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Brazilian Decimetric Array (BDA)

Comparison with a hypothetical array extension

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Abstract. Brazilian Decimetric Array (BDA) is the project of a radio interferometer under development which is located within INPE campus at Cachoeira Paulista city, latitude ≈22.7 degree South and longitude ≈45.0 degree West. Current array configuration is composed of twenty six fixed 4-m diameter antennas, distributed on an East-West and South "T" shaped configuration. It can operate in a selectable frequency in the range 1.2-1.7 GHz with a 10 MHz bandwidth, and a time resolution ≥ 0.1 s. It is planned to observe solar transient energetic as well as galactic and extra-galactic phenomena. One key aspect in a radio interferometer design is the array configuration which defines its usage in terms of scientific targets which can be observed. This is so important that requires a careful analysis. We analyze the current fixed array configuration and its main properties. Also, we study a supposed extension of the current configuration which improves the spatial resolution and sensitivity in at least one order of magnitude. That enlarges BDA usage to observations of extended sources with higher resolution and sensitivity as well as to those sources varying in a middle to long time scales.

Resumo. O Arranjo Decimétrico Brasileiro (BDA) é o projeto de um interferômetro rádio em desenvolvimento, instalado dentro do campus do INPE, em Cachoeira Paulista, latitude ≈22.7^o S, longitude ≈45.0^o W. A configuração atual é composta de vinte e seis antenas fixas de 4 m de diâmetro, distribuídas numa configuração em formato de "T" Leste-Oeste e Sul. O interferômetro pode operar numa freqüência selecionável dentro da faixa 1,2-1,7 GHz com largura de banda de 10 MHz, e resolução temporal ≥ 0.1 s. O BDA foi projetado para observar tanto fenômenos solares energéticos transientes quanto galáticos e extra-galáticos. Uma questão fundamental do projeto de um interferômetro rádio que precisa de análise é a configuração do arranjo de antenas, a qual determina o uso do instrumento com relação a alvos científicos que podem ser observados. Apresentamos uma análise da configuração atual fixa e suas principais características. Também analisamos a hipótese de uma extensão da configuração atual que melhora resolução espacial e sensibilidade em pelo menos uma ordem de grandeza. Isso ampliaria o uso do BDA para a observação tanto de fontes extensas com maior resolução e sensibilidade quanto daquelas fontes com variação temporal de média e longa escalas.

Keywords. Instrumentation: interferometers – Galaxies: general – ISM: jets and outflows – Sun: atmosphere – Sun: activity

1. Introduction

A radio interferometer is a complex and extensive instrument composed by many antennas distributed on a determined configuration allowing scientific investigations of selected celestial objects. In order to function like an interferometer, the signals from all antennas must be in phase coherence, from the reception on each antenna passing by all receiver stages up to insertion in the correlator. Phase coherence depends on the geommetrical as well as instrumental delays. Besides, phase stability is critical to guarantee the long scale coherence among the signals from all antenas at the correlator input (Thompson et al. (2017)). In addition, several other aspects are involved in the project, planning and building of a radio interferometer. One key aspect is the array configuration, which is directly related to the resolution, number of Fourier components on the uv-plane coverage, sidelobe level, sensitivity, and at last to the science (Holdaway & Helfer (2003)). Many articles on interferometric array configuration exist. Those directed to the design of radio interferometric array configuration differ by many aspects, mainly when devoted to some determined application. Part of them refers to application of determined-source observations (Roy et al. (2012)), a fraction analyze a multi-objective optimization (Zhang et al. (2021)), another addresses the design of a specific array, like the SKA (Lal et al. (2011)). There is the one which directs to interference suppression (Wang et al. (2018)), as other which dedicates to maximize uv-plane coverage at the same time it minimizes sidelobes (Kiehbadroudinezhad & Noordin (2013)), some are dedicated to the optimization, some other consider the multiple use, while one of them takes into account both, mainly for the new generation of radio interferometric arrays (Cohanim et al. (2004)). It has to be emphasized that BDA current configuration is composed of 26 fixed antennas (Sawant et al. (2000)). With the purpose to enlarge potential scientific targets available to observations using the BDA, we analyze the current array configuration as well as one hypothetical extension of it, in terms of resolution, uv-plane coverage and sensitivity. The hypothetical configuration, cause significant although not proibitive budget enhancement. By the other side, the offered flexibility of that configuration is accompanied by advantages, a better uv-plane filling, increase in resolution and also sensitivity maintaining the relatively broad field of view. That results in a more detailed image of extended and relatively weaker sources. All that at the cost of increase in time of observation of middle/long time-scale sources. We conclude with a comparison between the two BDA configurations, and respective discussion in terms of possible additional sources which become potentially observable. This paper has an introduction in this section. Various interferometry concepts are in section two. Next two sections are a description of the current as well as the hypothetical array configurations with their main properties including respective uv-plane and resolution. Sensitivity for both configurations are described and calculated in section five. An analysis and comparison of both array configurations is performed in section six. Discussion and conclusion are in the last section.

