center: Both of these shifts are relatively small. At quadrature, however, one will see the spectra of the two stars, but with each displaced in wavelength relative to the eclipsed wavelengths. Observing this split sounds easy but turns out to be not so, especially not with marginal 2A resolution on a relatively faint star.

While the 7.7mag of the star greatly restricts the available signal, it proved to be a good test for learning how to handle poor s/n while seeking to measure small effects! Although there are more absorption lines available in more blue wavelength bands, for most of this work I chose to continue in the 6100-6800 band due to the availability of the Ha line from the source and the 6183 telluric line.

Given the full 8 hr cycle of the WUMa, one can combine about 6 five minute images without introducing more than 10% error in the Doppler velocity. Obviously, it is desirable to perform the averaging so that the averages are centered on the orbit quadratures, thus requiring accurate knowledge of the ephemeris. Caution: many standard tables of ephemeri are outdated: not only are some periods in error, but also the periods change over years and decades. For most of the interesting binary stars, Bob Nelson and AAVSO maintain a valuable updated catalog on the web (Nelson). I also found it sometimes useful and reassuring to verify the timings by performing the necessary photometry.

Even with 30 min averaging, the WUMa data were rather noisy. In some runs (depending on the quality of focus, night clarity, etc.), the deep Ha line shows the splitting very clearly, as shown in Fig 9 along with a double Gaussian fitted to the points.
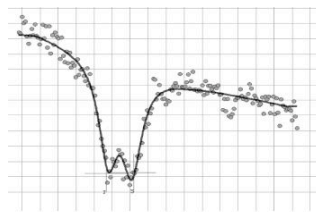

Fig. 9. WUMa Line Split

Using only Ha lines wavelength measurements from quadrature data averaged over three nights, calculations yielded WUMa star velocities of 260 and 77 km/sec. This result may be compared with other measurements from the literature such as those of Worden (Worden1977) that showed 243 and 131 km/s. The relatively impressive agreement may be fortuitous, given the data noise levels and the early stage of this analysis.

However, because most of my data were not as good as these sets, there is need for a better approach that takes advantage of all the lines in the spectrum even though affected by noise. One answer is to obtain a reference spectrum of a similar class star with undisplaced. Then using the target spectrum, one computes the correlation coefficient (CC) between the two, thus measuring the relative similarity of the two. If one then calculates the CC for a range of displacements (eg., +/- 15A) between the two spectra and graphs the result, the value of the CC vs displacement wavelength will actually be an accurate graph of the shape of the split spectral lines!

Professional astronomers have spent much effort refining this general approach and developing similar analytic methods; however, this one is easy to implement in Excel.

It was fairly easy to prove that the method was workable by generating a synthetic spectrum in Excel. The spectrum included Gaussian noise and Gaussian shaped lines of adjustable width and spacing. Fig. 10 and 11 show low and high noise spectra, and the CC results. This test shows the ability of the method to pull data out of noise and the feasibility of spreadsheet implementation.
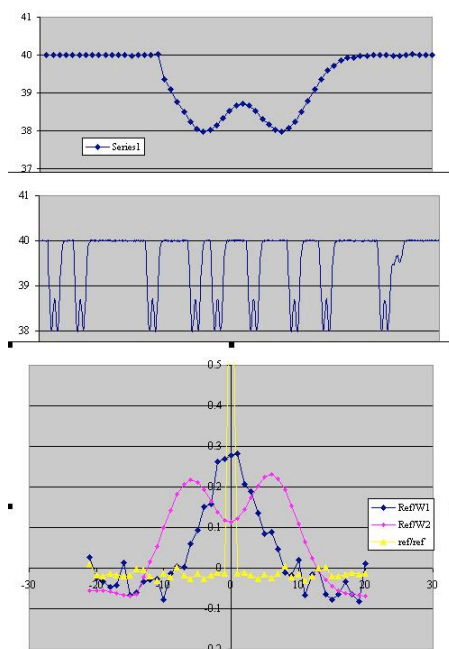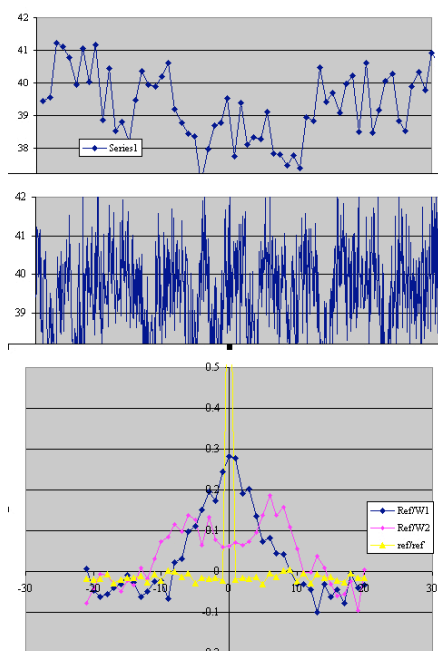
Fig. 10. Synthesized Spectra-Low Noise

