20-FOLD RESOLUTION IMPROVEMENT

IN RADIOASTRONOMICAL SINGLE-DISH IMAGE SCANNING

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Abstract

Scanning image resolution using small radio telescopes suffers very strongly from the diffraction limit. Since interferometers are so efficient in terms of resolution, no efforts were made to develop solutions for single dishes.

An iterative multi-frame superresolution technique using an imaging model combined **with Bayesian optimization and stochastic regularization** turned out to be most advantageous. Apriori information about the imaging process as well as an adaptive procedure regarding the pixel intensity statistics allows to reconstruct the fine-structure content in the subpixel domain to an unexpected high extent. Generally, Bayesian optimization is very sucessful in artificial intelligence applications, multi-frame superresolution algorithms are already standard in some mobile phones.

Images from an 18-hours-scan of the northern part of the milky way with a 2.6-meter single dish equipped with 7 feeds for 21cm will be shown. Combined with the above mentioned algorithm, an image resolution improvement down to 0.25° is achieved, instead of the standard resolution comparable to the beam size (5.5°). A comparison with images from the EBHIS HI survey will be shown. A 40sec-YouTube-Video shows the development of the final high resolution image during processing

https://youtu.be/Qc1C4JNTGXk

Introduction

The resolution of radio images obtained by small single-dish radio telescopes suffers very strongly from the **diffraction limit** of the antenna dish. Since interferometers are so efficient in terms of resolution, no efforts were made to develop solutions for single dishes up to date. A work-in-progress image **post-processing** method is presented here which achieves up to 20 times gain in image resolution using multi-frame image aquisition from the same scene with sub-pixel shifts between the frames as an input.

Amateur astronomers often use "***stacking***" of a series of noisy and maybe slightly laterally shifted input images of the same object to improve image quality. This technique is mainly advantageous in terms of image noise reduction, not for substantial image resolution improvements.

The **multi-frame super-resolution** technique applied here considers **additional information**, which is not used in *stacking,* such as existing *a-priori* information and statistical knowledge about the lowRes images and the unknown hiRes image as well as the imaging process itself.

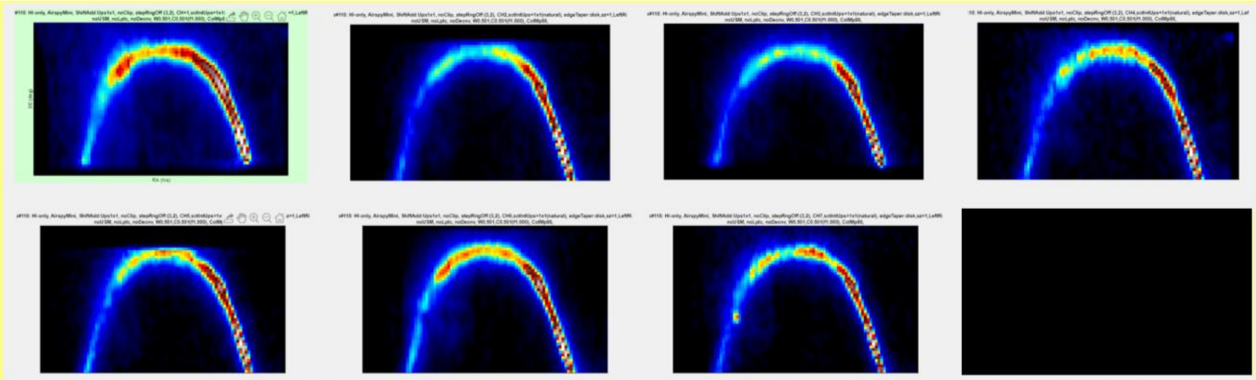
In detail, it's necessary to have an appropriate

- mathematical **observation model** comprising a-priori information about the size, lateral sub-pixel shift and shape of the point spread functions (PSF) of all feeds (even including PSF modifications due to coma aberration),
- an a-priori **probability density distribution** for the pixel intensities of the unknown hiRes image ***X*** and an
- algorithm with **Bayesian optimization** controlled by **stochastic regularization**

