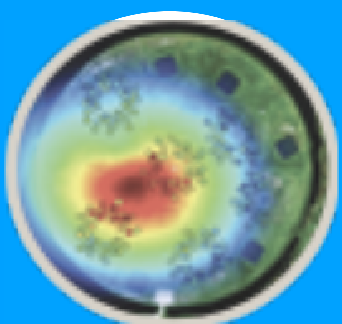
ASTRON
Netherlands Institute for Radio Astronomy

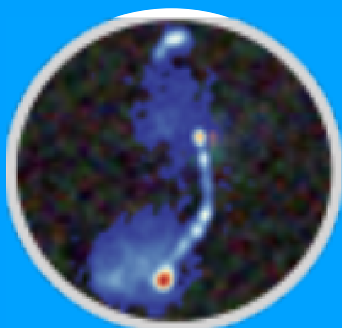
STELLAR

LOFAR

Processing beamformed data: Pulsar Pipeline (PulP)

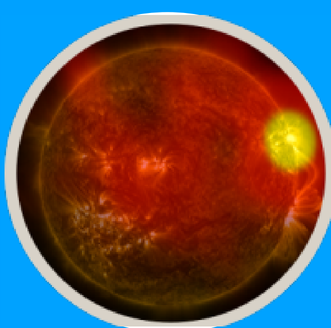
Vlad Kondratiev
(ASTRON)

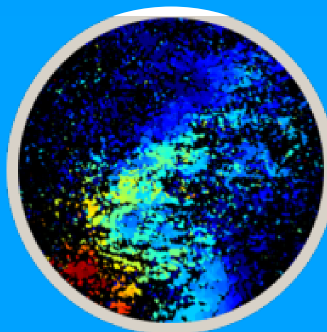




6th LOFAR Data School

March 22-26, 2021





Outline:

- PulP overview
- In a nutshell about (de-)dispersion, folding
- PulP flowchart
  - → DSPSR pipeline
  - → PRESTO pipeline
- PulP output data
- Hands-on prerequisites

PulP overview

PulP is LOFAR **Pul**sar **P**ipeline for *known pulsars*. The essential goal of the PulP is to get the average profile of the pulsar(s) and provide a user with freq/time/phase/pol data cubes for further analysis. It is ***not*** the *search* pipeline, i.e. you can not do periodicity and single-pulse searches for a large range of dispersion measure trials. However, PulP can provide both PSRFITS/filterbank data and raw data converted to 8-bit for further searches.

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- Bookkeeping, service functions
  - → Logging
  - → Cluster configuration/settings
  - → User options
  - → Where input data are?
  - → Observing setup (HDF5 metadata / *parset*)
  - → Coordination of processing data for different TABs/frequency parts
  - → Feedback files for LTA ingest
- The actual data processing
- Diagnostic summaries and pipeline output data products

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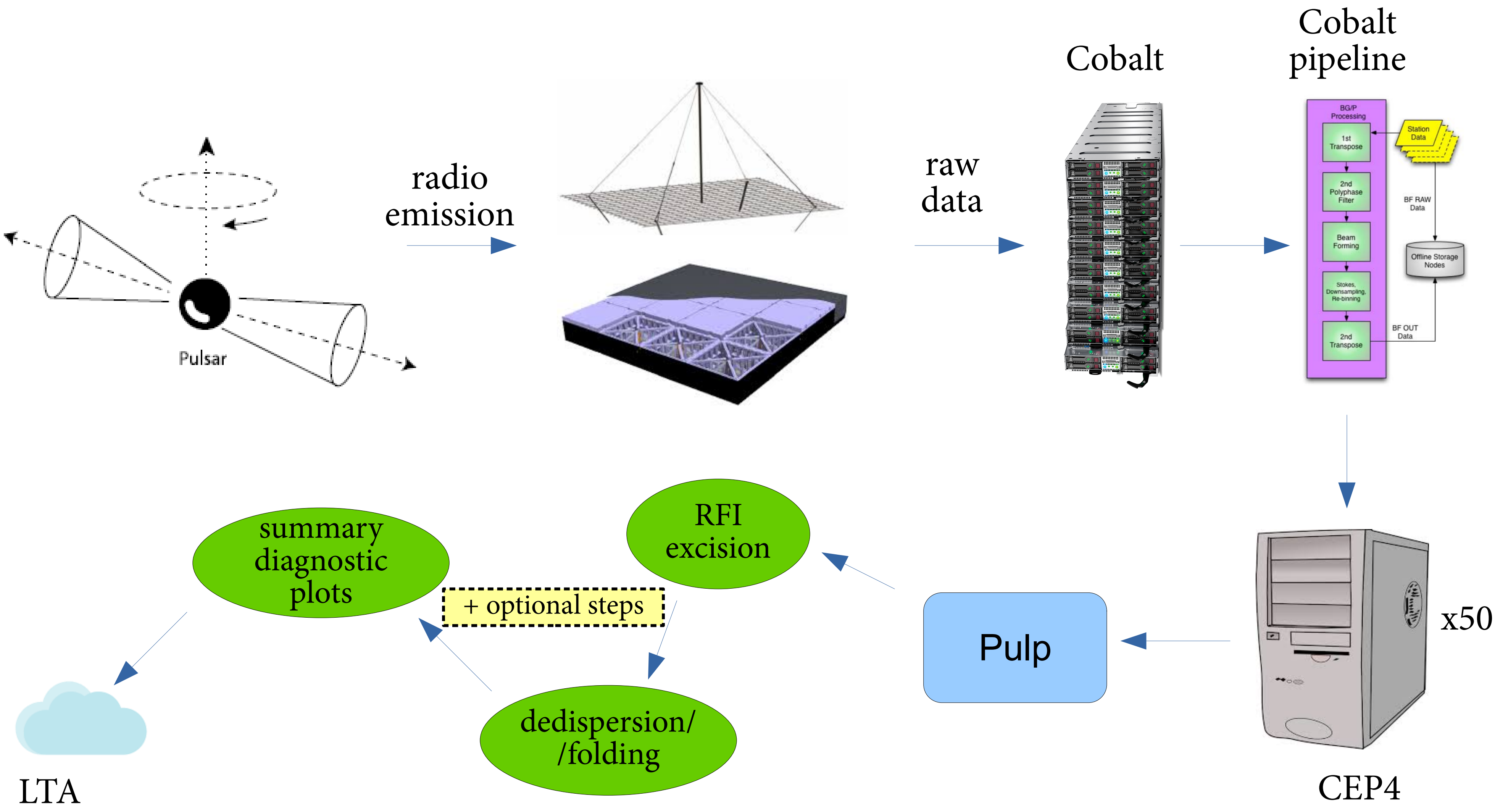
- **Diagnostic summaries and pipeline output data products**

Data flow


Pulsar
radio emission
raw data
Cobalt
Cobalt pipeline
BG/P Processing
1st Transpose
2nd Polyphase Filter
Beam Forming
Stokes, Downsampling, Re-binning
2nd Transpose
Station Data
BF RAW Data
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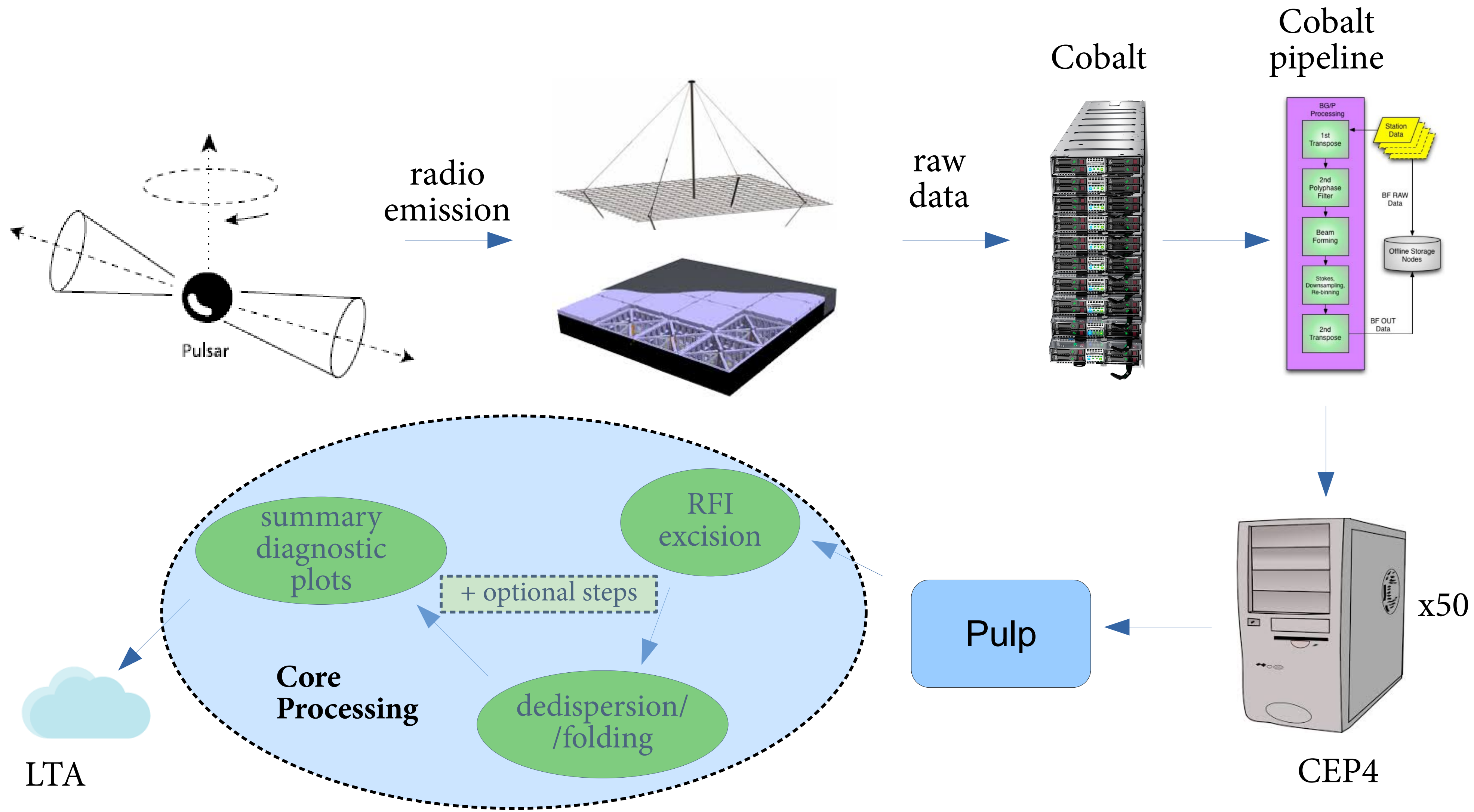
BF OUT Data
x50
CEP4
Pulp
RFI excision
dedispersion/ /folding
+ optional steps
summary diagnostic plots
LTA

Data flow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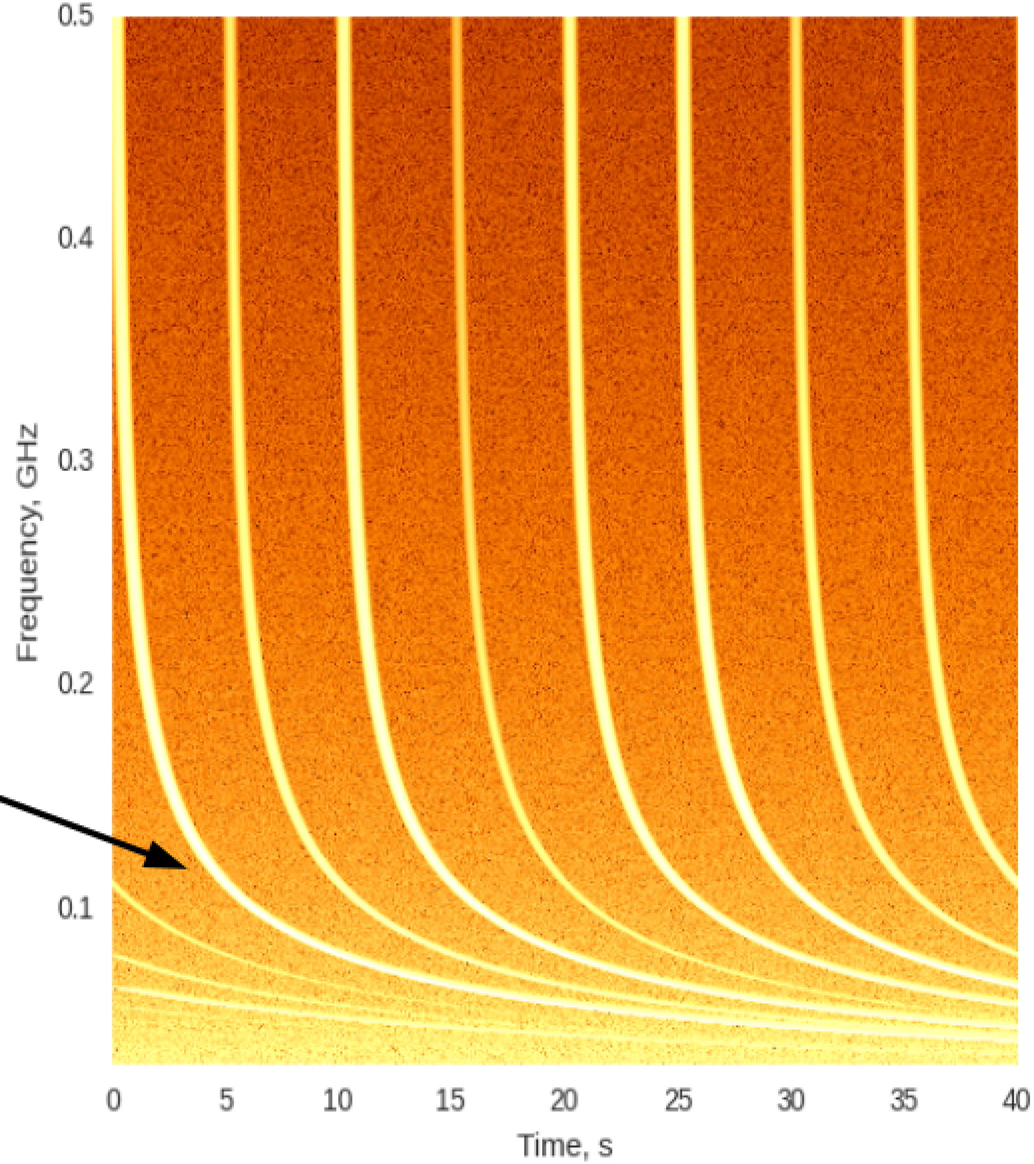
Dispersion

