MEMO: how to produce OVSA images

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Purpose: to preserve expertise in producing OVSA images given that more emphasis will be on new EOVSA data soon.

Significance: even though the anticipated EOVSA data are supposed to be superior, the OVSA database will long remain the only microwave spectrally AND spatially resolved data in support of X-ray RHESSI database.

Requirements to the SSW installation

Gen tree and radio tree including OVSA tree.

Data location and access

"*.arc" raw data files may be also downloaded from http://ovsa.njit.edu/data/archive/

"*.rec" calibration files are available at http://ovsa.njit.edu/data/archive/calibration_files/

"radioflux.noa" is also available at http://ovsa.njit.edu/data/archive/calibration_files/

Calibrating the data

Reference Calibration

Several times per year, a series of observations at the standard frequencies is done to perform the reference amplitude and phase calibration for a block of time ranging typically over several months. The assumption is that the amplitudes and phases of the instrument will change slowly over time unless a physical change is made to the system (e.g., a cable is changed, or a component in the front end or receiver). As long as no physical change is made between the time of the reference calibration observations and the solar observations to be analyzed, then the reference calibration is expected to be valid. Even when a change is made to one antenna, the reference calibration will be valid for the other antennas.

Thus, the first step in calibrating the data is to check for the existence of the AMPCAL and PHZCAL segments in the raw-data ARC file. This can be done by browsing the ARC file content in the SSW IDL Launcher application. The records should exist under the Houskeeping header. To check the validity of these data segments, one must dump the data by selecting the **DumpData** option from the **TaskList** dropbox.

In most cases the AMPCAL and PHZCAL placeholder segments are available in the ARC file, but they are not valid. In such cases a valid calibration (.rec files) must be inserted in the .arc file. There are two ways of getting the valid .rec file: (1) extract them from an .arc file having valid records using the **ExtractRaw** option from the same dropbox menu or (2) download the valid .rec files from the OVSA web site. These operations will result in creating two files, namely AMPCAL.REC and PHZCAL.REC, corresponding to the amplitude and phase calibration, respectively, for the period you are interested in. These need to be inserted into the data file, using the routine INSERT_REC.

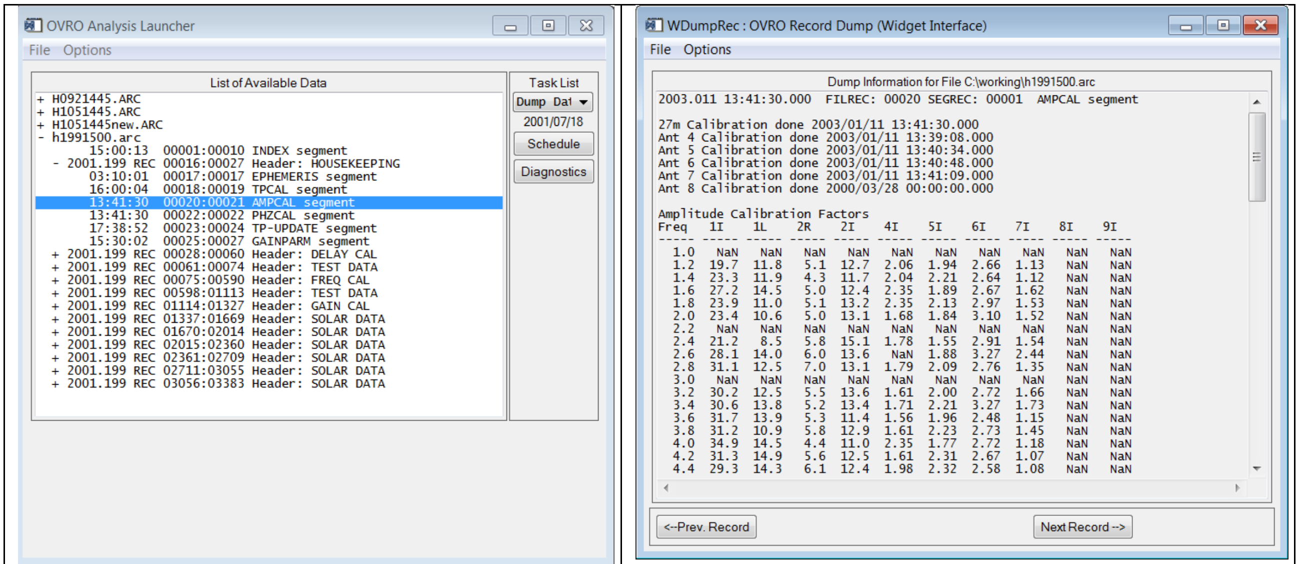

Figure 0. To launch the OVRO Analysis Launcher, type **defparms** (enter; this will define valid paths for OVSA tools); then type and hit **launcher**. A widget shown in the left will appear. Right: check for a valid .rec files. Although there are occasionally older valid rec files (like from the year 2003 in this example), most of the valid .rec files are from the year 2014.

To use the routine, do the following:

- type `insert_rec` at the IDL prompt (no arguments)
- choose the .arc file that you want to insert the record into (defaults to DATADIR directory)
- choose the .rec file that you want to insert (defaults to EPHEMDIR directory)
- choose the .arc file that you want as output (defaults to WORKDIR directory). The default output name is the same as the input name. It is legal (and usual) to specify the same output file as the input file, in which case the record is simply inserted into the file.

This procedure must be performed twice, once for the AMPCAL.REC and once for the PHZCAL.REC. Perhaps, this can be done automatically for a bunch of files pertaining to the same calibration data.

Daily Calibration

The gain calibration is based on a "noise source" in the front end, and a special sequence that runs every day before "sunrise" called a GAINCAL. Typically, this is done automatically and it should not be necessary to worry about it. The phase calibration is typically done several times per day, roughly every 2 hours, by observing a phase calibrator (a quasar point source, such as 3C84, 3C279, 3C454.3, etc.). Occasionally, the calibrator is 3C273, but this is not a point source at some frequencies, and so should be avoided if possible. By way of terminology, each calibrator or solar observation is termed a *scan*. The set of calibrator observations for a given day are then called *calibrator scans*.

To analyze the daily phase calibration scans, run the routine DAILY, whose general syntax is:

```
refscan = daily([filename][,ref=refscan | ,iref=iref] [,/update]$
               [,/noprinter][,/nowrite][,/interactive])
```

where the switches in square brackets are optional. The shortest form of the command,

```
ref = daily()
```

works fine, but does an automatic fit to each scan, and often the fits need adjustment. A more typical form is

```
ref = daily(/interactive)
```

which lets you do some adjustment when the automatic fit fails.

The use of DAILY is likely to be difficult initially, although with some practice it generally goes smoothly and is conceptually easy to understand. By way of illustration, let us go through an example using the data of 2002 April 11.

The first step that DAILY performs is to run ANALYZE automatically on each of the phase calibration scans. For each scan, a progress meter will be displayed to indicate progress on analyzing the scan. Normally, there is no need to do anything but wait for the analysis to finish. However, you can abort the current scan by clicking on the ABORT button of the progress meter. If you click soon enough, no data are analyzed for that scan. However, once data are starting to be analyzed, aborting results in a short, but otherwise valid scan. Note: if you have run DAILY once on a file, and do not need to re-analyze the scans, you can skip this step by using the `/UPDATE` switch.

After all of the scans have been analyzed, DAILY enters the next phase, which is to fit straight lines to the phases of each scan. DAILY first determines which scan has the best phases, in terms of signal to noise, and uses this as the *reference scan* (not to be confused with the reference calibration discussed in the previous section). It is possible to override this automatic determination of the reference scan by using the `IREF` keyword, which specifies the (zero-based) index of the scan to use for the reference scan (e.g. `IREF=2` means to use the 3rd scan as the reference scan).

DAILY then plots the phase differences between the current scan and the reference scan for each of the baselines involving at least one 27-m antenna, along with linear fits to the phase differences. Here is the result for the first scan:

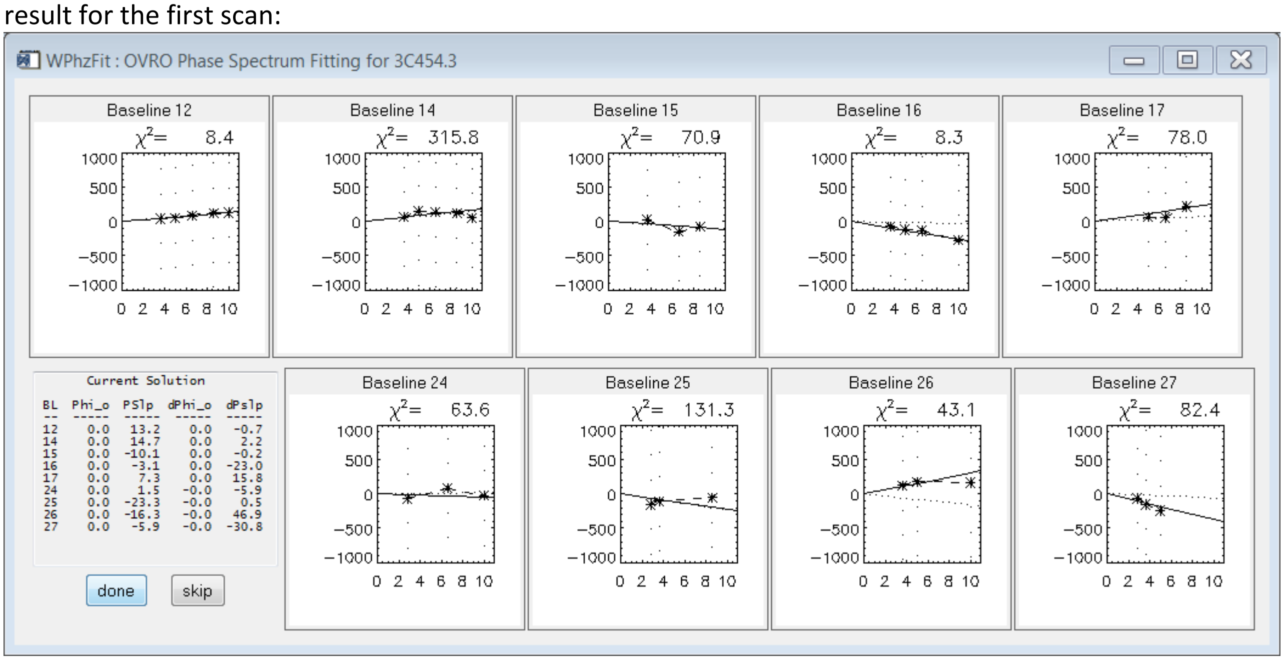

Figure 1: Initial fits to first scan of 2002 Apr 11. The command `ref=daily(/interactive,/nowrite,/noprinter,iref=2)` was used in this case Upper text tells which scan is being displayed (3C454.3 in this case).

Each plot represents the phases at up to 6 frequencies, measured on a single baseline involving a 27-m antenna, as identified by the title above each. Nominally there should be 6 points, but when a measurement is deemed too noise (S/N < 2 in amplitude), the point is omitted.

Phase Closure

There is a relationship among triads (or triplets) of baselines, called closure phase. The phases around any triangle of antennas must close to zero. Let us use the notation $\phi_{ij} = a_{ij}\, f_{\mathrm{GHz}} + \phi_{o,ij}$, where the slope (degrees/GHz) for baseline *ij* is a_{ij}., and the offset is $\phi_{o,ij}$. We make the assumption that the phase offsets are identically zero. The slopes of the fits for a triad *ijk* obey the closure relation $a_{ij} + a_{jk} + a_{ki} = 0$. For triads 12*n* ($n$ = 4,5,6,7), the slopes for baselines 14, 15, 16, and 17 (top row) then represent $a_{ik} = -a_{ki}$ (minus sign due to switching order of indexes) while the slopes for baselines 24, 25, 26 and 17 (bottom row) represent a_{jk}, so the closure relation becomes $a_{12} + a_{2n} - a_{1n} = 0$. In the fits, the solid line represents the best fit to each baseline, but the dotted line shows the best fit that obeys phase closure. Because the solid and dotted lines do not agree for baselines 16, 26 and for 17, 27, it is apparent that the fits are not correct.

Lobe Ambiguity

Note, however, that there is no difference between a phase ϕ_{16} and a phase $\phi_{16} + 2\pi n$, where n = (… –1, 0, 1, …) (we call this the *lobe ambiguity*). The dots in each plot show where the phases (asterisks) would fall if they were shifted by multiples of 2π. We can adjust the phases up or down by one lobe by clicking above or below the phase to be shifted. Whenever a phase is shifted, the fit will be automatically recalculated. In the figure below, we have shifted the phases for baselines 26 and 17 down by one or two lobes, after which the solid and dotted lines agree (although not so well for baselines 16 and 26.

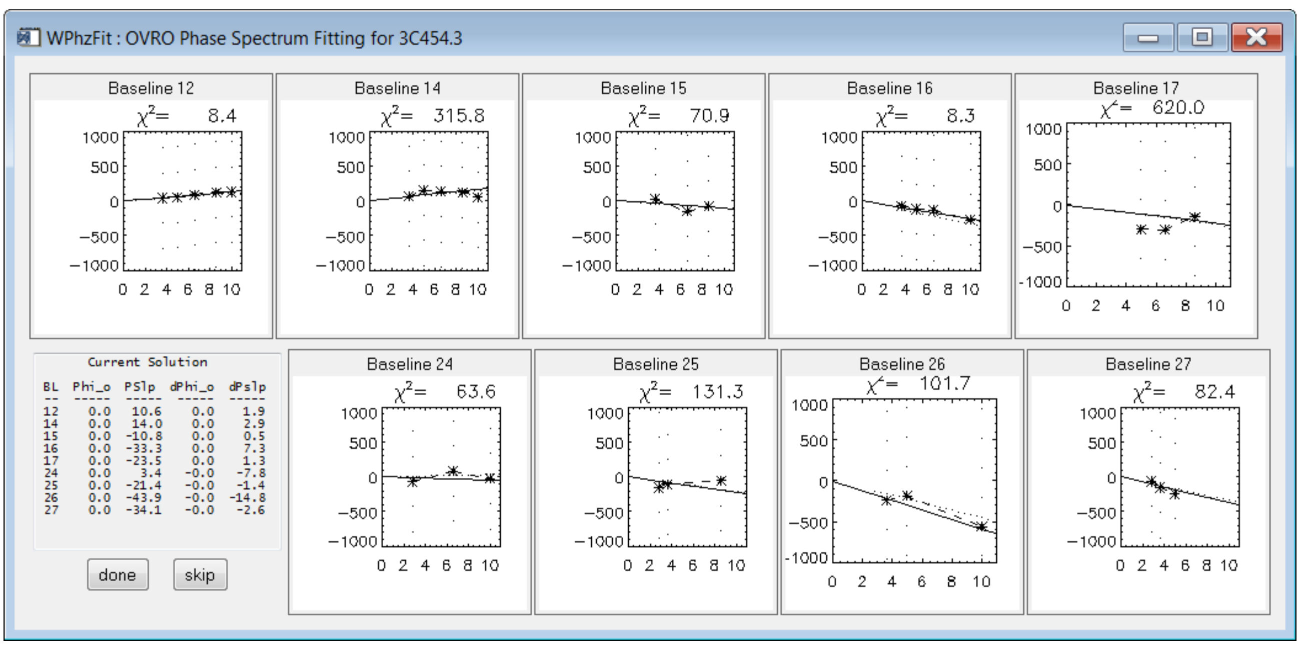

Figure 2: Adjusted fits to first scan of 2002 Apr 11, after correction for lobe ambiguity.

The phases for this particular scan are rather poor, since the scan is a short one. If you look at the .ARC file itself you will see that another scan on the same calibrator was started immediately after this one, so likely this one was aborted for some reason. In any case, the above fits are not great, but are the best to be had for this scan. Click the “skip” and this scan will not be used in the final daily calibration. If you select the "done" button the scan will be used in the final daily calibration. In any case the program will proceed to the next scan. You will see a new plot, as shown in Figure 3, representing the second scan. Since these fits are okay after a few adjustments, we can click the "done" button and go on to the 3rd scan, shown in Figure 4. The third scan is the reference scan, which we forced to be so by setting the IREF keyword to 2 in the call to DAILY. We will continue to adjust the lobe of the phases if necessary until the very final reference calibration.

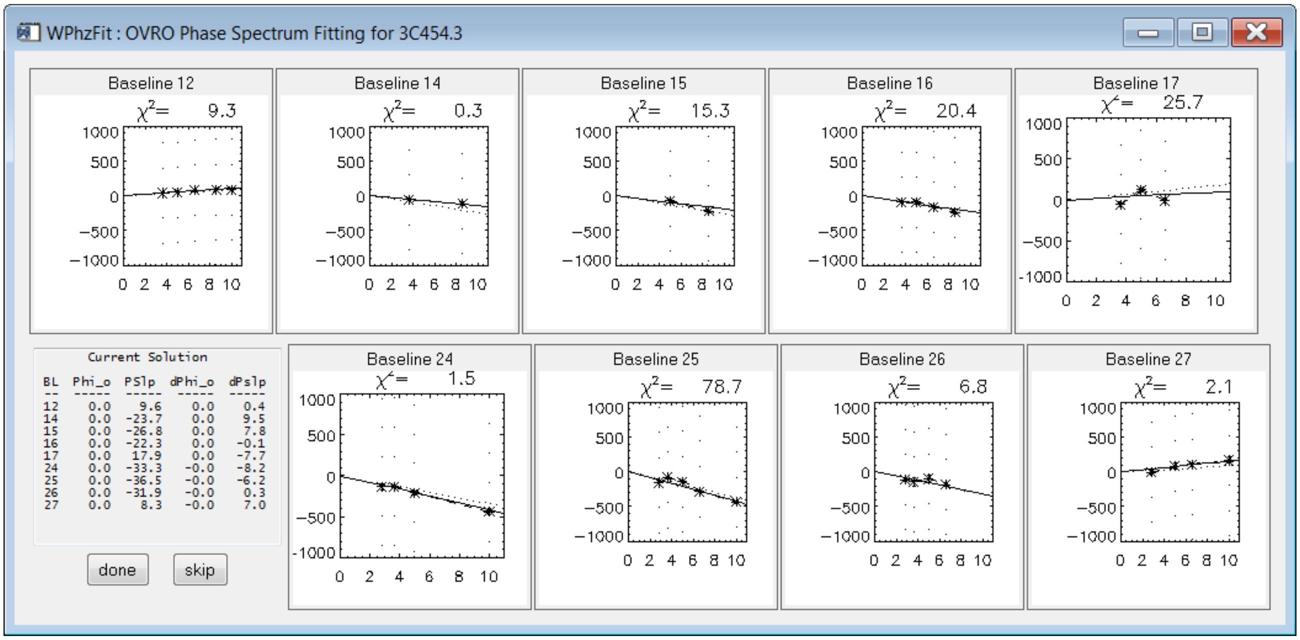

Figure 3: Fits to second scan of 2002 Apr 11 after minor adjustments.