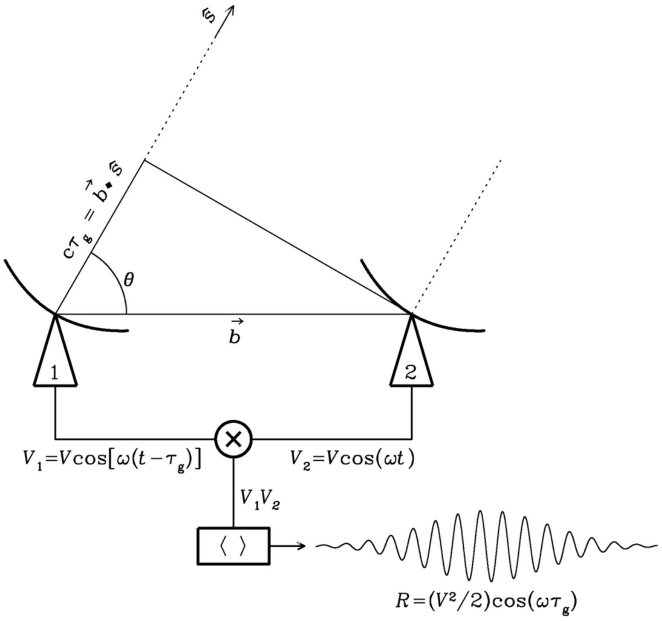

Figure 1. Basic two element radio interferometer (Condon & Ransom (2018)).

2. Interferometry concepts

A basic radio interferometer is composed of two elements and one correlator as shown in Fig. 1. Each element is an antenna with its own feeder, tracking system, receiver, and cabling. The signal from each antenna is adjusted in phase coherence with a reference antenna for all signals to be in phase at the correlator input. About the correlator, it correlates the signal from each pair of antennas, or baseline, building and recording the set of all visibilities in the output file. Visibility is a complex function which has the real and imaginary components necessary to obtain amplitude and phase information on each baseline of the array. All those visibilities are processed and calibrated to build the image of radio source brightness distribution. In relation to resolution, for a single dish the spatial resolution is approximately given by the ratio λ/D, where λ is the wavelength, and D is antenna diameter. In the case of a basic interferometer, resolution is given by λ/b, where b is the baseline size, or the distance between the two antennas. Each pair of antennas with a different baseline corresponds to a sampled point in uv-plane, a Fourier component, an elementary fraction of the interferometer sensitivity, and a spatial scale on the source. Due to the fact an interferometer generally has many baselines, it produces a set corresponding to distinct spatial scales of the source. In practice, each pair of antennas at a given moment in time samples a point in the Fourier plane. The more the distinct baselines, the greater the number of points in the Fourier plane, and so the better the recovery of the brightness distribution or image of the radio source. That number of points can be increased by different ways: changing antennas positions by taking more time of observation, using the Earth rotation, or a combination of both. In any case, that means improve in image-quality and sensitivity, and at last the possibility to observe relatively weaker sources. Various interferometric array configurations are possible – linear, T-shaped, Y-shaped, circular, spiral, and “irregular” – each one with its own advantages and disadvantages. For instance, a “T-shaped” array presents a reasonable 2D snapshot Fourier-plane coverage. However, it also presents a kind of grating in the point spread function. BDA configuration is T-shaped, although do not be a regularly spaced array what means lower sidelobes. In order to analyze uv-plane coverage and respective synthesized beams we made use of the “uvbeam” code. The inputs are antennas position, latitude of the interferometer, source position on the sky, and time of observation. Both modes the snapshot, and +/- 6 h tracking using the Earth rotation have been selected. Source position is the one which best filled the uv-plane coverage with circles.

