MeerKAT—The South African Array With Composite Dishes and Wide-Band Single Pixel Feeds

This project aims to develop and prove novel technologies that can reduce construction and operation costs for future large radio telescope.

By Justin L. Jonas

ABSTRACT | The MeerKAT is a precursor for the “small dish plus single-pixel wide-band feed” scenario for the Square Kilometer Array (SKA). The current goal specification is for an array of 80 12-m dishes operating over a continuous frequency range of 0.7–10 GHz, thus the individual receptors match the SKA draft specification for midband dishes. The proposed array configuration is centrally concentrated with 70% of the collecting area within a 700-m-diameter circle and the remaining 30% extending out to baselines of 10 km. The site for MeerKAT lies within a radio quiet reserve established in the remote and Northern Cape province of South Africa. The technologies and techniques that MeerKAT will develop and evaluate include wide-bandwidth feeds, low-cost dish antennas, instrumentation for high dynamic range observations, packet-switched array processing architectures, shielding of component radio-frequency interference (RFI), mitigation of external RFI, and low-cost and reliable remote telescope operation.

KEYWORDS | Antenna feeds; antennas; digital signal processors; radio astronomy

I. INTRODUCTION

The Square Kilometer Array (SKA) will consist of a combination of receptor types that match the scientific requirements and technical constraints relevant to the various frequency bands covered by the telescope. SKA Memo 100 [1] provides the draft specifications for the SKA and outlines the various technology options for realizing the telescope. The expectation is that the lower frequency regime of the SKA will be implemented using sparse and dense aperture arrays, with dishes covering the higher frequencies. The lower operating frequency of the dishes will be between 300 MHz and 800 MHz, depending on the highest frequency that the dense aperture array will achieve. The baseline dish solution for the SKA is a large number of small/medium reflector antennas, the so-called large number small diameter (LNSD) scenario, illuminated with single-pixel wide-band feeds. The MeerKAT is a science and technology demonstrator for this implementation scenario for the SKA radio telescope.

MeerKAT is scheduled for completion in 2013 and will be preceded by a series of prototyping phases and technology development programs. Two of the major prototype exercises are the XDM, a single 15-m dish located at the Hartebeesthoek Radio Astronomy Observatory (HartRAO); and KAT-7, a seven-element interferometer consisting of 12-m dishes located within the Karoo Radio Astronomy Reserve. The final MeerKAT specifications will be modulated by the need to build the instrument for a fixed capital and operational cost and within the specified time-scale.

II. THE KAROO RADIO ASTRONOMY RESERVE

The SKA will have a sensitivity that is orders of magnitude greater than existing radio telescopes and will operate in
frequency bands outside of those allocated to the radio astronomy service by the ITU. To achieve the scientific goals that require this extreme sensitivity and frequency coverage, the SKA will have to be located at a site with low radio-frequency interference (RFI) across the entire band from 70 MHz to 30 GHz, or higher. By association, the MeerKAT will also require a pristine RFI environment in order to achieve its own scientific objectives.

The South African government has proclaimed the Karoo Radio Astronomy Reserve, the location and extent of which is shown in Fig. 1, to provide a site and infrastructure support for new-generation radio telescopes (including the SKA and MeerKAT). This arid region is an intrinsically radio-quiet area because of its low population density, its low economic activity, and the shielding effect of the flat-topped hills that encircle the southern boundary of the site. The reserve is protected by legislation designed to ensure the maintenance and improvement of the current low RFI levels into the future. The Astronomy Geographic Advantage Act No. 21 of 2007 provides the Minister of Science and Technology with powers to prohibit terrestrial transmissions within the reserve and control emissions that enter the reserve from the surrounding area. This reserve will be the location for the inner core of the SKA if it is located in South Africa. The extensive reserve area will be available for other radio astronomy instruments requiring stringent RFI control, including MeerKAT.

In developing infrastructure in this region to support MeerKAT and other telescopes, care has been taken to ensure that the radio quietness is not compromised. In particular, extensive theoretical and experimental studies have been undertaken to determine the best way to supply electrical power via the national utility grid network. Corona discharge and arcing on overhead pylons has been avoided by appropriate component selection and pylon design, and the final section of the power line to the MeerKAT site is buried underground.

