RFI-mitigation using a PAF

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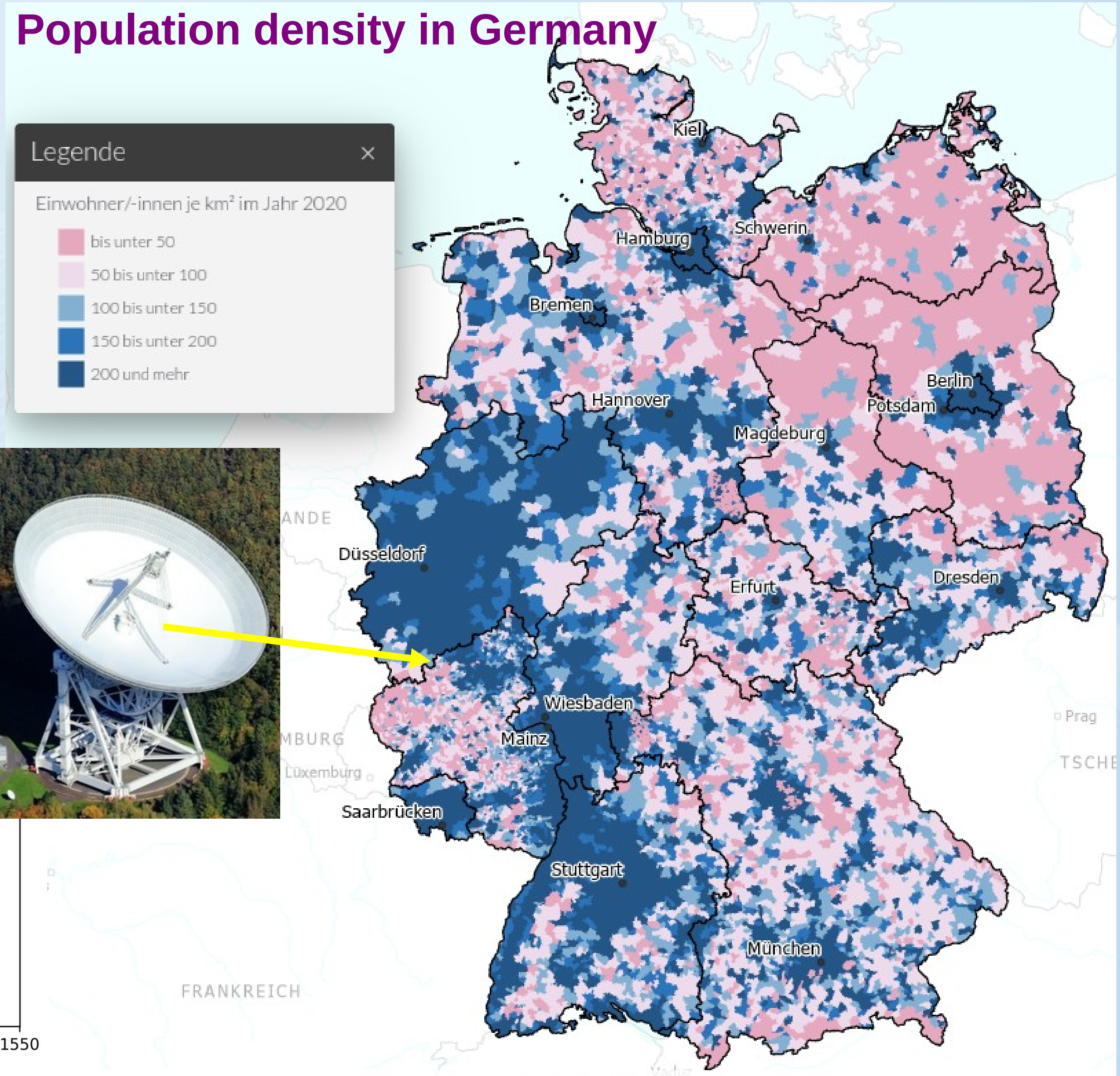
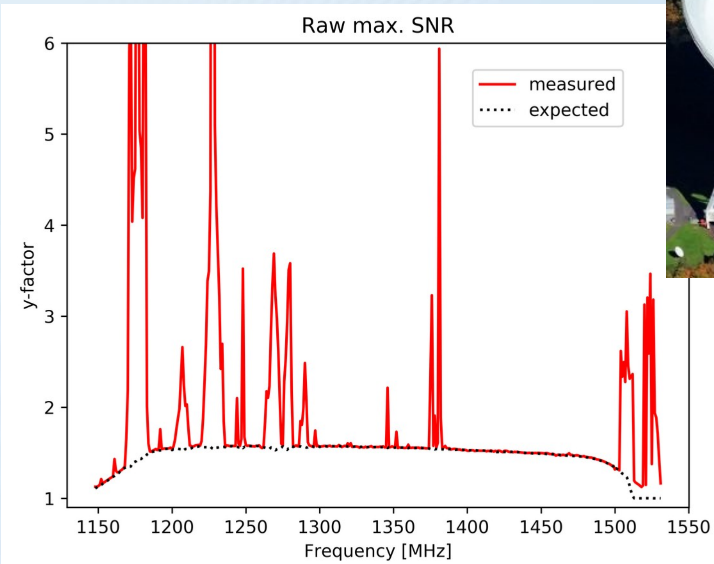
Outline

- Introduction
- Theoretical considerations
- Various “algorithms” and their effects
- Next steps
- Outlook

Introduction

- The 100 m telescope is located close to one of the densest populated areas in central Europe
- Suffering from massive human made RFI
- Can a PAF help here?

