Broadband Feeds for VGOS

Miroslav Pantaleev[1], Leif Helldner[1], Bhushan Billade[1], Marianna Ivashina[2], Oleg Iupikov[2], Carlo Bencivenni[2], Jian Yang[2], Per-Simon Kildal[2], Terese Ekebrand[3], Jan Jönsson[3], Yogesh Karandikar[3], Anders Emrich[3]

Abstract The upcoming VGOS network aims at using dual polarization observations and a much wider bandwidth than traditional geodetic VLBI. This requires a new type of broadband feeds. Several such broadband feeds have been developed during the last years, among them the Eleven-feed and the Quadruple-Ridged Flared Horn (QRFH). In this paper we give an overview of broadband feeds for VGOS and compare their performance.

Keywords Very Long Baseline Interferometry, radio telescope, Eleven feed, QRFH, wideband feed, cryogenic technology

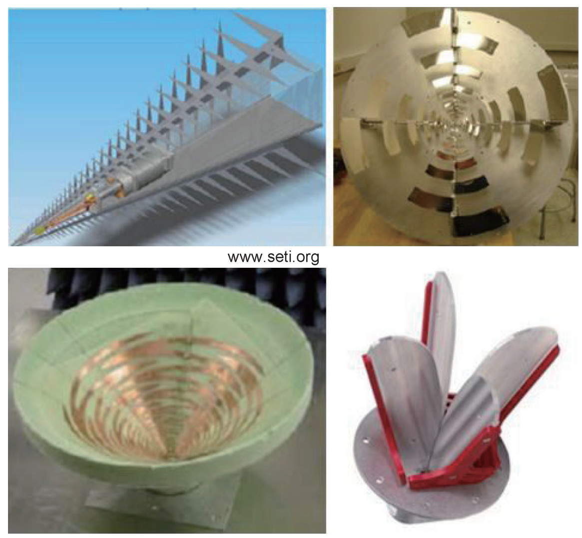

Fig. 1 Various UWB feeds: (top left) ATA feed, (top right) QSC feed, (bottom left) Inverted Conical Sinuous antenna, and (bottom right) ETS Lindgren feed.

1 Introduction

The future development of geodetic VLBI (Very Long Baseline Interferometry) requires the design of observing systems based on small, fast-moving, single-beam, dual-reflector antennas covering the frequency range 2.2–14 GHz [1]. Similar are the requirements for the mid-frequency dish array of the SKA (Square Kilometer Array) [2] which currently entered design phase. Both projects pushed for the development of a variety of UWB (Ultra Wide Band) feeds. Among them are worth noting the ATA Feed [3], QSC (Quasy Self Complementary) Feed [4], and Inverted Conical Sinuous antenna [5] (see Figure 1). UWB feeds for different applications and different frequency ranges are also available as commercial products. For example, vivaldy type antennas from ETS Lindgren [6] were used for the VLBI2010 proof-of-concept tests at MIT Haystack Observatory [7]. Since the requirements imposed on the radiation performance and reflection coefficient for the UWB feeds for the VLBI2010 applications are quite complex and strict, not all of the research groups working on feed development were able to continue their work with the integration of the feed into a cryogenic system for use on a radio telescope. It is also that each UWB feed has certain disadvantages. For example, the ATA feed's beam width and phase center location vary with frequency, which leads to a low aperture efficiency. The quasi self-complementary antenna is also a log-periodic dual-dipole-like antenna,

1. Onsala Space Observatory
2. Antenna Group, Department of Signals and Systems, Chalmers University
3. Omnisys Instruments

but it has a polarization that squints with frequency and no hardware has yet been realized above 4 GHz.

The two feeds which have good radiation properties and were integrated into cryogenic systems for installation on a telescope are the QRFH (Quad-Ridged Feed Horn) [12] and Eleven Feed [13], and they are discussed and compared further in this paper with the main goal of providing a high level description of the two VGOS feed design alternatives using published results based on simulations, tests, and scientific observations performed by various research groups and institutions. References are cited for the detailed descriptions of various designs and tests. In this way, the interested reader may obtain more detailed information.