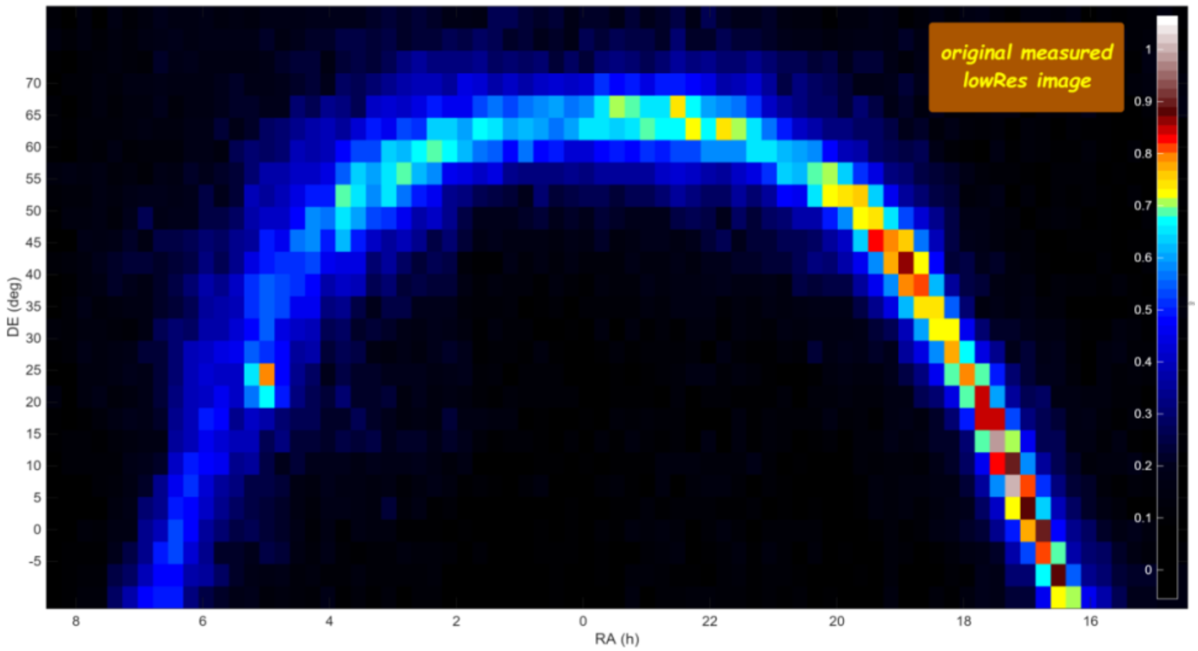
Robotic 2.6m radio antenna dish with seven HI-feeds (21cm) for sucessive meridian scans in order to compose seven slightly different sub-pixel-shifted lowRes images of the radio sky

Data acquisition, data reduction and preprocessing

Data aquisition: 7 SDR receivers (“*Airspy mini*“, bandwidth 6 MHz), **VLNAs**: 7 Sawbird H1t
Scan: columnwise along the meridian, pixel integration time: 25 sec, total scan: 18 hours - image column distortion by earth rotation: removal by spheric geometrical transformation
Preprocessing: with *“GNU radio“*, 1024-FFT, average of 2048 raw spectra for each pixel
RFI reduction: outlier removal in radio spectra with Hampel- and Savitzky-Golay filters
Flatfield: each average pixel spectrum is processed as follows: split it into inner HI range (bandwidth 1.4 MHz) and continuum part. For the pixel intensity value, divide the average of the inner HI range by the average of the continuum. This substantially removes the effects of atmospheric bias, spill over and even the effects of temperature drifts in electronic parts