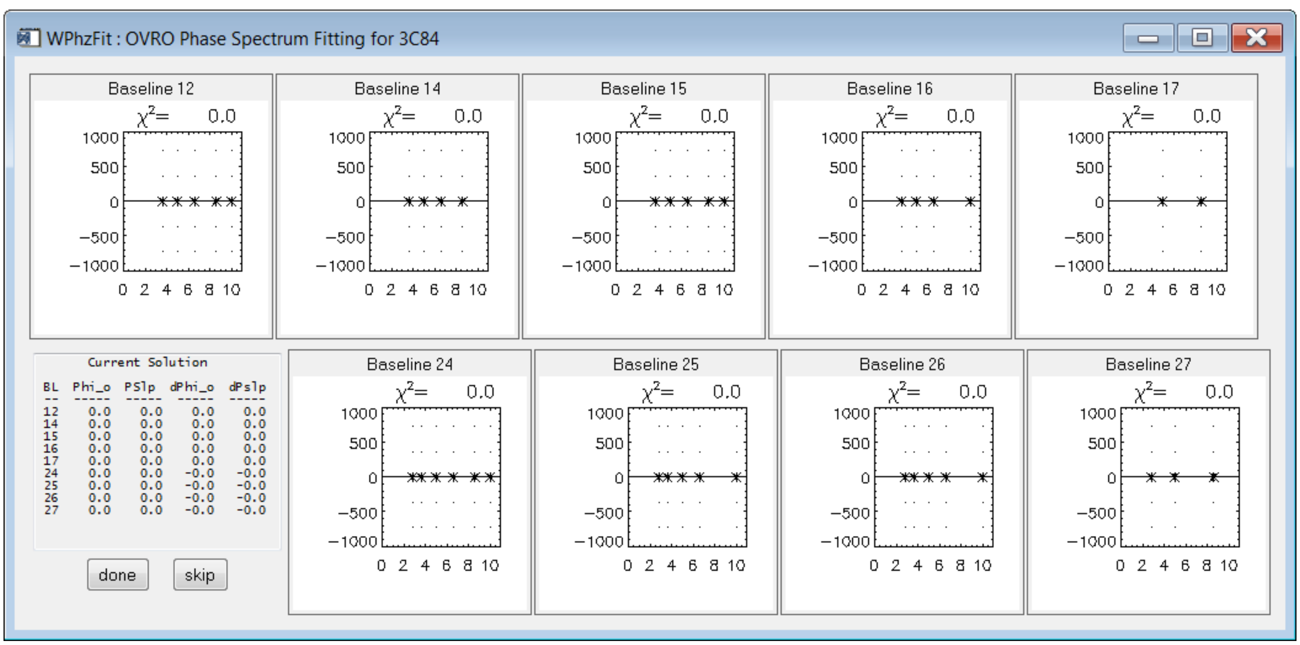

Figure 4: Fits to third scan of 2002 Apr 11. They are all identically zero, because this is the reference scan.

The final step is the final reference calibration (it is stated in the upper lane of the widget), which cannot be skipped, as it adjusts the daily scan to the reference calibration. In this case (Fig. 5) the baselines 14 and 26 (and, perhaps, 17 and 27) need adjustment. An apparently good solution is shown in Figure 6.

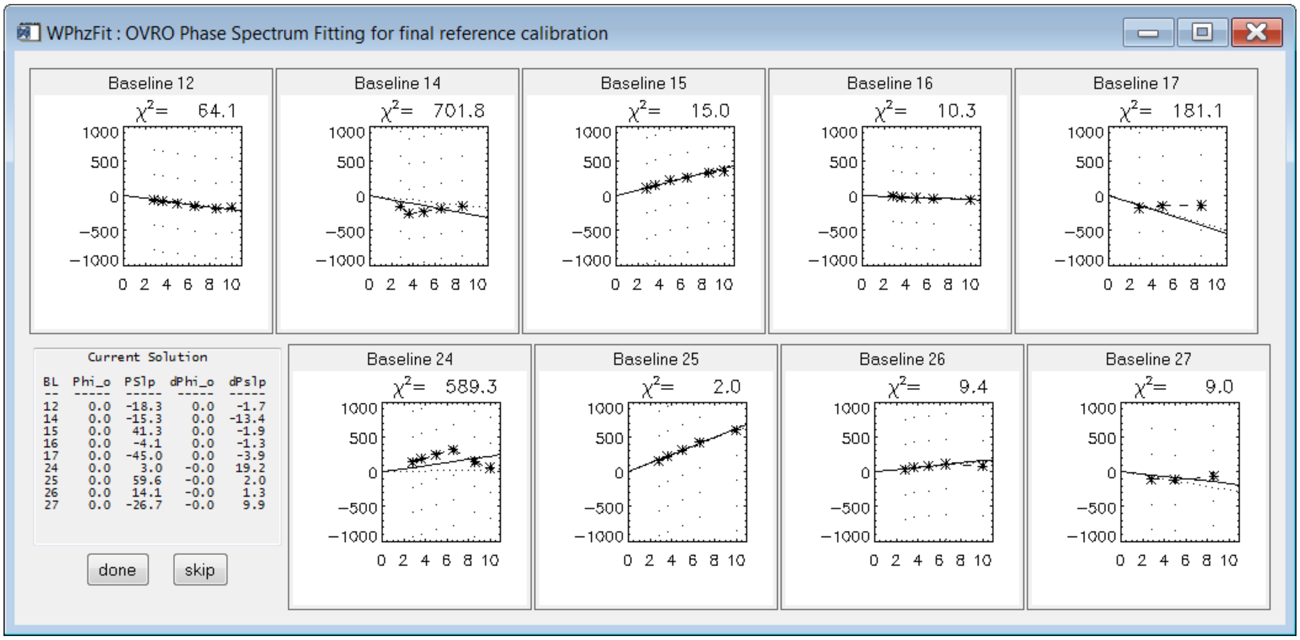

Figure 5: Initial fits to the final reference calibration of 2002 Apr 11.

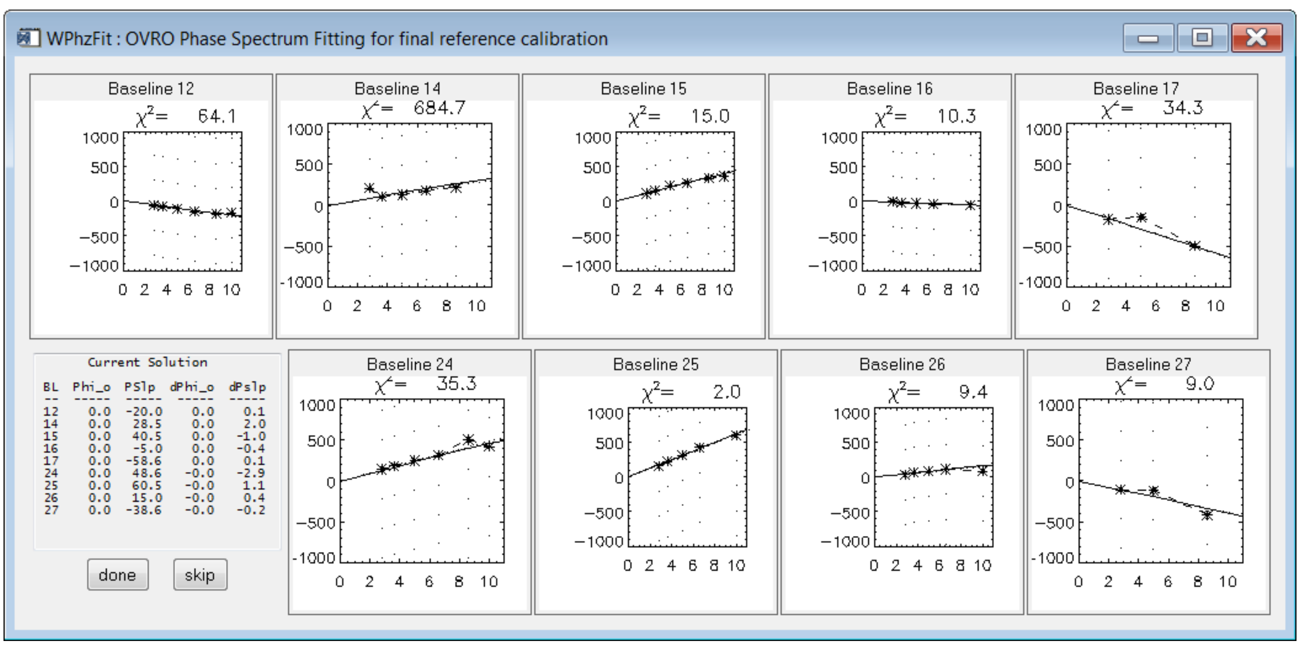

Figure 6: Final fits to the final reference calibration of 2002 Apr 11.

Once the acceptable fits have been obtained, select "done" button, so the results of the calibration will be saved to the original .ARC file and a plot with the summary of all fits will appear at the screen; you can visually inspect it and eventually close.