2 VGOS Antennas and Feed Requirements

Sensitivity calculations show that the goal of 2400 Jansky is achievable with 12-m antennas equipped with a receiver with a noise temperature of about 35–40K. For the VGOS frequency range the feed is compact enough for cryogenic integration. This approach reduces the contribution of feed resistive loss to the receiver noise and also simplifies the feed–LNA interface, since for a system with the feed at ambient temperature a vacuum feedthrough is required to interface to the LNAs in cryostat. This feedthrough introduces extra losses compared to an entirely cryogenically integrated feed. An additional disadvantage of a feed at ambient temperature is that the system is more complex mechanically. Consequently, size and cryogenic cooling concerns (such as outgassing and thermally induced mechanical stress) play important roles in the design of decade-bandwidth feeds for VGOS radio telescopes. Due to the wide opening angle of the UWB feeds the usual choice for the reflector optics design is the dual-reflector, axisymmetric design with ring-focus sub-reflector [14]. There are several antenna manufacturers (Intertronics Solutions, MT Mechatronics GmbH, and Vertex Antennentechnik GmbH) offering such designs with 12-m or 13-m main reflector diameter. The main advantage of the ring-focus design is that the aperture efficiency is kept at a reasonably good level and the blockage of the feed cone and supporting struts is minimized. In addition, the construction of the feed tower is mechanically very rigid and also allows easy access to the receiver and electronics as compared to primary a focus dish. The f/D for reflector systems from different manufacturers spans the range 0.35–0.5; thus, these systems are well suited for UWB feeds.

3 Eleven Antenna

The Eleven antenna is a decade-bandwidth, log-periodic, dual-dipole array. It was originally proposed in 2005 by P. S. Kildal [8]. It was designed as a feed for reflector antennas and has been demonstrated for radio telescope applications because of features such as a nearly constant beamwidth width, directivity of about 11 dBi, a fixed phase center location (over the entire decade bandwidth), and low profile and simple geometry. Several hardware implementations, operating in frequency bands ranging from 400 MHz to 2 GHz and 2–14 GHz, were realized. The first successful attempt to make a high frequency model working up to 10 GHz was developed in 2007, but it suffered from some mechanical and cryogenic problems. These problems were solved with the design developed in 2009 and described in [13]. The hardware realization of the current VGOS version of the Eleven feed is shown in Figure 2.

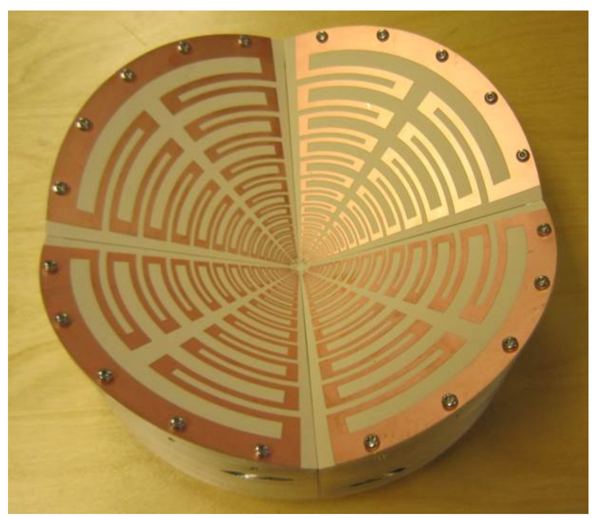

Fig. 2 Hardware realization of the current VGOS version of the Eleven feed.

The Eleven feed can receive dual linearly polarized waves, or, alternatively, it can be configured to receive circular polarization by means of quadrature combination of the two orthogonal linearly polarized ports, either by hardware or by software after detection. The antenna, for each linear polarization, consists of two oppositely-located log-periodic dipole arrays, i.e., two dipole petals. The opposite dipole pairs are separated by half a wavelength and located above a ground plane. Each pair constitutes a so-called petal and the pair of two opposite petals is forming one linear polarization. The dual-polarized Eleven antenna has four equal petals, as shown in Figure 2. The radiation field function of the Eleven feed is determined by the geometry of the four petals, which also has a strong impact on the input reflection coefficient. The goal of the electric design of the present Eleven antenna is to minimize the reflection coefficient at the input port of the petals, and at the same time to retain a good radiation performance, between 2.2 and 14 GHz.