Simulated ultra-broadband pulse recording

DM = 15 pc cm^{-3}
P = 5 s

Dispersive delay

$$\delta t \sim DM / \nu^2$$



Credit: Anya Bilous

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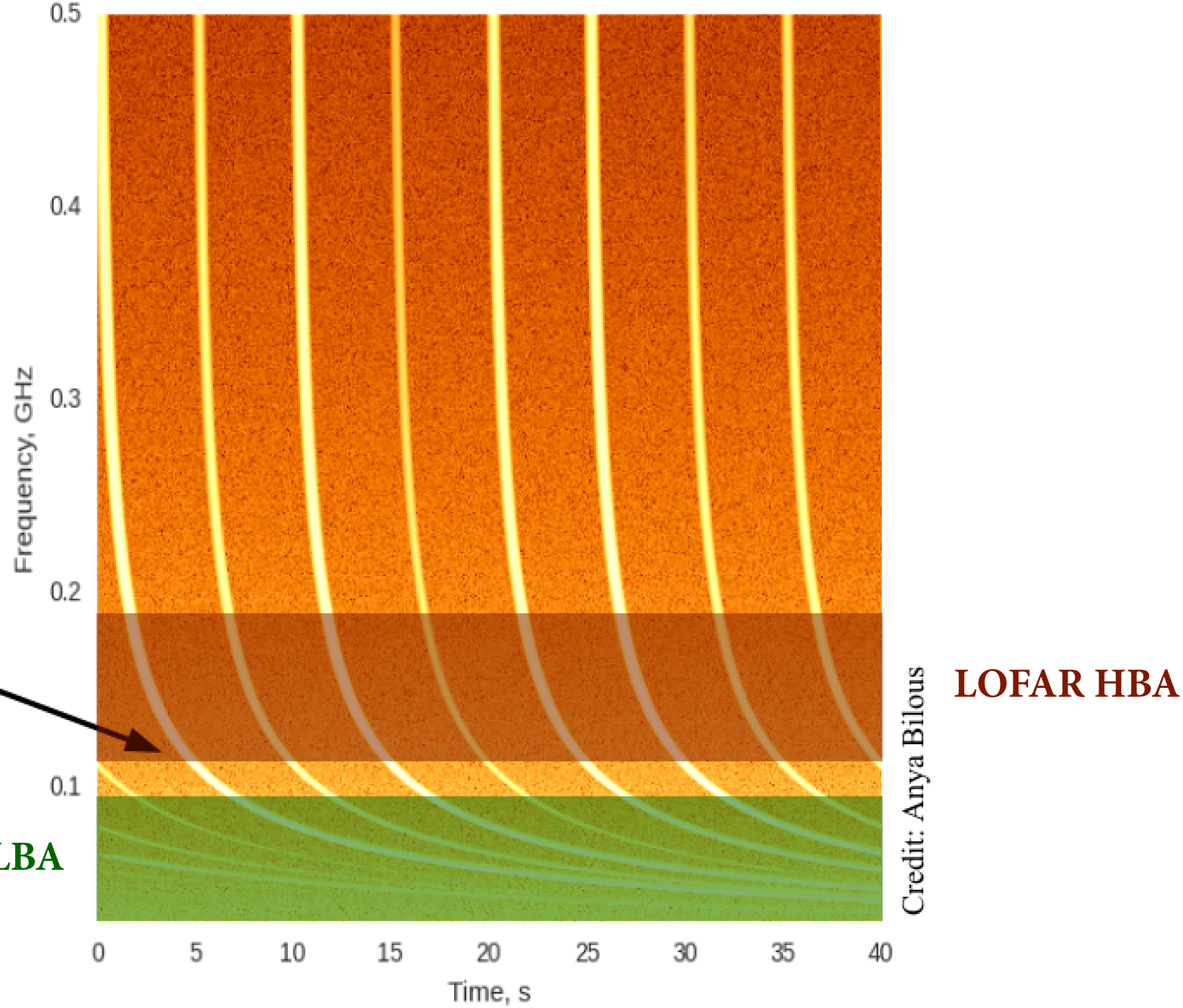
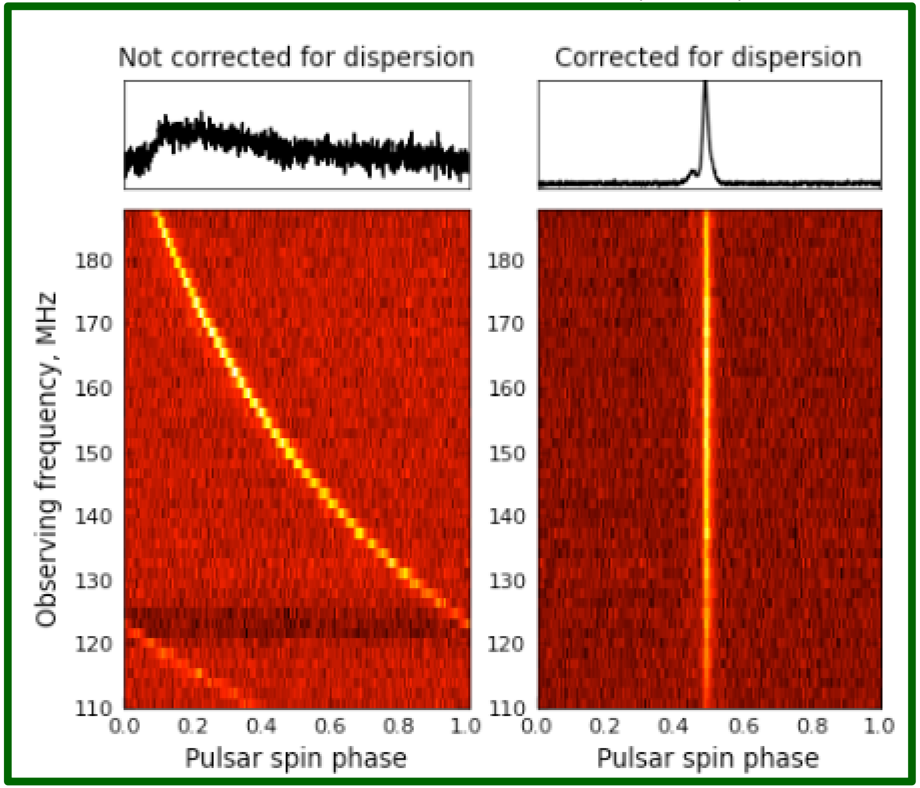
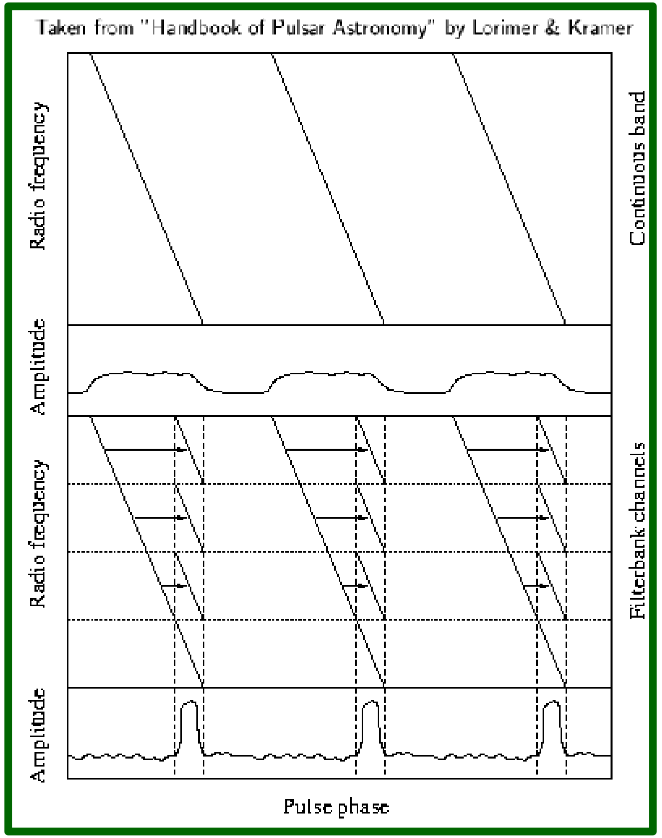


Dispersion

PSR B2021+51 **DM is off by only 3 pc/cc!**



Credit: Anya Bilous

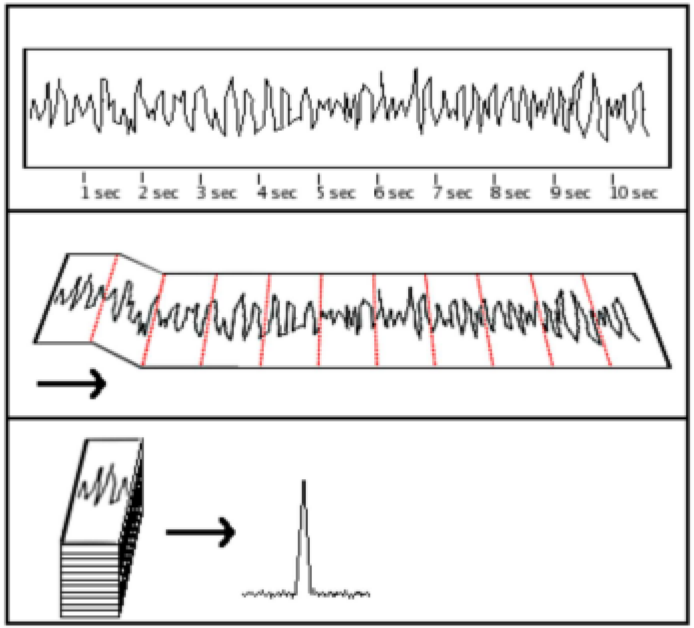


- DM [pc cm^{-3}] measures the integrated column density of free electrons along the line of sight
- Can be corrected using (in)coherent dedispersion

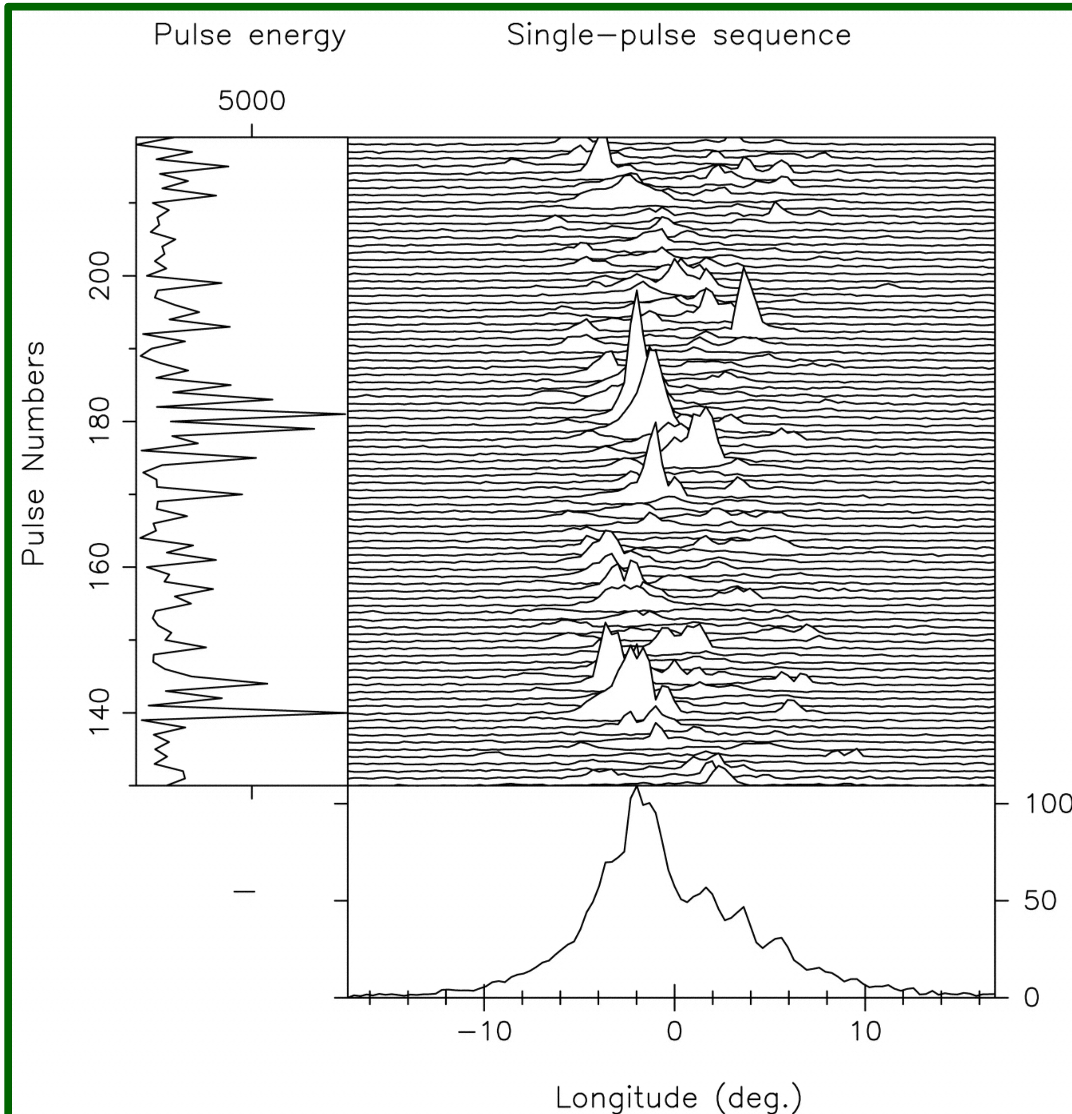
- Incoherent dedispersion – shifting channels in time
- Coherent dedispersion – requires complex-voltage data and is more computationally expensive

