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Millimetre-wave aperture synthesis for remote sensing of the Earth

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ABSTRACT

Millimetre-wave radiometry of the earth's surface from Low Earth Orbit (LEO) with a resolution of a few km requires antenna apertures several metres across and sub-second scanning times. Fulfilling these requirements with a mechanically scanned real-aperture antenna presents formidable mechanical challenges. An attractive alternative described here is to use synthetic aperture techniques employing a sparse-array of antennas that trade the mechanical complexity of real-aperture imaging for the electrical complexity of synthetic aperture imaging. We present results of an ESA-sponsored study aimed at seeking the optimum technique for high performance synthetic aperture mm-wave radiometry from LEO.

Keywords: mm-wave aperture synthesis radiometry

1. INTRODUCTION

Recent years have witnessed a growing interest in passive microwave and millimetre wave imaging for space-based remote sensing of geophysical parameters and features. Applications include measurement and classification of snow and ice cover¹, sea and land surface temperatures², sea surface salinity³, soil moisture content⁴ and wind velocity^{5,6}. Mechanical, mm-wave pencil beam scanners (PBS), such as AMSR and SMMR have previously been employed for earth observation, but for ground resolutions of a few kilometres the antenna size must be several metres across. The problems associated with launching deploying and scanning a large mechanical dish make this approach unattractive. This article addresses the design of a thinned-array synthetic aperture interferometric radiometer (SAIR) for mapping of snow and ice cover with ground spatial resolutions of a few kilometers. Sparse array SAIRs have been used to synthesise large antenna apertures for many years by the radio astronomy community⁷ and these offer the potential of a large, ostensibly flat antenna structure that may be a small fraction of the weight of a filled dish and also enable electronic scanning. Operation at millimetre-wave frequencies is desirable for the improved classification of snow and ice and for the smaller antennas that are afforded by the shorter wavelengths. Small antenna size is a particularly important goal in reducing the weight and launch cost of the imaging system. The design of mm-wave SAIR for Earth observation is also pertinent to terrestrial real-time microwave and mmw imaging⁸ for applications such as detection of land mines, foul weather flying aids and surveillance.

Aperture synthesis differs from conventional imaging in that the microwave field is sampled (by measuring a set of radio frequency correlation functions) in the plane that is the equivalent of the pupil plane in a conventional imager. Post detection processing is then used to synthesise the image from the sampled measurements. This synthesis executes in microwave and computer hardware that function that is normally executed by focusing optics, namely mapping image pixel position onto wavefront direction through a Fourier-transform relationship. Two L-band (1.4 GHz) aperture synthetic imaging systems for Earth observation from space are currently under development in Europe and the United

States; MIRAS by ESA⁹ and ESTAR by NASA¹⁰. These research programmes have emphasised that the requirement for short integration times and real-time snapshot imaging across a wide field of view introduces additional problems to those encountered in astronomy. For example, in radio astronomy, long observation times and a technique called Earth rotation synthesis⁷ enable high quality images to be synthesised using a small number of antennas and correlators whereas for Earth observation the need for snapshot imaging means that the required number of antennas and correlators is much larger. A typical mm-wave SAIR for radio astronomy might employ four receivers and antennas and six complex correlators whereas in the case of MIRAS, as an example, there are 130 receivers and antennas with 8386 correlators. An additional calibration problem arises from the Earth observation requirement for wide field of view imaging and the need to sample low spatial frequencies. This calls for small antennas on short baselines which leads to increased mutual coupling between antennas and associated errors in the measured correlations. These errors need to be calibrated in real time. Image processing is also more problematic; the Earth source scene is extended and warm with low contrast whereas astronomical scenes are characterised by small high contrast sources on a cold background. This means that many of the calibration and image processing techniques developed for astronomy cannot be readily transferred to Earth observation aperture synthesis imagers. In consequence, aperture synthesis for earth observation requires a different set of techniques and algorithms from those required for astronomical aperture synthesis.