An analytic or quasi-analytic analysis of the radiation field function of the Eleven antenna is only available for the basic geometry, i.e., for one pair of folded dipoles over an infinite ground plane, which provides the optimum ranges of the dimensions of each radiating dipole pair for the best radiation pattern shapes. An analytical impedance model for the multiple cascaded folded dipoles is not yet available. Therefore, the optimum dipole petal geometries for low input reflection coefficients must be determined by numerical analysis, using a general electromagnetic solver. Unfortunately, this is very time consuming, as the size of the whole log-periodic dipole petal geometry is very large in terms of wavelengths at the highest frequency. Numerical optimization becomes almost impossible, unless the log-periodic variation is accounted for in some way to reduce computation time. Therefore, a special computational approach, referred to as the partial array method for log-periodic geometries, was developed. The partial array method can be used to predict the reflection coefficient of a complete large log-periodic array from the S parameters of a sub-component of the log-periodic pattern. With this technique, the computation time is considerably reduced, and thereby allows for extensive optimizations. The partial array method and genetic algorithm is used to optimize the dimensions of the dipole petals, which provides the lowest reflection coefficient for a linearly polarized Eleven antenna. This means that only two opposing dipole petals are analyzed at a time, with both being correctly excited (equal amplitude and phase), and the dimensions that give the best radiation field functions are chosen. The radiation performance of the feed is judged by the values of the feed efficiency, i.e., the aperture efficiency of the blockage-free prime focus reflector with a certain subtended angle, as seen from the focal point. A goal of the simulation is also to keep the resulting reflection coefficient of the optimized linearly-polarized Eleven antenna, as simulated by CST Microwave Studio [9], low (preferably below −10 dB) over 2–14 GHz, when referred to an input balanced port impedance of 200 ohm on both dipole petals. The 200-ohm balanced input port impedance appears to be intrinsic to the Eleven antenna.

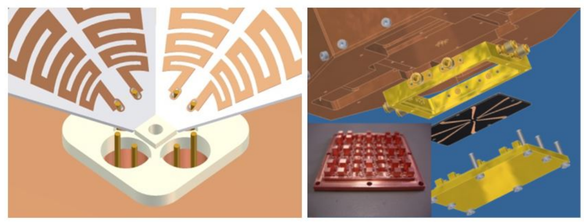

Fig. 3 View of the central region of the Eleven feed (left) and back side of the ground plane of the Eleven Feed with the 8-port and SMA connectors (right).

In the center of the geometry each dipole petal is connected to a balanced twin-lead transmission line, with a characteristic impedance of 200 ohms (Figure 3). The so-called center puck supports the petals and provides alignment for the twin lead lines. The two twin-lead transmission lines are connected to an impedance transformer realized in microstrip and located on the back side of the ground plane. The transformer output is a 50-ohm standard SMA connector. The four ports of the oppositely-located petals must be combined with the same amplitudes and phases in order to receive one linear polarization. This is usually achieved by connecting the two ports of each array to quadrature hybrid and then feeding the output of the hybrids connected to opposite placed dipole arrays via power combiner. Similarly, the two opposing pairs of orthogonal petals must be combined to receive the orthogonal linear polarization. The feeding network for a single polarization configuration is shown in Figure 4.

The reflection coefficient of the Eleven feed is overall less than −10 dB over the 2.2–14 GHz range. The simulated reflection coefficient of the Eleven feed is shown in Figure 5. The measured performance is quite close to the simulation. The same applies for the mea-

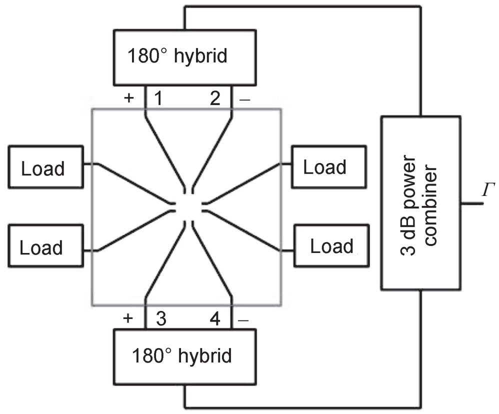

Fig. 4 Feeding configuration for the Eleven feed.

sured refection coefficient of the Eleven feed at cryogenic temperature. The use of SMA connectors and tin solder that are well suited for cryogenic applications minimizes the possibility of getting cracks in the solder after multiple thermal recycling.