Folding

in a nutshell



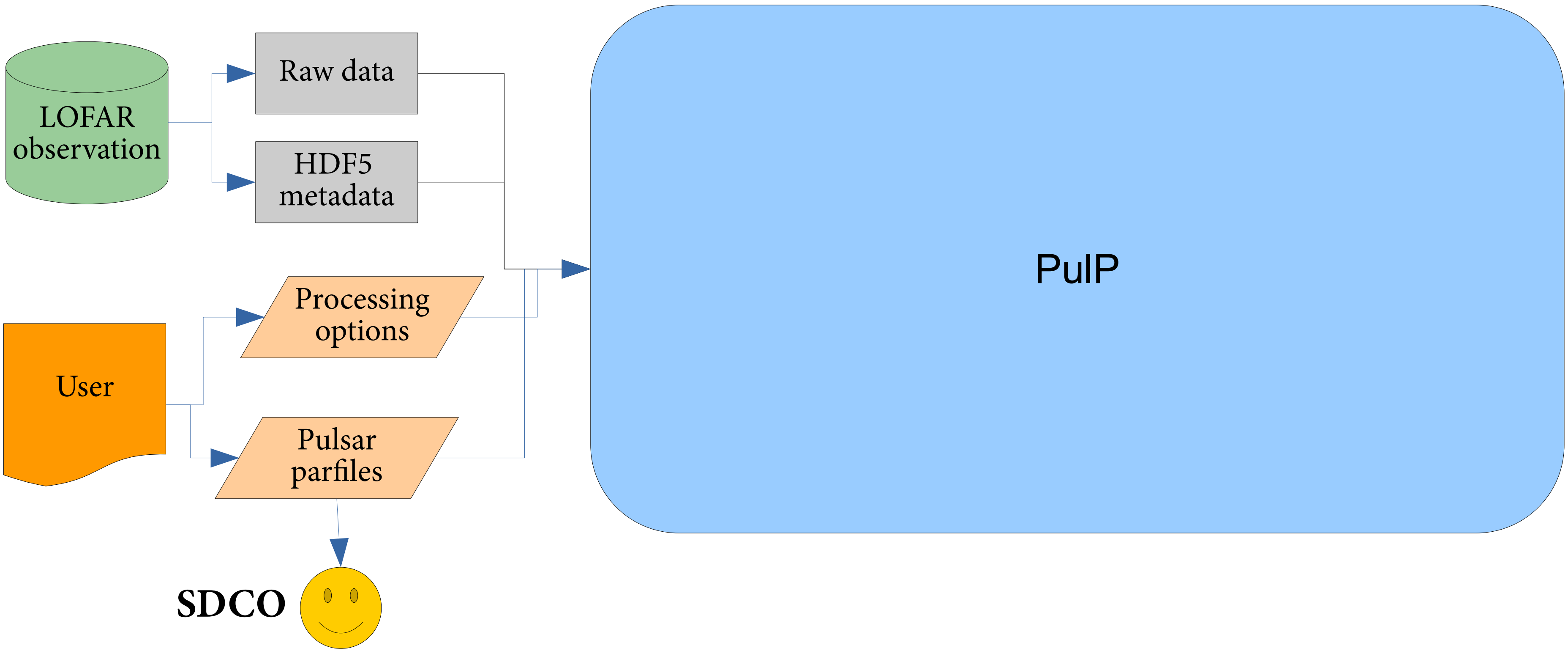
PSR B0943+10



Deshpande & Rankin (1999)

PulP flowchart (1)

Demo



Parfiles: if parfiles are not given toPulP, then based on the target name it will try to find the corresponding pulsar in the ATNF catalog. If no pulsar is found in the catalog, PulP will look for the brightest pulsar in a given SAP and fold it.

Pulsar ephemeris (parfiles)

```
PSRJ           J0034-0534
RAJ             00:34:21.8320019          1   0.00068844071120754594
DECJ           -05:34:36.81231            1   0.02161483083208828989
F0             532.71342977772821597      1   0.00000002836577022925
F1             -9.33246370730386516 3e-16 1   4.92605919201583764 76e-17
PEPOCH         49550.037311801294202
POSEPOCH       49550.037311801294202
DMEPOCH        49550
DM             13.764894275846959064      1   0.00004430172861405973
DM1            0
PMRA           8.0823671616462304792          0.13169130726699274092
PMDEC          -9.5157740417196312044         0.30750778304651565920
BINARY         ELL1
PB             1.5892817926966151351      1   0.00000000792094121129
A1             1.4377774324431148653      1   0.00000359435416977026
TASC           49550.704855759820283      1   0.00003326831506895045
EPS1           6.4089927497823510916e-05  1   0.00000873904414835617
EPS2           -3.0385531645805153 1e-05  1   0.00001349161624088706
START          55959.632675467299123      1
FINISH         56448.301487586140865      1
TZRMJD         56190.012138005647902
TZRFRQ         137.15199999999998681
TZRSITE        t
TRES           31.090
EPHVER         5
CLK            TT(TAI)
MODE 1
EPHEM          DE421
NITS           1
NTOA           218
CHI2R          132.9672 207
```

can be as simple as this:

```
PSR      J1706+35
RAJ      17:07:03.61
DECJ     +35:55:54.5
P0       0.159764851
P1       0.0
PEPOCH   58244.04308936660
DM       19.240
EPHEM    DE405
CLK      UNCORR
```

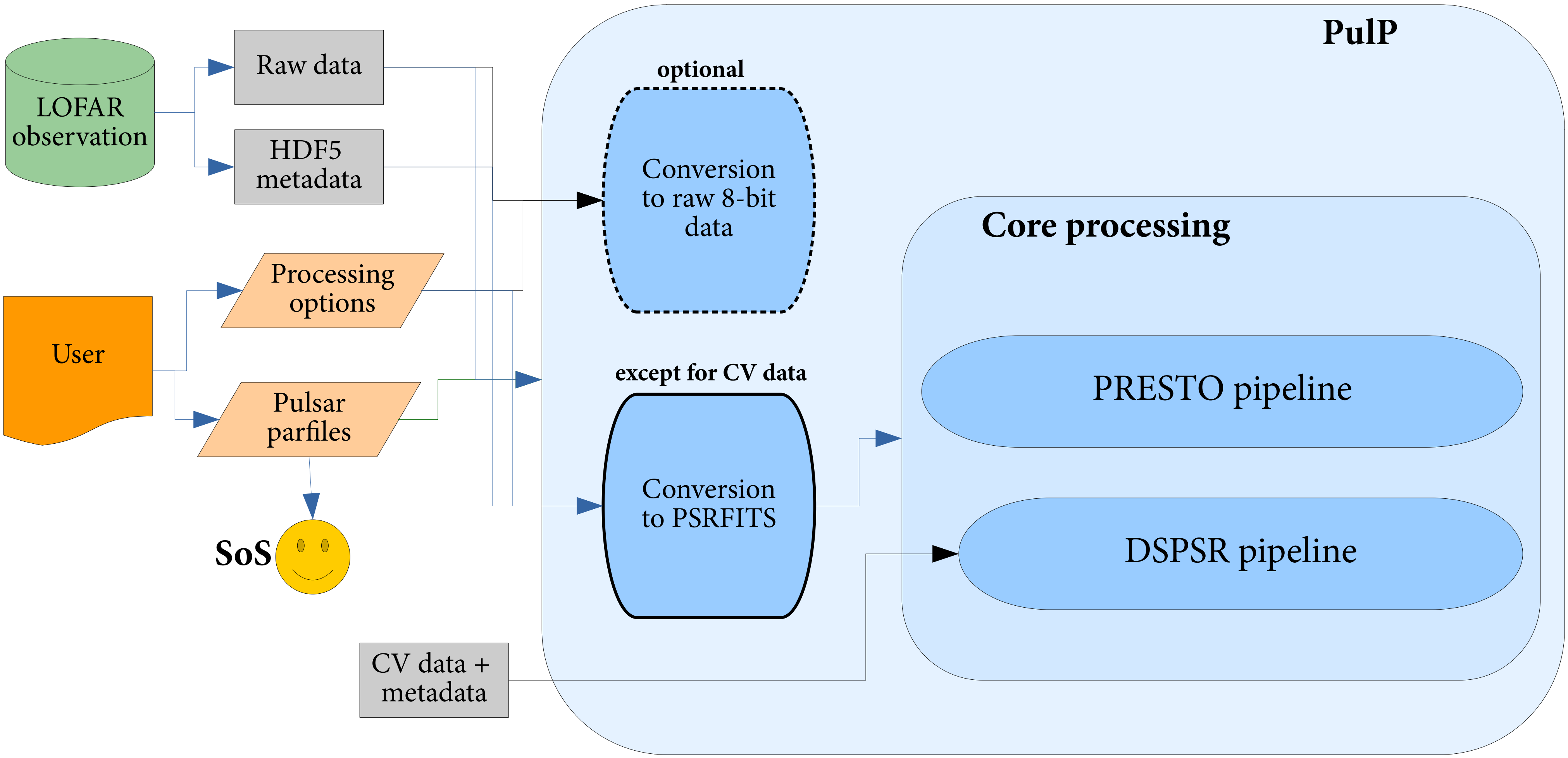
Input raw data

- HDF5 format
- Header information (metadata) is stored in **_bf.h5* file
- The raw data itself is stored in **_bf.raw* file
- This *.raw* file is linked from within *.h5* file and can be accessed directly via opened *.h5* file

- Filename structure:
  → Lnnnnnn_SAPxxx_Byyy_Sz_Pmmm_bf.h5

  - Lnnnnnn – LOFAR observation ID (ObsID)
  - xxx – Sub-array pointing (SAP) number
  - yyy – Tied-array beam (TAB) number
  - z – Stokes parameter, can only take values 0,1,2,3
    - Stokes I observation – have only S0 files
    - Stokes IQUV observation: S0 – I, S1 – Q, S2 – U, S3 – V
    - Complex-voltage data: S0 – Xreal, S1 – Ximag, S2 – Yreal, S3 – Yimag
  - mmm – Frequency part, i.e. when every file has only fraction of subbands

PulP flowchart (2)



Data conversion

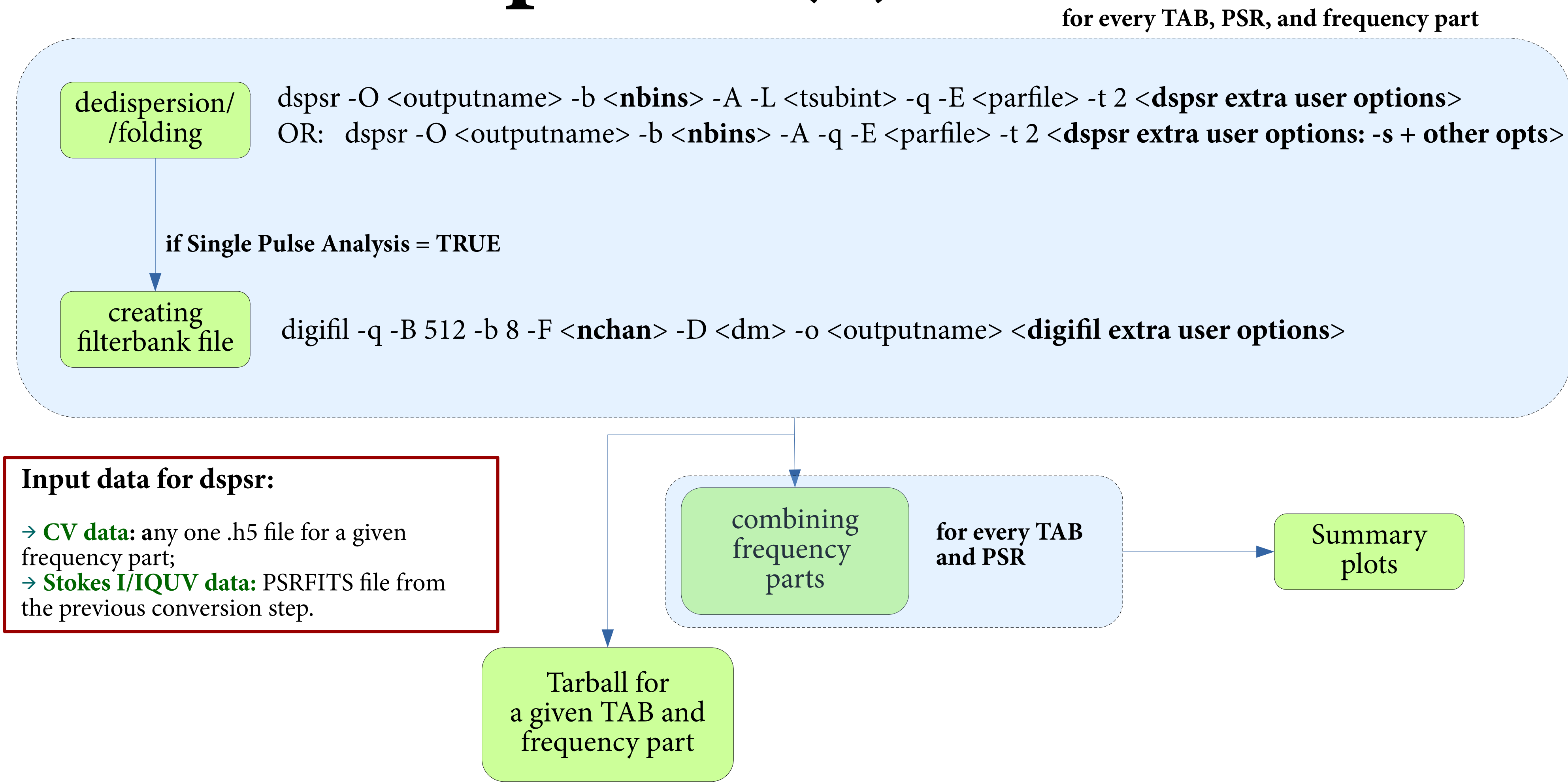
- Conversion to raw 8-bit data (optional)
  - → *digitize.py*
  - → written by Marten van Kerkwijk
  - → available at: *https://github.com/mhvk/scintellometry/blob/master/scintellometry/lofar/digitize.py*

  - → *digitize.py -s 5 -o <output dir> <input .h5>*

- Conversion from raw 32-bit data to PSRFITS (for non-CV data)
  - → custom-made program *2bf2fits*
  - → written by Tom Hassall, Patrick Weltevrede, with contribution from Vlad Kondratiev
  - → currently available at LOFAR Users Software Repository
  - → will make it available at Github as well
  - → does not save scales/offsets in PSRFITS
  - → needs major revisiting…

  - → Command example (very detailed input):
    - *2bf2fits -CS -H -append -nbits 8 -A 100 -sigma 3 -nsubs 400 -sap 0 -tab 0 -stokes 0 -o L667444_SAP0_BEAM0 -nsamples 24 -nchans 16 -ra 2.15980858832 -dec 1.30000703891 -psr B0809+74 -clock 200 -band HBA_110_190 -startdate 2018-09-12 -starttime 20:17:00.000000000 -samptime 0.0104858 -duration 299.977 -subs 54..453 -obsid L667444 -observer Pizzo /data/projects/PipelineTests/L667444/cs/L667444_SAP000_B000_S0_P000_bf.raw*

DSPSR Pipeline (1)