The majority of the work in microwave aperture synthesis to date as typified by MIRAS and ESTAR and others has been at microwave frequencies and the extension to millimetre wave frequencies introduces additional problems associated with working at these higher frequencies. In seeking to develop a mm-wave SAIR it is crucial to consider the ramifications of operation at higher mm-wave frequencies. Significant factors are increased demand on component tolerances whilst the performance of active components is significantly poorer at these higher frequencies and the losses in passive components are very much higher. Very importantly, the absence of a large established commercial market for mm-wave components means that component costs are high. Furthermore, the difficulties in operating at high frequencies tend to be compounded, for example, at 1.4 GHz losses are so low that it is feasible to propagate and combine raw RF signals within the antenna structure whereas at mm-wave frequencies the signal is attenuated so rapidly that down-conversion and/or amplification is necessary prior to propagation over distances of greater than a few 10s of cm. In consequence, not only are components more expensive and perform more poorly at mm-wave frequencies, but more of them are required. When choosing the optimum aperture synthesis the increased cost and poorer performance of mm-wave components is of vital importance.

2. THE REQUIREMENTS

The guideline technical requirements (GTR) requirements of the SAIR for snow and ice mapping are summarised in Table 1 below and the imaging geometry is depicted in Figure 1. It is to operate in a polar Low Earth Orbit and will image at an angle of incidence of approximately 50° across a total swath width of 1300 km. The oblique angle of incidence is required to enable polarimetric data for wind mapping to be gathered by an additional low resolution imager. The swath width is required to ensure a revisit time of 2 to 3 days. The operating frequency and available bandwidths are determined by the optimum frequencies for snow and ice mapping and the available ITU radio-quiet windows reserved for radio astronomy.

Four methods for scanning the SAIR image across the Earth's surface have been considered; a simple pushbroom scan of a one-dimensional aperture synthetic image footprint, a pushbroom scan of a two-dimensional aperture synthetic footprint image and hybrid pushbroom-conical scans of both one-dimensional and two-dimensional footprints. For the hybrid conical-pushbroom scan the SAIR rotates about the vertical axis so that the each pixel in the image traces out a spiral on the Earth's surface. The along track field of view and rotation speed are chosen so that the footprint moves a distance equal to one footprint during one rotation so that each point within the swath width is imaged at least once.

The footprint of the imager is distorted by the projection onto the Earth's surface so that the along track resolution cell is increased by the secant of the angle of incidence and a line of constant elevation in the image represents an arc on the surface of the Earth. Thus for a pixel on the ground to have unity aspect ratio, the angular resolution of the SAIR must be greater along the track than across it.

Figure 1 Imaging geometry for the SAIR

Orbit altitude	800 km
Angle of incidence, ϑ	$\sim 50^\circ$ ($40^\circ < \vartheta < 65^\circ$)
Swath width	>1300 km
Centre operating frequency	31.5 GHz and 89 GHz
Available bandwidth	0.4 GHz at 31.5 GHz 2.4 GHz at 89 GHz
Polarisation	Horizontal and/or vertical
Spatial resolution	6 km at 31.5 GHz 2.5 km at 89 GHz
Radiometric resolution	1 K
Radiometric accuracy	2 K

Table 1 Summary of guideline technical requirements (GTR) of mm-wave aperture synthesis technique for snow and ice mapping

The aim of this study is to devise the most appropriate mm-wave aperture synthesis technique for operation at mm-wavelengths. This has involved considering all feasible aperture synthesis techniques and selecting for further consideration those that could approach the GTR in

Table 1. Fundamental criteria for comparing SAIR systems are:

1. Fulfillment of the GTR
2. System complexity, particularly the product BN_{corr} of the total bandwidth and the total number of correlators and N_{ant} , the total number of antennas.
3. Total weight (launch cost)
4. Realisation and deployment of the antenna structure
5. Calibration

The most promising mm-wave SAIR techniques that have been considered are:

1. Two-dimensional aperture synthesis using a Y-shaped array (like MIRAS).
2. One-dimensional aperture synthesis combined with a pushbroom scan (like ESTAR).
3. Mills Cross
4. RadSAR and supersynthesis

Principles fundamental to all of these techniques are discussed in section 3. In section 4 an overview of each of the techniques is given with an analysis and the results are discussed in section 5.