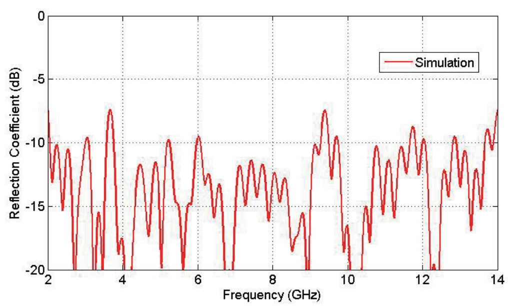

Fig. 5 Simulated reflection coefficient of the Eleven feed.

As seen in Figure 6, the beam width of the Eleven feed is nearly constant over the VGOS frequency range. The phase efficiency is high due to the nearly constant location of the phase center over the frequency range. The cross polarization level for the 2.2–14 GHz is relatively low. The radiation efficiency (ohmic loss) of the Eleven feed is between −0.1 dB and −0.4 dB over 2–8 GHz, and between −0.4 and −0.5 dB up to 14 GHz. The impact of the ohmic losses on the overall system noise is minimized since the petals are at a physical temperature of about 30 K. Y-factor tests done at Onsala Space Observatory showed that the receiver noise is about 20 K over the 4–10 GHz range slightly rising to about 30 K at the lowest and highest edges of the band.

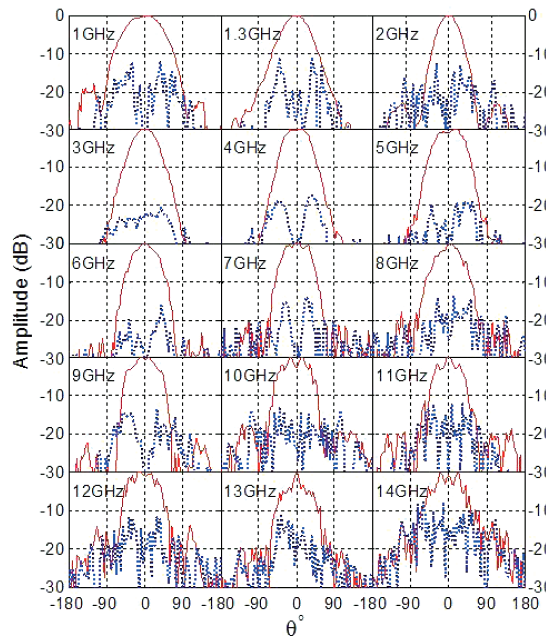

Fig. 6 Measured co-pol (red curve) and cross-pol (blue curve) patterns of the Eleven feed.

The cryogenic integration of the Eleven feed for commercial applications suitable for VGOS is done by Omnisys Instruments [10]. Figure 7 shows a CAD model of the cryostat developed at Omnisys. The Eleven feed is integrated at 20K physical temperature together with LNAs from Low Noise Factory [11] installed on a temperature-stabilized bracket to improve the gain and phase stability of the system. The system also incudes directional couplers for phase- and noise calibration signals injection.

4 QRFH

This section builds upon the recent publications of Akgiray [12, 16] and also on recent work done at Chalmers University during 2013 and reported in [18]. The most distinct feature of the Quad-Ridge Flare Horn (QRFH) with respect to the Eleven feed is its capability to form a nearly constant beam width pattern and to be optimized for a relatively large range of reflector subtended angles. This feed requires one single-ended

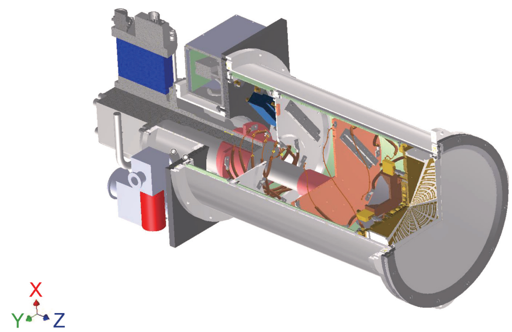

Fig. 7 Commercial realization of the cryogenic front-end for VGOS. [Courtesy of Omnisys Instruments.]

Low Nose Amplifier (LNA) per polarization; and its input impedance can be optimized for a reference (interface) impedance value between 50–100 ohms.

The QRFH is a circular horn with four perpendicular inset ridges. Three main sections are identifiable: (i) the tapered transition from the circular waveguide to the radiating aperture of the horn), (ii) the feeding section, and (iii) the back short section (see Figure 8). The taped profile realizes the transition from the circular waveguide to the radiating aperture, while supporting the dominant modes. Both the horn and profiles of the ridges are tapered. Each pair of the oppositely oriented ridged is associated with a separate polarization. The feeding of each pair is realized via a coaxial cable connected to a port on the external wall of the horn. Below the feeding section, a back short cavity is realized. This section is realized to support the transition from the coaxial line to the ridge propagation section, while radiating only in the direction of the horn aperture.