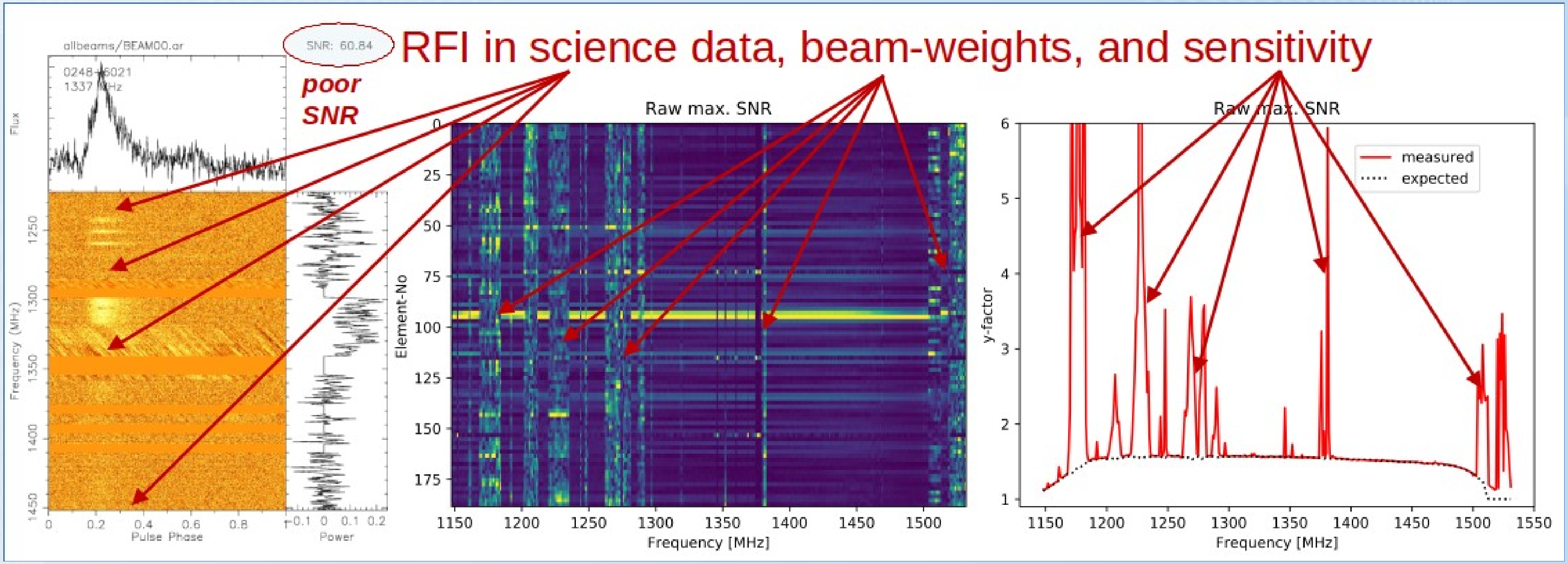




The situation in L-band

- we operate a CSIRO PAF at Effelsberg
  - we use it for testing, e.g. of the RFI environment
  - and of our algorithms
- we so far still hesitate with RFI during beam-forming
  - can be transferred to online RFI mitigation easily
    - ✓ e.g. by orthogonal projection

Top: CSIRO chequerboard PAF for the Effelsberg 100m telescope during it's fist installation (March 2017)



Theoretical considerations

- The signal to noise ratio of the formed beam can be written as

$$SNR = \frac{P_S}{P_N} = \frac{P_{on} - P_{off}}{P_{off}} = \frac{P_S}{P_N} - 1 = \frac{\vec{w}^H R_{on} \vec{w}}{\vec{w}^H R_{off} \vec{w}} - 1$$

- The sensitivity therefore results in

$$\frac{A_{eff}}{T_{sys}} = \frac{2 k_B}{10^{-26} S} \left(\frac{\vec{w}^H R_{on} \vec{w}}{\vec{w}^H R_{off} \vec{w}} - 1 \right)$$

- Maximization of SNR+1 corresponds to solving the generalized eigenvalue problem

$$R_{on} \vec{w}_{mSNR} = \lambda_{max} R_{off} \vec{w}_{mSNR} \Leftrightarrow R_{off}^{-1} R_{on} \vec{w}_{mSNR} = \lambda_{max} \vec{w}_{mSNR}$$

- If we assume that the noise is
  - statistically independent from the signal
  - following a Gaussian (normal) distribution and is white

  this is equal to solving $R_{on} \vec{u} = \kappa \vec{u}$

  → *all solution vectors give the eigenvector decomposition of the ACM* R_{on}

➔ the solution space includes beam-weights which correspond to RFI sources
➔ all solution vectors are mathematically orthogonal to each other
→ RFI can / will cause a loss of efficiency → calibration must be maintained !