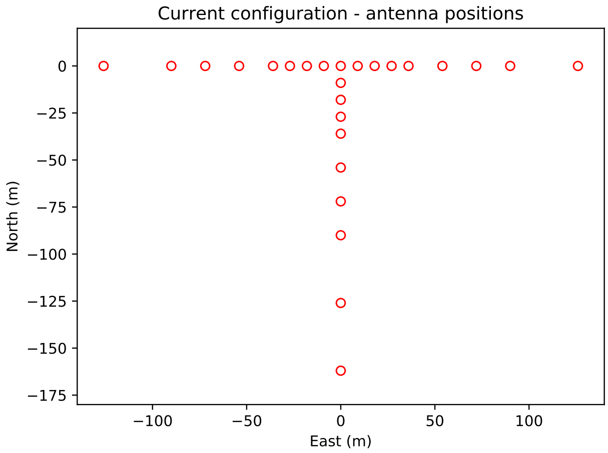

Figure 2. Antennas distribution of BDA’ T-shaped array configuration. East-West and South baselines have respectively 252 m and 162 m.

3. Current array configuration and corresponding uv-plane

Current BDA configuration is composed of 26 fixed wire-meshed 4 meter (m since now) diameter antennas. The mesh size permits the antennas operate up to 6 GHz without a significant aperture efficiency loss, and wind overload. Assuming an aperture efficiency of 50% within the 1-6 GHz, this corresponds approximately to the area of a 20 m diameter antenna with same efficiency. In reference to the current array configuration, the baselines range from 9 m up to 252 m and 162 m respectively on East-West and South directions, as shown in Figure 2. For this, we present corresponding uv-plane coverage in the snapshot mode, as seen in Figure 3. Also, Figure 4 shows, uv-plane coverage with a +/- 6 hour (h since now) tracking mode using Earth-rotation.

4. Hypothetical array extension and uv-plane occupancy

Suppose we can go ahead and implement a hypothetical more flexible array configuration in the future. In practice, it corresponds to the current configuration added by three moveable elements beyond its extremes. The flexibility should be obtained using those three elements successively moved on rails of about 1.1 km long and distinctly positioned in a number of locations as to filling the uv-plane better. This hypothetical configuration is shown in Figure 5, selecting 21 new positions for those three additional and moveable antennas. As consequence, the array size is extended by one order of magnitude as well as its resolution. Current array is in red at the center of "T". As for the case of the hypothetical configuration, Figure 6 shows the correspond-

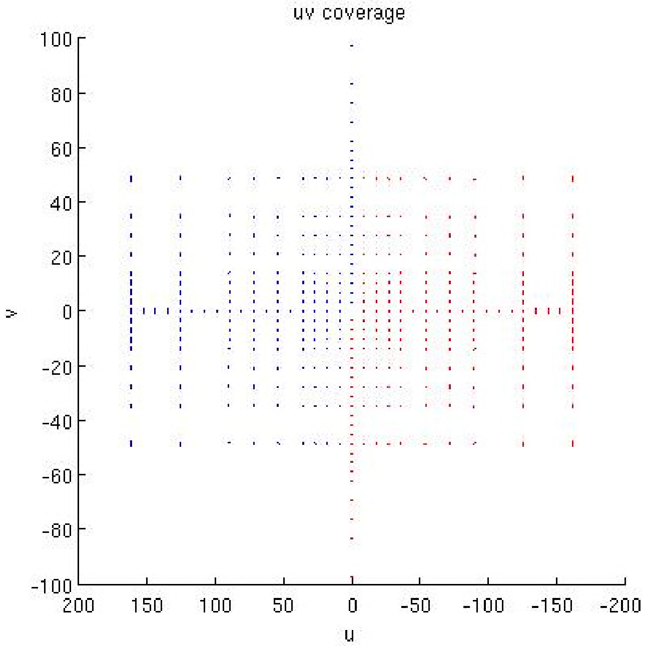

Figure 3. BDA' uv-plane coverage for the snapshot mode. Blue are the sampled components and red their respective conjugates in the uv-plane.