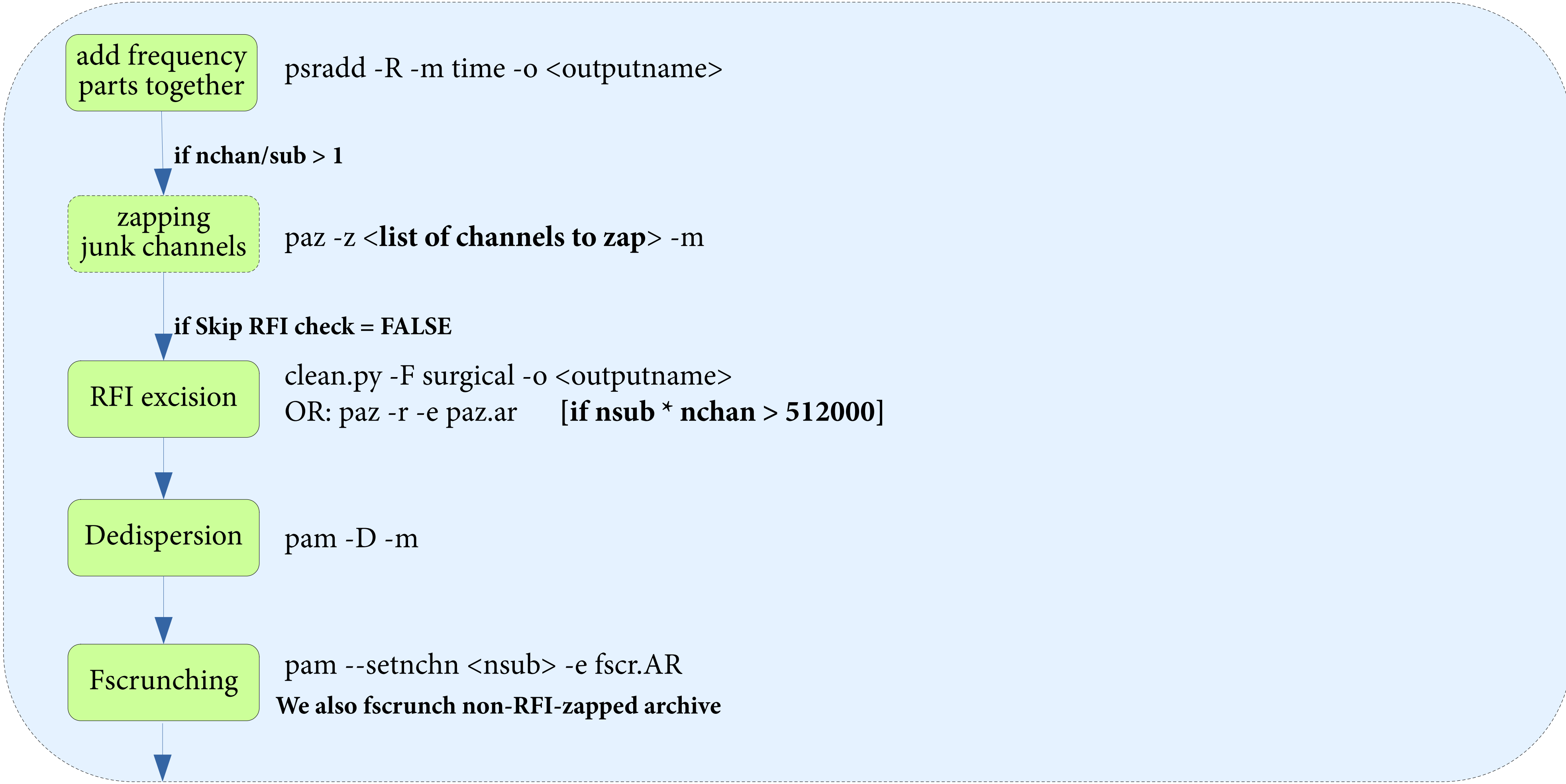


<nbins> - calculated automatically based on the sampling time and F0/P0 from the parfile.
Maximum possible <nbins>=1024

<nchan> - number of channels in a given frequency part. If number of channels = 1, then <nchan>=2

DSPSR Pipeline (2)

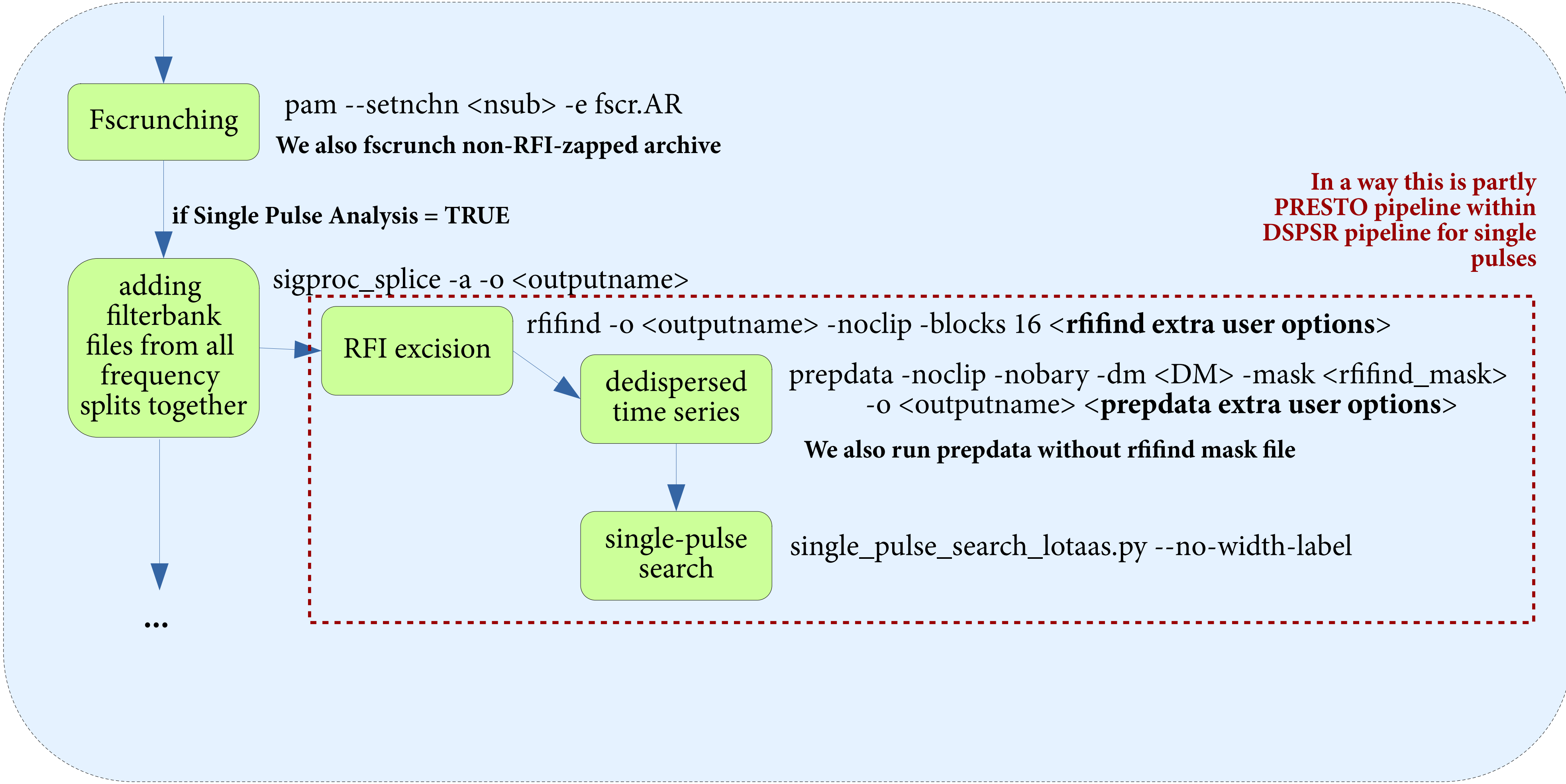
combining frequency parts;
for every TAB, PSR



<**list of channels to zap**> - if there are 16 chan/sub, we need to zap every 16th channel, then list becomes «0 15 31 47...»
This is necessary, as when 2nd PPF is used, the first channel in each subband gets corrupted

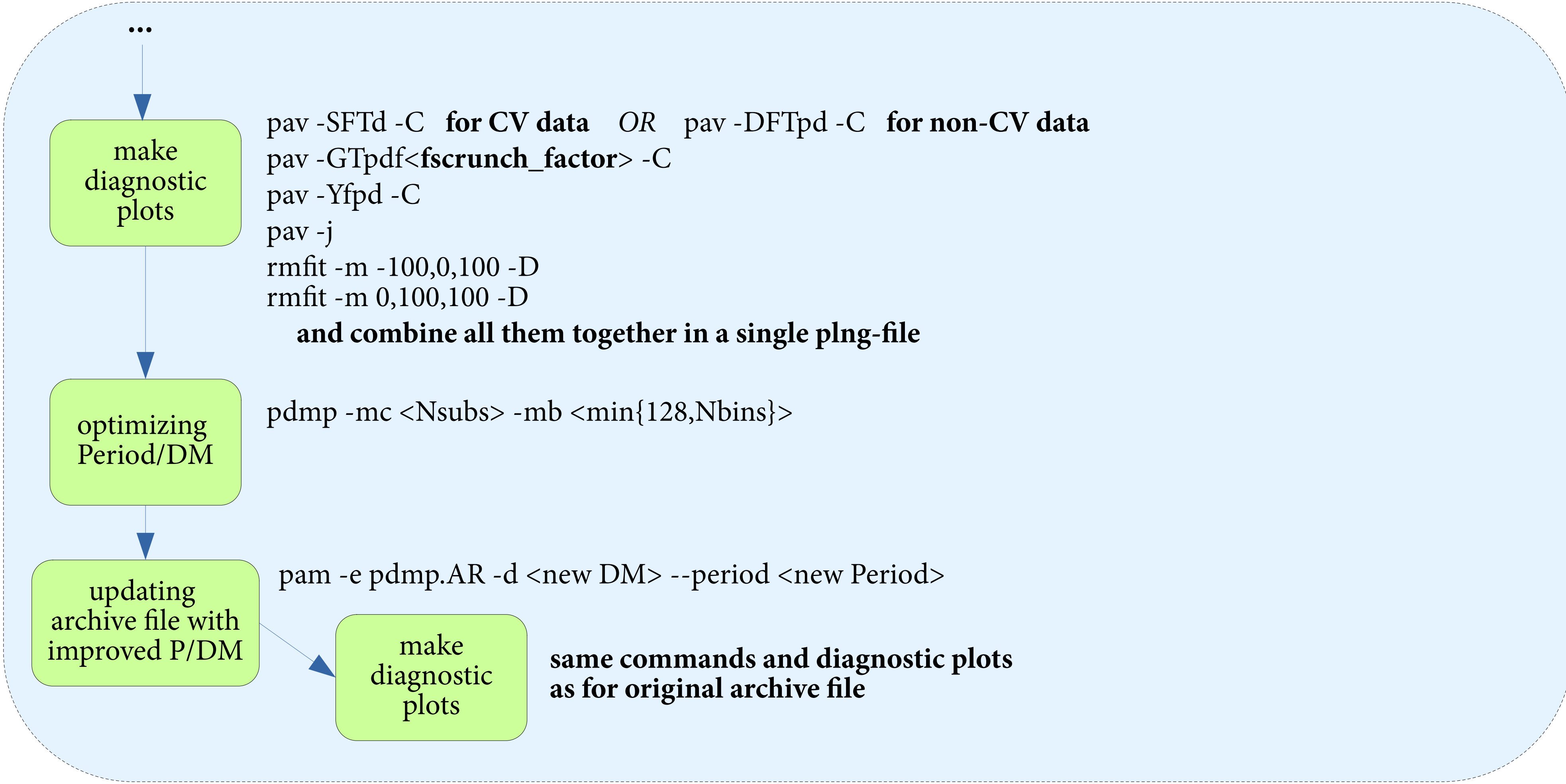
DSPSR Pipeline (2, cont.)

combining frequency parts; for every TAB, PSR



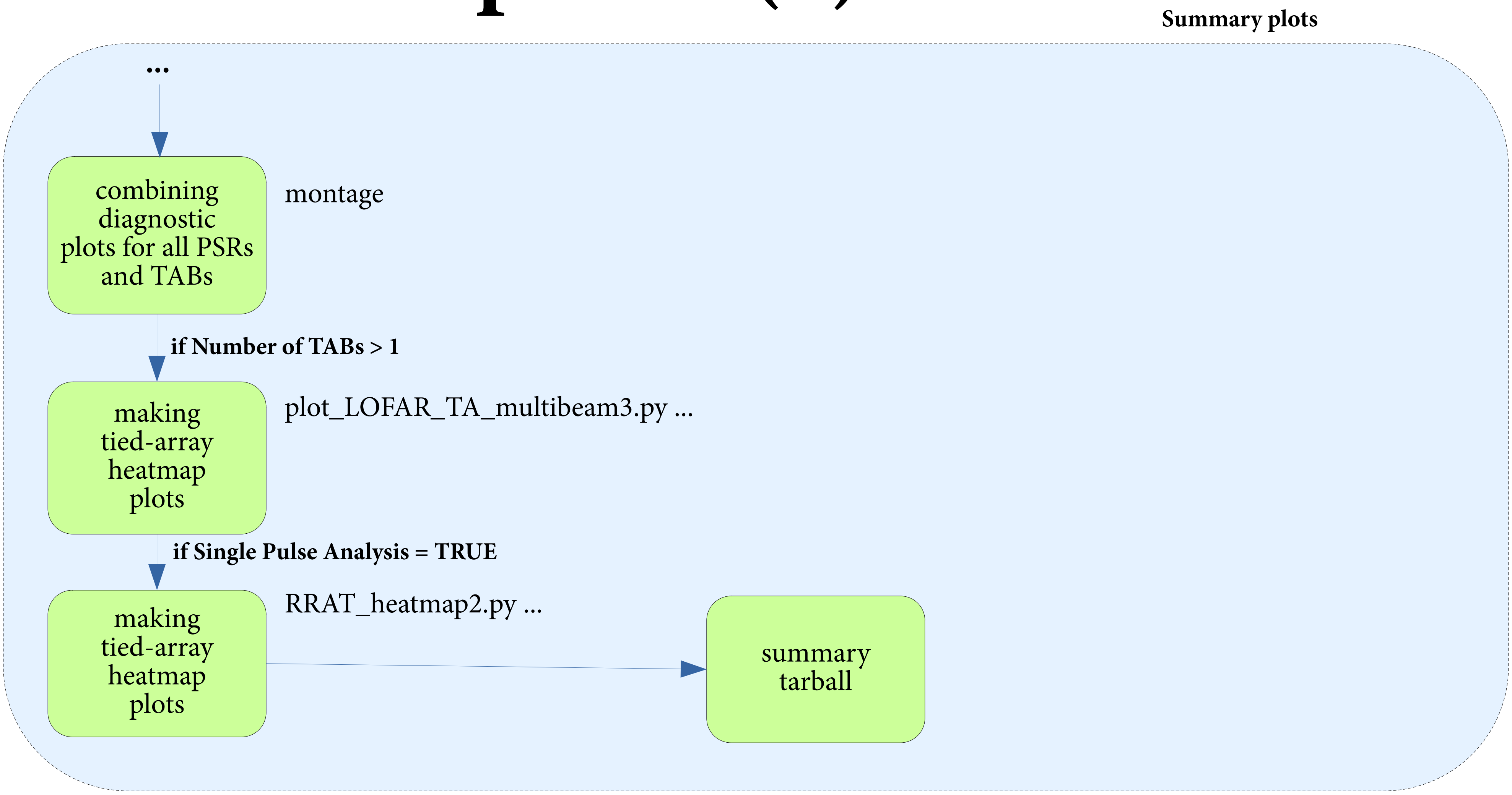
DSPSR Pipeline (3, cont.)