RFI mitigation algorithms (1)

- Using the eigenvector decomposition of $\boldsymbol{R}_{on}$ and $\boldsymbol{R}_{off}$
  - eigenvector decomposition of the array correlation matrix (ACM) give
    - ✓ steering vector towards source (ACM of an ON measurement only)
    - ✓ steering vector(s) towards RFI sources (ON and OFF measurement)
    - ✓ noise contributions
      - ✘ "steering vectors" towards noise sources
        (areas of different noise levels like termination on ground, or on sky)
  - the eigenvector decomposition allows for filtering if
    - ✓ eigenvalues of the RFI are higher than those belonging to noise or signal
    - ✓ problem is to distinguish between RFI, noise, and signal
      → hard filtering will/can remove good data
  - eigenvectors identified as RFI can not simply just be removed
    - ✓ this would lead to a lower rank of the matrix
      → not all mathematical operations would be allowed
    - ✓ therefore we just attenuate them (poor mans version)
      (cleaner would be to calculate a sub-space orthogonal to RFI via projection)

➔this is a filtering along the signal strength of the eigenvectors
➔can potentially remove the signal ...

RFI mitigation algorithms (1)

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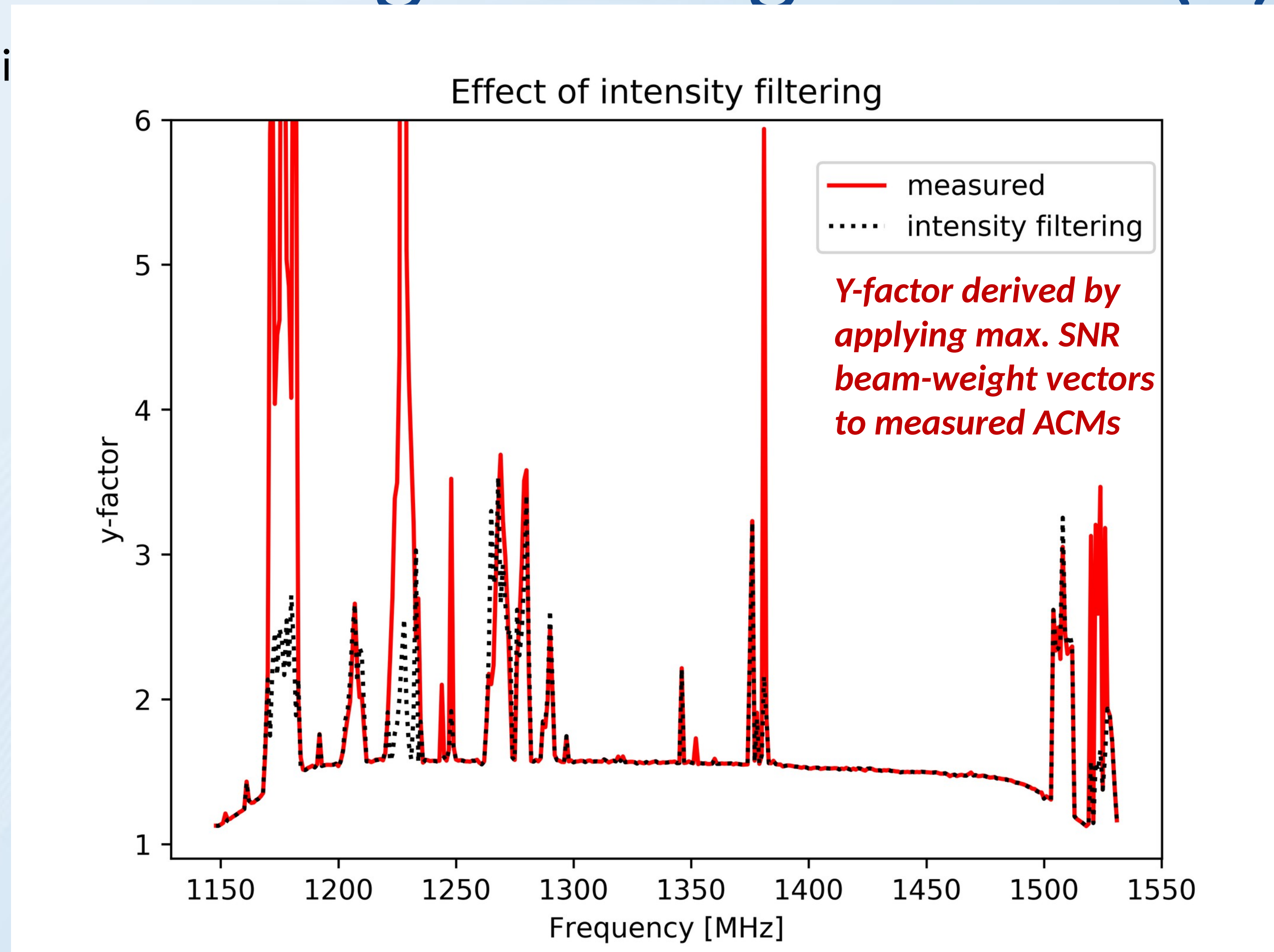

➔this is a filtering along the signal strength of the eigenvectors
➔can potentially remove the signal ...