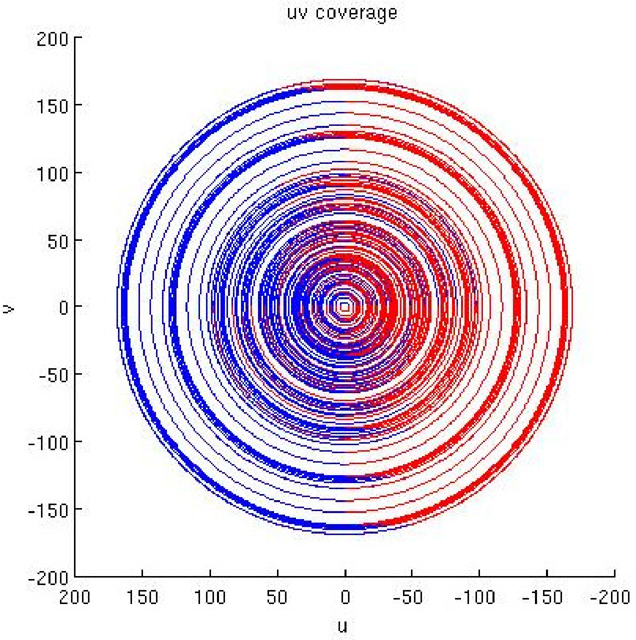

Figure 4. BDA' uv-plane coverage for the +/- 6 h tracking observing mode. The radio source has been chosen in a convenient location with purpose to provide the best uv-plane coverage. Blue and red are the tracks and respective conjugates filling the plane.

ing uv-plane coverage for the snapshot mode. The uv-plane coverage, using Earth rotation, for the case of +/- 6 h tracking is shown in Figure 7. For a comparison, Figure 8 shows the same as previous figure restricted to uv-plane coverage of the current configuration. It is evident the uv-plane becomes better occupied with relatively fewer gaps.

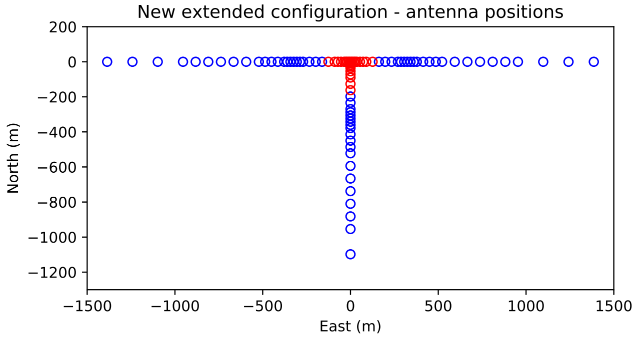

Figure 5. BDA' hypothetical array configuration. In red the antennas position of the current configuration. In blue the supposed antennas position of the new extended configuration.

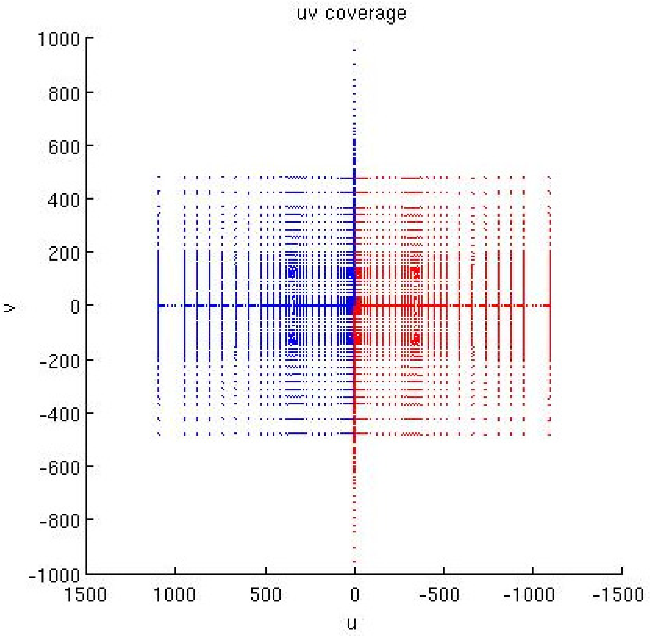

Figure 6. uv-plane coverage for the snapshot-observing mode using the new configuration. Blue and red are components and respective conjugates in the plane.

