Overview of developments of the eleven Feeds

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***Abstract*—An overview of different versions of the Eleven feed and recent development is presented in the paper. Eleven feeds have a nearly constant beamwidth and a fix phase center, with a performance of an aperture efficiency higher than 60%, -10 dB reflection coefficient, -0.2dB radiation efficiency, and -15dB cross-polar level, over a decade bandwidth. The Eleven feed can be very compact after applying newly developed optimization algorithms, and some new results of the feed in dual-reflector antennas are reported here.**

***Index Terms*—decade-band feed, reflector antenna, radio telescope, VLBI, SKA**

I. Introduction

Next generation radio telescopes, with two well-known examples of SKA (Square Kilometer Array) and VLIBI2010 (Very Long Baseline Interferometry), requires ultra-wideband systems. Several new feed technologies for such decade-bandwidth radio telescopes have been proposed, such as the Eleven feed, the quadruple-ridged flared horn [1], the sinuous feed [2] and the quasi self-complementary antenna [3].

Different versions of Eleven feeds for different applications over different bands have been developed during the recent years [4]–[9], ranging from low frequency such as 150 MHz to high frequency of 14 GHz; see Fig. 1. The newly developed opposition algorithms and the novel design approaches allow to design light weight, low profile design, with different alternatives for feeding and improved aperture efficiencies. The main advantages of the Eleven feed compared to the alternative decade band feeds mentioned above are the nearly constant beamwidth and the fixed phase center location. Furthermore, the Eleven feed is one of the most compact decade-bandwidth feeds for reflectors.

We present an overview of the development of Eleven feeds, report new results and discuss the future development in the paper.

II. Applications

The main applications of the Eleven antenna is as a feed for reflector antennas in radio telescopes because the Eleven feed can provide a nearly constant beamwidth and a fix phase center location over a decade bandwidth. We have been working on the 2–14GHz Eleven feed for the VLBI2010 project and 1–10GHz Eleven feed for the SKA project. The Eleven feed is also very attractive for low frequency applications, due to its compact size; see Sect. VI.

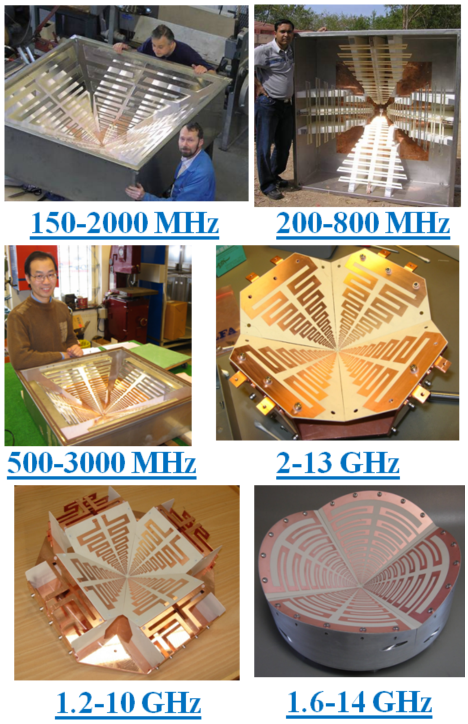

Fig. 1. Different Eleven feeds

The Eleven antenna can also be used in other applications, such as monopulse tracking [10], dual-band Satcom feed [11] and wideband MIMO antenna [12].

III. Performance Improvement

We present the performance improvement of Eleven feeds in this section.

A. Aperture Efficiency

It is noticed that all proposed UWB feeds are non-BOR (Body of Revolution) antennas [13]. Therefore, increasing BOR_1 efficiency [14], [15] is critical in order to have a high aperture efficiency for a UWB feed. The BOR_1 efficiency, therefore the aperture efficiency, of the Eleven feed has been improved by using the circular folded dipoles [9]. Fig. 2 shows a comparison of the aperture efficiency and its sub-efficiencies between the straight Eleven feed [7] and the circular Eleven feed [9]. It can be seen that there is a significant improvement at both low and high frequency ends.