RFI mitigation algorithms (2)

- Selecting the "right" eigenvector from $\boldsymbol{R}_{on}\boldsymbol{R}_{off}^{-1}$
  - the highest eigenvalue not necessarily belongs to the astronomical signal source
    - ✓ can well be an RFI source!
  - how to identify the signal weight vector?
    - ✓ signal weight vectors must be nearly "parallel" to neighboring signal weight vector
    - ✓ frequency average of strongest eigenvector is a good starting point for a source steering vector
    - ✓ weight vectors towards RFI have a different "direction" then the once towards source
      - ✘ can be identified using e.g. the dot-product with the neighboring source beam-weight vector

    → this will lead to problems if RFI and undisturbed source vector are not orthogonal
  - weight vectors can be interpolated over "empty" frequency areas
    - ✓ we are using an independent linear interpolation over real and imaginary part
- is used in science operation (for FRB search) since August 2020

➔this is a spacial filtering of the signals
➔works reliable on noisy ACMs (short integration time)
➔interpolation can cause problems

RFI mitigation algorithms (2)

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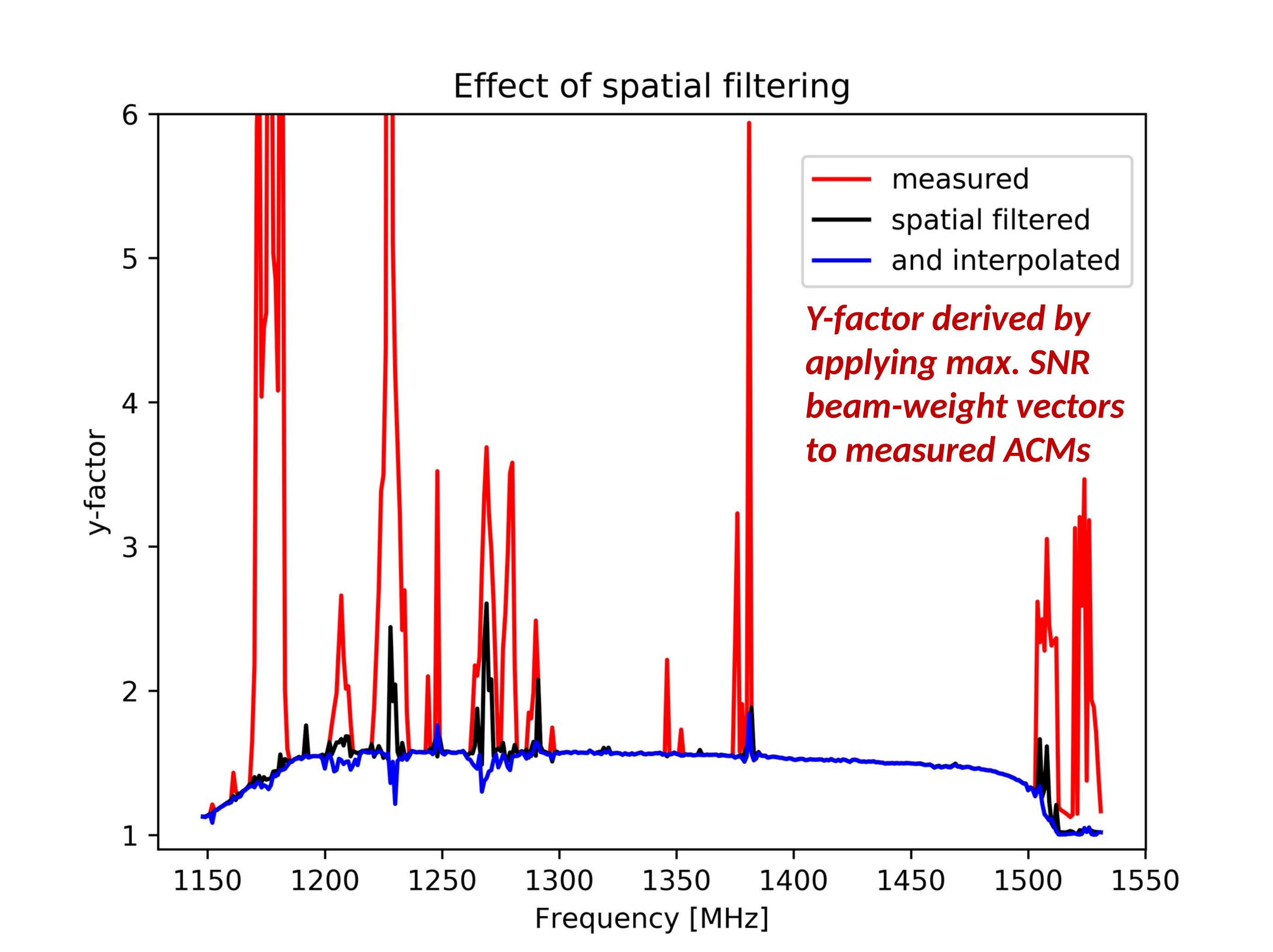
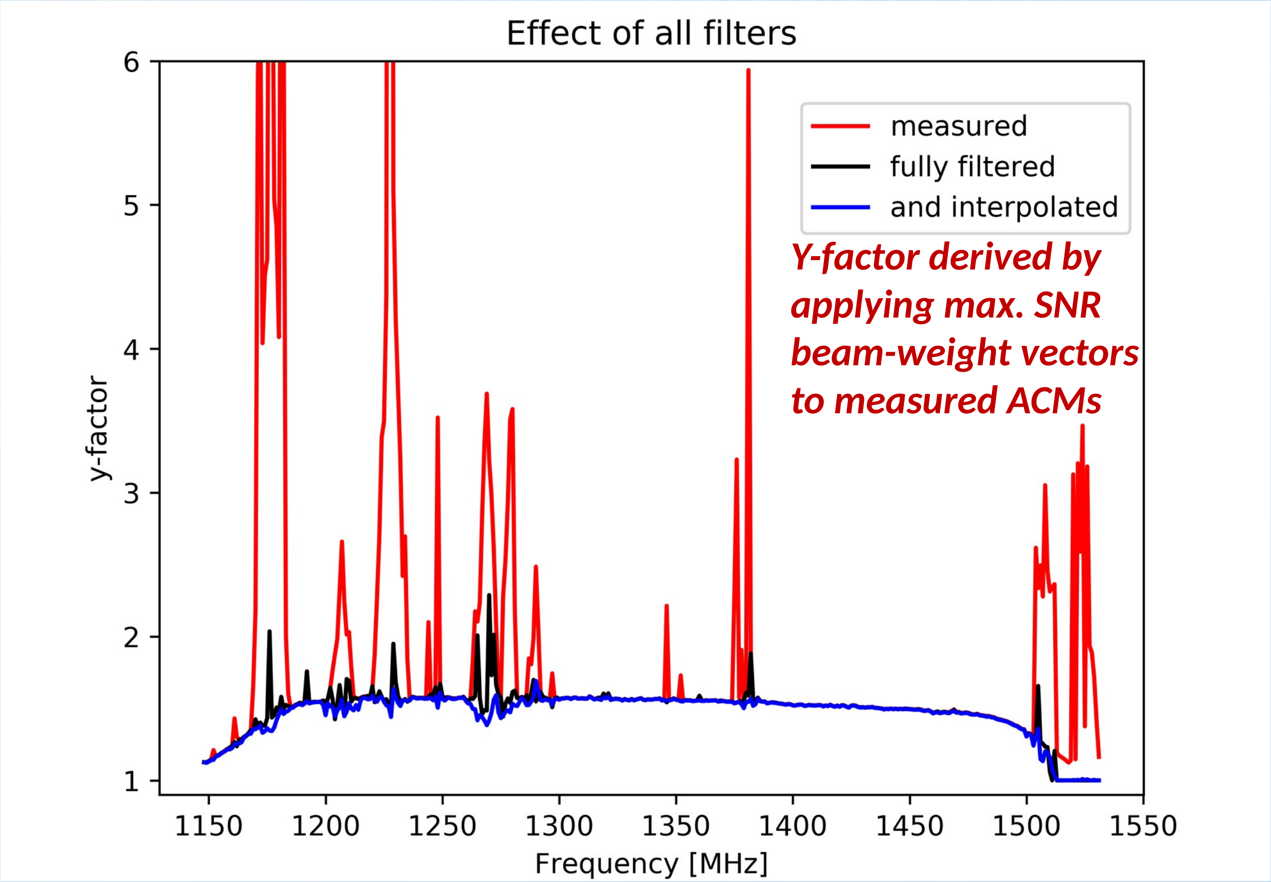