3. FUNDAMENTALS

In aperture synthetic imaging the aim is to form a high resolution image using an array of small antennas that synthesis the resolution of a much larger dish. This is achieved using an array of antennas to sample the field in the u - v plane (equivalent to the pupil plane of a conventional imager) and using correlation imaging or phased arrays as depicted in Figure 2. The availability of low-cost correlators and the greater ease of calibration of correlating arrays has meant that correlation imaging has now largely superseded the use of phased arrays for imaging. Phased arrays are described briefly here because they are employed by the RadSAR and Mills Cross techniques discussed in the next section. Mathematically, correlation imaging and phased arrays perform the same function (apart from a bias term), but the hardware used to implement each is quite different.

In correlation imaging the voltage output from each antenna is correlated with every other antenna and each correlation yields a complex value (the visibility function) that represents the complex amplitude of a spatial frequency in the source field. The sampled spatial frequency is determined by the vector separation of the antenna pair, measured in wavelengths. Correlation imaging is therefore dispersive and is essentially a Fourier decomposition of the scene that requires a computer to calculate an inverse Fourier transform and the extended source intensity distribution. Complex amplitude errors in the correlation process can be calibrated and corrected by the computer. The phased array executes the same function as a lens in that the Fourier transform is accomplished at the signal frequency prior to detection and a network such as a Butler matrix¹¹ can be used to form multiple beams on the sky. The antenna output voltages are summed with the appropriate phase delays for each beam and the output of each beam is a complex voltage function that can be used for further interferometric processing (this is done with RadSAR and the Mills Cross) or can be quadrature detected. It is generally necessary to apply weighting and complex calibration correction at each antenna prior to summation. We will now discuss correlation imaging in more detail.

Figure 2 Architectures for (a) correlation imaging and (b) phased array imaging

As outlined above, the aim of correlation aperture synthesis interferometry is to synthesis an image from a measurement of the spatial mutual coherence function of the microwave field in the plane of the antenna array (the u - v plane). This is achieved by sampling the field with a set of coherent receivers and calculating the time average correlation between all pairs of antennas on differing baselines. From the Van Cittert-Zernike theorem there is a Fourier transform relationship between the spatial complex coherence function in the u - v plane, $V(u, v)$, and the angular source intensity distribution¹². At mm wavelengths this is proportional to source temperature brightness distribution $T_b(\xi, \eta)$ where ξ, η are the direction cosines with respect to the plane of the antenna array. The complex coherence function measured between the analytic output signals $b_1(t)$, $b_2(t)$ of antennas labelled 1 and 2 is

$$\begin{aligned}
 V_{12}(u, v) &= \frac{1}{2} \langle b_1(t) b_2^*(t) \rangle \\
 &= K_1 K_2 \iint_{\xi^2 + \eta^2 \leq 1} \frac{T_b(\xi, \eta)}{\sqrt{1 - \xi^2 - \eta^2}} \tilde{r}_{12}(\tau) F_1(\xi, \eta) F_2^*(\xi, \eta) e^{-j2\pi d(u\xi + v\eta)} d\xi d\eta
 \end{aligned} \tag{1}$$

where u, v are measured in wavelengths, $F_n(\xi, \eta)$ is the normalised antenna voltage pattern of antenna n and $\tilde{r}_{12}(\tau)$ is the fringe-wash function which accounts for decorrelation effects due to finite signal bandwidth and the time delay τ_d between antennas 1 and 2 and may be written as $\tau_d = -(u\xi + v\eta)/f_o$ where f_o is the centre frequency. The effects of the frequency responses of the receiver chains are contained within the calibration constants K_1 and K_2 . In the ideal case K_1 , K_2 , $F_n(\xi, \eta)$ and $\tilde{r}_{12}(\tau)$ are accurately known and equation (1) can be inverted to enable calculation of the temperature brightness distribution. Inevitably errors in the calibration of these parameters introduce errors into the final determination of the temperature distribution. For both MIRAS and ESTAR it has been found that calibration of the antenna voltage patterns has been the major limitation on the accuracy with which the image can be synthesised^{13,14}.