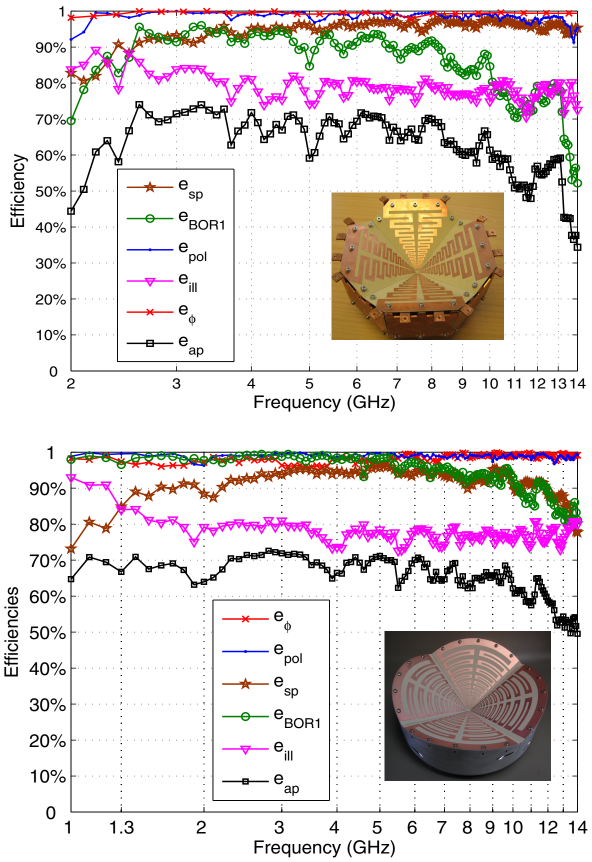

Fig. 2. Improvement of aperture efficiency which is calculated based on measured radiation function with a subtended angle of $2 \times 60^{\circ}$ of straight and circular Eleven feed.

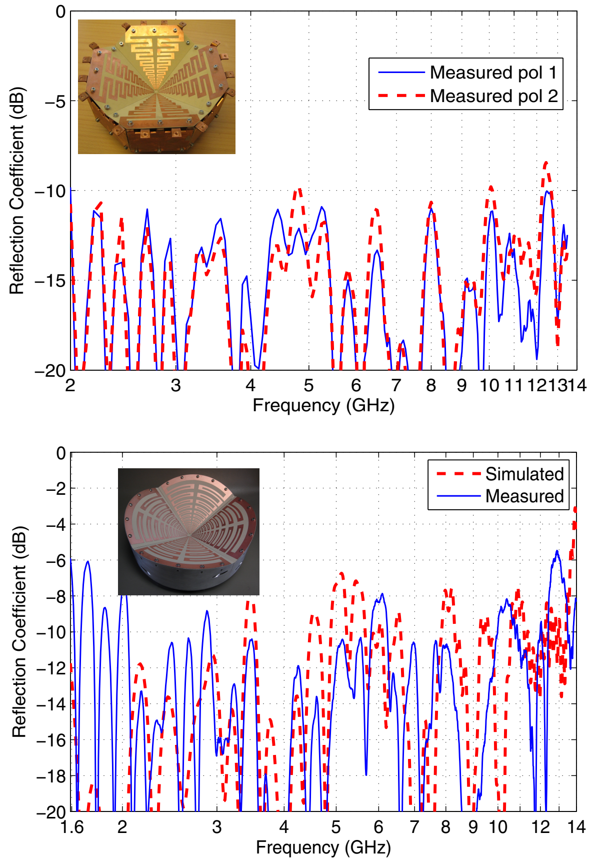

Fig. 3. Measured reflection coefficients of straight and circular Eleven feeds.