### III. Specifications and Performance

Table 1 lists the specifications for both the current MeerKAT reference design and a more ambitious alternative design. The alternative (or goal) design indicates the direction in which the telescope parameters and technology choices might evolve as products from various technology development programmes become available. The 2.5 GHz upper operating frequency for the reference

<table>
<thead>
<tr>
<th>Subsystem/specification</th>
<th>Current Reference Design</th>
<th>Possible Alternative</th>
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<tbody>
<tr>
<td>Feed</td>
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<td>single-pixel wide-band</td>
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<tr>
<td>Lower frequency</td>
<td>500 MHz</td>
<td>700 MHz</td>
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<tr>
<td>Upper frequency</td>
<td>2.5 GHz</td>
<td>10 GHz</td>
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<tr>
<td>Dish diameter</td>
<td>12 m</td>
<td>12 m</td>
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<tr>
<td>Surface accuracy (RMS)</td>
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<td>1 mm</td>
</tr>
<tr>
<td>Optical configuration</td>
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<td>offset or symmetric Gregorian</td>
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<tr>
<td>Mount geometry</td>
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<td>equatorial</td>
</tr>
<tr>
<td>Number of dishes</td>
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<tr>
<td>Tsys</td>
<td>30 K</td>
<td>25 K</td>
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<tr>
<td>Polarization isolation</td>
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<td>25 dB</td>
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<tr>
<td>Instantaneous bandwidth</td>
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<td>1024 MHz</td>
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<td>Spectral channels</td>
<td>16 384</td>
<td>65 536</td>
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<tr>
<td>Minimum baseline</td>
<td>20 m</td>
<td>20 m</td>
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<tr>
<td>Maximum baseline</td>
<td>7 km (70% within 700 m)</td>
<td>10 km (70% within 700 m)</td>
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<td>Correlator architecture</td>
<td>FX</td>
<td>FX</td>
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Fig. 1. The location and extent of the radio-quiet reserve within the Northern Cape province of South Africa. The purple dot marked "SKA Site" near the center of the region is the proposed location for the inner core(s) of the SKA and is also the location of the MeerKAT. The green line traces the roughly 90 km road between the site and Carnarvon, the closest small town.
design reflects the nominal SKA midband specification as it was prior to November 2007. SKA Memo 100 [1] indicates that the upper frequency limit for SKA Phase 1 and Phase 2 has subsequently increased to 10 GHz, and the goal upper frequency for MeerKAT matches this value. The lower frequency limit for both SKA and MeerKAT will be determined in part by the upper operating frequency demonstrated by aperture array technologies currently being investigated in the EU-funded SKA Design Study program.

Three key aspects of the MeerKAT antenna design are still under discussion: the reflector optical configuration, the antenna mount geometry, and the array configuration. These are known to be major factors in determining the dynamic range of radio interferometers. Discussion of these antenna performance characteristics is to be found in Section IV-A. The array configuration will be centrally concentrated with a large fraction of the collecting area within a 700-m-diameter circle, which is intended for high dynamic range imaging of extended structures, and also reduces the data rates required for wide-field transient detection. Some fraction of the antennas will extend out to 10 km to provide imaging capability at higher resolution and also assist with the localization of point sources and image calibration. Detailed studies will be conducted using the AntConfig tool\(^2\) to optimize the final MeerKAT configuration, which will require a trade-off between surface brightness sensitivity, data rates and imaging resolution. The FX correlator (see Section IV-D) is being designed to handle all three 3160 baselines and will implement phase tracking and fringe stopping in the digital domain. Dump rates as fast as 0.1 ms will be available for transient searches and pulsar data processing.

