CASA Sit-together session 6

Solar continuum data at 20cm from VLA

29th October 2010, EU ARC, CZ node at Astronomical Institute in Ondřejov

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0. For impatient

Data file: **DULK16081984.UVFITS**
Script: **sun-vla.py**

1. Introduction - Specifics of solar radioastronomy

The Sun is our closest star and this simple fact has a few consequences for its observations, also on the radiowaves:

1. Its is bright, in fact on many wavelengths much brighter than other sources usually observed. This has both pros and cons – shorter integration time is sufficient, on the other hand one can get into problems with calibration.

2. Linear scales (in km) which we can resolve are many orders of magnitude smaller than for the remote radio sources. Having a speed at which disturbances propagate in the source (typically Alfven speed) this also means that the resolved sources at the Sun can be much more variable than usually - source dynamics does matter and we are frequently interested in time evolution.

Second peculiar feature of solar radio emission is the specific emission mechanism that applies mainly on lower frequencies (<5GHz): so called plasma emission. It can produce very bright non-thermal (T_b up to 10^{15} K while coronal temperature is 2MK), rather narrow-band ($\Delta f/f < 0.001$) and highly time-varying radiation at plasma frequency or its harmonics. In addition to that, also 'standard' emission mechanisms (brehmstrahlung, gyro-synchrotron and in the lowest-temperature regions also molecular transitions) occur.

2. The raw data

For the current sit-together session we have got solar radio imaging data from the NRAO VLA archive (*https://archive.nrao.edu/archive/e2earchivex.jsp*). It is observation of the entire solar disk in continuum at 20cm (VLA L-band) made by George A. Dulk on 16/08/1084. Besides the Sun, two calibrators have been observed: B0212+735 and B0945+664. Scans are described in files **dulk1.html - dulk3.html** obtained from the VLA archive.

VLA uses the special mode (`VLAMODE='S'`) for solar observations - the nominal sensitivities which are usually applied on-line for other sources are not taken into account for the Sun; correlation coefficients are written to the main table instead of that, supplied by system temperatures written in the TY table – see *http://www.aips.nrao.edu/CookHTML/CookBookse29.html#x42-820004.8* for details. Therefore the `importvla()` task in CASA should not be used in this case and we had to do some preliminary steps in AIPS.

3. Preparing the data in AIPS

Because of peculiar calibration of solar data with VLA we prepared the dataset in AIPS including some calibrations. See AIPS cookbook at *http://www.aips.nrao.edu/CookHTML/CookBook.html* for meaning of parameters used.

3.1. Importing the archive files

```
DEFAULT FILLM
DATAIN 'INDATA:/DULK_
NFILE 0
NCOUNT 3
VLAOBS 'DULK'
BAND 'L'
VLAMODE 'S '
CPARM(2) 16
CPARM(8) 0.16
CPARM(9) 0
BPARM(2) 1
OUTNAME 'SUN20CM'
GO
```

3.2. Write VLA on-line flags with level > 3 from the on-line flag table OF to standard flag table FG

```
DEFAULT OFLAG
DOFLAG 3
FPARM 0
DETIME 5.0
GO
```

3.3. Only antennas VA11, VA12, VA17, and VA18 are equipped with noise calibrator for the Sun, the data in the TY table for the rest of antennae is faked. Bootstrap the data form working antennae to the entire array, changing the gain factors in the CL table appropriately at the same time.

```
DEFAULT SOLCL
INNAME 'SUN20CM'
SOURCES '*'
ANTENNAS 11 12 17 18
STOKES ''
GO
```

3.4. Keep the multi-source measurement set, applying the calibration accumulated in the CL table – i.e. gain-curve and opacity written there during FILLM and system-temperature corrections applied in the previous step. Drop the flagged data written in the table FG. The task is undertaken now because CASA does not understand the FG and CL tables to be able to apply them later. From the two observed IFs in the L-band (1441 MHz and 1627 MHz) keep only the latter one since the IF1 is corrupted for a large interval of observed time.

```
DEFAULT SPLAT
INNAME 'SUN20CM'
BIF 2
EIF 2
DOCALIB 1
GAINUSE 2
DOPOL 0
DOBAND 0
OUTNAME 'SUN1627'
SOLINT 0
FLAGVER 1
GO
```

3.5. Export the data in UVFITS

```
DEFAULT FITTP
INNAME 'SUN1627'
DATAOUT 'UVFITS:DULK16081984.UVFITS'
GO
```

4. Data reduction in CASA

Having the data **DULK16081984.UVFITS** in UVFITS format we can proceed in CASA as usually. We have only continuum data what makes the calibration process much easier. Since the Sun provides strong signal, we would like to improve the calibration done with external sources by self-calibration. The time-evolution of the source is frequently essential in solar research, let us split the total integration time into a few time windows and provide imaging and self-calibration separately in each time window. The steps can be summarised as follows:

1. Import the data: `uvfits()`
2. Set the model for the primary calibrator: `setjy()`
3. Do gain calibration for primary and phase calibrator: `gaincal()`
4. Set flux scale for the second calibrator: `fluxscale()`
5. Apply calibration tables to target: `applycal()`
6. Split the data to form single-source (Sun only) measurement set: `split()`
7. Invert & clean the images. Divide the total integration time to three parts in order to trace the time evolution somewhat – this is performed by selecting only continuous sub-sets of all scans:

    7.1. First `clean(),` not so deep
    7.2. `gaincal()` with the MODEL_DATA column set in the previous step by clean(), short solution interval
    7.3. `smoothcal()` to get the gaintable smoother
    7.4. `applycal()` to correct the data.
    7.5. Second, deeper `clean()`

5. Closing remarks

Loading the three resulting images into CASA `viewer()` and starting the blink-mode one can see some variability in the emission. First of all, the rotation of the Sun is visible. This has an consequent effect : A new source is emerging at the western solar limb. In addition to that, another small source appears approximately in the middle between north-east limb and center. Given data does not represent real example of solar variable emission, this is usually much brighter and on shorter time-scales. However, it should illustrate the specifics of solar radio physics.

Solar radio emission may be both continuum or rather narrow-band, its important feature is time variability. Usually the brightest, strongly non-thermal features (at lower frequencies) are narrow-band, compact and highly time-varying. Until now two kinds of solar radio data are available: 1) Solar radio spectra with high temporal and frequency resolution and broad-band frequency coverage, but without spatial resolution, and 2) interferometric data at a few single frequencies, like that analysed during current session. When parameters inside the source change, it can disappear from the radio imager at given frequency, despite the source continues to radiate – only at a slightly different wavelength. ALMA has, on the other hand, both good frequency and spatial resolution, giving the possibility to track the actual physical dynamics in the source. In addition to that, the frequency range observed by ALMA is almost completely (with exceptions of few mm-wave radiometers) uncovered in solar radio astronomy. Also the resolution provided by ALMA is unprecedented. From all these reasons, expectations of solar community concerning ALMA are enormous. Some sophisticated models – e.g. those for solar convection – actually rely on the tests with mm and sub-mm observations. As an illustrative example, the picture modelled for solar convection is shown in the attached Fig. **chromosphere.fits** (courtesy of Dr. M. Lukitcheva and Dr. S. White).