B. Reflection Coefficient

Obtaining a low reflection coefficient is always a focus in design of Eleven feeds. Several optimization methods have been developed, together with genetic algorithm (GA) [16]–[18]. Fig. 3 shows the measured reflection coefficients of the 2–13GHz straight Eleven feed [7] and the circular Eleven feed [9], by using GA optimized scheme. We are now designing a 0.2–1.6GHz Eleven feed by using so-called social civilization algorithm (SCA). Fig. 4 shows the simulated reflection coefficient of this feed, which is almost below -14 dB over the whole band. A prototype of this feed is under fabrication, and we believe that the measured reflection coefficient of the Eleven feed can achieve to the simulated level.

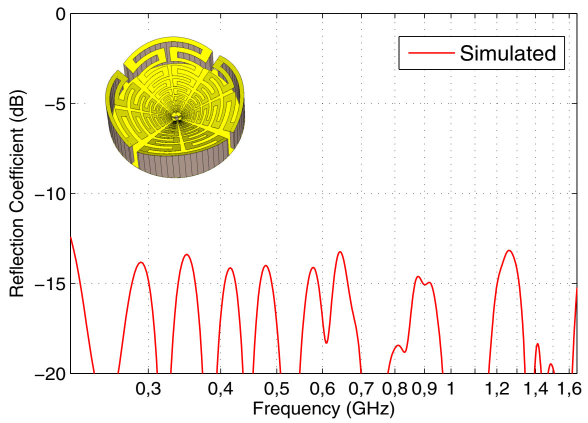

Fig. 4. Simulated reflection coefficient of a new designed 0.2–1.6GHz Eleven feed.

C. Radiation Efficiency

Fig. 5 shows the radiation efficiency which states the ohmic loss of the straight and the circular Eleven feeds. A -0.2dB radiation efficiency corresponds to a 1.4K increase in noise temperature when the feed is cooled down to cryogenic temperatures of 20K.

D. Cross-polar Level

The cross-polar radiation pattern has been improved from a level below -10 dB for the straight Eleven feed [7] to a level below -15 dB for the circular Eleven feed [9], as shown in Fig. 6.

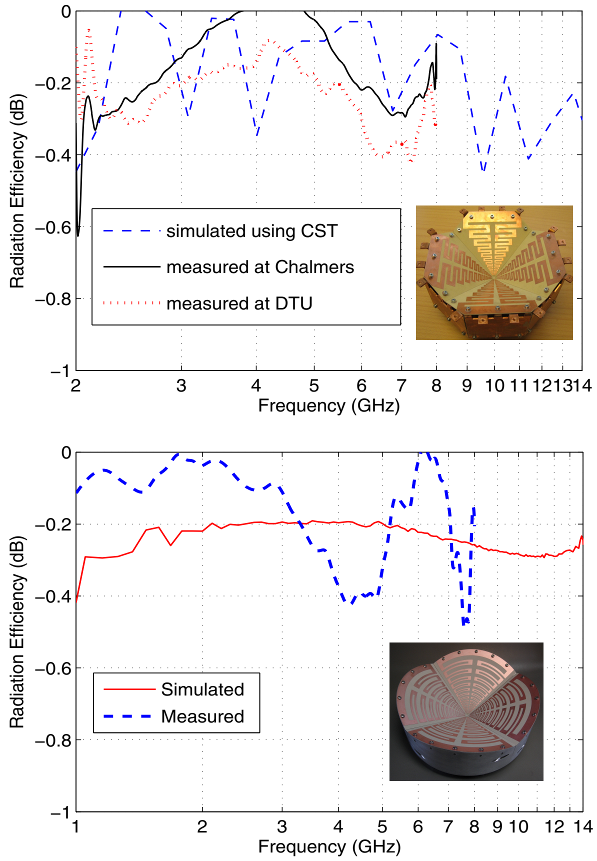

Fig. 5. Radiation efficiency of the straight and the circular Eleven feeds.