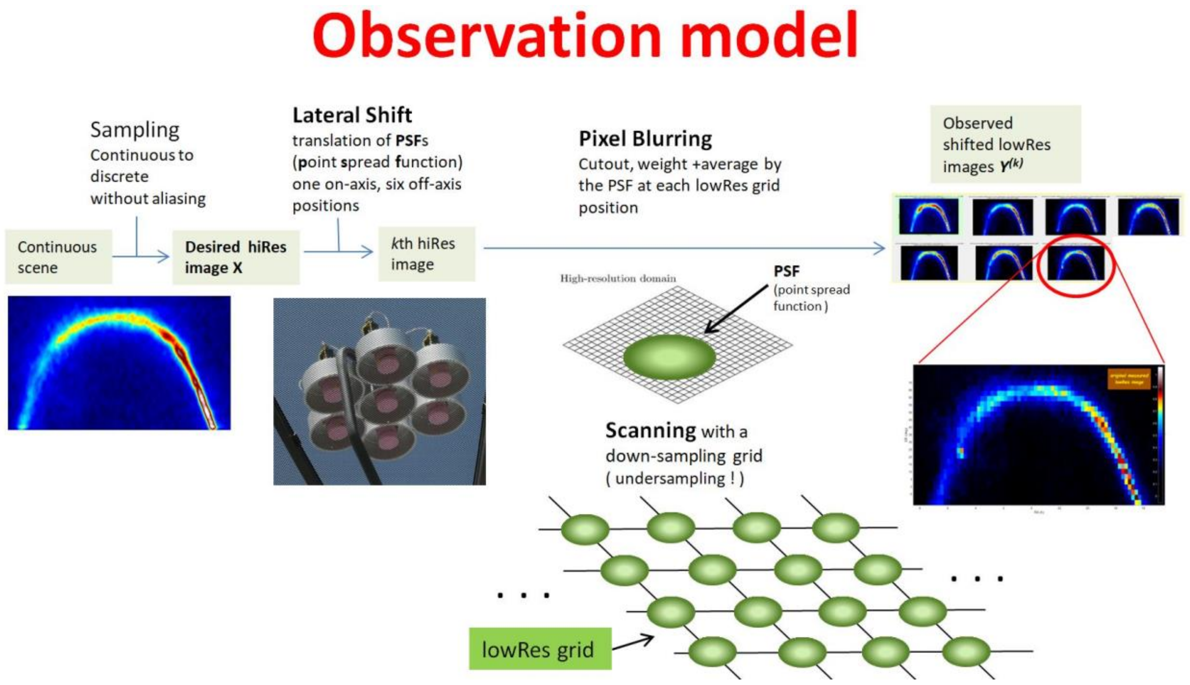
seven recorded subpixel-shifted low-resolution images obtained by scanning the milky way for about 18 hours with seven 21cm-feeds simultaneously



One of the seven measured original 90x27 lowRes frames $Y^{(k)}$ from the northern milky way with the 2.6m radio antenna. Radio intensities are displayed using a pseudo-color representation, see color bar on the right side

Details on the observation model used

The description shown here is how to modelize the way from the real world continuum to the image generated by scanning the sky with a small radio antenna dish.



In the super-resolution algorithm the purpose of the observation model is to **generate lowRes pixel values artificially** to compare them with the measured ones in order to minimize their residuals. Because the generation of the artificial lowRes pixels needs already the unknown super-resolved image, it's not that easy. It's necessary to **iteratively refine an estimation X_o** for the unknown super-resolved image, i.e. start with a preliminary hiRes image followed by a kind of "*evolution*" or "*machine learning*" process, called Bayesian optimization.

The images are reshaped into vectors in order to have the capability of using a 2-dimensional matrix to modelize the observation process. The columns of the images are stacked one over the other to build a very long single vector. This is done for the unknown hiRes image ***X*** as well as the measured lowRes images $Y^{(k)}$. These $Y^{(k)}$ are again piled up to form a huge single linear vector ***Y*** for all *k* lowRes frames. So, all lowRes images can be calculated with parallel processing using a precalculated 2-dim **system matrix *W***, which is huge, but sparse. Therefore very efficient algorithms for sparse matrices can be applied. The system matrix carries all lateral microshifts and properties of the point spread functions and the lowRes-sampling grid. The imaging equation is simply the following:

$$Y = W \cdot X, \quad X = \text{unknown hiRes image}, \quad Y = \text{lowRes images}$$

One important point for the lowRes grid is **undersampling** in the spatial frequency domain, [1]:

It causes a**liasing**, that means that the high-frequency content of the desired hiRes image is embedded in the low-frequency content of each of the observed images. Given a **sufficient number of observation images,** and if the set of observations **vary in their phase** (i.e. if the images of the scene are shifted by a sub-pixel amount), then the **phase information** can be used to separate the **aliased high-frequency content** from the **true** low-frequency content, and **the full-resolution image can accurately be reconstructed**.