NOTE: if you are interested in only one (of a few) solar scans in the given .ARC file (you know time of your radio burst of interest) you can skip all the calibration scans rather than the ones just before and just after your solar scan of interest. In this case it is reasonable to assign one of these two to be the reference scan (by identifying a correct iref=n keyword).

Total power calibration

The OVSA total power calibration relies on the radioflux.noa text file assumed to be located in "c:\ephem" directory. If such directory, with such content, does not exist, it should be created, or the path to the directory containing the radioflux.noa file should be indicated launching the **wpreferences** IDL GUI. The valid file radioflux.noa can be downloaded from here.

Assuming that this file exists in the right location, one should locate in launcher the CENTER CAL segment and select the CtrCalCheck option from the task list.

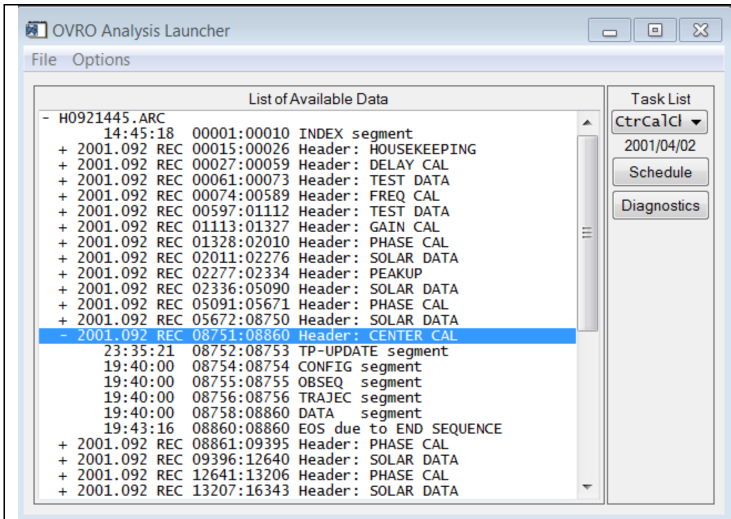

Figure 7. Interface of OVRO Analysis Launcher, where the Center Cal Check is being performed.

This selection will expose a calibration window in which the user should perform the following operations:

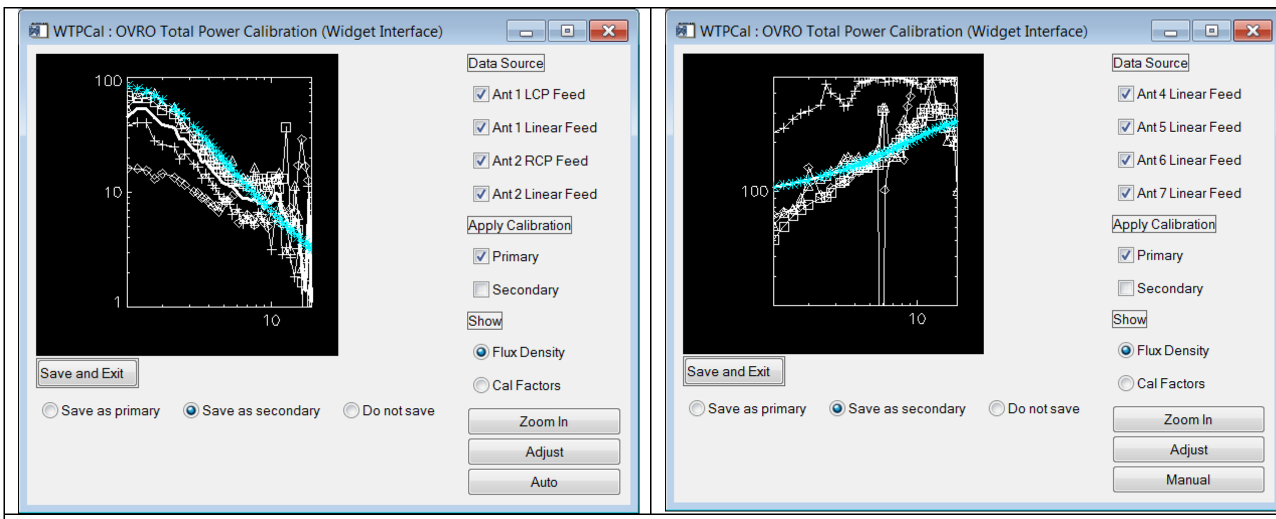

Figure 8. Two steps of the total power calibration.

1. Press the Auto button (this operation will toggle its state to Manual, which signals that auto calibration was performed)
2. Select the **Save as secondary** radio button

3. Save and Exit

The window is closed and a second similar window is exposed, in which the same steps must be performed.

Note: If no cyan symbols are displayed in the plot areas, the operation has failed most likely due to the absence of the radioflux.noa file.

Producing the OVSA sav file

In the next step of the calibration process, one must launch **WCALIBRATE** and select the ARC file to produce calibrated data from.

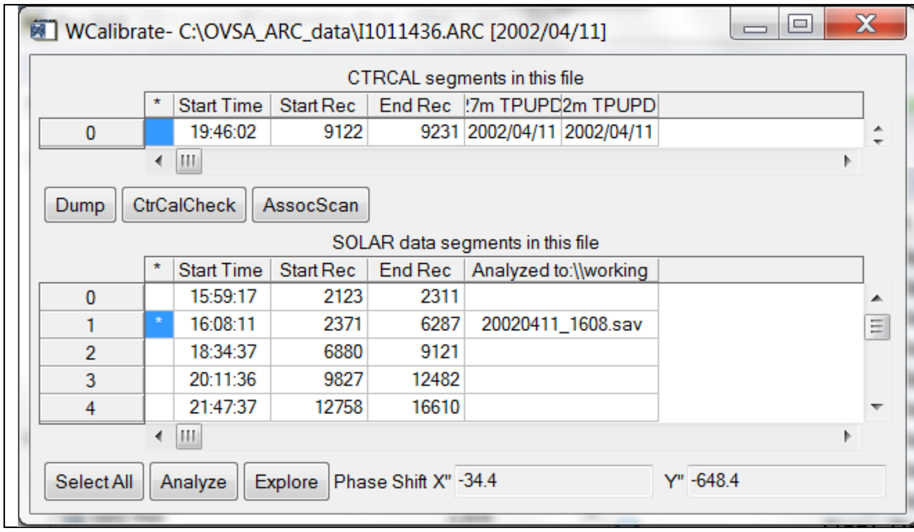

Figure 9. Interface of WCALIBRATE, where the solar segment for the 2002 Apr 11 is being analyzed.

In this window, one may select (by the left mouse click) the SOLAR DATA segment of interest and **Analyze** it. **WCALIBRATE** applies calibration automatically. The only possibly needed adjustment is a correction of the phase center as explained below.

Phase center correction.

You run Launcher, find and highlight the desired solar scan, then from the task menu select AR_location. That shows the current phase center. If you click somewhere on the disk, it will print in the plot the offset of the clicked point relative to the phase center. To specify a phase shift in wcalibrate, just type in the X and Y shift before doing the analyze step, and the phase shift will be applied. Note that these shifts the phase center, i.e. the map center, in the direction +W and +N. I used AR_Locator to find that for 2002 Apr. 11 the array was pointed at AR 9893, while the radio burst occurred at AR 9904, thus, a shift of X = -34.4" and Y = -648.4" is needed (i.e. a shift to the SE). If you type these values in wcalibrate, the source should be shifted to close to the map center. It should not affect overlays with other data, but this should be checked.

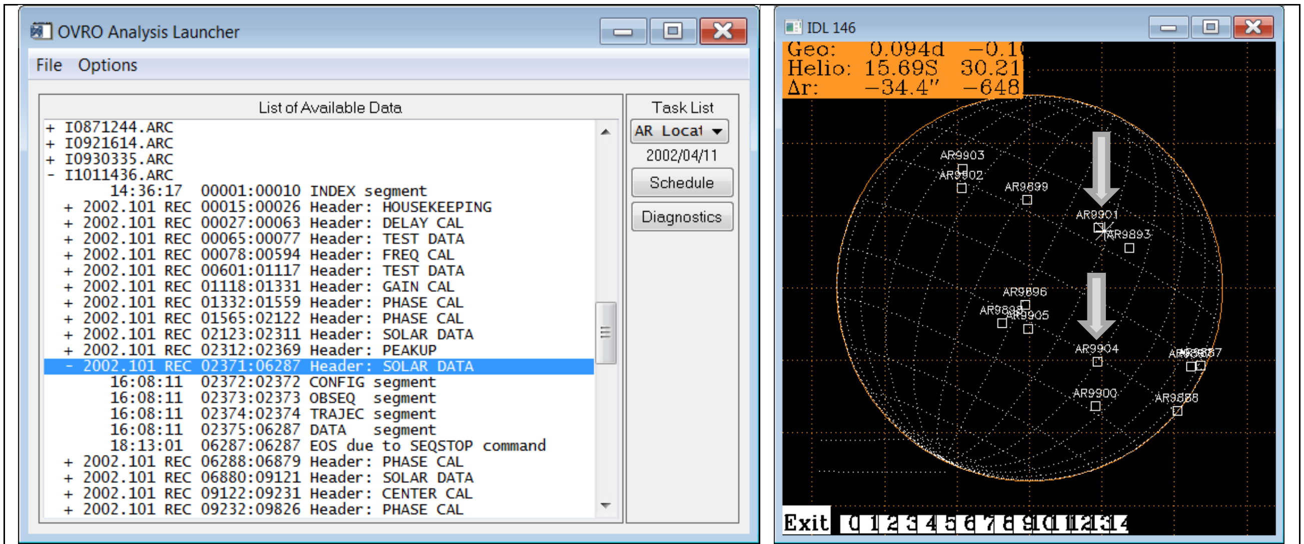

Figure 10. Interface of OVRO Analysis Launcher, where the AR location is being inspected. The asterisk (and upper grey arrow) shows where the array was pointed. The other arrow shows the AR, where the flare of interest happened.