**combining frequency parts;
for every TAB, PSR**



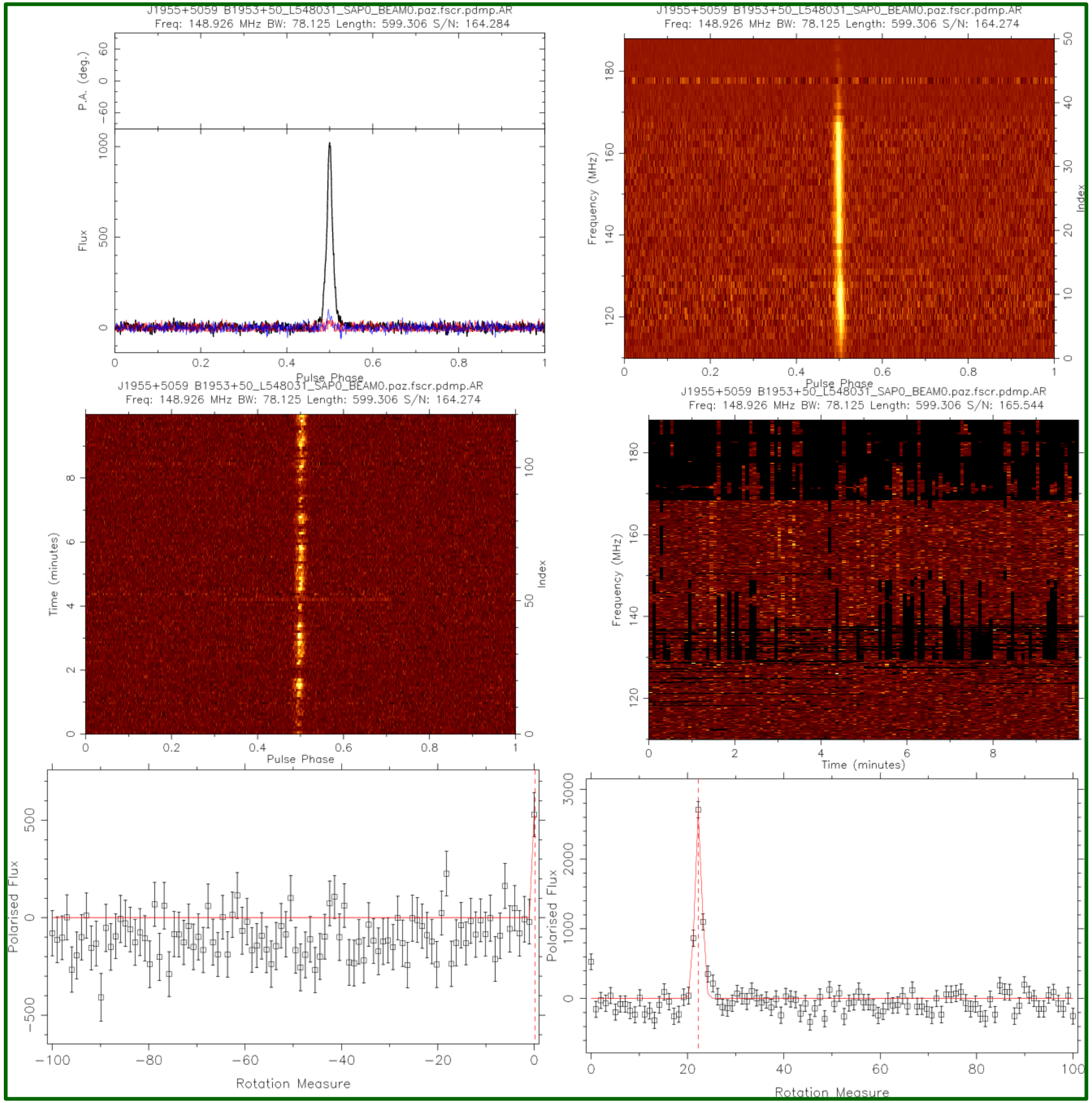
<**fscrunch_factor**> = Nsubs / X, where X = highest common denominator of Nsubs between 1 and min{Nsubs, 63}

DSPSR Pipeline (4)



Diagnostic plots (1)

pav
rmfit

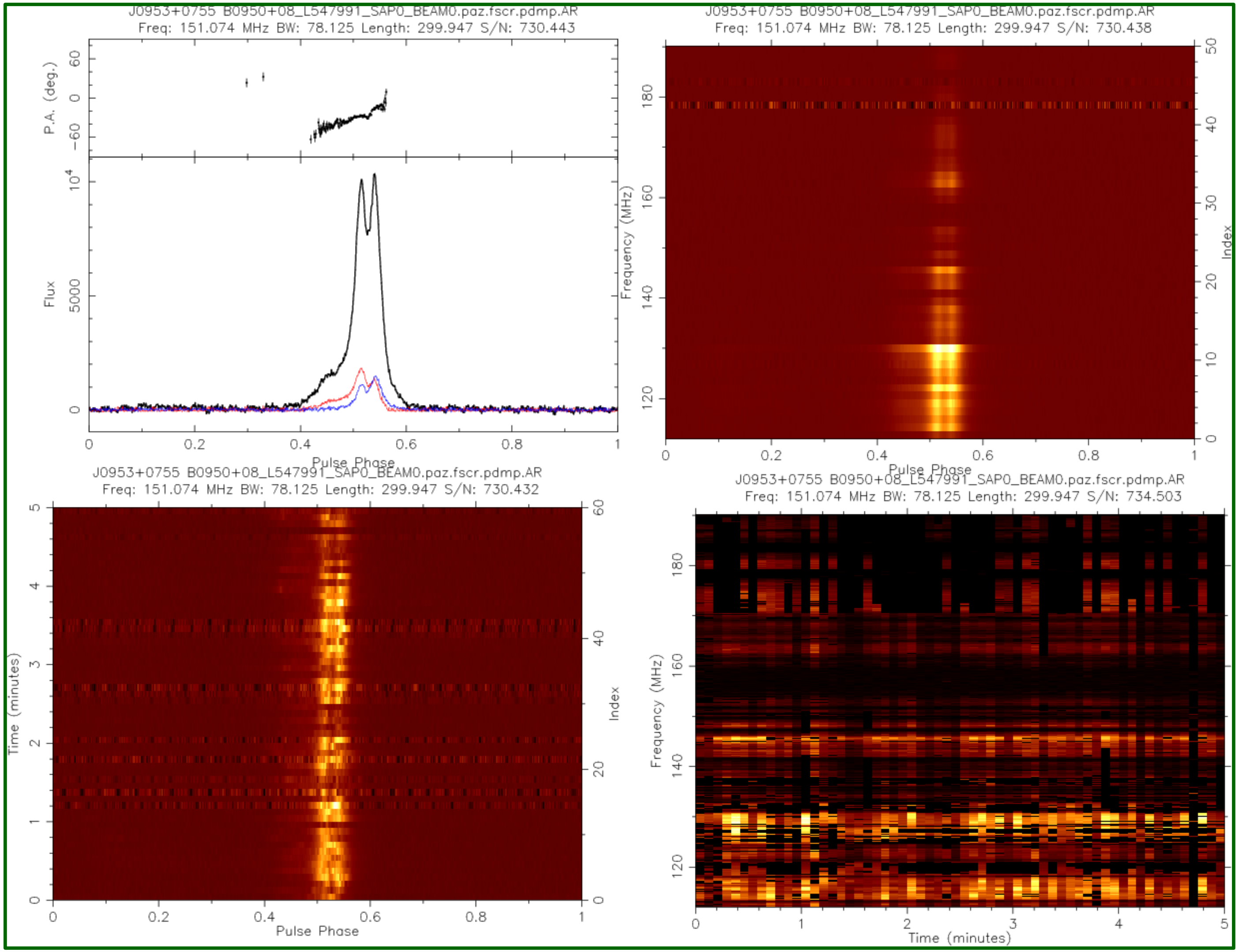


status.png

*_diag.png

*_diag_pdmp.png

Diagnostic plots (2)

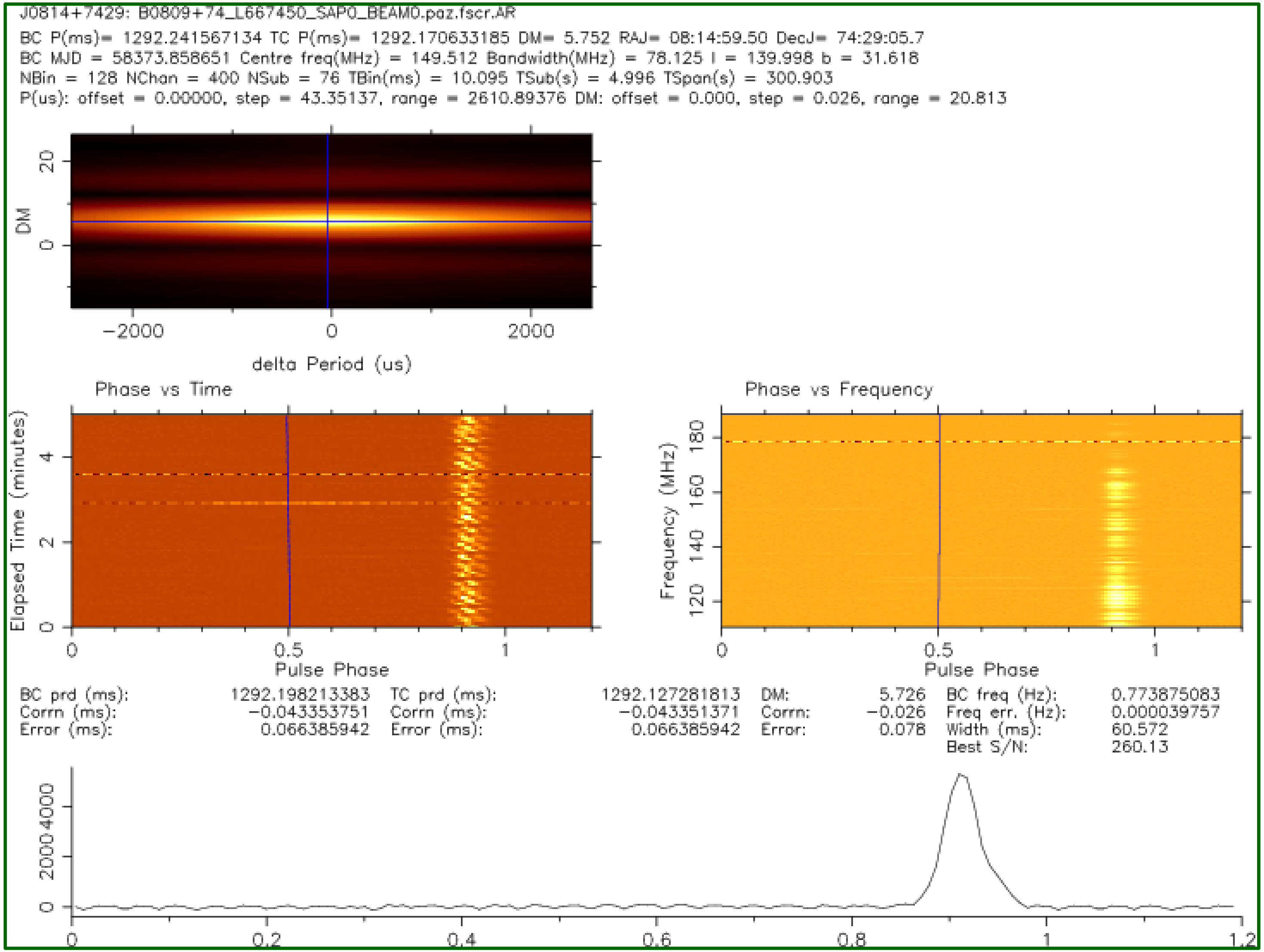


status.png

*_diag.png

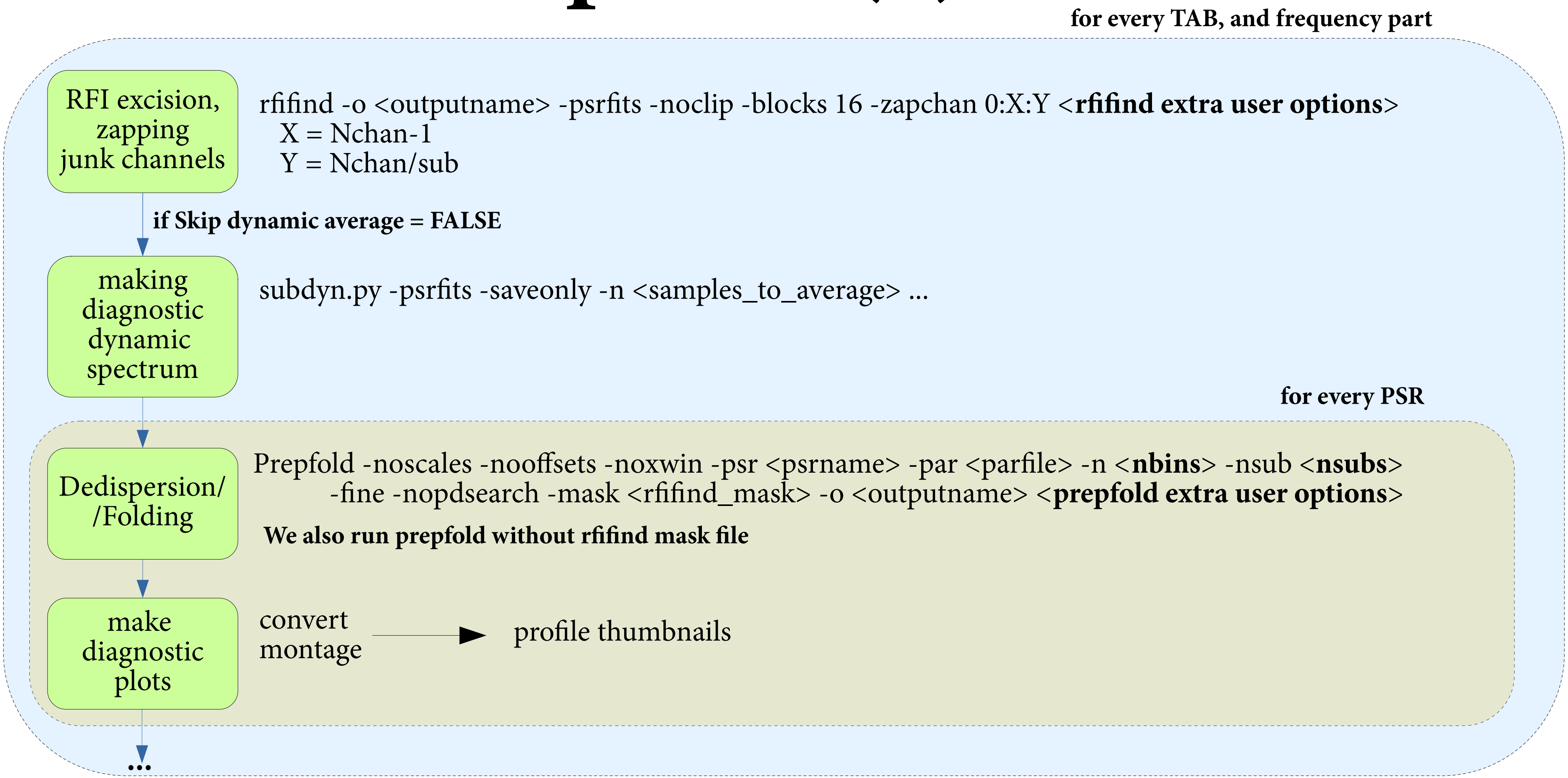
*_diag_pdmp.png

Diagnostic plots (3)