Table 2 is a list of performance metrics derived at 1420 MHz for the MeerKAT reference design, using the specifications from the middle column of Table 1 (MeerKAT Reference Design). The relevance of these metrics is discussed in various SKA memos ([1]–[3], amongst others). The point-source sensitivity of 211 m\(^2\) K\(^{-1}\) for the reference design is close to the L-band performance of the Expanded Very Large Array (EVLA).\(^3\) This metric is relevant to deep integration observations towards individual objects or small fields or the detection of weak transient signals. The mapping speed and brightness temperature sensitivity at 1 arcminute resolution outstrip the EVLA and other existing compact interferometer arrays because of the high filling factor within a diameter of 700 m and the relatively large field-of-view provided by the primary beam of the 12-m dishes. “Survey speed” metrics are relevant to large-scale survey observations and to the detection of brighter transients. These performance metrics will locate MeerKAT in a unique position in observation parameter space, allowing the telescope to provide new insight into the evolution of galaxies, the nature of cosmic magnetic fields, extended low-brightness radio sources, and the detection of radio transients and pulsars. The MeerKAT observing programme will consist largely of shallow wide-field and deep narrow-field surveys of radio continuum, HI emission and absorption, OH maser lines, recombination lines, and radio transients (including pulsars). Full Stokes polarimetry will be available, and the dish optical configuration will be designed to contribute low instrumental polarization.

### IV. TECHNOLOGY DEVELOPMENT PROGRAMMES

As an SKA pathfinder, the MeerKAT project includes a range of technology development programs that investigate novel technologies and techniques that are relevant to modern radio telescopes, with the aim of reducing the technical and cost risks associated with these new instruments. Technology challenges that are common to the SKA and MeerKAT will be pursued by the various MeerKAT subsystem development teams. This work will be coordinated with the SKA Preparatory Phase Programme, dubbed PrepSKA.\(^4\) The entries in the right-hand column of Table 1 represent goal specifications that might be achieved by MeerKAT if these development activities are successful.

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1www.skads-eu.org.
3http://www.aoc.nrao.edu/evla.
4www.jb.man.ac.uk/prepska.


The technology development programs are underpinned by prototyping and early deployment phases, including extensive laboratory investigations, a prototype 15-m composite material dish with feed, receiver and digital back-end (XDM) at HartRAO, and a seven-antenna prototype array of 12-m dishes at the Karoo site (KAT-7). Formal systems engineering processes are employed to minimize risks associated with integration and commissioning, and cost overruns.

Four of the most prominent development programmes are briefly described in the following sections. In addition to these specific areas of development, the MeerKAT programs will include investigation into other technical and operational issues, such as analog and digital data transport, the reduction of RFI emission from all classes of telescope and infrastructure equipment, the shielding of residual RFI emissions from these systems, RFI mitigation in the signal-processing path, pipelined data processing and quality assessment, remote operation of a large scientific instrument, RFI-silent provision of grid and backup power, and the use of renewable energy technologies for power and cooling. The progress and prioritization of these research programs is dictated by the implementation schedule of the MeerKAT (e.g., control of RFI emissions takes precedence over RFI mitigation in the signal path).

A. Dish Diameter, Optical Configuration and Mount Geometry

The choice of 12 m for the KAT-7 and MeerKAT dish diameter resulted from tradeoff studies using the SKA costing model SKAcoast [4]. SKA Memo 100 [1] provides details of these studies, which mainly trade antenna structure costs against electronics and computing costs. Smaller dishes are cheaper per unit aperture than larger dishes, but this is balanced by increased electronics and computing costs associated with the larger number of antennas. Slightly different optimal diameter solutions result from using sensitivity and survey speed as target metrics [1]. An implicit consequence of this choice of 12 m is the restriction of the lower operating frequency to about 500 MHz because of the effect of diffraction losses. Because the antenna mechanical structure is a dominant cost component, even for relatively small dishes, it appears that antenna mechanical structure is a dominant cost component, because of the effect of diffraction losses. Because the lower operating frequency to about 500 MHz is to be achieved, hence the goal T_{sys} of 25 K in Table 1.

In order to achieve thermal noise limited sensitivity with the SKA, the instrument will require an imaging dynamic range of 70 dB and a high spectral dynamic range. The individual components in the signal path (both analog and digital) will need to be designed to support these performance metrics, and the spatial and temporal characteristics of the antenna beam pattern are of particular concern in this regard. Stray sidelobes allow contamination of the primary field of view by sources outside of that field, and if the beam pattern is time-variable on the sky, then it is technically difficult and computationally expensive to remove contamination and perform reliable calibration during postprocessing.