Details to Bayesian optimization with stochastic regularization

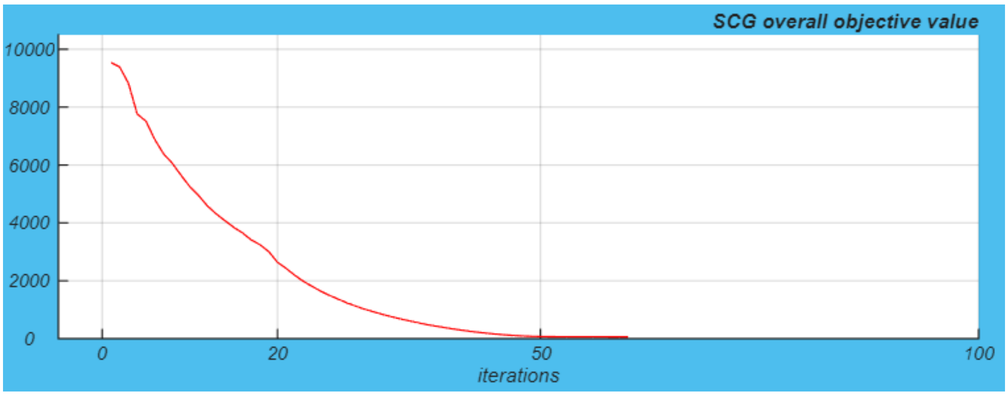
It's reasonable to start with a preliminary hiRes image $\boldsymbol{X_o}$ generated by averaging the measured lowRes images by **stacking**. The residuals between artificial and measured lowRes pixels contain statistical informations about the unknown super-resolved image ***X.***

A preliminary *a-priori* probability distribution (called ***prior***) is assumed to characterize the statistics of the pixels in the unknown super-resolved image ***X***. To find an optimum amount of confidence, this *prior* is improved by a Bayesian optimization process using a scaled conjugate gradient with a framework of **fidelity** and **confidence functions** to steer the stochastic regularization procedure.

If the *prior* is combined with the measured pixel values, it can be updated to produce a new (*a-posteriori*) probability distribution with an extended statistical knowledge content. This modified distribution can be used as a new *prior* to modify the preliminary super-resolved image from $\boldsymbol{X_o}$ to $\boldsymbol{X_1}$. Then, the imaging model can be reapplied to $\boldsymbol{X_1}$ to produce new artificial lowRes pixel values. A new comparison with the measured lowRes pixels provides new residuals as well as confidence and fidelity functions - and so on. After about 50 to 60 such cycles the result stabilizes and the algorithm provides $\boldsymbol{X_{60}}$ as a final super-resolved image.

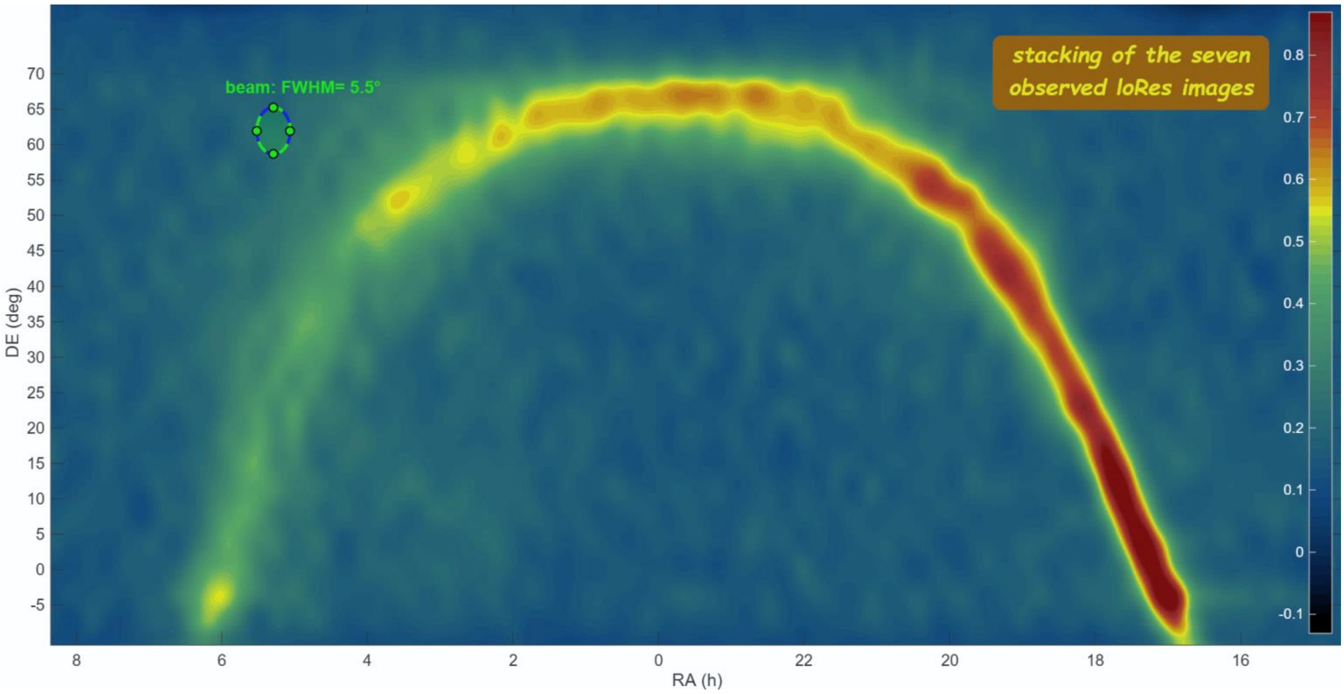
Several modules of the "multi-frame super-resolution" Matlab Toolbox from the Pattern Recognition Lab of Erlangen University [5] were used and adapted for this project. A variety of super-resolution algorithms, such as MAP („maximum a-posteriori estimation", [2]) or IRLS ("iteratively re-weighted least squares", [3]) and others were tested. The **best result** was achieved by a BEP type algorithm ("bilateral edge preserving", [4]) combined with a (non-gaussian) "Huber loss function" as a prior for the stochastic regularization procedure.