*_pdmp.ps

PRESTO Pipeline (1)



<**nbins**> - calculated automatically based on the sampling time and F0/P0 from the parfile.
Maximum possible <nbins>=1024

<**nsubs**> - if Nchan > 512, nsubs = 512. Otherwise, nsubs = Nchan

PRESTO Pipeline (2, cont.)

for every TAB, and frequency part

...

if Single Pulse Analysis = TRUE

for every PSR

dedispersed time series

prepdata -noscales -nooffsets -noclip -nobary -dm <DM> -mask <rfifind_mask>
-o <outputname> <**prepdata extra user options**>

We also run prepdata without rfifind mask file

single-pulse search

single_pulse_search_lotaas.py --no-width-label

<**nsubs**> – greatest common denominator of Nchan between 1 and 1024
<**lodm**> – DM - 0.5*dmstep*numdms. If lodm<=0, then lodm=0.01

if RRATs analysis = TRUE

dedispersed time series for a range of DMs

prepdata -noscales -nooffsets -noclip -nobary -dm 0.0 -mask <rfifind_mask> -o <outputname>
<**prepdata extra user options**>

We also run prepdata for DM=0.0 without rfifind mask file

prepsubband -noscales -nooffsets -noclip -nobary -nsub <**nsubs**> -lodm <**lodm**> -dmstep 0.01
-numdms 1000 -mask <rfifind_mask> -o <outputname> <**prepsubband extra user options**>

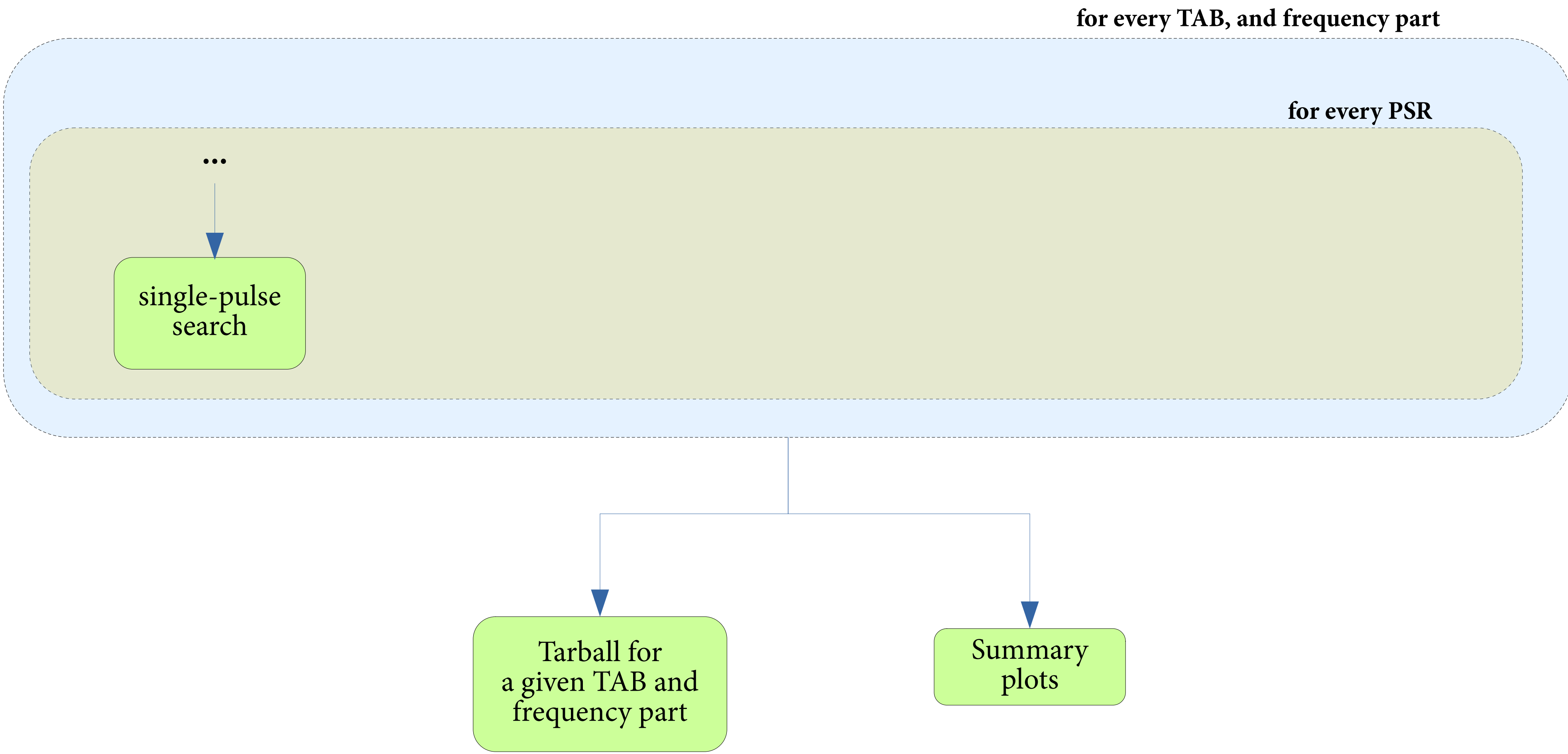
We also run prepsubband without rfifind mask file

single-pulse search

single_pulse_search_lotaas.py -p -g *.dat
single_pulse_search_lotaas.py -t 5.5 —no-width-label -g *.singlepulse

Also running similar command but excluding DM=0

PRESTO Pipeline (3)



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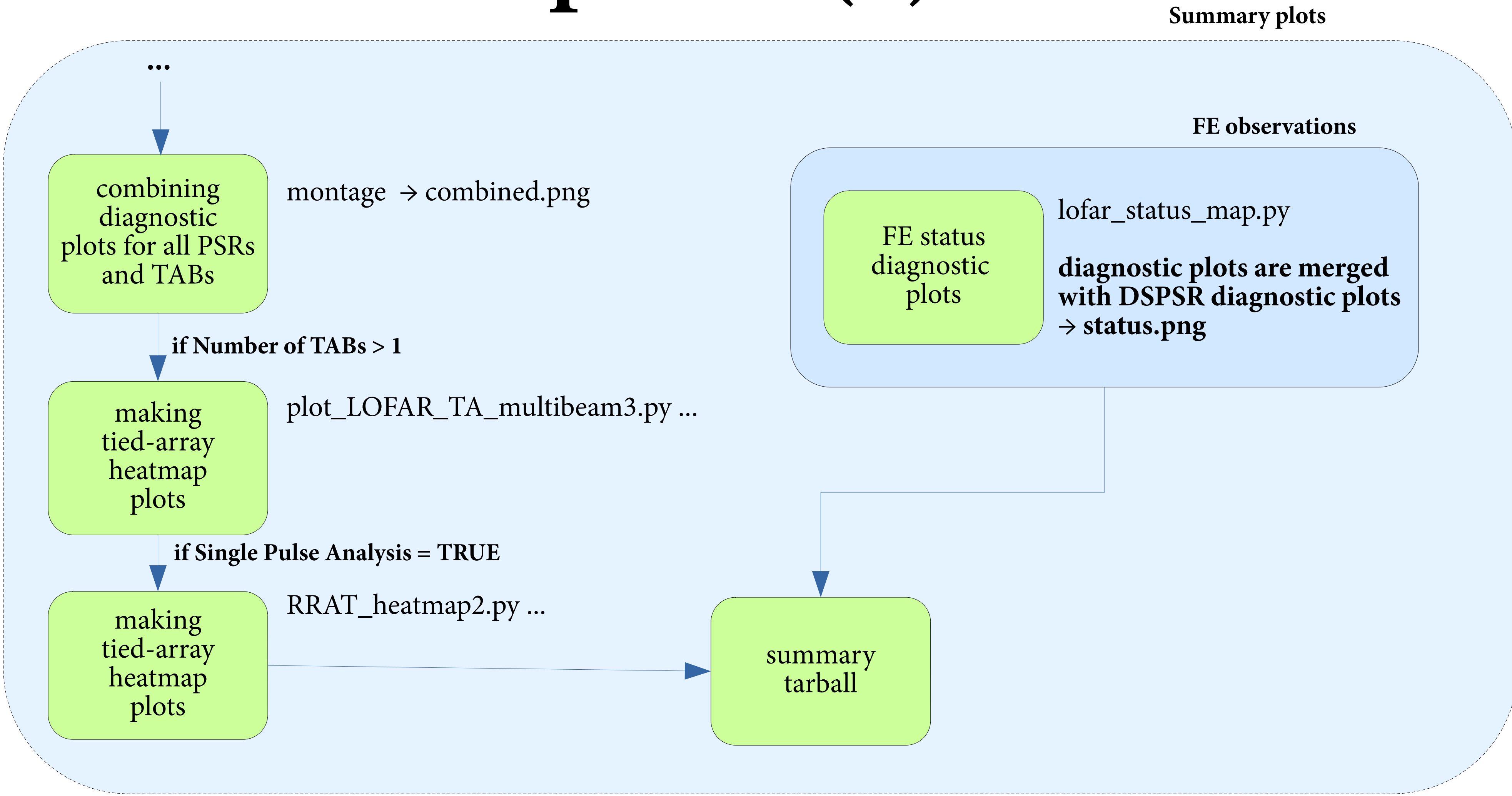
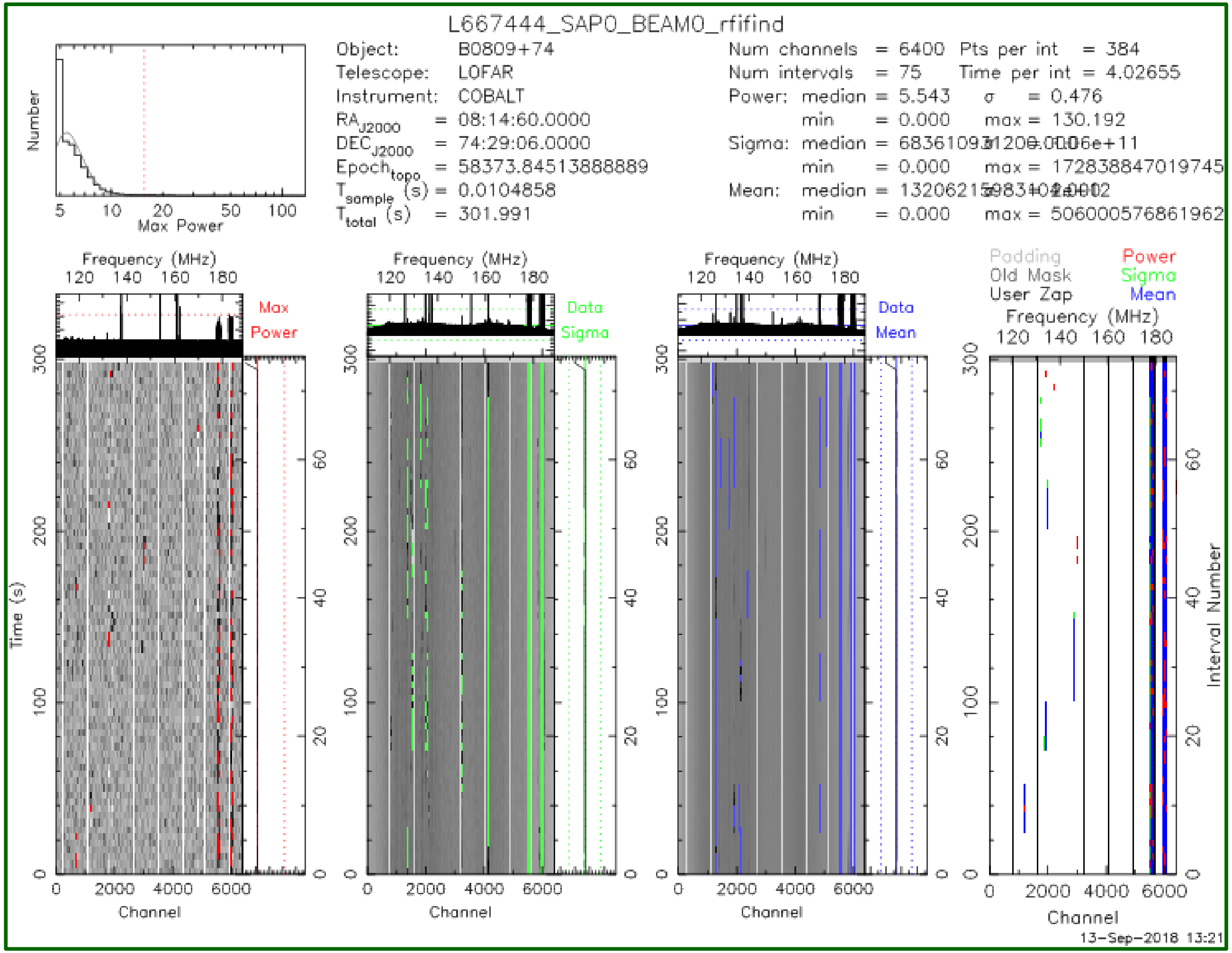
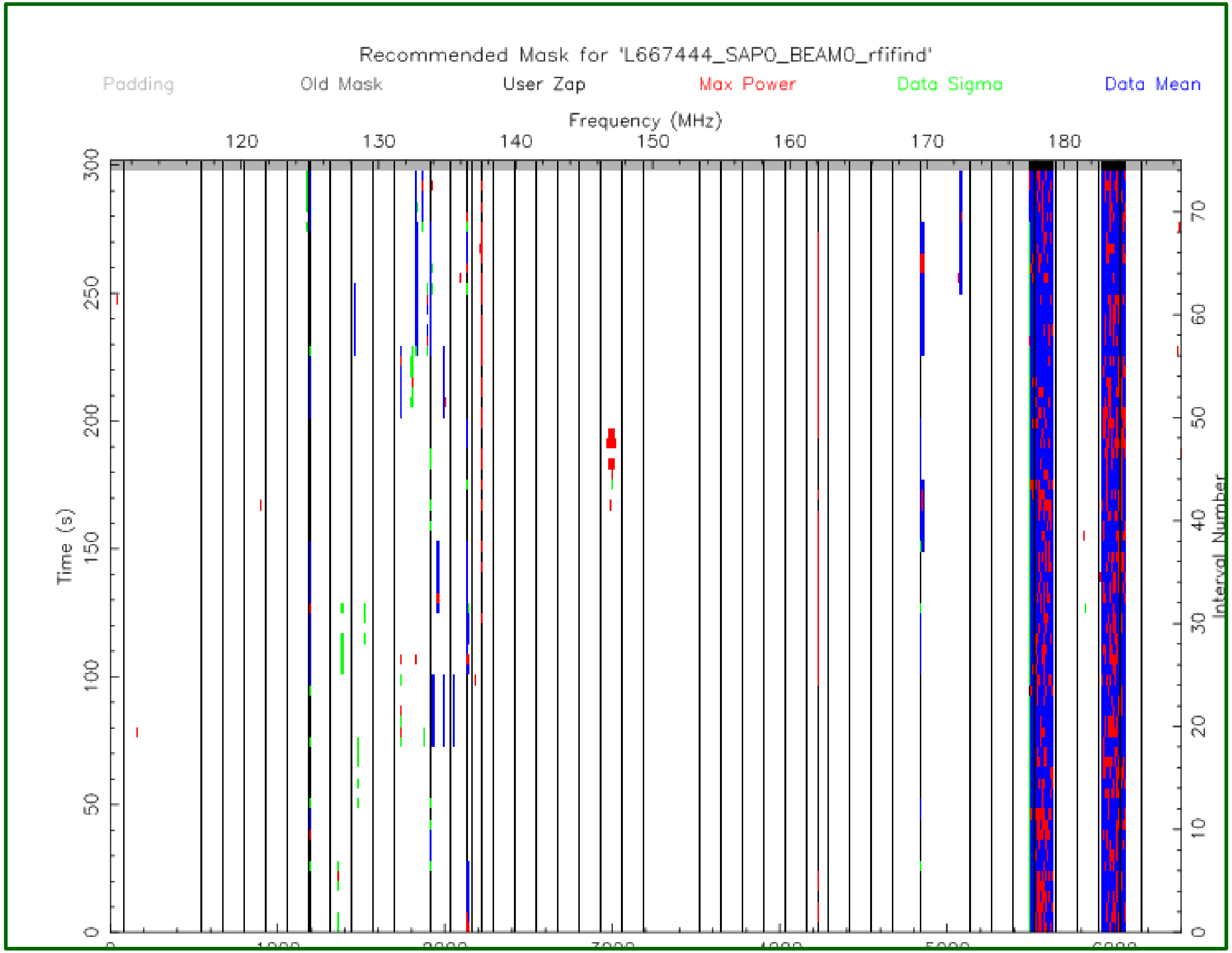