Wide-field, high dynamic range imaging introduces severe requirements for the pointing performance of the antennas in order to reduce time-varying image plane effects. This is particularly true in the L-band, where the sky is full of strong sources that will appear to vary in flux if the primary beam is not stable in the plane of the sky. Although there is currently no definitive study of the pointing specification for the SKA (or MeerKAT) antennas, it is likely that the pointing accuracy should be less than 1% of the full-beamwidth at half-maximum when operating at L-band. The MeerKAT and its antenna prototyping phases have adopted this preliminary guideline for pointing accuracy.

Although dynamic range is an important driver for the SKA, there is no clear consensus on the best design choices for fundamental characteristics of the SKA antennas. The relatively small sample of existing radio interferometers does not sample the mount/optics/array-configuration parameter space sufficiently to unambiguously untangle the factors influencing image dynamic range and polarization purity. For instance, the Westerbork Radio Synthesis Telescope routinely exceeds 100 000 : 1 imaging dynamic range and has excellent polarization performance. This performance might be attributed to the fact that the equatorial geometry does not rotate the primary beam on the sky during a scan, hence keeping a constant parallactic angle, but it might also be attributed to redundancy in the array configuration, or the symmetric optical configuration provided by the center-fed prime-focus layout.

To satisfy its role as an SKA pathfinder, and to achieve its own telescope specifications, the MeerKAT programme includes simulations and design studies to investigate various permutations of optical configuration and mount geometry to evaluate their ability to achieve high dynamic range observations and to determine their cost. Full-field physical optics simulations will be used to predict complex beam patterns for various optical configurations, and metrics that characterize the beam efficiency, sidelobes, and cross-polarization will be determined for each case. An attempt will be made to determine how these primary beam metrics impact on the eventual dynamic range of the array.

Included in the options being considered are symmetric and offset Gregorian optical paths that show promise to produce a clean primary beam with low cross-polarization. The Greenbank Telescope5 and Allen Telescope Array [5], [6] have already demonstrated that the unblocked

\[ \frac{A_e}{T_{sys}} \]

apertures provided by offset optics have good beam performance. Unblocked signal paths clearly provide the promise of good aperture efficiency, and folded optical paths can reduce the system temperature contributions from ground spillover suffered by prime-focus configurations. Ground spillover is a particular concern for wideband feeds that have reduced control over illumination taper.

Elevation over azimuth mount geometries are commonly used for radio telescopes because they are cost-effective and simplify the pointing model for the telescope. Rotation of the beam pattern on the sky is a concern, however, because this introduces a time-varying image-plane effect that complicates the downstream image calibration process. This is particularly true for polarimetric observations. A parallactic angle derotation stage or an equatorial mount geometry can be used to mitigate this effect but add to the construction cost. An alternative is to ensure that the beam pattern is circularly symmetric, or nearly so, to reduce rapid changes in the all-sky beam as it rotates against the sky background. Unblocked aperture systems, or systems with circularly symmetric blockage, may provide the required mitigation.

The complex beam patterns determined for each optical and mount configuration will be used to simulate array observations, using realistic radio continuum and neutral hydrogen sky models and a standard array configuration. The visibilities provided by these simulations will be processed using standard imaging and calibration processes, and the reconstructed images will be compared with the original sky models to determine the achieved dynamic range, polarization purity, and overall image fidelity.

B. Composite Antenna Design and Fabrication

One-piece molding or pressing techniques for antenna reflectors are an attractive option for the LNSD scenario for both scientific and manufacturing reasons. The mold or press tool provides a convenient mass-production facility and ensures manufacturing repeatability within tight tolerances for the large number of reflector antennas required. The single-piece reflector is free of regular surface errors associated with panel misalignment that lead to spurious “grating” sidelobes and removes the need for labor-intensive and error-prone manual panel adjustment. The reflector surface becomes part of the mechanical structure, thus reducing the need for extensive backing structures that add to the mass and cost of the reflector. One-piece pressing of metal reflectors larger than about 6 m presents significant challenges, but molding of composite structures is not limited by size constraints. The MeerKAT dishes will be fabricated using composite structures unless hydro-forming of large aluminum reflectors proves to be technically feasible and more cost effective.