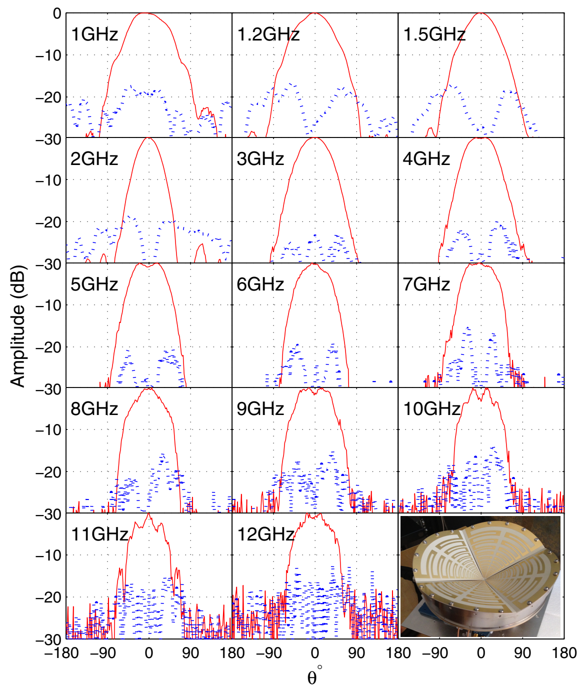

Fig. 6. Measured radiation patterns in 45° plane of the circular Eleven feed. Red solid line–co-polar; Blue dash line–cross-polar.

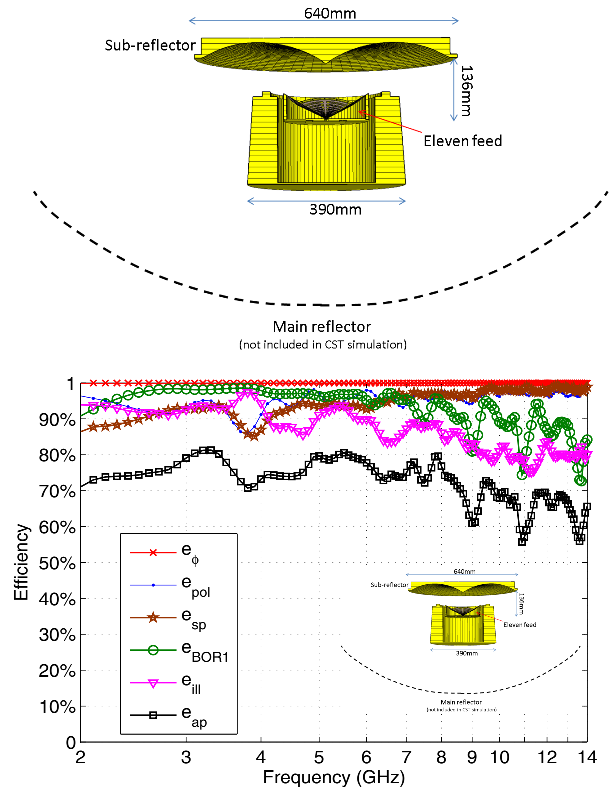

Fig. 7. Calculated aperture efficiency and its sub-efficiencies based on simulated radiation function when the circular feed illuminates a dual-reflector antenna (including a sub-reflector) with a subtended angle of $2 \times 80°$ for the main reflector.

IV. Dual-Reflector System

Both VLBI2010 and SKA projects are using dual-reflector antennas. We have studied the performance of the Eleven feed in a dual-reflector antenna, as shown in Fig. 7. The subtended angle is $2 \times 67°$ and $2 \times 80°$ for the sub-reflector and the main reflector, respectively. The reflection coefficient of the feed is almost not affected by the sub-reflector and the aperture efficiency of the whole antenna is calculated, as shown in Fig. 7, which indicates a good performance. As reported in [7], Eleven feeds provide an optimal performance when the subtended angle is from $2\times55°$ to $2\times70°$ for primary reflector systems. By using a dual-reflector arrangement, the Eleven feed can be used in an optimal performance for different subtended angles. We are investigating more cases and will report results in future publications.