Diagnostic plots (1)



*_rfifind.ps

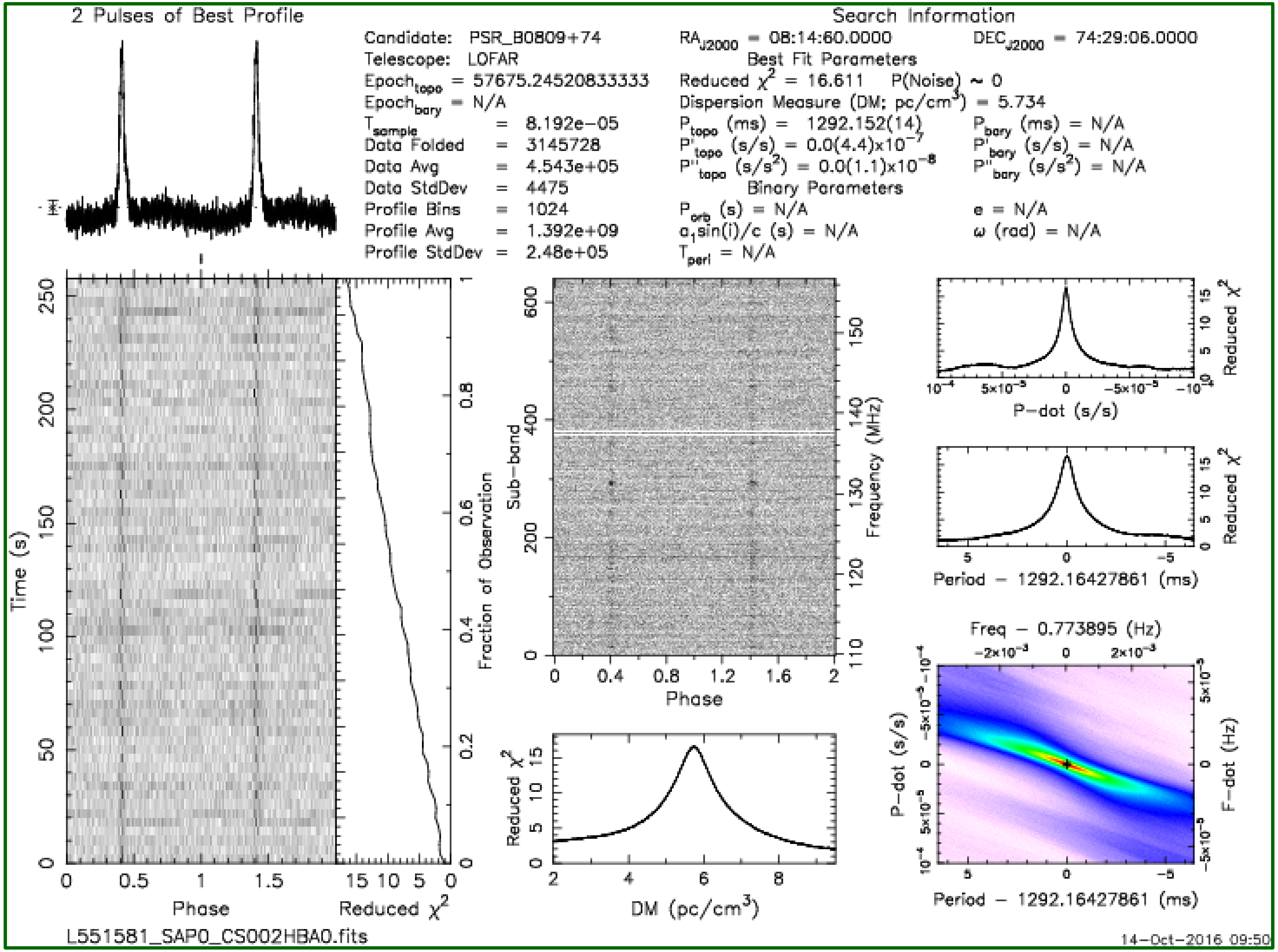
Diagnostic plots (1, cont.)



*_rfifind.ps

Diagnostic plots (2)

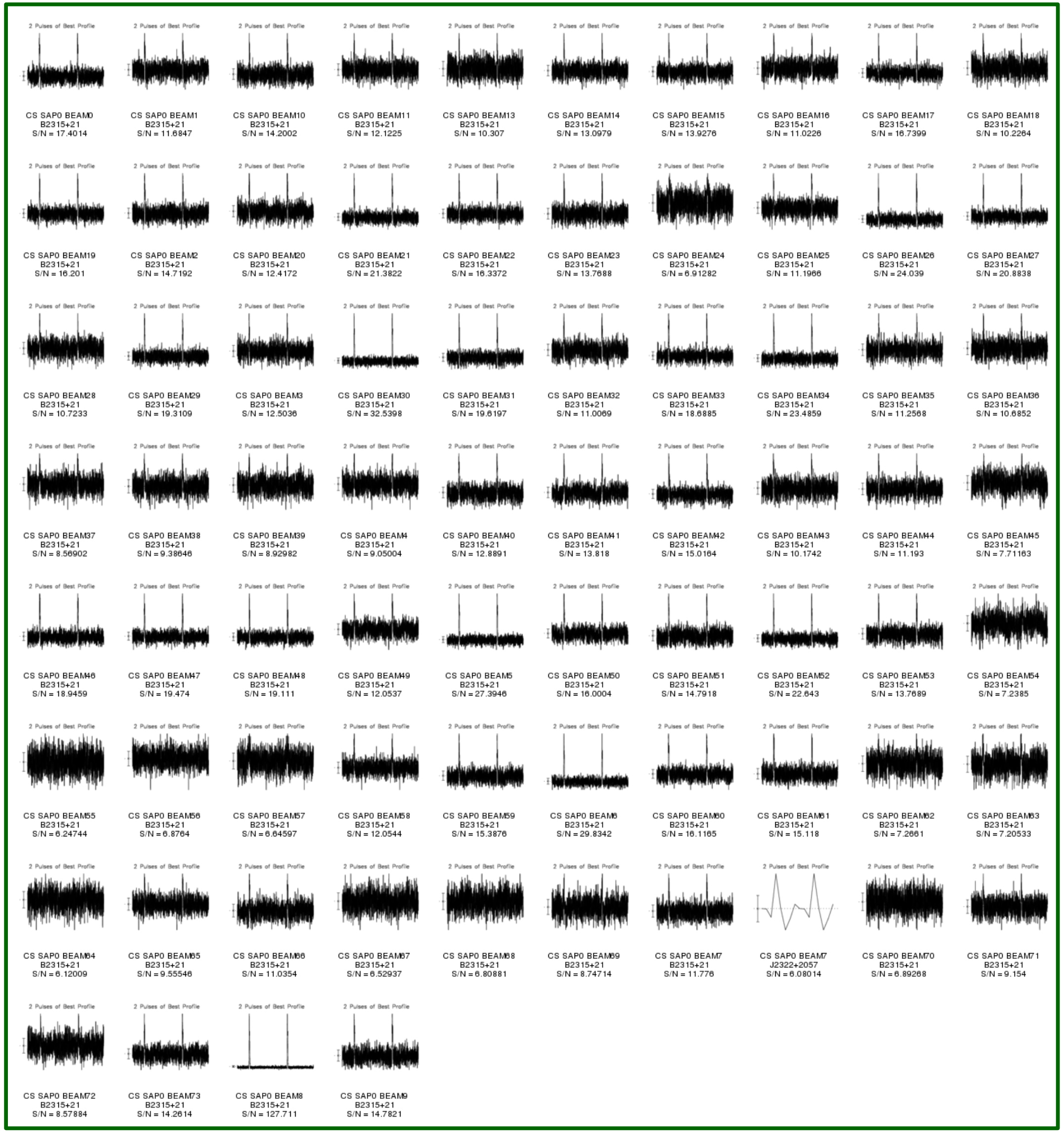
prepfold



*_pfd.png

Diagnostic plots (3)

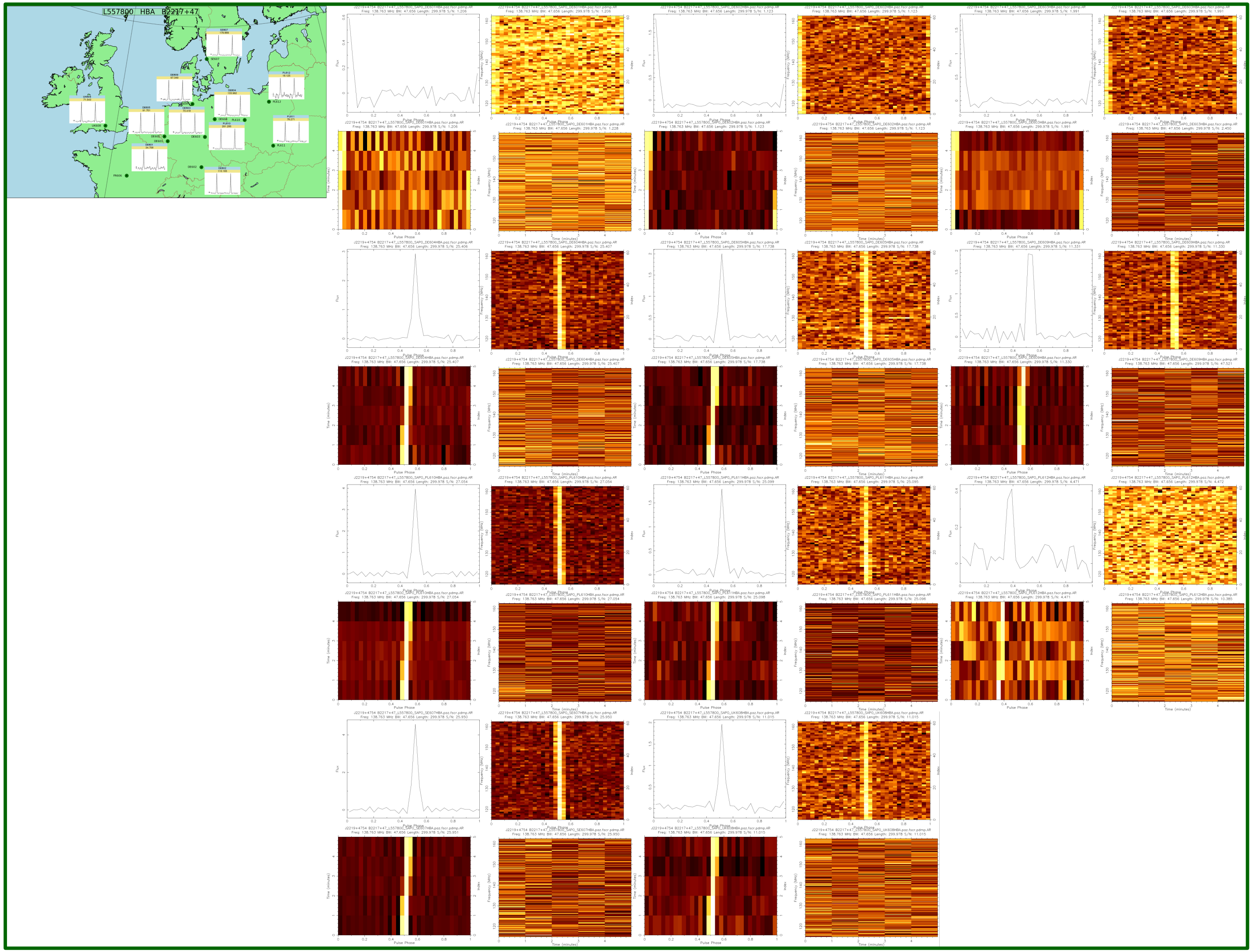
multiple TABs
prepfold



combined.png

for FE observations

Diagnostic plots (4)