→this is a spacial filtering of the signals
→works reliable on noisy ACMs (short integration time)
→interpolation can cause problems

RFI mitigation algorithms (3)

- Combining the intensity and spacial filtering is possible
  - (1) intensity filtering of $\boldsymbol{R}_{on}$ and $\boldsymbol{R}_{off}$
  - (2) using eigenvector selection on resulting $\boldsymbol{R}_{on}\boldsymbol{R}_{off}^{-1}$
  - (3) interpolate over still empty frequency ranges
- Is used in science operation (for FRB search) since June 2021



RFI mitigation algorithms (3)

- Combining the intensity and spacial filtering is possible
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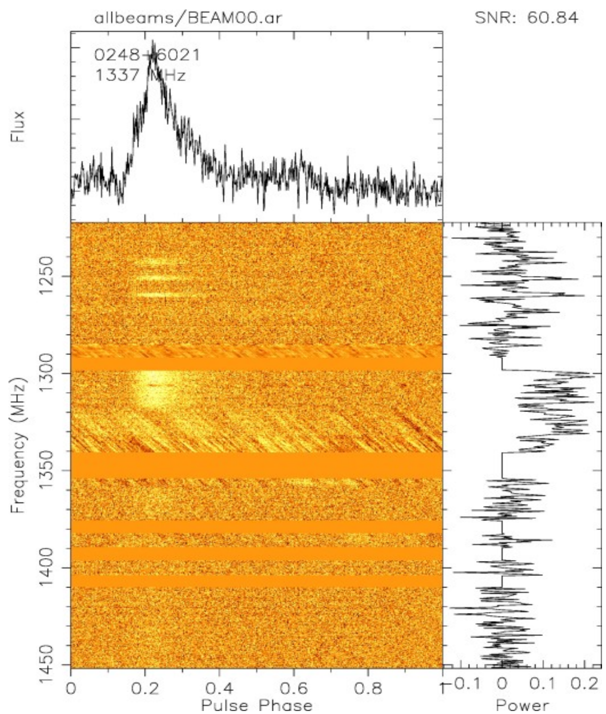
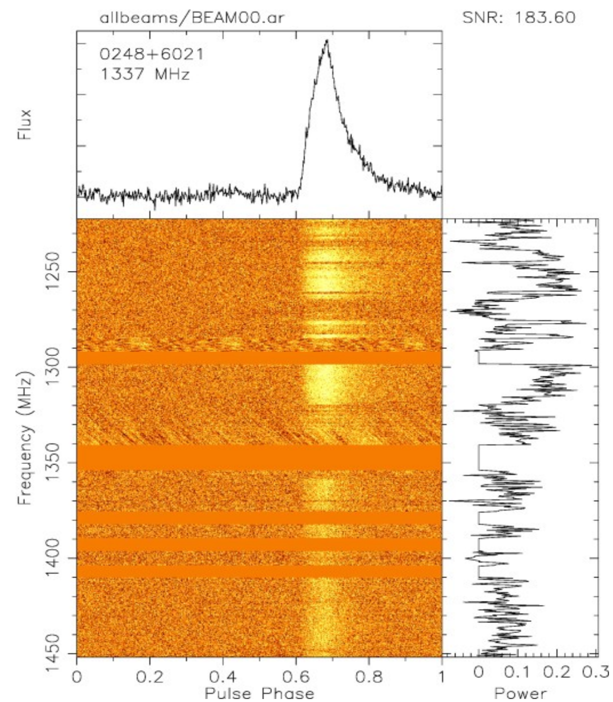
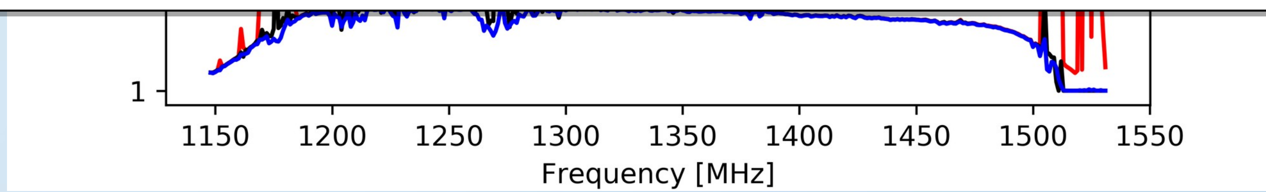