*This **YouTube video** shows the development of the preliminary hiRes image X_o to the final super-resolved image X_{60}*

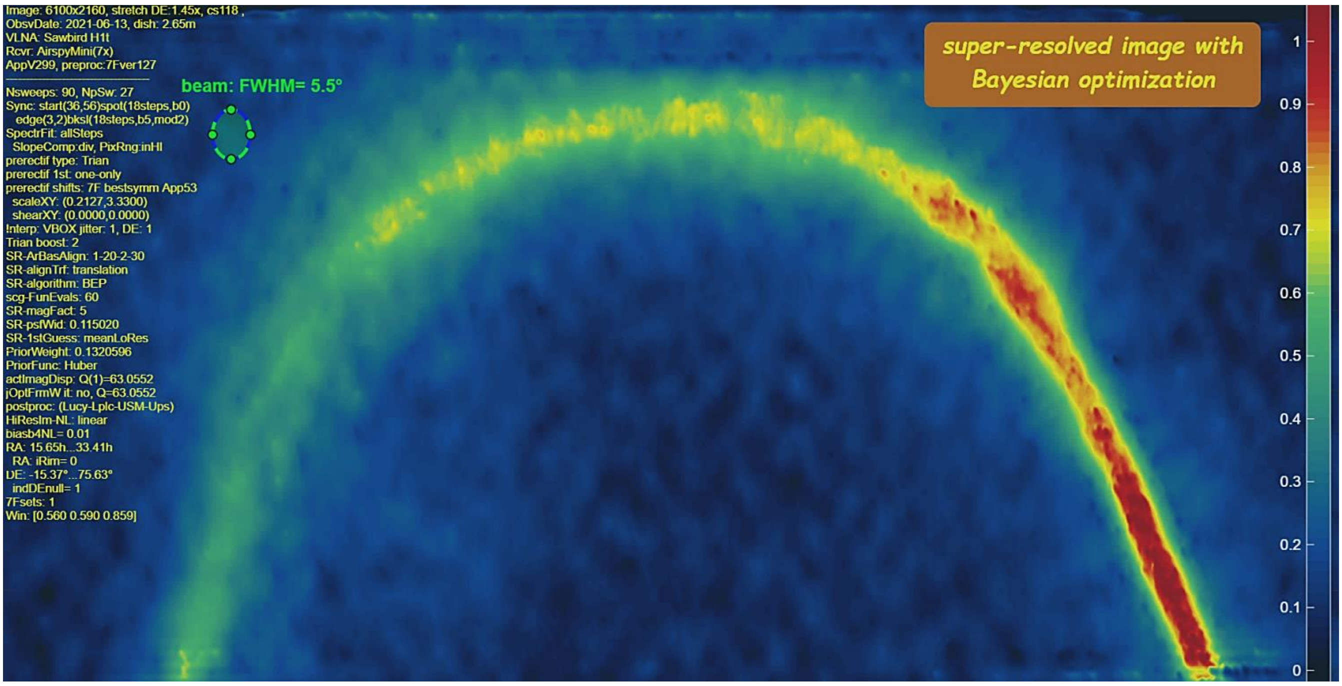


Remaining inconsistencies between model and measurements during iterations

First hiRes images with the 2.6m-dish: northern milky way at 21cm

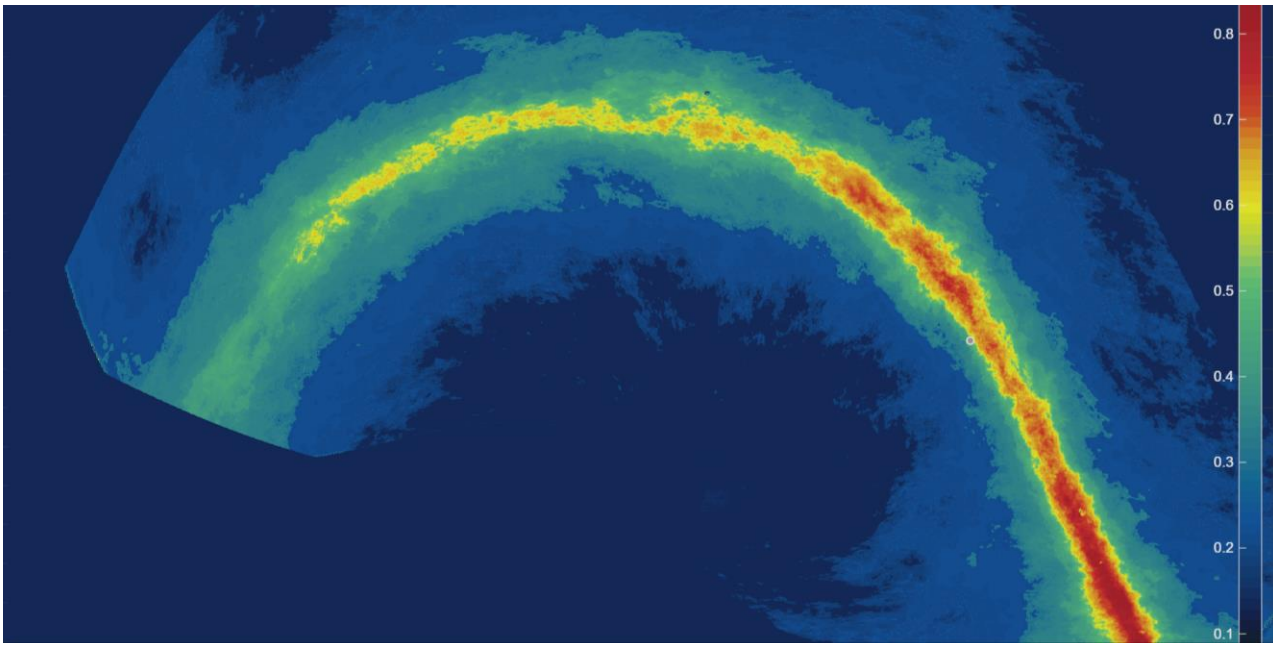


This image is used as a 1st estimation of the super-resolved final image below. The seven lowRes frames $Y^{(k)}$ were averaged with "stacking", upsampled, spline-interpolated and sharpened with a hi-pass filter



Preliminary super-resolved image obtained from the same seven input images by Bayesian optimization after 60 iterations. An observation model with a-priori information, a Huber loss function as a prior and a super-resolution algorithm with bilateral edge preserving were used