A calibrated IDL sav file is created in the default **c:\working** directory (it must already exist or wpreferences must be used to select a user defined directory).

The content of the IDL sav file created by these means has to be inspected using the **Explore** button, which launches **OVSA_EXPLORER** data visualization/analysis tool.

Data processing

Now, one has to 'select background', 'apply background', and save a selected data segment for further analysis. Also, fit results and antenna selection can optionally be saved. It is recommended to checkmark "High Time Resolution" before manipulations with the data.

Processing prior to imaging

After carrying out all the calibrations, it is necessary to remove background and cut out a flare from the solar observation segment. The background can be defined as a linear function or approximated by a polynomial of higher degrees. This is done using the Set Background command in the OVSA_Explorer tool. In the case of 2002 Apr 11 event it is reasonable to select a linearly falling background by selecting "Set Background" in the "Mode" tab and then selecting two regions to be used to set the background (four left clicks: the first left click in each region is shown as the solid line, the second one—the dashed one; right click removes the most recent selection). After checking "Apply Background" a strong interference around 2 GHz becomes apparent. This can be removed by selecting "Flag Bad Freq" from the "Mode" menu and left click on the bad frequencies. Details of how to work with OVSA_explorer can be found by selecting help/contents from the menu.

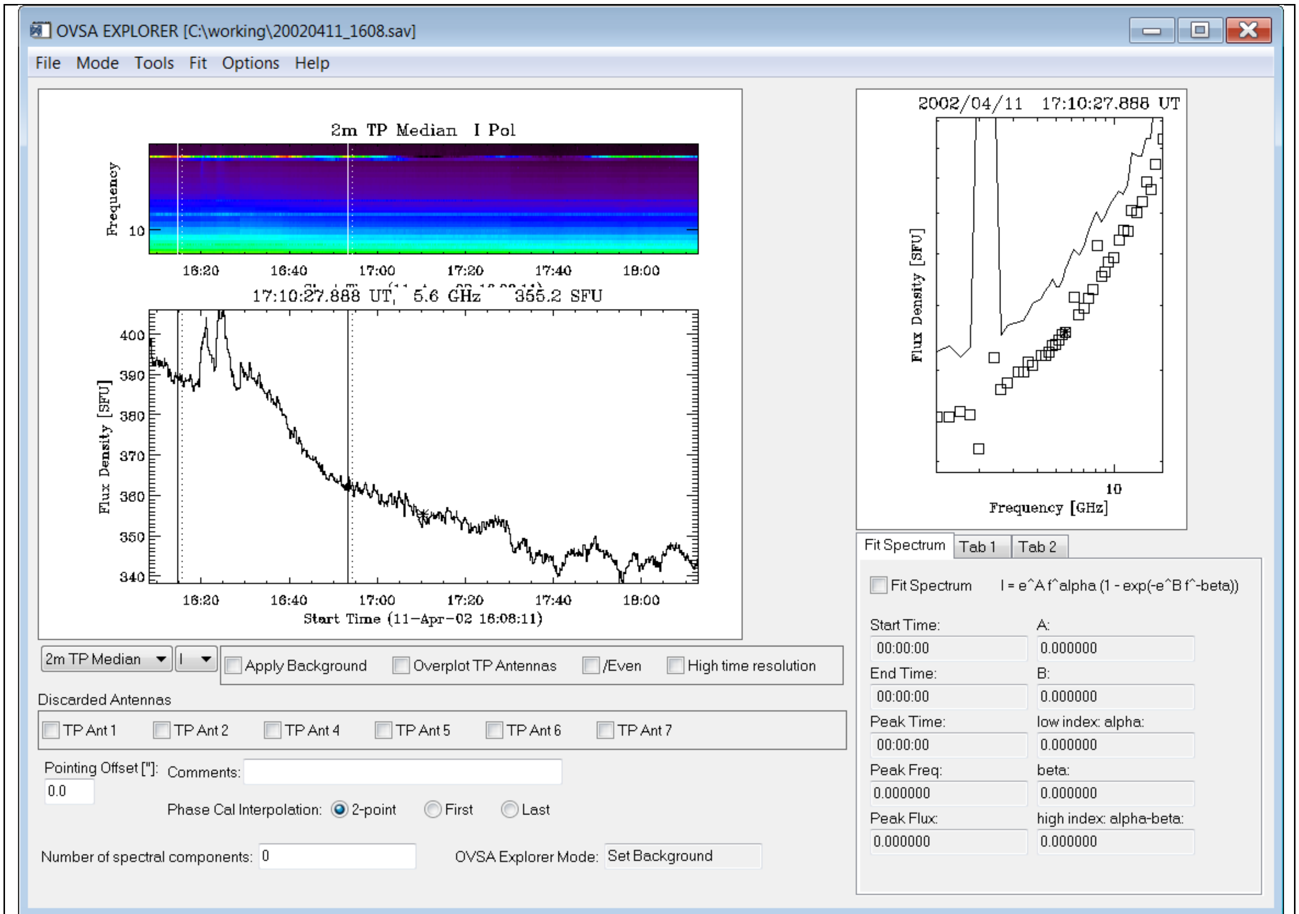

Figure 11. Interface of the OVSA_EXPLORER tool, where the background is being selected ad removed. A ''bad'' frequency interference around 2 GHz is apparent.

The next step is to zoom in to the event durations, select fit intervals, perform sequential spectral fit (it is advisable to exclude some of the antennas, e.g., 1 and 2 and sometimes one or more of small antennas if they produce a jitter or other artifacts). If the array was off pointed relative to the burst location, it is possible to correct the flux for large antennas at high frequencies by specifying a Pointing Offset in arcseconds. The final step in this "pre-imaging" stage is to save the calibrated data for the radio bursts by selecting "File/Save as." This command will generate three files: .sav, .med, and .uv. In particular, .med file contains the results of spectral fitting, which can later be restored and used for research. Still, there are final choices for the .uv file before saving the data: it is how to use the phase calibration needed for imaging. One have three options to select from: 2-point; First, and Second. If 2-point is selected then the Phase Cal will be linearly interpolated between solutions obtained before and after the solar segment in the stage of Daily calibration described above, while selection of First (Second) will freeze the solution before (after) the solar segment. This freezing of the Phase Cal solution can be needed if one of the calibration scans is invalid or noisy.

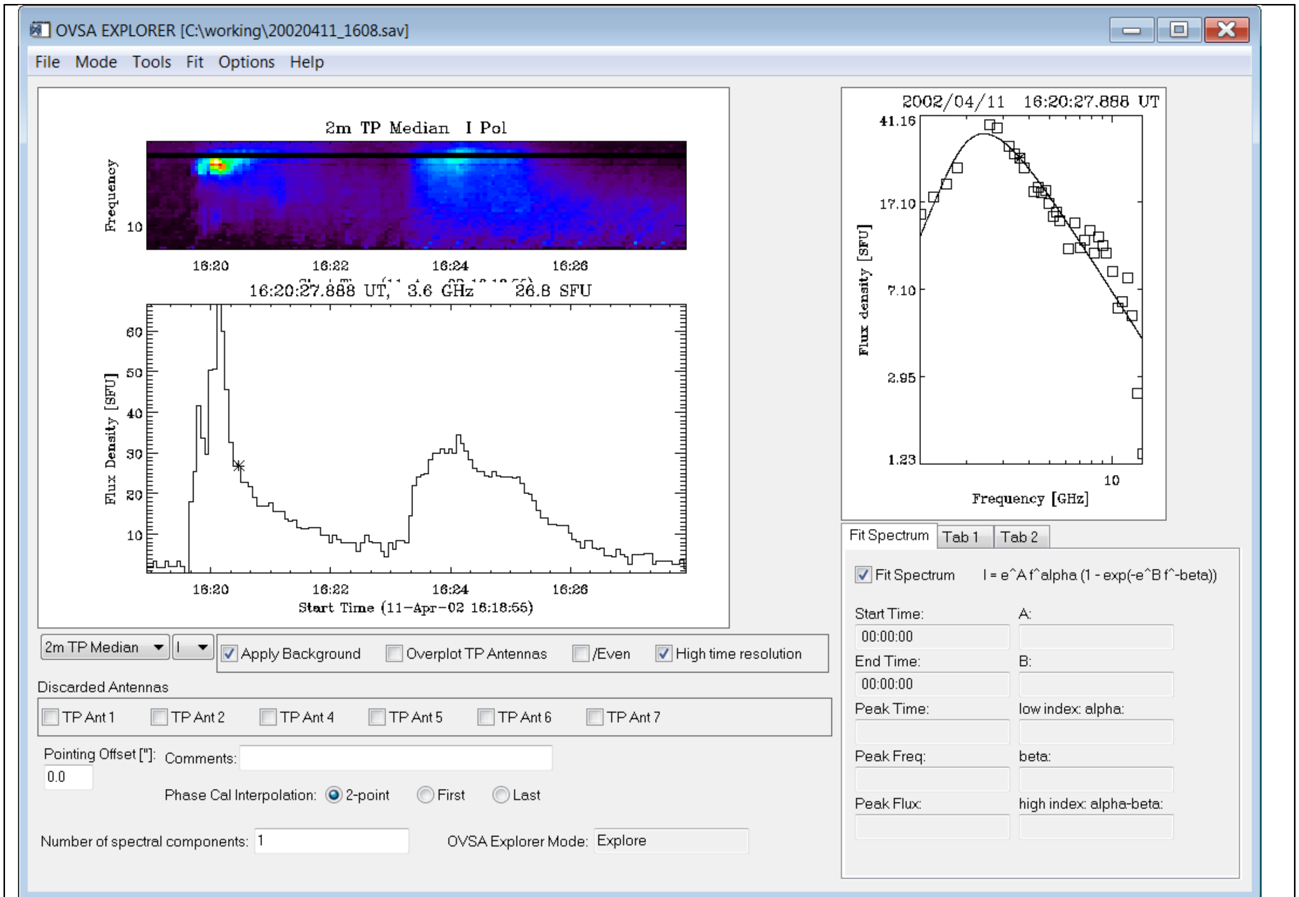

Figure 12. The dynamic spectrum of the 2002 Apr 11 burst with a removed background (top) and flagged bad frequencies, the flux density light curve at 3.6 GHz (bottom), and the spectral fit at a given time frame (on the right)