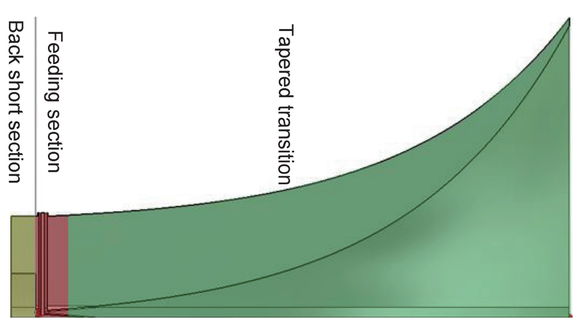

Fig. 8 Cross section of the QRFH.

Among all the parameters describing the quad-ridge horn geometry, parameters defining the ridge and sidewall profiles play a critical role in determining the performance of the horn. A number of different profiles were considered in [12], but the most promising type was found to be the exponential profile.

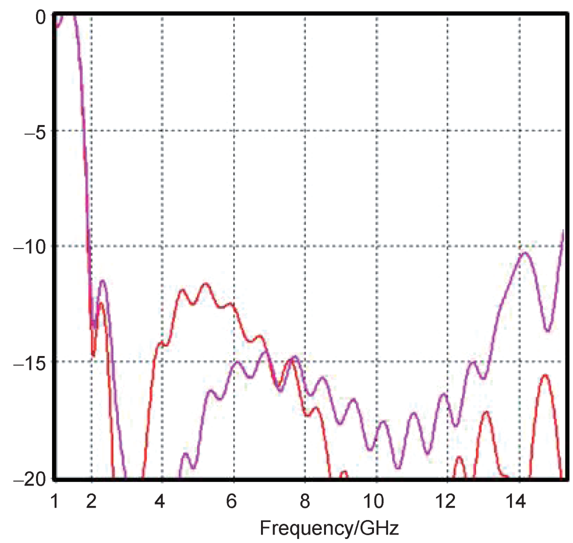

Fig. 9 Reflection coefficients of the QRFH – Chalmers design.

Reflection coefficients for different designs of the QRFH were presented in [16] and similar results were achieved in the design reported in [18]. The reflection coefficient for the QRFH design done at Chalmers is shown in Figure 9. Beam patterns from the same study are shown in Figure 10; as can be seen, the beam width is constant over the frequency range.

The QRFH designed at Caltech was successfully implemented and is currently used at MIT Haystack Observatory [17]. Figure 11 shows a 3D CAD drawing of the QRFH integrated in a 20 K physical temperature cryostat together with UWB LNAs from Caltech University. The system also incudes directional couplers for phase- and noise calibration signals injection.

5 Comparison

A document providing a comparison of the different VGOS feed alternatives was published in February 2013 [19]. In the document both the Eleven feed and

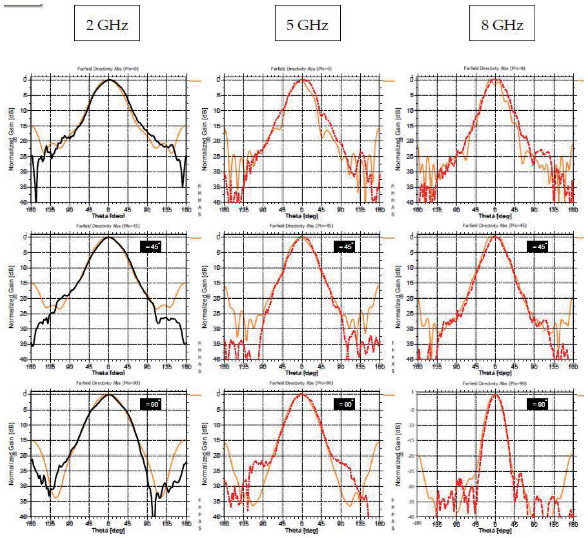

Fig. 10 Beam patterns of the QRFH – Chalmers design.

