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# SATCOM Retrodirective Array

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*Abstract*— **We present an in depth look at the challenges involved in using analogue retrodirective arrays for satellite communications. The main technical issues surrounding the development of a retrodirective (self-steering) Satellite Communications (SATCOM) system are given and techniques for mitigating these issues provided. Detailed results are given for a prototype high performance circularly polarized retrodirective array architecture suitable for mounting on an un-stabilized mobile platform. The paper concludes with practical retrodirective L-band array results with the array used to acquire actual broadband satellite data signals from a commercial L-band satellite system. Received satellite signals as low as -130dBm at the antenna elements are tracked. Accurate self-tracking occurs over the azimuth range of up to ±40°.**

*Index Terms*— **Antenna arrays, Beam steering, Phase conjugation, Phased arrays, Phased Locked Loop**

## I. INTRODUCTION

Retrodirective, self-steering, antennas (RDA) have the advantage of being able to automatically return a signal back in the direction along from which it originated, [1]. If a retrodirective array could react to fast signal variations with sufficient sensitivity then it could be used as a transceiver in a mobile satellite communications (SATCOM) system, or indeed as a self-steered transceiver in other mobile applications where the requirement for automatic beam alignment between un-stabilized platforms exists.

One application that could benefit from a retrodirective self-tracking arrangement is satellite communications, particularly when applied to terrestrial mobile scenarios. A service that is currently available globally at L band, 1.5 GHz receive (RX), 1.6 GHz transmit (TX), is the Inmarsat Broadband Global Area Network (BGAN) [2]. A study of the specification required for BGAN reveals that major step changes of the type discussed in this paper are required if retrodirective array technology is to be considered as a viable option for this type of application.

The BGAN ground terminal is required to transmit an Effective Isotropic Radiated Power (EIRP) of up to 50 dBm, and the signal level it receives, at a single low gain antenna element, can be down to -130 dBm. The stringent specification on receiver sensitivity rules out the majority of known retrodirective antenna array architectures, which fall into two broad classes, either the frequency offset Van Atta type [3] or the Phase Conjugating Pon type [4]. In addition to lack of receive sensitivity these basic architectures are unable to deal with complex modulation scenarios where transmit and receive phase modulated signals are required to operate in full duplex mode, e.g. for L-Band BGAN 16QAM at 150 kbps. The top level specification needed for L-Band BGAN SATCOM is compared with what is currently achievable with reported self-steered antennas, and with the new architectural approach presented in this paper in Table 1.

If retrodirective array technology is to be used in actual SATCOM systems, then a fresh look at the approach used for carrying out phase conjugation within the beam forming circuitry is required. In this paper, we will describe an all analogue phase conjugation circuit solution. The rationale for this was given in [10], where analogue circuits were found to be significantly more conservative with regards to power consumption and simplicity when compared to digital techniques. For example, it was calculated in [10] that a 4x5 RDA operating with data at a bit rate of 20 Mbps requires a dc input power level of 16 W for Digital Signal Processing (DSP) implementation, whereas an analogue implementation consumes only 2 W and is largely bandwidth independent. In addition to the power consumption issue, analogue electronics are not governed by DSP throughput limitations, i.e. they allow for real time instantaneous processing.

The type of analogue retrodirective antenna proposed here operates without a priori knowledge of the target positon, and therefore provides near instant signal acquisition., <10 mS, in comparison to current motorized tracking antennas (for example, the Hughes 9350 BGAN mobile satellite terminal) that take approximately 1 minute to acquire since they require a certain acquisition phase before switching to a tracking phase.

The main contributions of this paper over previous works are: (1) First presentation of practical results of a retrodirective array with comparable performance to a commercial SATCOM user terminal, (2) An in depth analysis of the many design challenges of using analogue retrodirective arrays in a SATCOM application (3) Six significant changes to the pre-existing retrodirective architecture (Detailed in Sec. III).

## II. HIGH PERFORMANCE PHASE CONJUGATION CIRCUIT

The generic block diagram for a 'fit for SATCOM purpose' phase conjugator shown within the context of a single element, after considering the features in Table 1, is proposed

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TABLE 1
FEATURES OF REPORTED RETRODIRECTIVE ARRAYS IN THE LITERATURE.

| **Retrodirective Antenna:** / **Feature:** | PON [4] | Triple mode PLL [5] | I/Q phase conjugator [6] | Recent Phase conjugating mixers [7] | Phase detection and phase shifting [8] | DSP [9] | This Work |
|---|---|---|---|---|---|---|---|
| Self tracking (retrodirective) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Low power consumption (per element) | ✓ | Not Specified | 1.5W | ✓ | Not Specified | × | 100mW |
| Low signal level operation | × | -60dBm | -110 dBm | × | -60dBm | Not Specified | ✓ |
| Ability to retransmit a high power, low phase noise signal | × | ✓ | ✓ | × | ✓ | ✓ | ✓ |
| Simultaneous Modulation capability on both transmit and receive | × | × | Pulse mod. TX/RX | TX only | × | ✓ | ✓ |
| Ability to provide beam pointing error correction for TX/RX frequency offset | × | × | × | × | ✓ | Not Specified | ✓ |
| Utilization of antenna array factor on receive as well as retransmit | × | RX only | × | × | × | ✓ | ✓ |

in Fig. 1.