Test on pulsar J0248-6021:
massive increase in signal bandwidth



raw beam-weights



Intensity & spatial filter plus interpolation



RFI mitigation algorithms (4)

- Poor mans version for “static” RFI mitigation
  - RFI is usually not stable over time
    - ✓ WiFi signals or mobile phone signals have varying frequencies
    - ✓ telescope tracking changes directions all time
  - but observatory made RFI is often stable (CPU clock, LO-signal)

→ summing up many ACMs will result in better beam-weights

➔this is a poor mans “filtering” over time of the signals
➔takes a lot of time
➔comes for free if relative amplitudes and phases between elements are maintained

RFI mitigation algorithms (4)

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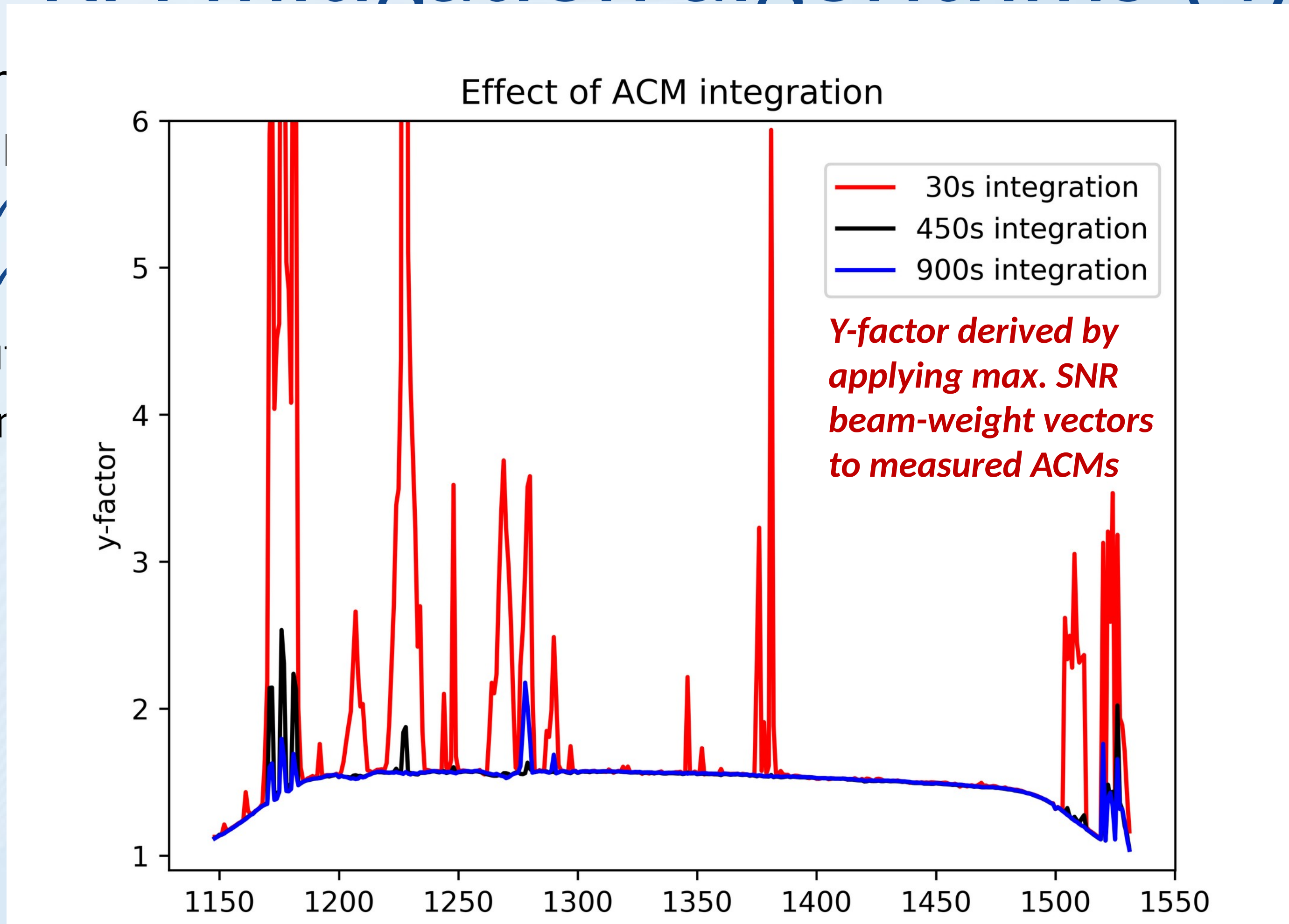