A prototype 15 m dish fabricated using composite materials (glass-fiber, foam, and steel) was constructed at HartRAO during early 2007 (XDM). The prime contractor for this project was IST Dynamics (now BAE Land Systems Dynamics), and the composite reflector fabrication was subcontracted to MMS Engineering. The relatively large diameter and flat focal ratio \( f/D = 0.5 \) seem inappropriate for the MeerKAT Reference Design, but this is because the dish specifications were frozen at a time that multipixel feed technologies that required a larger focal plane were being considered for MeerKAT. Extensive finite-element modelling (FEM) analyses were performed in the design phase to ensure the surface and pointing specifications would be met under operational environmental conditions. FEM was used to test the effects of gravity loading, wind loading, and differential temperature on the entire structure, including concrete pedestal, steel alidade, composite reflector surface, and steel feed support legs.

Fig. 2 shows the XDM mould under construction at HartRAO. The individual mold segments are themselves composite structures, formed on a common pattern. Reflector metallization was achieved by depositing a thin layer of aluminium in the mould surface prior to laying up the composite materials. The resin infusion process is shown in Fig. 3, and Fig. 4 shows the completed reflector being mounted on the pedestal. The dish saw “first light” in July 2007, just seven months after the foundations were laid in December 2006. This prototype has shown that the
use of composite materials is viable and financially competitive. The dish surface was measured using standard photogrammetry techniques. The overall root mean square (rms) surface accuracy is 2 mm, with the inner 12 m section achieving better than 1.5 mm rms. The measured reflector distortion was not a precise match to the FEM predictions, particularly for the annulus beyond the radius of the leg attachment points (unpublished internal communication). Stresses introduced into the reflector when the backing structure was attached have been identified as the cause of this anomalous distortion. A new technique for attaching the feed legs and backing structure has been devised that will reduce these distortions significantly, and future reflectors should achieve 1 mm rms accuracy.

The next phase of prototyping is the construction of the KAT-7 array near to the eventual MeerKAT site. These dishes will have a diameter of 12 m and have a focal radio \( f/D = 0.38 \), which is more appropriate for the wide-band feeds being considered. The company that built the XDM has undertaken an extensive cost optimization exercise based on their experiences with the 15-m dish. This study has provided a new design that will be lighter and cheaper than the original and will have improved surface accuracy (goal of 0.5 mm rms to support a 10 GHz upper frequency specification). The KAT-7 12-m dish design is illustrated in Fig. 5. The composite reflector is only 15 mm thick (compared to 150 mm for the XDM) and the backup structure is fabricated from folded steel components. The azimuth drive system uses a single motor and spring-
loaded pinion to provide antbacklash motion control. Elevation actuation is provided by a linear ball screw jack, in contrast to the pinion and bull gear used for the XDM. The decrease in static and dynamic loading for the 12 m KAT-7 antenna made this cheaper option possible. The KAT-7 dishes will compare the performance, cost, and manufacturability of various reflector surface metallization options, including plasma spraying of a surface aluminium layer and mesh embedded in the front surface of the composite structure.

Having determined performance metrics for the various permutations of optical configuration and mount geometry (see Section IV-A), fully costed engineering designs for the most promising candidates will be pursued to identify viable implementations for MeerKAT. In particular, we will be exploiting the fabrication opportunities presented by the use of composite materials and the different optical path configurations. For instance, the offset Gregorian optical configuration allows for substantial subreflector and feed support structures without causing unacceptable aperture blockage. Should one of these candidates prove more cost-effective than the existing symmetric centre-fed KAT-7 design, then it will be adopted for MeerKAT, perhaps requiring a further preproduction prototype antenna to be constructed.

C. Wide-Band Feeds and Receivers

The MeerKAT Reference Design calls for a dual-polarization feed with a 5:1 frequency span, and the goal frequency range is more than double this. Conventional waveguide orthomode transducers (OMTs) and feeds cannot operate optimally beyond octave frequency ranges, so a novel wide-band feed antenna will be required if a single feed/receiver package is to be employed. The ATA already uses a log-periodic feed that boasts an 11:1 frequency coverage with good impedance matching across the band [7], but this feed suffers from the drawback of a frequency-dependent phase center.