Sensitivity relations

Sensitivity is a critical parameter for a SAIR system that is subjected to careful trading between application requirements, complexity and cost. Its value depends on the scene contrast and the aperture synthesis technique used, but it is generally

given by¹⁵

$$\Delta T = \frac{T_{\text{sys}} A_{\text{synth}}}{\sqrt{B\tau} n A_e} \quad (2)$$

where T_{sys} is the system noise temperature, B is the bandwidth, τ is the integration time and A_{synth} is the area of the synthesised aperture of n antennas, each of area A_e . The sensitivity is equal to the sensitivity of a PBS multiplied by the reciprocal of the 'fill factor' (ratio of the total antenna area to the area of the synthesised antenna). For the PBS, the radiometer is mechanically scanned across the scene and τ is the integration time available for a single pixel, whereas the SAIR is a fully staring system and so τ is the total time that a pixel remains with the field of view. The sensitivity lost by the reduced collecting area of a SAIR is generally cancelled by the sensitivity gained by the increased integration time so that the sensitivity of a PBS with a single radiometer and a SAIR system tend to be approximately equal. It can be seen from equ. (3) that for good sensitivity it is important to obtain large bandwidths and a large fill factor.

Bandwidth

SAIR suffers the same bandwidth limitation as the phased array technique so that bandwidth, field of view and antenna dimensions are restricted to values for which the decorrelation term, $\tilde{r}_l(\tau_d)$, in equation (1), is approximately equal to unity, or equivalently one requires that the beam squint with frequency at the peripheral pixel is no greater than (for example) the angular resolution. This specification requires that the maximum bandwidth B_{max} is restricted to

$$B_{\text{max}} \leq \frac{f_o d\vartheta}{\sin \vartheta_{\text{max}}} \quad (3)$$

where f_o is the centre frequency, $d\vartheta$ is the angular resolution and ϑ_{max} is the maximum angle of incidence to be imaged. If the maximum bandwidth does not enable the required sensitivity to be attained, then it is possible to channelise the total available bandwidth into contiguous frequency bands and perform correlation within each frequency band. This is equivalent to having a number of SAIR systems operating in parallel.

The impact of the bandwidth limitation is the same for all mm-wave aperture synthesis techniques and is derived here. The line of sight distance to the boresight pixel is 1159 km and the total swath width subtends a half angle field of view of 0.51 rad. For the boresight pixel, the required angular resolution along and across the track are approximately 5.2 mrad. and 8.1 mrad. at 31.5 GHz and 2.2 mrad. and 3.4 mrad. at 89 GHz. Inserting these values into equ. (3) for the required across track field of view yields maximum bandwidths of 334 MHz and 393 MHz at 31.5 GHz and 89 GHz respectively. Thus at both 31.5 and 89 GHz, the full available bandwidth cannot be exploited unless it is channelised into narrower bandwidths.

Angular resolution

The required angular resolution would require a real aperture with dimensions of about 2 metres across track by 3 metres along track for both 31.5 and 89 GHz at 50° angle of incidence if a Hamming-like weighting function is used. When a low-redundancy sparse array is used, the spatial frequencies in the image are more equally weighted than with a filled dish resulting in improved angular resolution at the expense of increased sidelobe levels. For the purposes of the trade off described here uniform weighting for both real and synthetic apertures has been used as a point of reference. However, this effectively super-resolves the scene and introduces very high sidelobe levels that would probably not be acceptable in a serviceable SAIR. If Hamming weighting is employed in place of uniform weighting it will be desirable to increase the linear dimensions of the SAIR by about 50% to reduce the side lobes to an acceptable level. The resolutions of calculated for one-dimensional and two-dimensional SAIR systems that have used data taken from Bara et al¹⁶.