➔this is a poor mans “filtering” over time of the signals
➔takes a lot of time
➔comes for free if relative amplitudes and phases between elements are maintained

RFI mitigation algorithms (5)

- Combine all the methods
  - take several (here 30) individual ACMs
  - apply intensity filter to each individual on and off ACM
  - sum up all on and all off source ACMs
  - determine solution space of $\boldsymbol{R}_{on}\boldsymbol{R}_{off}^{-1}$
    - ✓ select correct eigenvector (apply spacial filter)
  - interpolate over still empty areas

→ scan over time deliver fully undisturbed reference beam-weights (steering vector)

RFI mitigation algorithms (5)

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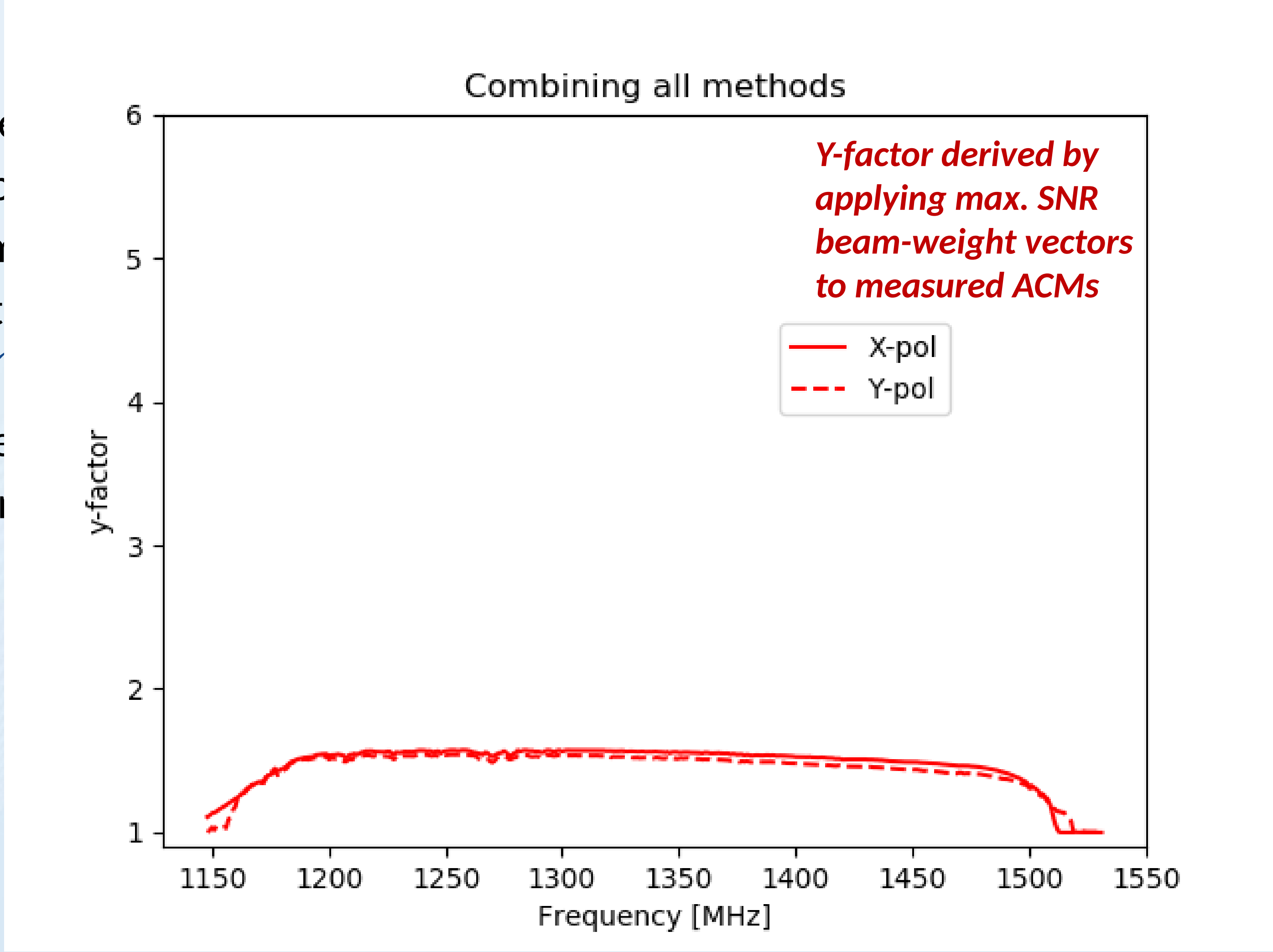