In order to recover weak receive signal levels, and also to provide a “clean” retransmit signal, a carrier recovery circuit (tracking PLL) is required. This tracks the phase of the received signal while concurrently removing its modulation for subsequent receive side processing. The recovered clean carrier is then phase conjugated, and transmit modulation is applied to the PA for self-aligned data re-transmission to the satellite.

For SATCOMs, a major challenge is that the system should be able to coherently combine on receive. Normally this is a feature not considered in retrodirective array design, where the emphasis is on un-modified re-transmission of incoming pilot and data. With the arrangement in Fig. 1, automatic optimal signal re-combination from the array receive elements can be performed since each of the array element’s carrier recovery circuits output identical phase signals such that phase does not vary with the angle of arrival of the received signal (RX IF, Fig. 1). This is achieved within the phase locked loop circuit by locking the received signal to a constant phase reference signal, as described in detail in [11]. Maximal signal recombining from all elements in the array then follows through simple scalar summation at the chosen IF frequency. This method allows optimal combination on receive over a wide range of angles of arrival, and thus permits the array factor of the retrodirective antenna to be used both on receive, and on retransmit.

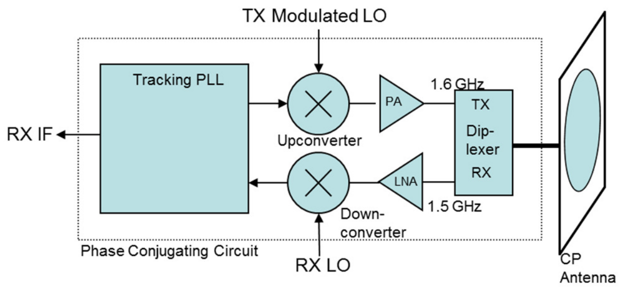



Fig. 1. Generic retrodirective element for SATCOM.

## A. G/T performance

As with any satellite system the G/T performance needs to be considered. Classical retrodirective antennas are not normally characterised in this way since they are usually only deployed for working with moderately strong signals. A typical G/T figure for a high bit rate L band SATCOM system [2] requires to be better than -10 dB/K. To analyse the G/T of a retrodirective antenna we use the generic receiver configuration [13] of Fig. 2. Here the low frequency IF signal presented to the phase detector is considered to be the final received signal, i.e. the one where signal to noise ratio will be critical for successful demodulation of the data signal. Hence it is essential to know what level of S/N the tracking PLL can operate with, such that the quality of the regenerated carrier used for retransmit is not adversely affected.

The G/T of a receiver can be characterized by using cascaded receiver noise temperature, $T_R$, [12] where:

$$T_R = T_{ANT} + T(1 - 1/G_{FEED}) + \frac{T(F_{LNA} - 1)}{G_{FEED}} + \frac{T(F_{MIXER1} - 1)}{G_{FEED}G_{LNA}} + \frac{T(F_{MIXER2} - 1)}{G_{FEED}G_{LNA}G_{MIXER1}} + \frac{T(F_{IF} - 1)}{G_{FEED}G_{LNA}G_{MIXER1}G_{MIXER2}} + \frac{T(F_{REC} - 1)}{G_{FEED}G_{LNA}G_{MIXER1}G_{MIXER2}G_{IF}} \quad (1)$$

*here:* $G/T = G_{ANT}/T_R$.

The results of the G/T calculation are given in Table 2. Here if we assume an array made up of reasonably low directivity elements (as required for wide retrodirective field of view) with 6.5 dBi gain, and an ideal array factor of 9.5 dB, then 9 elements (3x3) would be required to achieve G/T= - 9.1 dB/K. Wider retrodirective fields of view are

TABLE 2
RETRODIRECTIVE RECEIVER G/T PERFORMANCE BASED ON FIG.2 WITH REAL COMPONENT SPECIFICATIONS

| | | Noise Contribution (K) |
|---|---|---|
| Antenna Gain (dBi) | 16 | |
| Antenna Noise Temperature (K) | 80 | 80 |
| Antenna feed Loss (dB) | 1.1 | 84 |
| LNA Noise Figure (dB) | 1.5 | 93 |
| LNA Gain (dB) | 30 | |
| 1st IF Mixer noise figure (dB) | 12 | 3.3 |
| 1st IF Mixer Gain (dB), Inc 1st IF filter loss | 7 | |
| 2nd IF Mixer noise figure (dB) | 5 | 0.1 |
| 2nd IF Mixer Gain (dB), Inc 2nd IF filter loss | 17 | |
| IF Amplifier Noise Figure (dB) | 10 | 0.008 |
| IF Amplifier Gain (dB) | 53 | |
| Receiver Noise Figure (dB) | 3 | 4.47E-09 |
| **Receiver Noise Temperature, $T_R$ ($\Sigma T_e$)** | | **260** |
| **G/T (dB/K)** $G_{ANT}/T_R$ | | **-9.1** |

possible with lower gain elements [14] , or conversely, smaller numbers of higher gain elements could be used at the expense of steering coverage.