4. ANALYSIS OF MM-WAVE APERTURE SYNTHESIS TECHNIQUES

Two-dimensional aperture synthesis

For this study MIRAS was used as the exemplar of efficient two-dimensional aperture synthesis for Earth observation. MIRAS employs a Y-shaped antenna structure with antennas spaced at uniform intervals along the arms. This provides hexagonal coverage of the u - v plane and enables the array alias responses to be forced out towards cold sky with larger antenna spacings than with other configurations. The pixel shape is hexagonal and so is elongated when projected onto the earth at 50° angle of incidence. Advantages of MIRAS include ease of deployment of the Y-shaped structure, relatively simple antennas and the nearly-filled linear arrays ease calibration difficulties. However the synthesis of a two-dimensional image carries a heavy burden of electronic complexity.

The parameters for a MIRAS-like SAIR aimed at achieving the GTR are summarised in Table 2(a) for a conically scanned system and in Table 2(b) for a pushbroom scan. The antenna size given is determined by the across track resolution to meet the GTR; the along track resolution is a factor of $\secant(50^\circ)$ worse. The spacing of the antennas along the arms is determined by the requirement to point the field of view of the closest alias responses towards cold sky and this determines the total number of antennas and hence the number of correlators required. If the field of view is chosen to be that for which the maximum bandwidths (0.4 GHz at 31.5 GHz and 2.4 GHz at 89 GHz) can be used without channelisation then the across track swath width is restricted and a conical scan is required to image the full swath width. The smaller field of view of the 89 GHz instrument determines the rotation period of the platform to be 44.7 seconds and the integration time is equal to the time that a pixel remains within the field of view. The parameters of a conically scanned two-dimensional SAIR are summarised in Table 2(a). Clearly, the sensitivity of such a SAIR falls a long way short of the 1 K required and the number of antennas, receivers and correlators is very large.

Reducing the bandwidth enables the full swath to be imaged with a simple pushbroom scan and the integration time to be increased by a factor that is greater than the square of the fractional decrease in bandwidth. This results in a net increase in the $B\tau$ product and an improvement in sensitivity. Sensitivity is also improved by the increased fill factor. The parameters for the 31.5 GHz instrument are shown in Table 2(b). Although the sensitivity is improved it still falls short of the GTR and the required number of antennas, receivers and correlators and the $B N_{\text{corr}}$ product is very large.

f_o	Antenna Length	N_{ant}	Antenna separation	N_{corr}	τ	ΔT	$B N_{\text{corr}}$
31.5 GHz	0.83 m	322	0.82λ	69,337	7 s	4.39 K	27.7 THz
89 GHz	0.71 m	982	1.07λ	643,537	0.54 s	19.65 K	1.5 PHz

(a)

f_o	Antenna Length	N_{ant}	Antenna separation	N_{corr}	τ	ΔT	$B N_{\text{corr}}$
31.5 GHz	0.83 m	427	0.61λ	121,837	1.1 s	2.2K	40 THz

(b)

Table 2 parameters for a two-dimensional Y-shaped SAIR with (a) a conical scan and (b) a pushbroom scan

One-dimensional SAIR with a pushbroom scan

This is the method pioneered by the ESTAR programme. The synthetic aperture is a linear array of stick antennas that form overlapping fan beams on the Earth's surface. In ESTAR, these stick antennas are linear arrays of dipoles that are combined to form a single staring fan beam. One-dimensional aperture synthesis within the fan beam is accomplished by

correlating the outputs of the stick antennas. Since the image is synthesised by correlation in one-dimensional only, the total number of pixels and electronic complexity is lower than for two-dimensional aperture synthesis. However, the deployment of the more complex array structure is likely to be more problematic and the irregularly spaced antenna array may be more difficult to calibrate than filled linear arrays (as used in MIRAS). The construction of high gain stick antennas is likely to be considerably more problematic at mm-wave frequencies than at the L-band frequencies used by ESTAR.