V. Feeding Mechanism

Eleven feeds are multi-port antennas, which provides flexibility for system configuration. On the other hand, multiple ports require multiple low noise amplifiers (LNAs) in radio telescopes. Fig. 8 shows three different feeding methods: 8-port feeding [7], balun feeding [19]–[21] and center connection feeding. Fig. 9 shows the reflection coefficients for these three feeding methods. Further improvement on performance of these three feedings is under going.

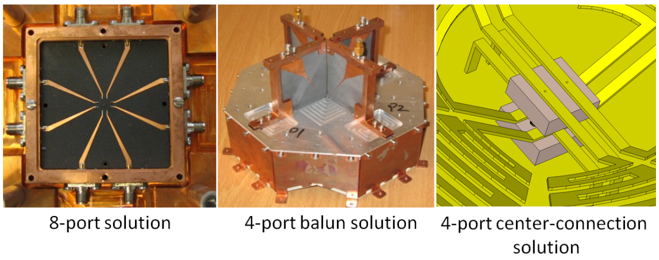

Fig. 8. Three feeding methods: 1) 8-port feeding; 2) 4-port balun feeding; 3) 4-port center connection feeding. All port impedances are 50 Ohms.

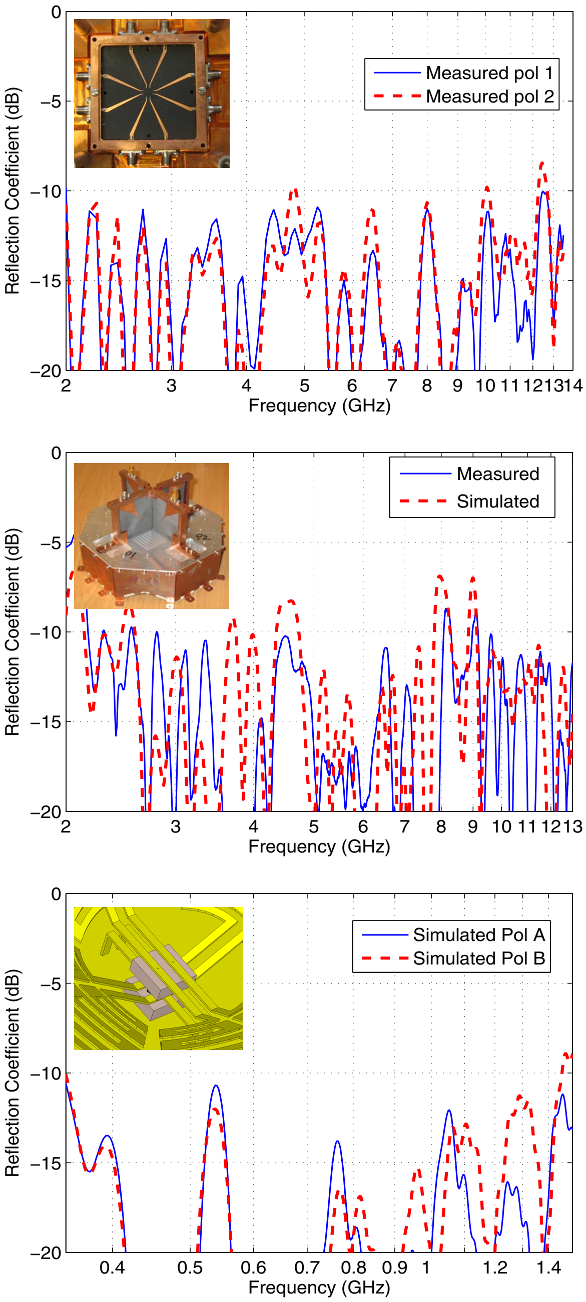

Fig. 9. Reflection coefficient of Eleven feeds of the three feeding methods.