Next steps

- “Static” RFI mitigation for beam-weight determination works
- within the cryoPAF we will have the capability to control

  the relative amplitudes and phases

  of all elements using our calibration unit

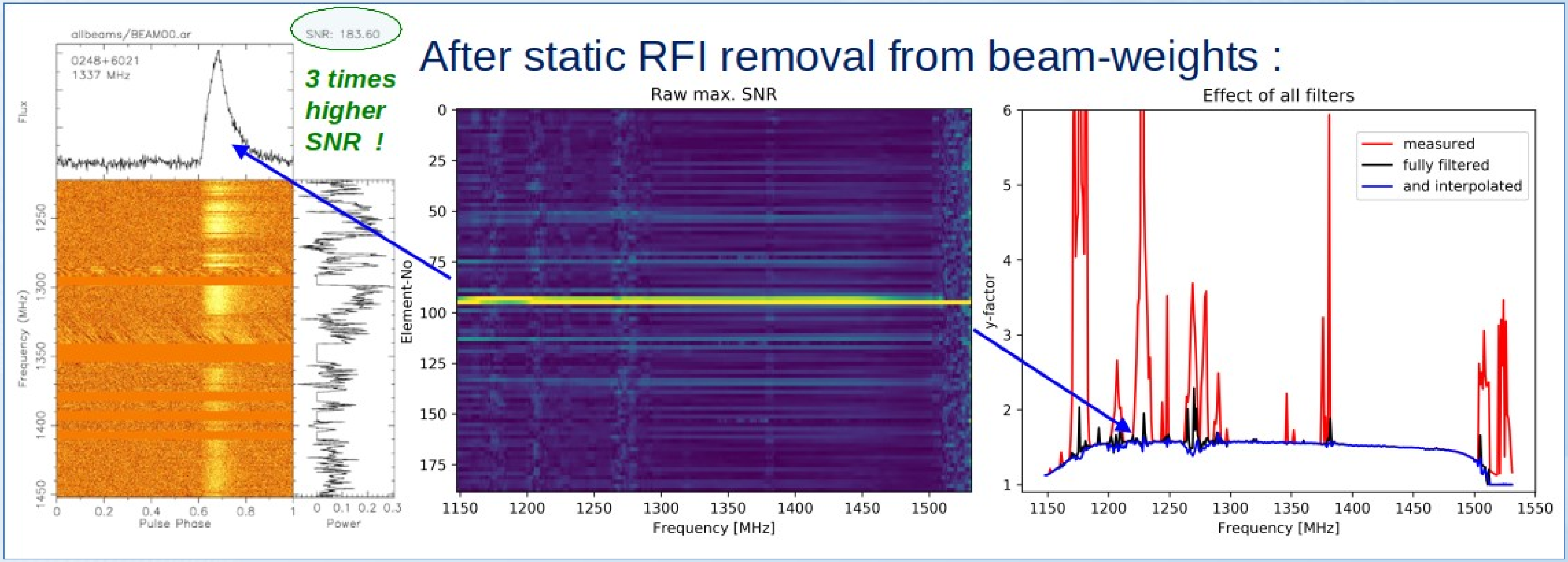
  → a beam-weight database is in planing
  - allowing for increasing accuracy of the beam-weights over time
- development of an online RFI mitigation is ongoing
  - projection of existing beam-weights to clean solution sub-space is required
  - main problem is to keep science data calibration fix
    - ✓ we will have a changing overall beam-efficiency
      - ✘ this can be calculated and therewith being removed
    - ✓ we will have a changing beam-pattern on sky
      - ✘ effect on main beam is small as long as efficiency change is small
      - ✘ but side-lobes will change

        → can have effects on (e.g. spectroscopic) mapping projects

➔we will need time to make our experiences with this new technology

Conclusion

- "Static" RFI mitigation during beam-weight determination works reliably



- for the first generation cryo-PAF for the Effelsberg 100 m
  - we are foreseeing all necessary hardware to perform online RFI mitigation
- development of online RFI mitigation is ongoing
  - the new hardware is required for testing
  - time to make experience and adjust system to science cases is required