Frequency synthesis concept

OVSA imaging is started from selecting a frequency range for mapping. Single frequency mapping is possible, although with a single frequency there is uncertainty in selecting the clean box because the resulting interference pattern is periodic in space for one frequency as seen in Fig. 13. Selecting a range of frequencies gives a clear clue of where to put the clean box. In the same example we select the range from 1.8 to 3.4 GHz to obtain the following picture, Fig. 14. Note that the clean box from the previous map production is kept and is shown by the dotted oval—that is need to use the same clean box for the next map (built for another frequency or another time instance). Now we can come back to a single frequency and produce image using this pre-selected clean box.

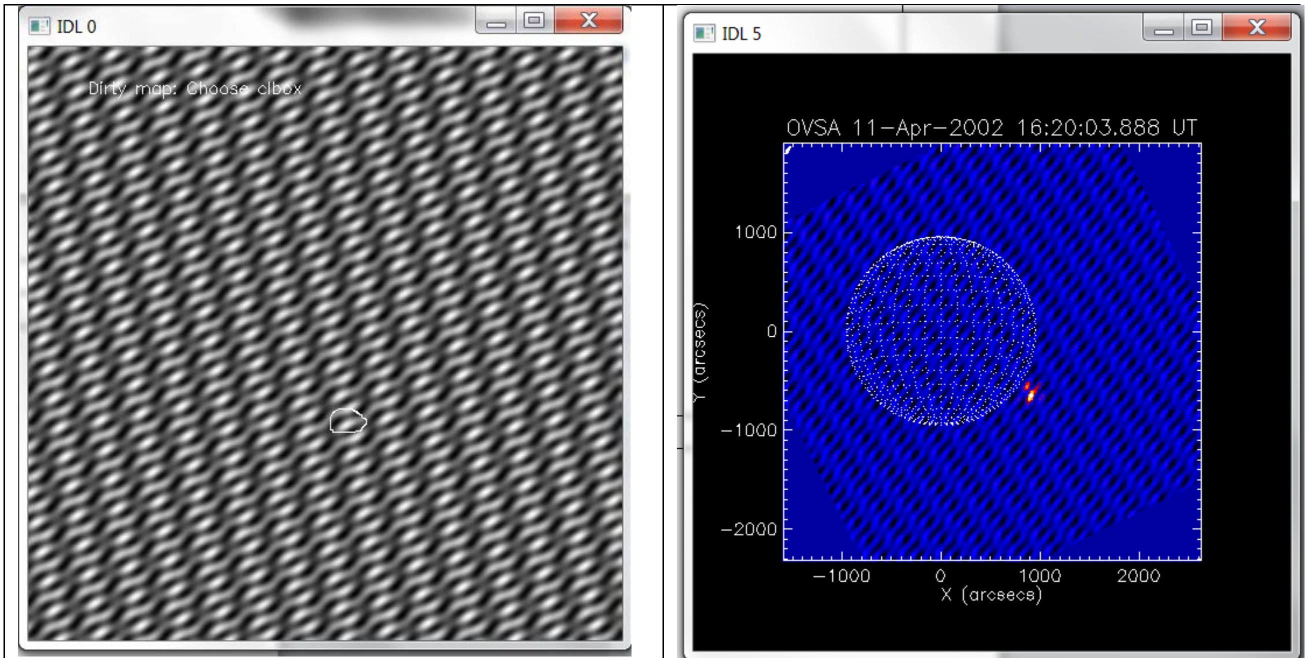

Figure 13. Attempt to select the clean box using one frequency only; f = 2.6 GHz in this example. Note, that the image is well outside the solar disk.

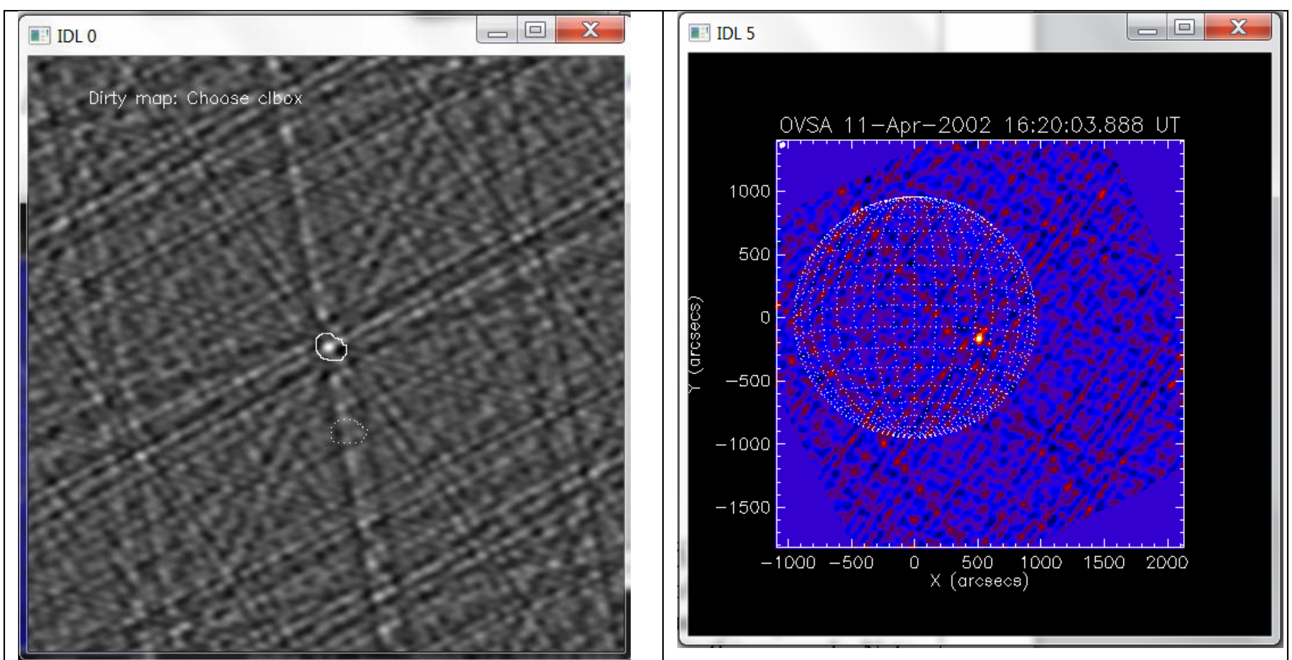

Figure 14. Dirty map for the frequency synthesis; f = 1.8—3.4 GHz in this example (left). Now, the image (right) is in a right place of the solar disk (in particular, it agrees with the RHESSI imaging for this flare, see Fleishman et al. 2013).

The image quality directly depends on the accuracy of the calibrations made. If the calibration was done correctly, interference patterns from the antennas will give a source on the dirty map. A smeared map or presence of multiple small periodic sources indicates that the calibration is not optimal (Fig. 15).