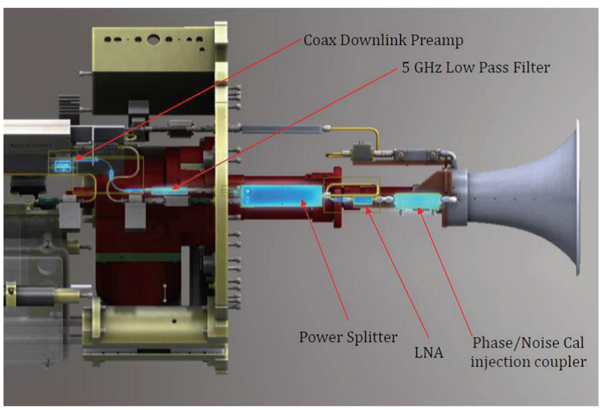

Fig. 11 QRFH integrated into a cryogenic front-end. [Courtesy of Chris Beaudoin, MIT Haystack Observatory.]

the QRFH feed as well as triple-band feeds were described. Here we concentrate on the UWB feeds and for completeness present the comparison table from [19]. The aperture efficiency calculations were performed in axisymetric, dual-reflector system with ring focus type sub-reflector. The data for the antenna geometry was provided by InterTronic Solutions Inc (Figure 12).

The beam pattern data set for the QRFH was provided by Ahmed Akgiray from Caltech University. The sampling in theta and phi was 1 and 15 degrees, respectively, with 100-MHz steps over the 2–12 GHz frequency range. The beam pattern data set for the Eleven feed was provided by Jian Yang from Chalmers University. The sampling in theta and phi was 1 and 5 degrees, respectively, with 150 MHz steps over the 1–14 GHz frequency range. Both data sets were for simulated feed patterns. The beam patterns were imported into GRASP with a MATLAB script and the position of the feed in the reflector system was optimized for the phase efficiency at the sub-reflector. Then GRASP was used to calculate the far-field pattern of the feed reflector system. The last step was to feed the far-field patterns into MATLAB and calculate the phase efficiency and cross-pol of the feed–reflector system.

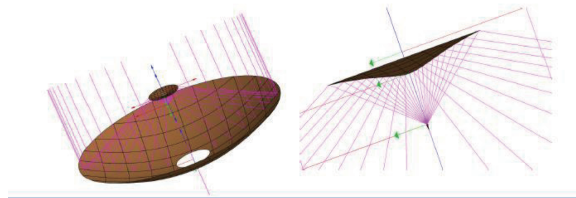

Fig. 12 Intertronics axisymetric, dual-reflector system with ring-focus sub-reflector.

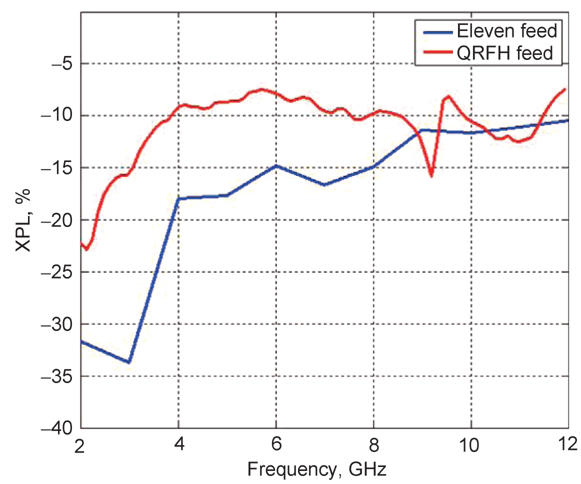

Fig. 13 Cross-pol for the Eleven feed and the QRFH feed.

The cross-pol for the QRFH and Eleven feeds are compared in Figure 13. As seen the cross-pol of the QRFH is worse than the Eleven feed. The dual reflection in the Cassegrain system minimizes this effect for both feeds but as Figure 14 shows the cross-pol level for the Eleven feed is well below −25 dB, while for the QRFH it is around −15 dB over the VGOS frequency range.