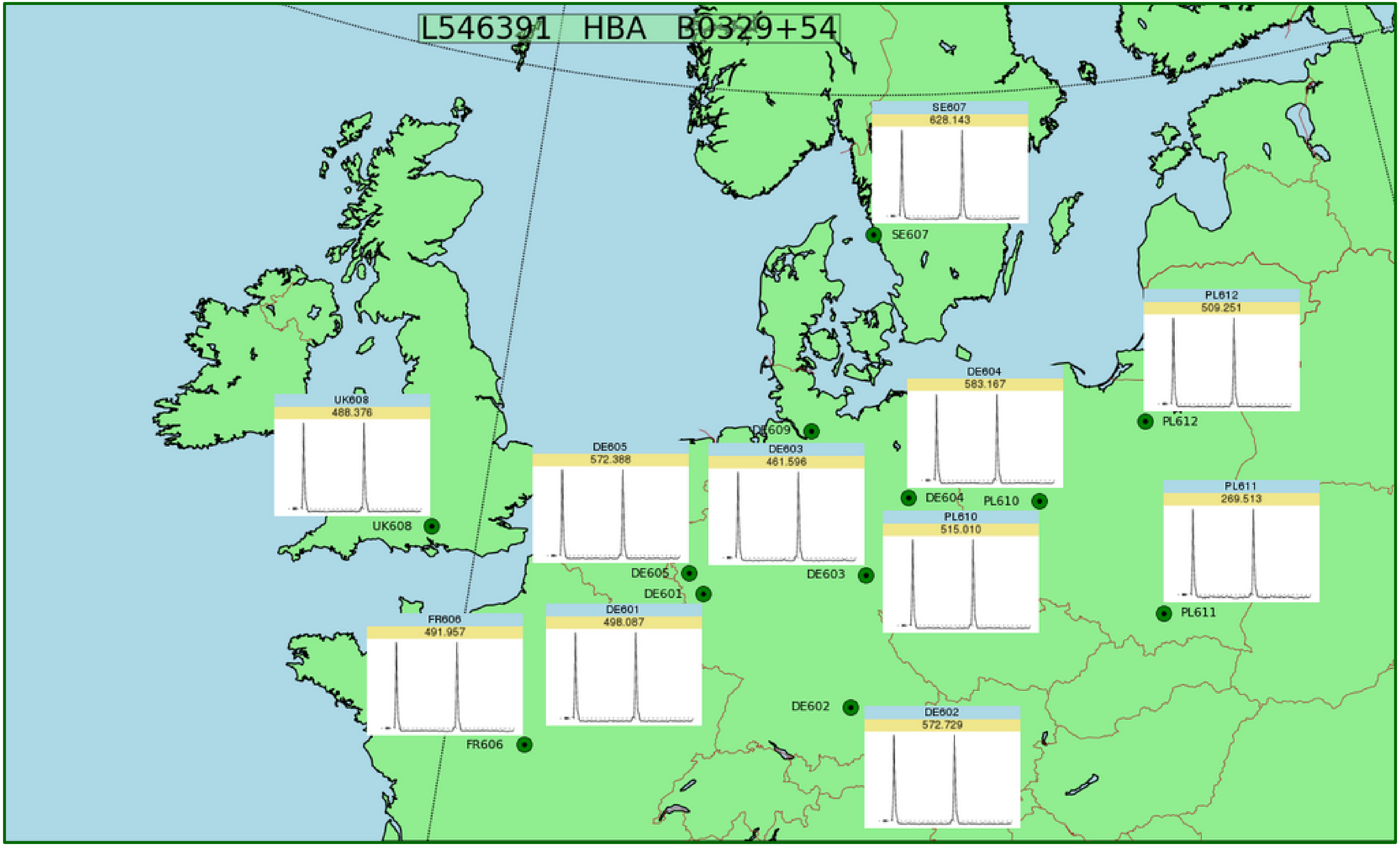


status.png

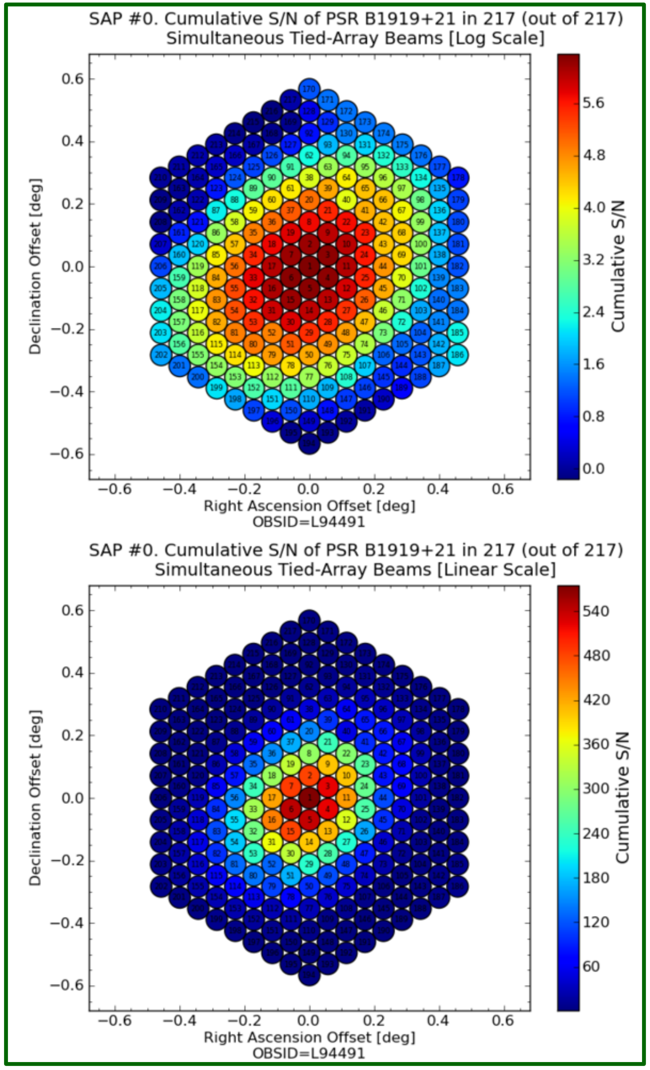
for FE observations

Diagnostic plots (4, cont.)

status.png



Diagnostic plots (5)



TAheatmap_*.png

PulP output data

- Raw data in 8-bit format (optional)
- Raw .h5 metadata files
- Pulsar data cubes (both from PRESTO and DSPSR pipelines)
- PRESTO pipeline:
  → rfifind mask
  → PSRFITS filterbank data
- DSPSR pipeline:
  → filterbank file(s) when SP analysis was done (optional)
- Single-pulse data (optional)
  → .singlepulse
  → Single-pulse plots
- Diagnostic plots
  → Plot with multiple profiles (multiple TABs, etc.) – *combined.png*
  → DSPSR diagnostic plots – *status.png*
  → Localization maps – *TAheatmap_*.png*

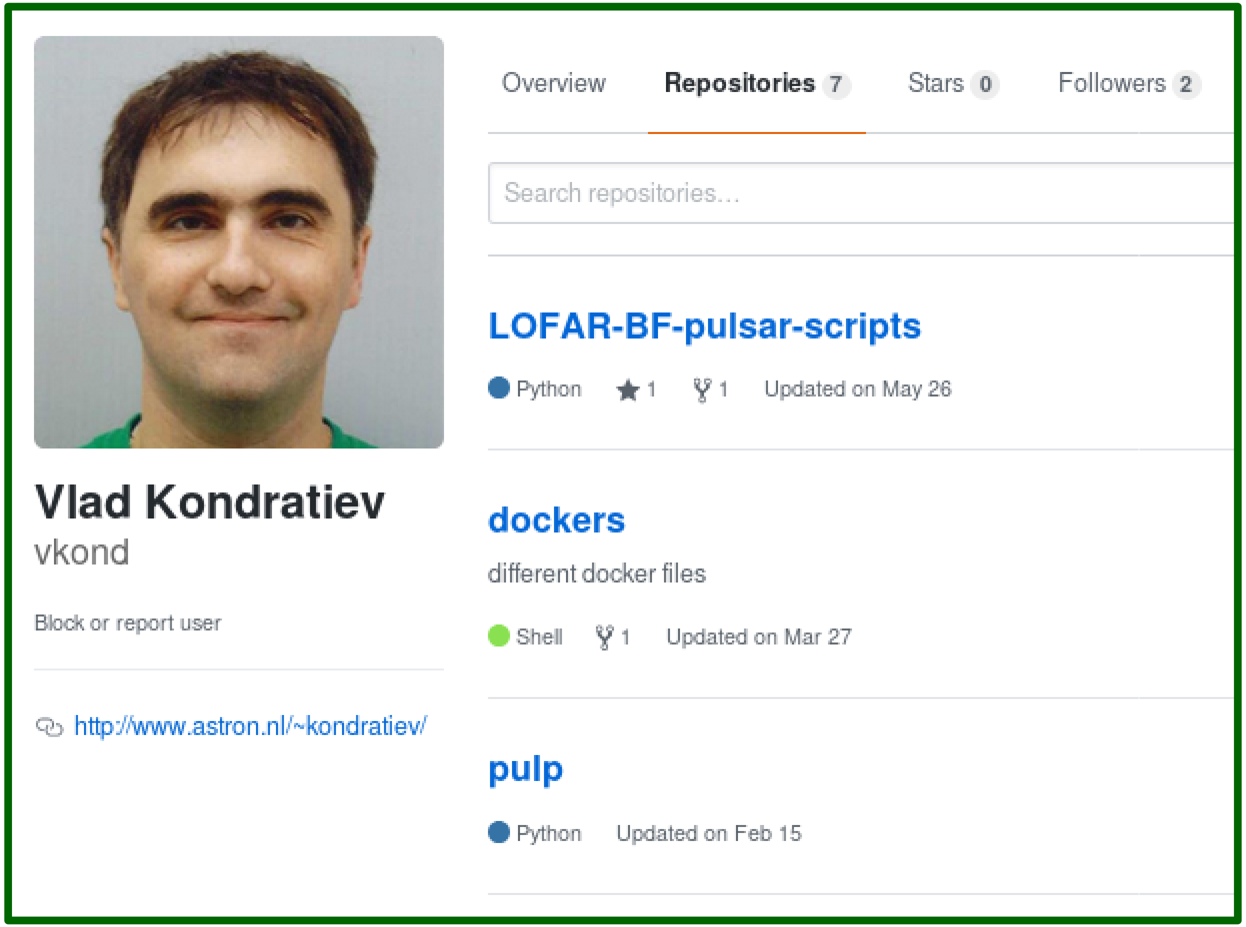
Pulsar software (needed by PulP)

- FFTW
- PGPLOT, + python bindings
- TEMPO
- TEMPO2
- psrcat
- Sigproc
- **PRESTO** (by Scott Ransom, https://www.cv.nrao.edu/~sransom/presto/)
- psrdada
- **PSRCHIVE** (by Willem van Straten, http://psrchive.sourceforge.net/)
- DAL
- **DSPSR** (by Willem van Straten, https://dspsr.sourceforge.net)
- COAST_GUARD (by Patrick Lazarus, for RFI excision)
- LOFAR-BF-pulsar-scripts

- in the future (needed for pulsar flux calibration):
  - → casacore
  - → python-casacore
  - → mscorpol

@github

https://github.com/vkond



Various scripts

https://github.com/vkond/LOFAR-BF-pulsar-scripts

Dockerfile for LOFAR

https://github.com/vkond/dockers

PulP:
https://github.com/vkond/pulp

Hands-on prerequisites

1. Docker / singularity container — psr-lds2021.[sif | tar] (~1.7 GB)
   → Follow the link to download from the instructions that were sent earlier

2. Download the raw input and PulP-processed data for **t4-pulp** following the link in the same instructions
   → **NOTE** — the total disk volume is very **LARGE** ~ 800GB!
   → However, if you have limited disk space, it is not a show-stopper, not all data are needed at once and for XXYY data (the largest) you can get by by downloading smaller tarballs with pre-processed data (dspsr step).

3. Minimum requirements:
   → very small disk space: CS_XXYY_light_noraw.tgz (~203 MB)
   → modest disk space: CS_XXYY_raw_light.tgz (17.5 GB)
   → large disk space: CS_XXYY_raw_p[0-3].tgz (~350 GB)
   → PulP-processed data: CS_XXYY_pulp_noraw_8bit.tgz (~800 MB) [Optional]

4. Extra data to explore different observing setups [raw tgz / pulp-processed tgz]: [Optional]
   → Coherent sum of the stations, Stokes I: CS_I_raw.tgz / CS_I_pulp.tgz
   → Both coherent & incoherent sum of the stations, Stokes I:
     CS_IS_I_raw.tgz / CS_IS_I_pulp.tgz
   → Coherent sum of the stations, Stokes IQUV: CS_IQUV_raw.tgz / CS_IQUV_pulp.tgz
   → Coherent sum of the stations, 6 rings of TABs: CS_6rings_raw.tgz / CS_6rings_pulp.tgz
   → Fly's Eye observation, Stokes I: FE_I_raw.tgz / FE_I_pulp.tgz

Test the container / software

1. If you are working on CEP3, follow the separate instructions on how to log in to a CEP3 working node and how to start your Singularity or Docker container there.

2. In general:
   → Docker:
   - *docker run --net=host -w ${HOME} -e ${USER} -e ${HOME}--rm -it psr:lds2021*
     [-u <uid>:<gid>] - you can even run it as root with -u 0:0 (be careful though!)
     -v <datadir>:<datadir> - make sure you have directory with the data that you“ve downloaded for the hands-on session
   - If you have problems with opening up GUI applications from dockers, try:
     - xhost +local:root (outside docker before starting it)
     - Add following options to your docker run command:
       - *-e DISPLAY -e QT_X11_NO_MITSM=1 -v /tmp/.X11-unix:/tmp/.X11-unix:rw*

   [simple, but not safe; There are other solutions as well]

   → Singularity:
   - *singularity shell --bind <your/path/to/school/folder>, psr-lds2021.sif*

3. Test the software:
   → Run, e.g.:
   - *dspsr -h*
   - *pdmp -h*

   → You should get the list of command-line options. If you get some errors instead, something is wrong. Let us know to help you out.

Hands-on session

1

- Following the PulP steps:
  → you will manually run PulP commands to understand them better for one of the beamformed (BF) observation with the setup usually used for pulsar timing observations (CS_XXYY).
  → compare the results with those from automated PulP
  → optional: play with other PRESTO/dspsr options
  → optional: add extra processing into the mix, e.g.:
    - converting to 8-bit
    - single-pulse analysis
    - RRATs analysis

2

- Pulsar flux calibration

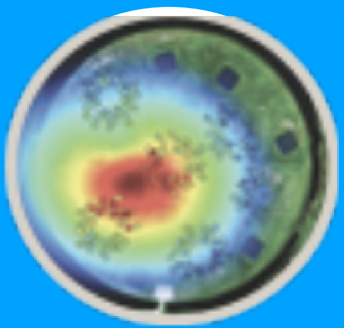
3

- Explore processing steps for other input data for the different observing setups

4

- Easier way to retrieve your «PulP'ed» BF data from the LTA

Questions?



6th LOFAR Data School

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