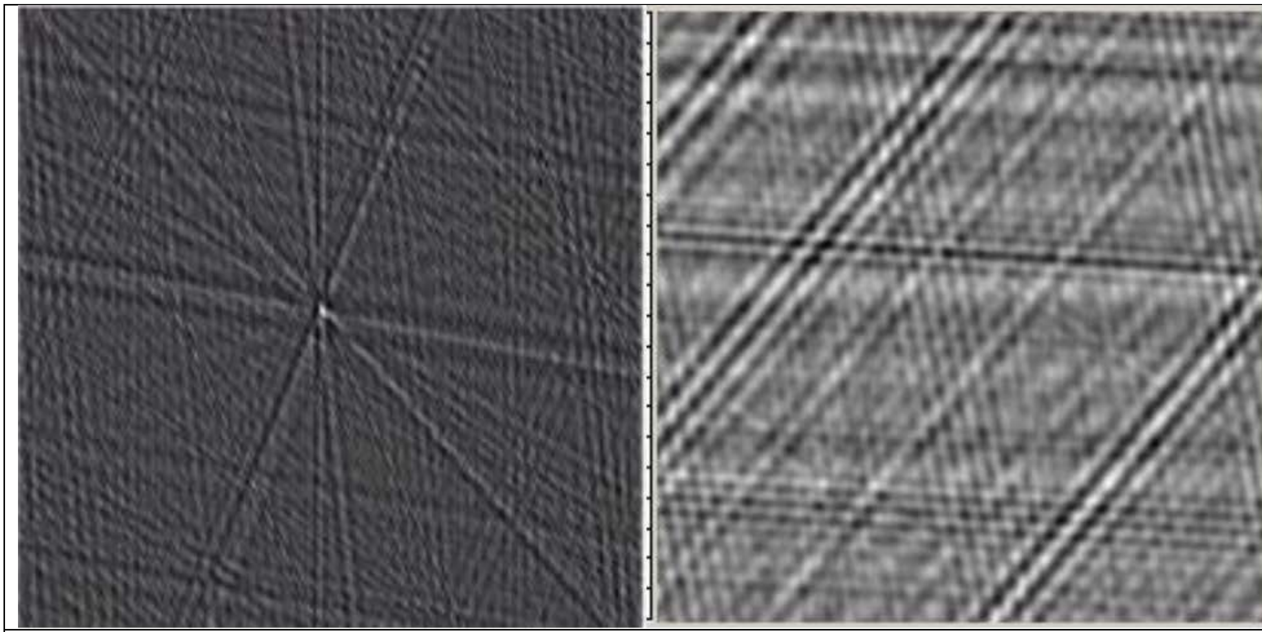

Figure 15. An example of a dirty map for a well-calibrated source (on the left) and an unsatisfactorily calibrated source (on the right)

Imaging a microwave source with Wimagr

The OVSA imaging is performed using another widget called "Wimagr." Using Wimagr, from a UV file we build an image and save it in the form of a FITS file or a Map structure.

Prior to image synthesis, it is needed to define the input characteristics of the burst (Fig. 16): select the time frame or time range on the dynamic spectrum (Data Selection / Time Selector), specify the set of frequencies (Data Selection / Frequency Selector), and also select the set of antennas or baselines (Data Selection / Baseline Selector). Dirty image displayed in the bottom right of the Data Selection tab plays a role of a guide that helps to select the most consistent set of frequencies for the frequency synthesis image. Once the data selection has been made, one selects the next tab "Image Production" (Fig. 17).

Here it is necessary to select the Computing Method, which can be either CLEAN or CLEAN+SelfCal (no other choice is now operational) and hit the "Compute Synthesis Map (Select Clean Box)." Then, the procedure is (i) to draw a clean box using the left mouse button (either consecutive clicks or continuous motion will work) which results in the oval-like shape in the dirty map; (ii) right-click on the dirty map to close the shape, and (iii) one more right click to create image. The selection can be adjusted as many times as needed to obtain the best result. Once all selections have been made, hit "Compute All Maps in Range" button to create a final image or set of images with which the user can work in the "Image Post Production" tab.

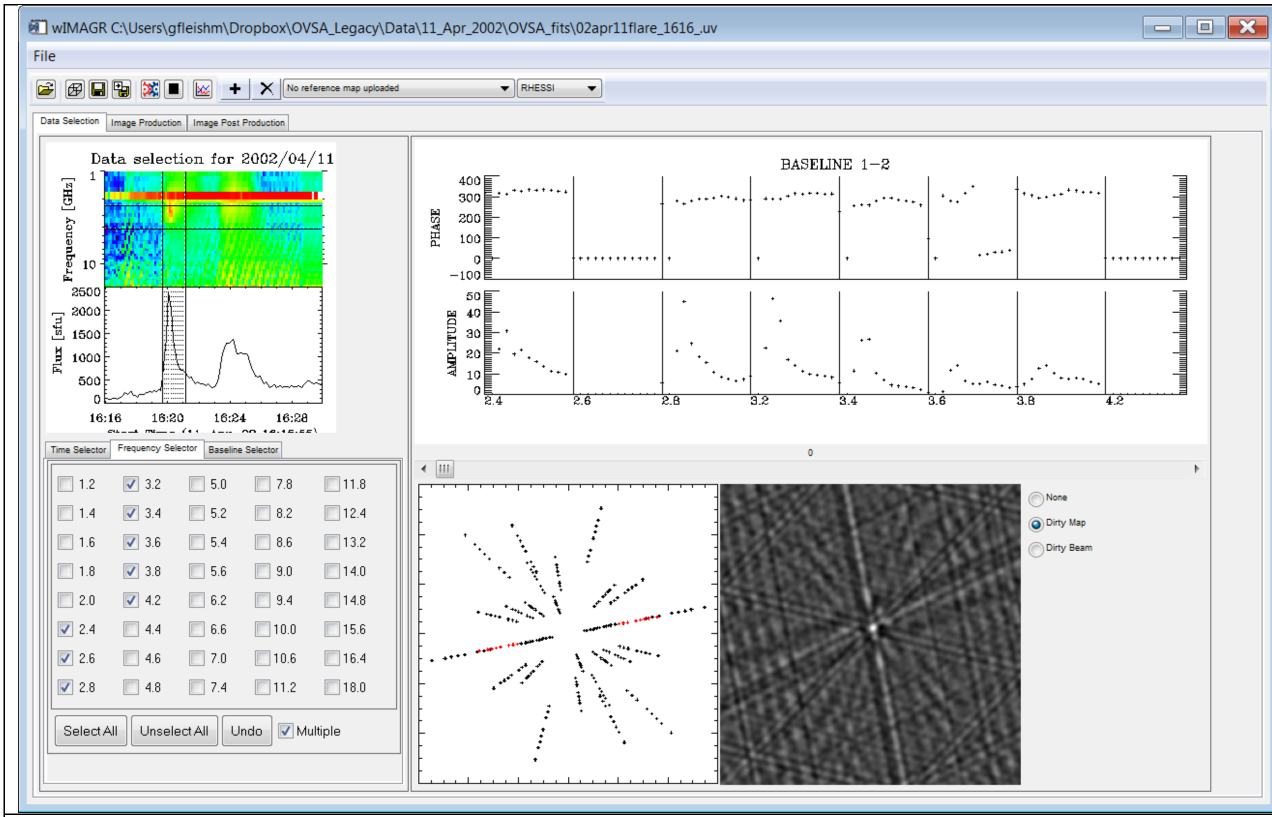

Figure 16. Widget Wimagr; Data Selection tab.

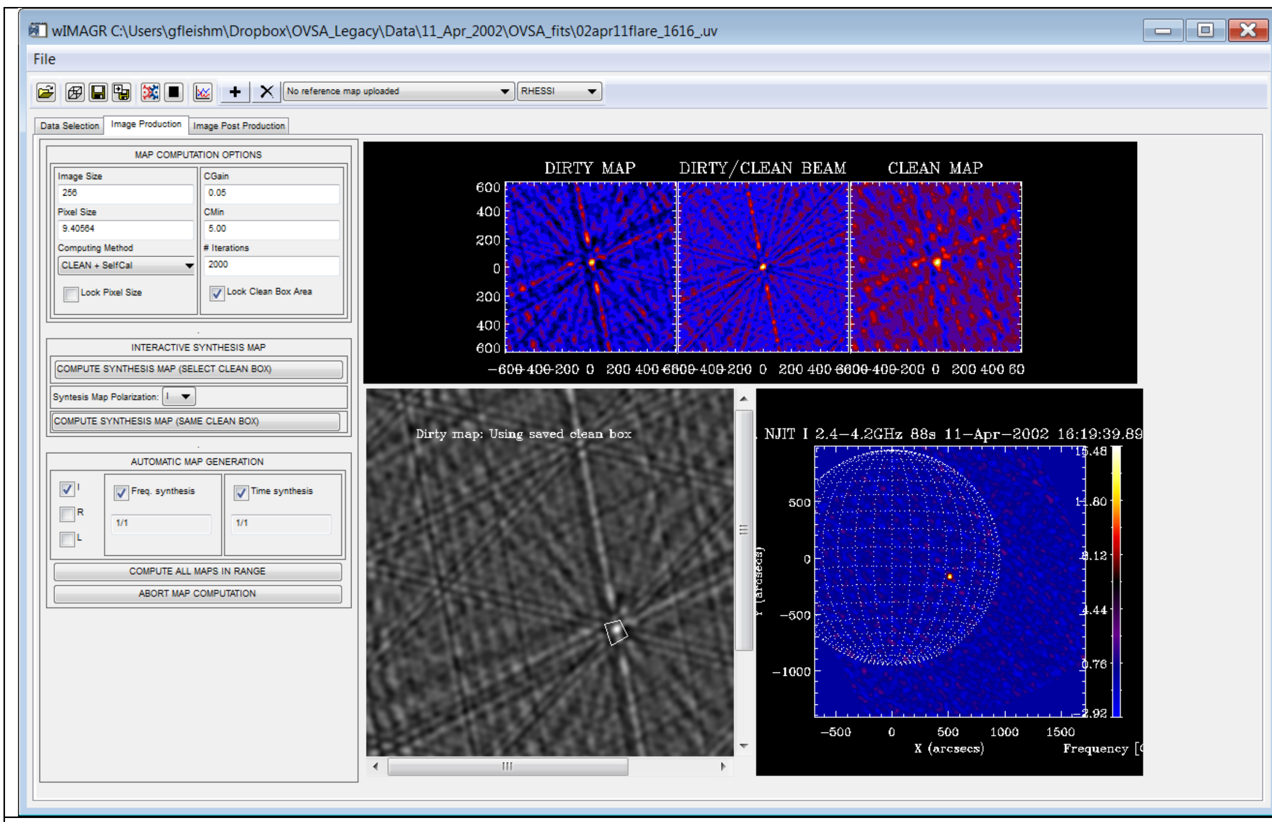

Figure 17. Widget Wimagr; Image Production tab.