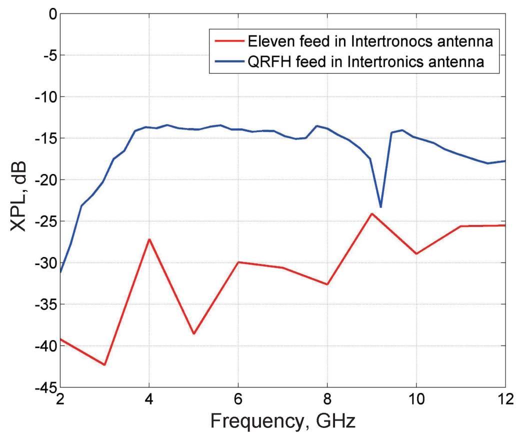

Fig. 14 Cross-pol for Eleven feed and QRFH in Intertronics axi-symetric dual reflector system with ring-focus sub-reflector.

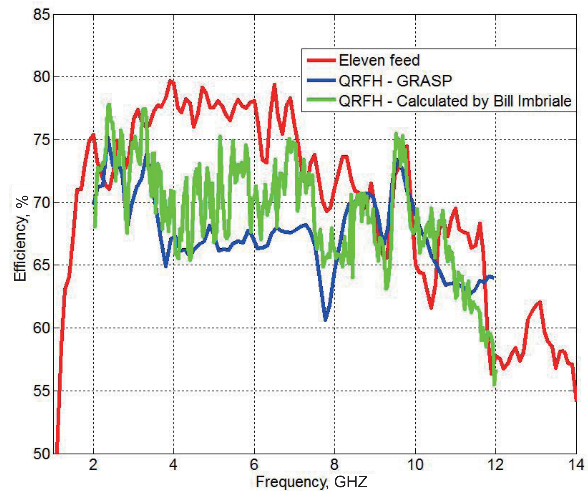

Fig. 15 Aperture efficiency for Eleven feed and QRFH in Intertronics axi-symetric dual reflector system with ring-focus sub-reflector.

The aperture efficiencies for the Eleven and QRFH feeds in the Intertronics axisymetric, dual-reflector system with ring-focus sub-reflector are shown in Figure 15. The GRASP analysis for both the Eleven feed and the QRFH feed used in the Intertronics reflector system was performed at Chalmers University using the method described above. The GRASP results are compared to aperture efficiency calculated by Bill Imbriale with Physical Optics Software available at Caltech University. The aperture efficiency of the Eleven feed is better over the 3–7 GHz band compared to the QRFH performance. The performance of both feed over the 2–3 GHz and 9–12 GHz bands is quite comparable. Data for the particular QRFH model was not available for the 12–14 GHz but according to [15] the aperture efficiency of the QRFH for this highest part of the band is similar to the Eleven feed. It should be noted that after providing the efficiency comparison plot for [19] an error in the convergency set-up for QRFH was discovered. Here in the problem in Figure 15 the results for QRFH are with the correct convergency setting.

Table 1 compares some of the main features and also the performance of the QRFH and Eleven feeds [19]. A disadvantage of the Eleven feed from a system integration point-of-view is that it requires a greater number of LNAs. On the other hand, the Eleven feed has better sensitivity and cross-pol for f/D in the 0.35–0.5 range. The QRFH has the advantage that it can be designed to match a wider range of f/D values, but currently (to our knowledge) there is no data about the efficiency of the QRFH in such systems over the VGOS frequency range.

6 Conclusions

As described above, both the Eleven feed and the QRFH feed are suitable for VGOS. The main advantage of the Eleven feed is the higher efficiency over some part of the band and better cross-pol, while the QRFH has the advantage that it is adaptable for a wider range of f/D values and requires less LNAs. Both systems are available for purchase as integrated in complete cryogenic system together with the LNAs. Depending on the particular antenna reflector system more detailed studies need to be done on the ground pick-up via the side lobes in order to get an accurate prediction of the Aeff/Tsys figure of merit.

Acknowledgements

The work on the Eleven feed has been supported by the Swedish VR Research Infrastructures Planning Grant “Swedish contributions to the SKA radio telescope in its pre-construction phase” Contract No C0546801. The work on the mechanical design, system integra-

Table 1 Feed comparison from [19].