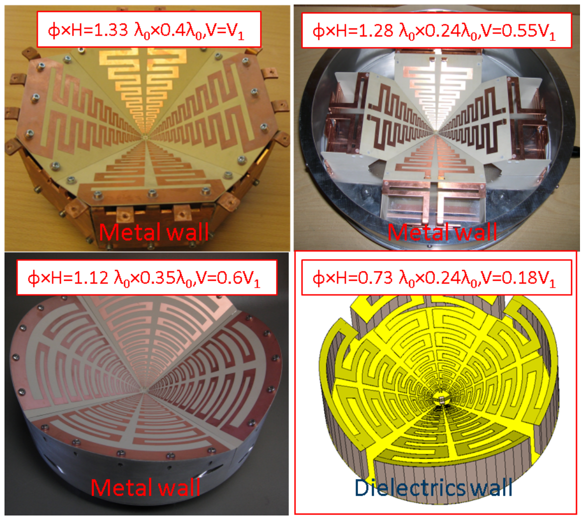

Fig. 10. Size reduction of Eleven feeds, where ϕ is the diameter of a feed aperture, H the height and V the volume of a feed, and λ_0 is the wavelength of the lowest operation frequency. It can be seen that the new developed feed (at right-down corner) has a volume of less than one fifth of the straight Eleven feed (at left-up corner), a significant size reduction.

VI. Size Compactness

Size compactness of a feed is important, especially in the case where the feed should be inside a cryostat or in low-frequency cases where the feed can be very big and heavy. Fig. 10 summarizes the development of the feed size reduction. From the figure, the newest Eleven feed can have a size smaller than one fifth of that of the feed presented in 2011 [7].

VII. Mechanical Design

The operational band of the Eleven feed, the particular application and the feeding network are setting up different challenges on the mechanical design. Parametric studies show that relatively thick dipoles (thickness of up to 1mm) can be used for the frequency bands up to about 4 GHz. This implies using low permittivity foam material (like the Rohacell foam) for dipole support and avoiding microwave substrates having the drawback of high tangent delta and permityvity coefficients. For frequencies higher than 4GHz, the thickness of the dipoles should be decreased to maintain low reflection coefficient which requires the mechanical design to use microwave substrate for the dipoles. The particular application, especially the cryogenic integration of the feed entails using of a substrate with well-matched coefficients of thermal expansion of the dielectric to the one of the copper. Furthermore the copper metallisation should be thick enough to have good thermal conductivity and allow cooling of the petal to temperature of about 25K. The feeding network is one of the most challenging tasks in mechanical design. The Eleven feed with 8-port feeding has relatively simple mechanical design, but the use of twin-lead lines sets very high requirements on the manufacturing and assembly tolerances. The central feeding has more complicated mechanical design but uses standard coaxial cables. Details on the mechanical design are published in [7] and [12].

TABLE I
SUMMARY OF ELEVEN FEED PERFORMANCE

	Examples
Aperture Efficiency	$>$ 60% over 1.2–12 GHz
Reflection coefficient	$<$ -10 dB over 2–14 GHz (measured) $<$ -14 dB over 0.2–1.64 GHz (simulated)
Radiation Efficiency	$\approx$ -0.2 dB over 2–14 GHz
Cross-polar Level	$<$ -15 dB over 1.2–12 GHz
Size (Diameter $\times$ Height)	$1.12\lambda_0 \times 0.35\lambda_0$ (with metal outer wall), $0.73\lambda_0 \times 0.24\lambda_0$ (with dielectric outer wall), (λ_0 is the wavelength of the lowest operating frequency)
Feeding Methods	8 coaxial ports for dual polarization, Balun feeding (4 or 2 coaxial ports for dual polarization), center connection feeding (4 coaxial ports for dual polarization)

VIII. CONCLUSIONS

Table I summarizes the overall performance of Eleven feeds. The Eleven feed can be used in both primary reflector antennas and dual-reflector antennas, where in the former case the optimal subtended angle is in the arrange of $2 \times 55°$–$2 \times 70°$ and in the latter case the optimal subtended angle for the main reflector may be adjusted by using different sub-reflectors. The size of Eleven feeds is very compact. Further developments on feeding structures, better reflection coefficient, and dual-reflector antenna systems are under going.

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