In the Image Post Production tab (Fig. 18), the user can zoom in to the image, import reference images (fits or map structure) for direct comparison, generate movies, save the results in various formats including postscripts, and apply various plotting options. In addition, the OVSA beam can be displayed (dashed white oval), the source brightness distribution can be fitted to a 2D Gaussian function (red oval), and the observed source can be analytically deconvolved from the beam to produce a "deconvolved" Gaussian source model (dark blue oval).

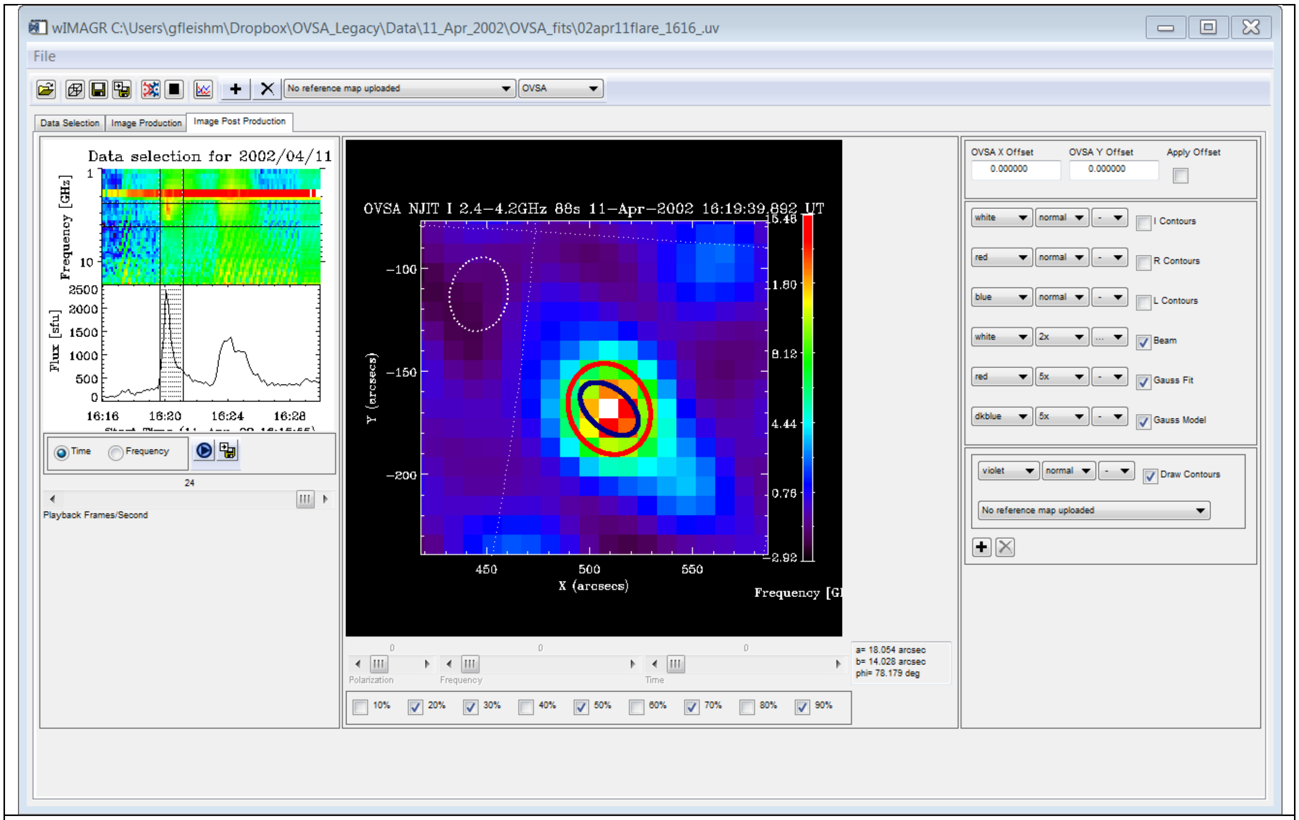

Figure 18. Widget Wimagr; Image Post Production tab. Dashed white oval shows the OVSA beam; red oval—the fitted Gaussian source; and dark blue oval—the Gaussian deconvolved model.

Detailed Step-by-Step Instruction by Joshua Martin & Marie Leung (2016 junior high school students; Union County Magnet Vocational School)

1. Create spreadsheet listing given date, start time, peak time, end time, peak flux, and peak frequency of solar event, with empty columns for the Active Region number (AR#), OVSA pointing AR# (the region where OVSA was pointing), and offset x- and y-coordinates.

2. Retrieve .arc files from the OVSA website (http://www.ovsa.njit.edu/data/archive) and place in a directory (by default c:\working in IDL programs).

3. Type "defparms" in IDL command line whenever a new IDL session is begun to set parameters needed for solar data-related programs.

4. In Launcher, select a given file, find the SOLAR DATA at the time of a given event, choose the "Check AR Location" from the dropdown menu, and determine the offset coordinates of the given AR of the event from the screen. Record the AR#, Pointing AR#, and offset coordinates on the spreadsheet and repeat this process for each .arc file.

5. Use most recent phzcal and ampcal files acquired from the OVSA web page to modify each file with the “insert_rec” command.

6. In Launcher, select the CENTERCAL for each .arc file and select “centercalchk”, then--once in the menu--select “save as secondary” then “save and exit” for all pop-ups.

7. Type “ref=daily(/interactive,/noprinter)” into the command line once; choose an .arc file and select “done” on all pop-ups. On the final pop-up, make note of which reading was the last one taken before the given solar event for that .arc file (times are listed on the left side).

8. Type “ref=daily(/interactive,/noprinter,iref=*x*)” into the command line, where *x* is the number of the reading before the event minus one (example: if the last reading taken before the event is the third reading, $x = 2$; if the last reading taken is the first, $x = 0$).

9. Select “skip” for all events until all graphs are horizontal lines (this is the reference scan). Select “done” for this pop-up. Then, complete the daily calibration as described above.

10. Type “wcalibrate” into the command line and select a given .arc file; in the pop-up window, select the last available time before the event took place, input the offset for the given event into the given boxes, and click “Analyze”. Once the loading is done, click “Explore” to open OVSA Explorer (if “Explore” is greyed out, deselect the given time and reselect it).

11. Once in OVSA Explorer, select “Mode; Set Background” from the top menu bar, then choose two intervals where there seems to be no sudden spike in activity; then, click the “Apply Background” box.

12. If there are any bars of out-of-place solid color on the graph, select “Mode; Select Bad Freq”, then click on the lines to negate them. Any remaining bursts of color and activity will be the solar event.

13. Select “Mode; Explore”, then draw a box around the solar event at the given time it occurred to zoom in on the event. Select “Set Fit Intervals” and choose the minimum and maximum frequencies of the event (the top and bottom of the given event representation), then select “Fit; Start Fit”. Close the pop-up menu.

14. Select “Save as” from the file menu, then save all files (.uv, .med, and .sav).

15. Type “wimagr” into the command line to run the wimagr program. Select the “Dirty Map” bubble along the right side, then use the sliders below the image in the top left to select the time in which the event occurred.

16. Under the “Frequency Selector” tab, check the boxes of all frequencies under which the event was observed.

17. Under the “Baseline Selector” tab, click the antennae necessary to make the lines upon the dirty map on the right converge onto a single obvious point (usually, Antenna 7 [A7] is the cause of some difficulty).

18. Under the “Image Selector” tab, select “CLEAN MAP” from the “Computing Method” dropdown menu. Then, select the “COMPUTE SYNTHESIS MAP” button.

19. On the dirty map in the window, draw a box around the most significant white “blob” at the point where the lines intersect by clicking points around the area one wishes to investigate; then, right click twice to process the image.

   a. If cross-referencing a Nobeyama image, select the “+” button and select the FITS file one wishes to compare to.

20. Click the “COMPUTE ALL MAPS IN RANGE” button.

21. Under the “Image Post Production” tab, check to see whether the event is in a feasible place upon the sun (if the event is located off of the surface of the sun, it is almost certainly incorrect).

   a. If cross-referencing a Nobeyama image, deselect the Nobeyama image under the dropdown menu at the top of wimagr and select it under the dropdown menu towards the bottom right. If the Nobeyama image is not clearly visible, one can change the color of the Nobeyama map to something more visible at the dropdown menu next to the one last used. If the OVSA image produced and the Nobeyama map center on the same point, the image is accurate; if not, an error was made at some point in the process.

22. Save the image as all necessary files from the File menu or the corresponding buttons along the top of wimagr.

23. Under the “Image Production” tab in the “AUTOMATIC MAP GENERATION” menu, determine whether a movie of the event over time or frequency-by-frequency is to be created; then, click either “Compute all maps in range” button.

24. Under the “Image Post Production” tab, use the slider at the bottom left corner of the wimagr window to choose the framerate. Then, click the “Play” button below the image in the top left to see if the movie is acceptable; if it is, click the “Save Movie” button to save the recording as a .mov file.

25. Repeat steps 23 through 24 to create the form of movie not created.

26. Repeat steps 7 through 25 for all events.

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