The parameters of a one-dimensional SAIR to meet the sensitivity and resolution requirements of the GTR are presented in Table 3. The stick antennas form a fan beam across the track with a dimension along the track that corresponds to that of a real antenna. The integration time at each frequency band is equal to the time taken for the SAIR to traverse the respective pixels. The minimum separation of the stick antennas is determined by the need to point the alias responses towards the sky and the antennas are assumed equal in width to the minimum separation which enables the full swath width to be imaged, although ΔT at the edge of the swath will be 46% higher than at boresight. The number of antennas is determined by the condition for low-redundancy for a linear array¹⁷. The parameters of one-dimensional SAIR systems that achieve the required resolution and sensitivity at boresight are presented in Table 3.

f_o	Stick Antenna Length	Array length	Antenna separation	N_{ant}	N_{corr}	B	$B N_{corr}$
31.5 GHz	2.00 m	1.36 m	0.68λ	23	422	280 MHz	118 GHz
89 GHz	1.78 m	1.22 m	0.68λ	37	2126	2 x 444 MHz	1.9 THz

Table 3 Parameters for a linear synthetic aperture array with a pushbroom scan.

The use of one-dimensional aperture synthesis method called QUARTZ that employs sub-arraying and a hybrid pushbroom-conical scan has recently been proposed¹⁸. In this case the stick antennas are oriented tangential to the circle of the conical scan and aperture synthesis is executed in elevation, in the radial direction. This enables the instantaneous field of view to be traded for rotation frequency, that is to say, electrical complexity can be traded for mechanical complexity. The use of a limited field of view enables a the introduction of sub-arraying in which contiguous antenna channels are composed of overlapping sub-arrays¹⁹. Increasing the separations of the phase centres of the sub-arrays introduces alias responses, but these can be attenuated by increasing the width of the sub-arrays. That is to say, aliases may point towards the warm Earth, but with careful design they can be at a low level that does not significantly degrade the image. The objective of introducing sub-arraying is to attain acceptable imaging performance with a less complex instrument than would be required from a SAIR instrument not employing sub-arraying.

Parameters for example QUARTZ SAIR systems that achieve the required radiometric resolution and sensitivity are shown in Table 4(a) for a design with low mechanical complexity and in Table 4(b) for a design with low electronic complexity. In the first case the instantaneous field of view (which determines the rotation rate) is limited by the allowed range of angles of incidence as defined in the GTR and in the second case it is determined by the field of view of the stick antennas. These factors give rotation periods of 104 secs. and 64 secs. respectively. Table 4(a) shows a SAIR with no aliases, but the use of sub-arrays enable wider antennas which leads to an increased fill factor and a lower required correlator bandwidth. (b) shows a SAIR with increased antenna spacing which introduces aliases that are suppressed by the antenna response of the 8λ wide overlapping antennas. The increased antenna spacing leads to a reduced number of antennas and correlators and an order of magnitude reduction in the value of $B N_{corr}$. The quoted fill factor is based upon low overall degree of overlapping and is consequently an upper limit.