5. Sensitivity

Sensitivity corresponds to the minimum level of a signal an interferometer can discriminate and measure above the receiver system noise. Assuming an interferometer composed of N identical elements - parabolic antennas - with a single polarization, complex correlator, antenna efficiency η_a, system efficiency η_s, bandwidth Δf, system temperature T$_{s}ys$, and an integration time of t$_{i}nt$, its sensitivity is given by (Wrobel & Walker (2003)):
$\Delta S_{min} = 2k_B.T_{sys}/(\eta_s.\eta_a.A.\sqrt{N(N-1).\Delta f.t_{int}})$ (Jy/beam)
where ΔS_{min} is sensitivity, η_s is system efficiency, η_a aperture efficiency, k$_B$ Boltzmann constant, T$_{sys}$ system temperature, A is area of one antenna, N the number of antennas, Δf bandwidth, and t$_{int}$ the accumulation time. At the input of BDA receiver there are 2 identical LNA in series, each of them has a noise

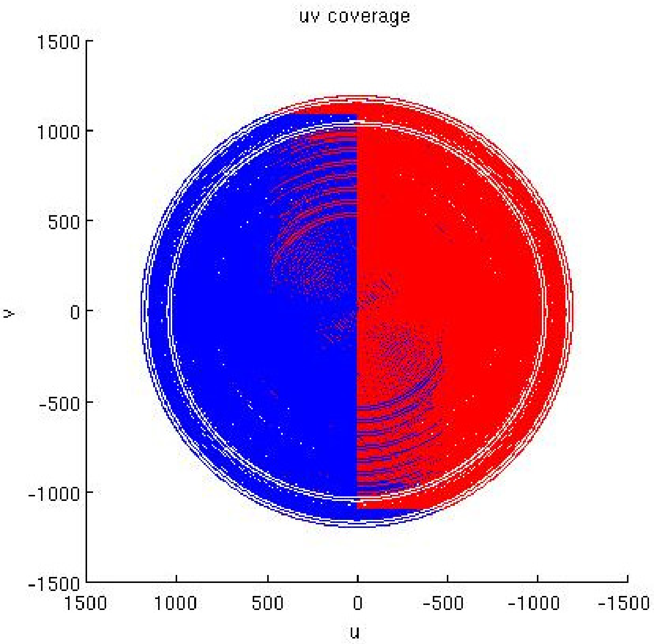

Figure 7. uv-plane coverage for the +/- 6 h tracking observing mode. A more convenient radio source has been chosen with purpose to provide the best uv-plane coverage using the new configuration. Blue and red represent the same as in the previous figure.

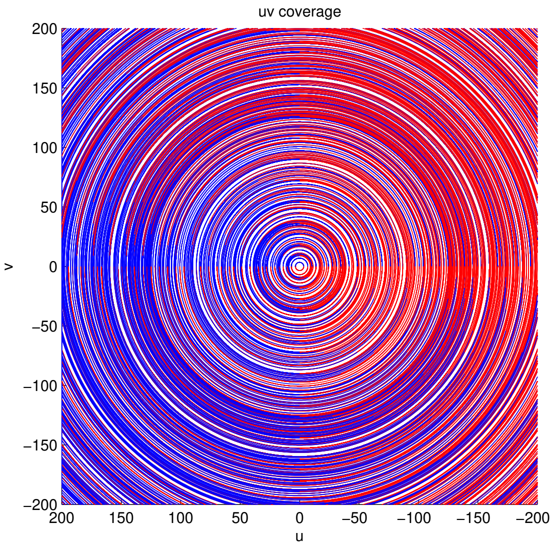

Figure 8. Same as Fig. 7 although limiting the uv-plane to the fraction corresponding to that of Fig. 4 above.

figure and gain respectively of 0.9 dB and 18.5 dB. So, we can take T$_{sys}$ ≈ 135 K. Let us estimate the current configuration sensitivity. We know $k_B = 1.38\times10^{-23}$ J/K, Δf = 10 MHz, t$_{int}$ = 1 s, N = 26, and being conservative we can assume η_a = 0.5, and η_s = 0.5. Using equation (1) above, we obtain $\Delta S_{min} \approx 3.0$ Jy/beam. Now, taking the hypothetical array configuration we have N = 90, and assuming t$_{int}$ ≈ 20 minute (min since now) for observing the source in each additional antenna position we estimate a sensitivity of $\Delta S_{min} \approx 25$ mJy/beam. Therefore, in case we include three new moveable antennas to the current array configuration, simultaneously positioned in 21 additional stations and observing along 20 min in each one, we take about 9 h in each source, including the calibration time. This means about two days of observations to improve sensitivity at the longest spacings by two order of magnitude.