	Eleven Feed	QRFH Feed
VLBI2010 compatibility	yes	yes
Frequency range (GHz)	1.2–14	2.2–14
Polarization configuration	dual-linear	dual-linear
Port configuration	differential	single-ended
LNAs per polarization	4	1
LNAs per feed	8	2
LNA balance requirements	1.6 dB amp 14° phase	none
Calibration signal injection	radiated or post-LNA	radiated, pre-LNA, or post-LNA
Aperture efficiency (f/D ∼ 0.375)	see Figure 15	see Figure 15
Ground noise contribution (f/D ∼ 0.4)	preliminary: 10–20K (needs research)	<20K (2.2–5 GHz) <10K (2.2–5 GHz)
f/D Range	0.35–0.5	adaptable for 0.3–2.5
Feed 10-dB half-beamwidth	65°	adaptable for 15°–70°
Size (half-beam-width ∼ 65°)	diameter 210 mm height 65 mm	diameter 160 mm height 150 mm
Cost	US$33,000 (to be confirmed)	US$15,000

tion, and tests for the Eleven feed (2008–2010) was supported by Onsala Space Observatory.

References

1. P. Petrachenko, et. al., "Design Aspects of the VLBI2010 System" Progress Report of the IVS VLBI2010 Committee, ftp://202.127.29.33/pub/VLBI2010/V2C/PR-V2C_090417.pdf.
2. P. Hall, The SKA: An Engineering Perspective, Springer, 2005.
3. G. Engargiola, "Non-planar log-periodic antenna feed for integration with a cryogenic microwave amplifier", Antennas and Propagation Society International Symposium, 2002. IEEE (Volume:4).
4. G. Cortes-Medellin, "Non-Planar Quasi-Self-Complementary Ultra-Wideband Feed Antenna", IEEE Transaction on Antennas and Propagation, Vol.59, No6, June 2011.
5. Gawande, R., Bradley, R. "Towards an Ultra Wideband Low Noise Active Sinuous Feed for Next Generation Radio Telescopes", IEEE Transaction on Antennas and Propagation, Vol.59, No6, June 2011.
6. "Open boundary quad-ridged horn", [online Available: http://www.ets-lindgren.com/pdf/3164-05.pdf
7. A. Niell et al., "First Broadband Results with a VLBI2010 System", IVS 2012 General Meeting Proceedings, pp. 13-17. http://ivscc.gsfc.nasa.gov/publications/gm2012/Niell.pdf
8. R. Olsson, P.-S. Kildal, S. Weinreb, "The Eleven antenna: a compact low-profile decade bandwidth dual polarized feed for reflector antennas", IEEE Trans. Antennas Propogat., vol. 54, no. 2, pt. 1, pp. 368-375, Feb. 2006.
9. CST Microwave Studion, https://www.cst.com/Products/CSTMWS
10. Omnisys Instruments, http://omnisys.se/
11. Low Noise Factory, http://www.lownoisefactory.com/
12. A. Akgiray, S. Weinreb, W. Imbriale, and C. Beaudoin, "Circular quadruple-ridged flared horn achieving near-constant beamwidth over multioctave bandwidth: Design and measurements," IEEE Trans. Antennas Propag., vol. 61, no. 3, pp. 1099 - 1108, March 2013.
13. J. Yang, M. Pantaleev, Per-Simon Kildal, B. Klein, N. Wadefalk, M. Ivashinna "Cryogenic 2 — 13 GHz Eleven Feed for Reflector Antennas in Future Wideband Radio Telescopes," IEEE Treansactions on Antennas and Propagation, vol. 59, no. 6, pp. 1918-1934, 2011.
14. C. Granet, "A simple procedure for the design of classical displaced-axis dual-reflector antennas using a set of geometric parameters", Antennas and Propagation Magazine, IEEE (Volume:41 , Issue: 6).
15. A. Akgiray, M. Pantaleev, C. Beaudoin, Private communicaitons, 2013.
16. A. Akgiray, "New Technologies Driving Decade-Bandwidth Radio Astronomy: Quad-Ridged Flared Horn & Compound-Semiconductor LNAs", http://thesis.library.caltech.edu/7644/1/Akgiray_PhDThesis_FinalVersion.pdf
17. C. Beaudoin, B. Corey, A. Niell, A. Whitney, "Haystack Observatory Technology Development Center", IVS 2011 Annual Report, ftp://ivscc.gsfc.nasa.gov/pub/annual-report/2011/pdf/tdhstk.pdf.
18. C.Bencivenni, M. Ivashina, "Quadruple-Ridge Flared Horn Feed design reoport", Onsala Observatory Internal Technical Report, June 2013.
19. B. Petrachenko, "VLBI2010 Feed Comparisson", In: International VLBI Service for Geodesy and Astrometry 2012 Annual Report, edited by K. Baver and D. Behrend, NASA/TP-2013-217511, 48–51, 2013.