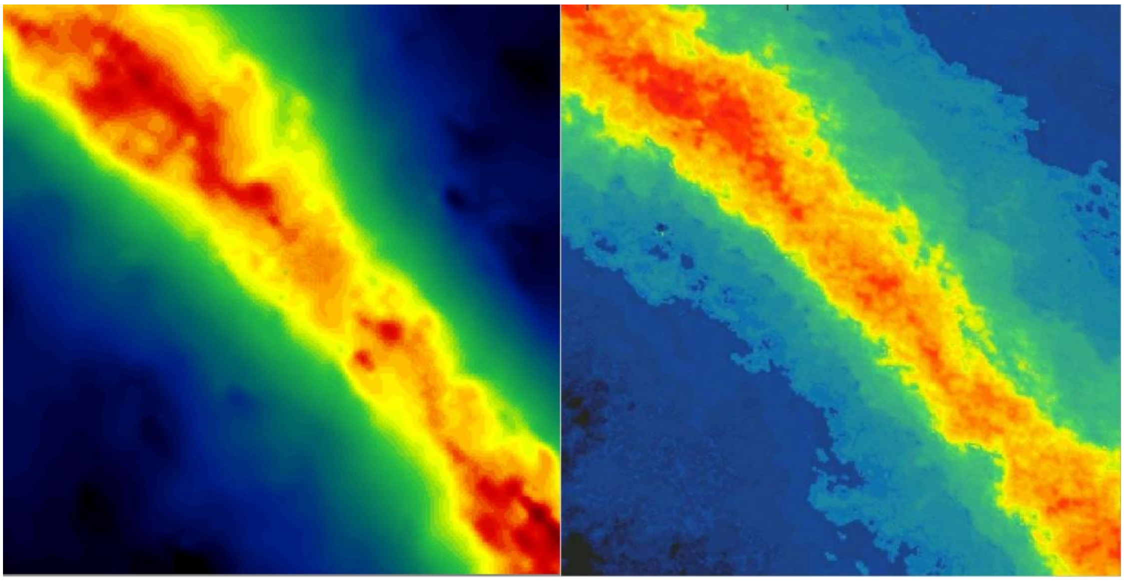
Comparison with an image from the EBHIS survey [7,8]



Reference image from the 100m Effelsberg antenna: compared to this image, the sharpness of the super-resolved image obtained by the 2.6m antenna is surprising, as well as lots of similarities in detail features

Nevertheless, the closeup images below reveal also some deformed or phase distorted detail features. Probably due to lack of data, some features are even missing, others seem to be "halluncinated". Therefore the number of **seven lowRes input images** (from a single 18h-scan) seems still to be **too low**. Better results could be expected from a combination of two or more scans with 14, 21 or more lowRes input images with different lateral shifts.

Closeups of the milky way at 21cm below the Cygnus complex
(galactic longitude range: about 20 degrees in diagonal direction)



Super-resolved image from 2.6m-antenna ***reference image (100m antenna)***

Open issues

A remaining problem is to find a final **unique solution**, not depending on tunable parameters. If the prior weighting factor in the regularization is varied, the appearance of the final solution changes to some extent. Futhermore, many solutions don't show good looking images, many look quite noisy, even if they have quite low residuals. So, in a first ride thousands of possible solutions were browsed visually to find some optimum. Thus, only a preliminary best solution is shown in this presentation. An additional criterium must be found to obtain a unique parameter-independent final solution in order to avoid such extensive manual inspection.

Some doubling of fine structures in some parts of the image may be an indication for small **mechanical glitches** during scanning. Improved mechanical stability of the 2.6m-dish may help to get still better results (…is now under construction).

Specific advantages

- **'nested' design** – seven simultaneously working radio telescopes available, but only one parabolic antenna dish necessary – more 'light' with only one dish
- **signal-to-noise ratio improvement** comparable to 'stacking'
- **automatic short-time RFI supression**: RFI is distributed to different positions in the final image. There is averaging with data from the same position but other subimages which are not disturbed at that position
- **15-20 times resolution improvement factor** beyond the diffraction limit
- **low noise** and **low image artefacts,** mainly **phase distortions** in detail features
- **large fields** possible

Conclusion

These are first encouraging results, showing the potential of multi-frame super-resolution methods at least for small single-dish radio antennas. The **surprising sharpness** of the final hiRes images is exciting, although there were only seven low resolution input images. If the number of input images is increased, even better result can be expected. It seems that image degradation due to the diffraction limit does not destroy all hiRes information in single-dish radio data. Information about the subpixel fine-structures is only deeply hidden in the lowRes images and can be recovered, if the subimages have mutual subpixel-shifts and if pixel and image formation is modelized thoroughly.

Outlook: An application to bigger single-dish radio telescopes seems to be promising. Maybe even scans from old data with multi-feed antennas could be reprocessed with this algorithm.

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2. Ebersberger, J., „Ein tiefer Blick in die Galaxis“, Sterne und Weltraum 2020-05, pp. 74-81
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4. Ebersberger, J., „Fortschritte bei der Auflösungssteigerung für Einzel-Radioteleskope“, Regiomontanus-Bote 2025-3, pp. 10-16

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