On Flexibeam for radio interferometry

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Abstract—Beamforming in radio astronomy focuses at and around a direction using matched beamforming or a derivative, to both maximise the energy coming from this point and reduce the data rate to the central processor. Such beamformers often result in large side-lobes, with influence from undesired directions. Moreover, there is a fundamental lack of flexibility when, for example, targeting extended regions or tracking objects with uncertainty as to their location.

We show how the analytic framework Flexibeam can be leveraged to achieve beamshapes that cover general spatial areas with substantially more energy concentration within the region-of-interest. The method is numerically stable, and scalable in the number of antennas, and does not magnify noise.

EXTENDED ABSTRACT

Beamforming in radio astronomy has mostly been a byword for matched beamforming: focus on and around one point in the sky by phase aligning the antenna signals. It is essentially dual-purpose: get information with high SNR around that point, while reducing the amount of data to send from a station to the central processing, so as to compress and reduce complexity.

While simple, there are quite a few drawbacks. The side-lobes induced are large, polluting substantially the data observed. Power is maximised from this one direction in the sky, but sees relatively little of the rest of it. Hence, surveying large portions requires multiple observations, steering towards various locations successively. Additionally, it is very sensitive to uncertainty in the target, and indeed only one point can be targeted at any given time.

Instead, it would be desirable to specify a general spatial sky filter, not necessarily contiguous, and determine how to beamform so as to approximate the filter. This framework is provided by Flexibeam [1]. A spatial filter is described over the sphere $\mathbb{S}^2$, from which an extended filter in $\mathbb{R}^3$ is chosen. A beamforming function is then obtained over Euclidean space $\mathbb{R}^3$. From this, the beamforming weight for an antenna is given by sampling the beamforming function at its position $\boldsymbol{p} \in \mathbb{R}^3$.

The analytical framework allows tractable, and numerically stable weight determination. It scales linearly with the number of antennas (just add additional samples for more antennas) – a key advantage in radio interferometers with thousands of antennas.

Suppose we wish to observe a specific region on the sphere. One good choice of extended filter is then the 3D ball indicator defined by $\hat{\omega}(\boldsymbol{r}) = 1$ if $\|\boldsymbol{r} - \boldsymbol{r}_0\| \leq R$ and 0 otherwise, where $\boldsymbol{r}_0 \in \mathbb{S}^2$, and $R > 0$ specifying the width of the targeted region. The resultant beamforming function, from which the beamforming weights are obtained, is given by:

$$\omega(\boldsymbol{p}) = R^{-1/2} \|\boldsymbol{p}/\lambda\|^{-3/2} J_{3/2}\left(2\pi R \|\boldsymbol{p}/\lambda\|\right) e^{-j2\pi \langle \boldsymbol{r}_0, \boldsymbol{p}/\lambda \rangle},$$

where $J_{3/2}$ is a Bessel function of the first kind, and $\boldsymbol{p} \in \mathbb{R}^2$. We can thus approximate beamshapes of various widths, as illustrated in Fig. 1 (for an LBA core LOFAR station composed of 96 antennas, with the frequency of 45MHz). Notice how Flexibeam dramatically reduces side lobes, and that we can get much more of the beam energy where we want it.

Suppose we wish to scan a region as shown in Fig. 2, which compares the use of multiple matched beams through progressive

(a) Matched beamforming.

(b) Flexibeam, $\theta = 15°$.

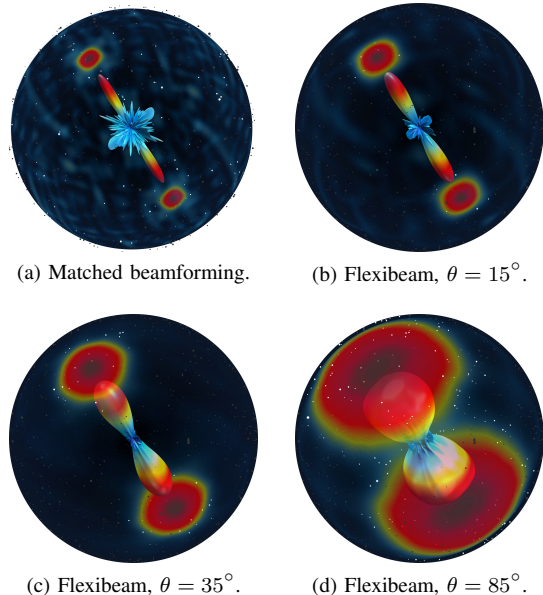(c) Flexibeam, $\theta = 35°$.

(d) Flexibeam, $\theta = 85°$.

Fig. 1: Beamshapes illustrating how Flexibeam can survey large portions of the sky in radio-astronomy with reduced side-lobes.
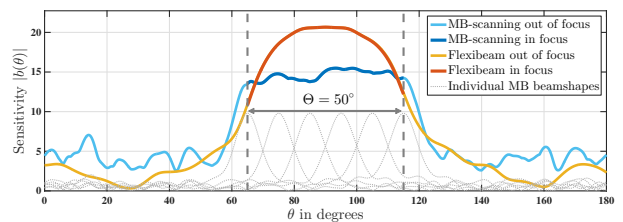

Fig. 2: Comparison, in 2D, of matched beamforming successive scan vs. a single Flexibeam beamshape with the same observation time.

scan, versus multiple observations using a Flexibeam-determined beamshape. More signal in the area of interest is obtained with Flexibeam. Here it amplifies the signal by 26.2% in the region of interest with respect to matched beamforming. Flexibeam also has 33% less energy in the side-lobes.

By use of the computationally low-cost Flexibeam framework we are able to use one instrument for many different use cases, designing spatial filters with corresponding beamforming functions so as to search in multiple areas or track a pulse. Recent work has also shown how these beamshapes can be incorporated efficiently into the imaging pipeline [2].

REFERENCES

[1] P. Hurley and M. Simeoni, "Flexibeam: analytic spatial filtering by beamforming," in *International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE*, March 2016.
[2] M. Simeoni, "Towards more accurate and efficient beamformed radio interferometry imaging," Master's thesis, EPFL, Spring 2015.