Two groups are working on wide-band feed antennas for radio astronomy use that have fixed phase centers, both of which employ a structure based on dual parallel dipoles over a ground plane. The “Eleven Feed” [8] developed at Chalmers University produces a circular beam with an illumination angle that is constant with frequency. Current implementations of this feed show poor matching performance across the band, and resistive losses contribute significantly to system temperature. A quasi self-complementary feed structure is being developed at Cornell University [9] that has been designed to overcome the mismatch and loss problems currently suffered by the Chalmers feed. The prototype of this feed is currently being fabricated and tested. A further class of wide-band feed with a variable phase center, based on a dual-polarization “quad-ridge” structure, has recently been installed on the Goldstone Apple Valley Radio Telescope (GAVRT) [10]. These feed structures, among others, will be considered and evolved for MeerKAT, with the possibility of cooling the entire feed antenna structure in order to mitigate the effects of ohmic losses and mismatches. Such cooling has been employed for the high-frequency GAVRT feed [10].

An interim waveguide feed has been developed for early use with the KAT-7 array, covering a frequency range of 1.2–1.95 GHz. This feed, shown in Fig. 6, has been optimized to maximize $A_e/T_{sys}$ and have an illumination pattern similar to the wide-band feed structures discussed above. The waveguide diameter was chosen to match the L-band OMT developed for the EVLA, but a novel OMT has been designed that is much more compact than the EVLA implementation, thus simplifying the cryostat design and reducing the heat load.

Cost/performance tradeoff studies using sensitivity ($A_e/T_{sys}$) as a criterion have indicated that it is advantageous to cryogenically cool various components of the receiver in the MeerKAT frequency band because the cost of the physical aperture dominates the overall telescope cost equation, even for small/medium diameter dishes. Following the lead of the ATA, the use of compact and reliable Stirling-cycle heat engines is being investigated to cool lossy signal path components and low noise amplifiers. Currently, a Stirling-cycle engine with a cooling capacity of 15 W at 80 K is being used in conjunction with a test cryostat to develop a prototype KAT-7 receiver package.

Having a single feed that covers the entire frequency range for MeerKAT (or the dish component of the SKA)
provides excellent opportunities for parallel observation scheduling and cost reduction, but these opportunities have to be traded with feed performance. To date, none of the wide-band receivers listed above match the $\frac{A_e}{T_{sys}}$ performance of existing radio astronomy receivers based on optimized waveguide feeds with suboctave bandwidths. Clearly the sensitivity performance is dependent on the optical configuration of the dish as well as the feed characteristics, and in particular the illumination and spillover efficiencies are key performance metrics to be considered in optimizing a receptor system. Both MeerKAT and the SKA may consider the use of multiple subband feeds, rather than a single wide-band feed, if it proves technically difficult or too expensive to achieve significant improvements in the performance of current wide-band receiver systems. The use of multiple receiver packages will add to the cost, and will provide mechanical challenges, but these issues will have to be traded against critical performance criteria. This tradeoff study will be folded in with the dish optimization study discussed in Section IV-A.

D. Packet-Based Signal Processing

The computational load and signal interconnection complexity for the correlator used to coherently combine individual antenna signals in a synthesis radio telescope array scale as the square of the number of antennas. Large-$N$ arrays, including MeerKAT, require computation platforms that match the demanding computation and data transport loads, and the architecture of these platforms needs to be scalable to allow future expansion of the number of antennas, or an increase in bandwidth. Most currently operating correlators are implemented using purpose-built hardware, often based on custom-design application-specific integrated circuit (ASICs). To achieve the correlator performance required by new large-$N$ arrays at an affordable cost, new correlators will need to take advantage of the opportunities provided by commodity devices and use technology platforms that track Moore’s law.

The Center for Astronomy Signal Processing and Electronics Research (CASPER) collaboration grew out of the pioneering work done at the University of California, Berkeley, on developing generic, reconfigurable signal-processing systems [11]. Signal digitization and front-end array processing for KAT-7 and MeerKAT will be implemented using hardware and firmware developed within the CASPER development environment, and the MeerKAT Digital Signal Processing team are active members of the collaboration. A novel feature of the CASPER architecture is the use of a packet-switched network fabric for data routing rather than the more conventional point-to-point or backplane interconnection systems. The digital signal processor built for the XDM at HartRAO was based on Interconnect Break-Out Board (IBOB) hardware [12], but the first prototypes of the Reconfigurable Open Architectu-
REFERENCES