6. Analysis

Considering the snapshot mode, each distinct baseline - distinct spatial scale at the radio source - corresponds to two sampled points in the array Fourier plane which is practically empty for the ordinary arrays. Basically, there are two ways to minimize the sparsity of the uv-plane. As each pair of antennas corresponds to one component as well as its conjugate in the plane, each distinct distance between two antennas (baseline) samples the plane with two points. Therefore, the more different baselines the more components in the uv-plane. Other way is by the use of Earth rotation to fill in the plane with ellipse tracks since the moving sampled points. So the original set of sampled points is converted to a set of elliptical tracks. And for a convenient position of the source the ellipses become circles. In consequence, the Fourier plane becomes more well covered and the image improved.

Taking into account for resolution, the hypothetical configuration allows to enlarge the maximum baseline by a factor 10 what corresponds to one order magnitude improve in resolution. As the shortest spacings are maintained in the hypothetical extension of the current configuration, the capability to imaging extended radio sources and largest source structures at high resolution is improved with the increase in sensitivity.

In respect to sensitivity, the inclusion of three moveable antennas observing simultaneously along 20 min in 21 additional positions we will be able to improve the sensitivity in at least two order of magnitude. This at expense of the significant increase in the array area and accumulation time in comparison to the current configuration. As shown in the Figure 8, the uv-plane coverage for the case of +/- 6 h tracking becomes improved mainly for the central region which corresponds to the shortest spacings. Even for that region some empty tracks are clearly seen although well less than for the case of longest spacings. So, the hypothetical array configuration can correspond to an improved image of the radio source. Hypothetical configuration is two order magnitude more sensitive at the same time becomes even more sensitive for the largest structures of extended sources.

Still about the sensitivity, it can be improved either in case we might increasing the time of observation, the number of additional moveable antennas positions, and/or changing to a lower noise-figure LNA. In case we might properly change to a LNA with a half noise figure, increasing the antennas positions and consequently the time of observation by 40%, the sensitivity could get down to the mJy/beam order enlarging even more the number of potentially observable radio sources. Beyond that, as for the fixed part of the array the accumulation time get multiplied by almost a factor 30 along the 9 h of observations, and so the sensitivity of the array for those larger scale structures and broad sources becomes at least half order of magnitude higher.

It has to be mentioned that original BDA project plan to operate at three distinct frequency bands, as known 1.2-1.7 GHz, 2.7 GHz, and 5.5 GHz. So, one additional possibility to use the interferometer is imaging bright radio sources at the same resolution at three different wavelengths.

7. Discussion and conclusion

Main advantages of the current fixed BDA array configuration is the possibility to observe extended and rapidly varying strong sources, for instance the Sun and solar flares. Also observable is a fraction of "fast radio bursts". In addition, some strong calibration sources such as Crab and Cygnus can also be observed. However, the fixed position of the current array antennas limits the targets can potentially be observed. This in terms of the small number of spatial scales, resolution, and sensitivity. In a glimpse of improvements, it is illustrative to assuming a flexibilization on this configuration including three new moveable antennas beyond the extreme of the arms of current array. We can assume those antennas are able to freely move over rails, which extends the array baseline size up to one order of magnitude, and analyze the advantages. Firstly, the spatial resolution increases by up to one order of magnitude with same field of view. So final image possess more details. Second, Fourier plane coverage becomes much more occupied specially when the Earth rotation mode is used. The consequence is an improved image quality. Third, the sensitivity is significantly increased by at least two order of magnitude or more when the increase in array area is accompanied by the Earth rotation observing mode. It can be improved even more in case of change for a lower noise pre-amplifier. All this can be obtained while the broad field of view allows us to observe extended sources with more sensitivity. Finally, the hypothetical array extension open one other possibility, the observation of bright sources with same resolution at three distinct wavelengths. Further, it has to be mentioned that hypothetical array configuration means an increase in the budget. Despite this, the added advantages mentioned above can clearly favor its implementation in the future.

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