Fig. 11. Synthesized Spectra-High Noise

The reference spectrum must of course have the same dispersion as the observed spectrum. Thus, I have used as reference spectra my own measures of stars or the sun; however, the reference spectrum that was most effective was generated from the website of R.O.Gray (Gray). Using the SPECTRUM program from that site, one can manufacture a digital reference spectrum of desired line widths and dispersion. Using such a reference, and using quadrature data from a noisy WUMa observing session, Fig 12 shows a typical set of promising CC results for the four quadratures from early tests of this method.
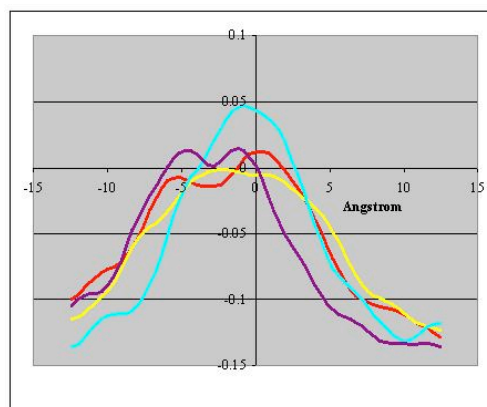

Fig. 12. Example Correlation Coefficient Results

With hundreds of data sets from many nights of data covering the entire orbital period (not just quadratures), one is tempted to massage it forever, or until one is exhausted or the computer crashes. While it is clear that substantial refinement of the methods are needed, the results already show that the general approach is correct and that this work is feasible for amateur equipment and skills.

8. Conclusions and Implications for SAS Members

This work has already shown that a shop-built spectrometer can be used for many advanced observing projects requiring rather stringent instrument stability. The initial observing projects have been a challenge to analyze, but the results already show the validity of the FS1 design and the promising work that can be performed.

There are many additional targets for this spectrometer including the planets, nebulae, novae, and following the shape changes in particular spectral lines. As an example of the latter, Christian Buele has led a major effort in this area, mostly following Be stars (these are hot B-stars with hydrogen emission features). Because we amateurs can spend as much time on a subject as we wish, time series spectroscopy would appear to be a very fruitful area for us. However, it will likely take a substantial expansion of the Pro-Am programs to identify research areas suitable for amateurs with this type of equipment and this level of skill.

When Dale Mais several years ago gave several talks on his spectroscopic work, he wowed me. And intimidated me with his encyclopedic knowledge of astrophysics, of this and that spectral line, and of the significance to astrophysics. But if one is not in a university setting, then even with the Internet, how does an amateur—even one with some knowledge of the physics of instruments and stars and research--ever get started? The Internet helps, but many papers of interest are essentially unavailable to the individual, thus making self-education in advanced spectroscopy difficult. In contrast, there are many websites and other resources that help one learn advanced photometric techniques, develop Pro-Am contacts, submit and publish data, etc.

That may be changing. As more of us move into spectroscopy, there will be more cross-fertilization among amateurs. And we are seeing an increase in organized Pro-Am work—witness AAVSO and especially the Lowell initiative that I hope will develop programs to build advance skills in spectroscopy. In the long run, these programs should help increase the ease of establishing Pro-Am collaborations and encourage amateur driven research (i.e., non-Pro-Am) as well.

So let me leave you with a dual challenge:
- To the Pros: Seek out amateurs who can contribute to spectroscopic astronomical research, both in support of your particular study area or to broader research objectives. It would seem that amateurs might be particularly helpful in long time series spectroscopy.
- To the Ams: Seek out the new challenges of spectroscopic research, and to learn how to do it—it is, after all, *The Dark Side…*

9. References

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Menke2011. Menke, J.L. See Menkescientific.com for several papers including "Spectroscopy Techniques I and II" and others that discuss DSS7 operations.

Nelson. Updated O-C files for many eclipsing binaries are hosted by AAVSO at http://www.aavso.org/bob-nelsons-o-c-files

Worden1977. Worden, S.P. & Whelan, John. "W Ursae Majoris: The parameters of a Contact Binary". Mon. Not. R. Ast. Soc (1973) **163**, p.391-400