Frequency	Stick Antenna Length	Array length	Antenna sub-array separation	Width of antenna sub-array	N_{ant}	Fill factor	N_{corr}	B	$B N_{\text{corr}}$
31.5 GHz	1.62 m	1.71 m	0.5λ	2λ	34	<0.37	720	22.3 MHz	16.1 GHz
89 GHz	1.37 m	1.45 m	0.5λ	2λ	63	<0.28	1776	93 MHz	165 GHz

(a)

Frequency	Stick Antenna Length	Array length	Antenna sub-array separation	Width of antenna sub-array	N_{ant}	Fill factor	N_{corr}	B	$B N_{\text{corr}}$
31.5 GHz	1.62 m	1.71 m	2λ	8λ	16	<0.71	180	14 MHz	2.52 GHz
89 GHz	1.37 m	1.45 m	2λ	8λ	26	<0.47	444	75 MHz	33.3 GHz

(b)

Table 4 Parameters for a hybrid conical-pushbroom scan employing sub-arraying for (a) low mechanical complexity and (b) low electronic complexity

RadSAR and Supersynthesis

RadSAR and Supersynthesis are two closely techniques that are based on matched filtering to the localised impulse response of a two-beam interferometer when illuminated with moving sources at a finite range. It can be explained as follows; if a single point source traverses with uniform velocity the overlapping beams of a two-port interferometer an temporal interferogram will be recorded that varies in frequency and has a maximum temporal frequency when the source is located at broadside to the antennas. This frequency chirping arises simply because the time delay between the source and the antennas varies non-linearly with displacement and approaches zero as the source moves to an end-fire position. For an extended source field, the time history of the interferogram is the superposition of many such chirped interferograms and an estimate of the one-dimensional source intensity distribution may be made by applying a matched filter to the time history of the interferometer output. This is the principle underlying the techniques of RadSAR^{20,21} and Supersynthesis^{22,23,24}. RadSAR is a one-dimensional imaging technique requiring two stick antennas and beam-forming to form overlapping fan beams on the ground and supersynthesis achieves a similar function employing one stick antenna and a single wide-field-of-view antenna.

Good sensitivity requires wide bandwidths and large antennas, whilst high resolution requires a long time history (and hence small antennas with a wide field of view) and a long baseline. These requirements tend to be mutually exclusive. Using expressions quoted for Supersynthesis^{22,23,24} we have calculated angular resolutions that are 2 and 9 times greater at 31.5 GHz and 89 GHz respectively than those stated in the requirements in

Table 1, although the sensitivity appears to be very high.

Mills Cross

The Mills Cross, first used in radio astronomy²⁵, represents what is probably the earliest SAIR system, although the concept has been recently proposed for microwave remote sensing^{26,27,28,29}. The basic concept employs two orthogonal filled linear arrays of antennas, each of which use beam-forming techniques to simultaneously form a set of orthogonal overlapping fan-beams. For n fan beams formed by each linear antenna array, there are n^2 directions, or pixels, where the fan-beams overlap. The intensity of the source filling each of these n^2 pixels is obtained by correlating the outputs of each of the fan beams. For narrow bandwidths or a narrow field of view the beams may be formed with a Butler matrix,

but for the wide bandwidths required here a true-time-delay beam-forming system is required and this introduces considerable complexity.

The parameters for a Mills cross designed to fulfil the imaging and sensitivity requirements in the GTR are summarised in Table 5. The antenna has been assumed to be composed of contiguous square antennas spaced so as to reject aliases from the image. Two prominent features in Table 5 are the wide bandwidth required to give the required sensitivity and the number of delay lines required. The required bandwidths are about an order of magnitude wider than the windows available and this relative lack of sensitivity is largely because of the low fill factor. In addition, each antenna requires a separate delay line for each fan beam formed and this yields a very large total number of delays. Multiplexing of RF signals onto optical fibre delay lines would enable one multiplexed optical fibre delay line to be employed for each antenna³⁰ enabling 2-3 orders of magnitude reduction in the number of delay lines, but the total number of high frequency photodiodes would then be equal to the total number of delays required (almost 400,000) which remains a challenging requirement in terms of cost and power consumption. Clearly, the required bandwidth is too great for a Butler matrix to be employed.

Frequency	Array Lengths,	Antenna spacing	N_{ant}	Number of delay lines	Fill factor	N_{corr}	B	BN_{corr}
31.5 GHz								
along track	1.11m	0.68λ	198	33,858	0.013	19,602	2.3 GHz	45 THz
across track	1.72 m	0.81λ	99	22,176				
89 GHz								
along track	0.94 m	0.68λ	474	193,866	0.006	105,228	27.4 GHz	2.9 PHz
across track	1.46 m	0.81λ	237	127,032				

Table 5 Parameters for a Mills Cross designed to fulfil the GTR.

5. DISCUSSION

The results presented for each mm-wave aperture synthesis technique are intended, not to be the optimum solution that is attainable by each technique, but to indicate the approximate degree of relative complexity and closeness to meeting the GTR. The differences between the techniques are large enough to justify this approach and conclude that a SAIR based on one-dimensional apertures synthesis, either ESTAR-like or QUARTZ-like, is the most attractive.

The Mills Cross cannot meet the sensitivity requirements for the allowed bandwidth and the degree of complexity required is too high using current technology. The poor sensitivity is largely due to the poor fill factor and although this could be increased by adding more antennas this would further increase the complexity. It appears that the RadSAR/Supersynthesis techniques cannot give the required angular resolution, although the published literature on these techniques is not detailed enough to enable a rigorous analysis. It is not impossible that a more detailed study would yield more promising results, in which case, the relative simplicity of the method could make it attractive. Two-dimensional aperture synthesis with a pushbroom scan comes quite close to achieving the required sensitivity and offers simple antenna deployment and a well-understood calibration problem. It is possible, that with development and some increase in complexity, acceptable performance may be achievable. However the required number of wide bandwidth correlators is daunting and the N_{ant} and BN_{corr} metrics of complexity are considerably higher than for the one-dimensional methods.

One-dimensional aperture synthesis, as might be expected, enables a less complex system to be designed than two-dimensional aperture synthesis. An ESTAR system offers a BN_{corr} value that is over 300 times less than for the

pushbroom-scanned two-dimensional Y array although for the wide bandwidths necessary it is probable that expensive analogue correlators would need to be used and the number is still rather high. A further reduction of one to two orders of magnitude in $B.N_{\text{corr}}$ is possible if the QUARTZ concept is employed and the reduced bandwidth may enable the use of lower cost digital correlators. Although the QUARTZ conical-pushbroom scan is less efficient than the simple pushbroom scan used by ESTAR, the QUARTZ concept offers considerable flexibility in trading mechanical complexity (number and total weight of antennas and rotation speed) for electronic complexity (number of correlators, receivers and required bandwidth). In particular, increasing sensitivity by increasing the fill factor can reduce the electronic complexity. One should not however lose sight of the fact that as $B.N_{\text{corr}}$ is reduced in the QUARTZ trade off and the fill factor is increased, the mechanical advantages of a SAIR over a conventional filled dish with a focal plane array of receivers is reduced. However there appears to be scope for the design of either a QUARTZ- or ESTAR-based system that offers lower weight and cost than a conventional PBS.

A significant source of complexity for both QUARTZ and the push-broom scan is likely to be the design of mm-wave antennas and their deployment. If Hamming rather than uniform weighting is used the antenna length will need to be increased to 2.5 m (QUARTZ) or 3 m (ESTAR) long. Critical issues are the cost, Ohmic loss and bandwidth of these antennas. Dipole arrays as used on the original ESTAR would require frequency conversion and/or amplification at each dipole and this would be very expensive to implement at this frequency. The losses and small bandwidth of slotted waveguides as used on a recently reported 37 GHz ESTAR³¹ will be a significant constraint for the long antennas required for this application. This will be less of a problem for QUARTZ, for which narrower bandwidths are possible. Other feasible approaches include linear arrays of sectoral and pill box antennas.

In summary, the choice of SAIR is dominated by the degree of complexity that can be tolerated and this favours the one-dimensional approaches of ESTAR and QUARTZ. More detailed analysis will be conducted to determine which of these techniques is the most attractive.

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