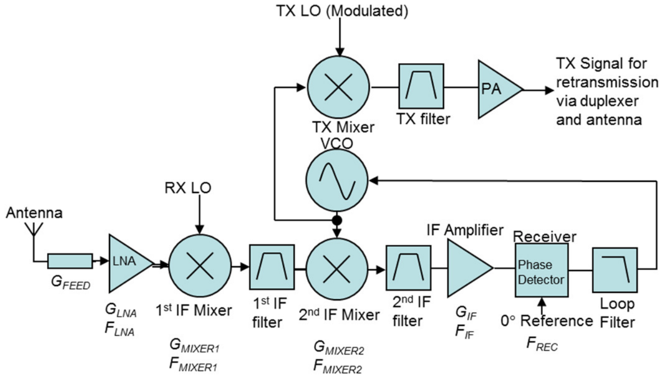



**Fig. 2. Retrodirective transceiver architecture for G/T calculation.**

*B. Receiver carrier recovery requirements and effect on re-transmitted signal*

One major challenge of operating a retrodirective array within satellite communications, is that the received signal at each element is generally much weaker than experienced in terrestrial applications. Levels as low as -130 dBm are present at each element, close to the noise floor of the receiver. The result is that the tracking PLL is required to lock to a signal with very low S/N ratio, typically an S/N close to 0 dB after the 2nd IF Filter (Fig. 2), resulting in phase jitter on the PLL output. The RMS phase jitter of a PLL type receiver is given by [15] as:

$$rms\ phase\ jitter = N\sqrt{\frac{B_l}{C/n_0}}\ rads \qquad (2)$$

Equation (2) shows that in order for the PLL to recover carrier information a sufficiently low cut off frequency ($B_l$) needs to be used as the PLL loop filter (Fig. 2).

In [15] for an input signal of -120 dBm, an IF filter bandwidth of 3 kHz, and a loop filter bandwidth of 99 Hz, an RMS phase jitter of 6° is predicted. This compares favorably with the measured results of the receiver in Fig. 2 which was 5° for a signal level of -120 dBm, and for -130 dBm, 8° predicted, 10° measured. These results confirm that provided the signal strength received at each individual element is above -130 dBm then accurate phase tracking and conjugation is possible. In an operational Inmarsat BGAN system the spot beam received signal strength should be in the region of -110 dBm per element. It is shown in [16] that for a retrodirective array to have the ability to retransmit a high quality retrodirected wavefront, that the conjugately phased re-transmit carrier signal phases need to be matched within 10° for a 16 element array, meaning that the worst case measured result reported here would be compliant.

Phase noise measurements at the IF output of the phase tracking PLL VCO (Fig. 2) for a -120 dBm input gives an output phase noise of -77 dBc/Hz @ 1 kHz offset and -125 dBc/Hz @ 1 MHz offset, thus offering a low phase noise, conjugately phased re-transmit carrier that is suitable to up convert for high quality signal retransmission.

Generating the retransmitted signal from the retrodirective array involves applying a modulated transmit LO signal (TXLO Fig. 2), to the TX mixer (Fig. 2) and multiplying it with a lower frequency signal from the tracking PLL VCO (Fig. 2), in this case 156 MHz derived from a phase locked 26 MHz Temperature Compensated Voltage Controlled Crystal Oscillator (TCVCXO). The lower sideband is filtered (to provide phase conjugation) via the TX filter and transmitted through a PA. Assuming the TX mixer and PA are operating in the linear region, then the quality of the retransmitted signal is dependent on the phase noise/phase jitter characteristics of the 156 MHz tracking PLL signal.

To determine the quality of the phase modulated retransmitted signal we measure the resultant Error Vector Magnitude (EVM). Using the configuration of Fig. 2, a 16QAM 151.2 kbps modulated signal was applied to the transmit LO signal and the up-converted retransmitted Error Vector Magnitude (EVM) measured. The results of Fig. 3 show that a signal with a 2.7% EVM is retransmitted when the retrodirective array is receiving a -110 dBm CW pilot beacon while simultaneously retransmitting a 16QAM 151.2 kbps signal. A received signal of -110 dBm per element is fairly typical of an Inmarsat spot beam, based on practical experience. If the array was receiving a global beam at -130 dBm, then the retransmitted EVM for an 8.4 kbps QPSK signal carried by that beam, is about 3.6%.

For a 9 element array, using (3), with a 9.5 dB array factor ($AF$), 6.5 dBi element gain ($G_{ELE}$), one PA per element, $N_{PA} = 9$, a transmit EIRP of 15 dBW can be achieved through ideal spatial combining with 19.5 dBm ($P_{PA}$) being radiated at each PA per element, suggesting that a single or dual stage PA at each up-converter output would be needed. Systems such as Inmarsat BGAN need to conform to ETSI [17] standard for retransmit spectral purity, so appropriate filters would be necessary in the transmit up-converter chain.

$$EIRP(dBW) = P_{PA}(dBm) - 30 + 10\log(N_{PA}) + G_{ELE} + AF \qquad (3)$$

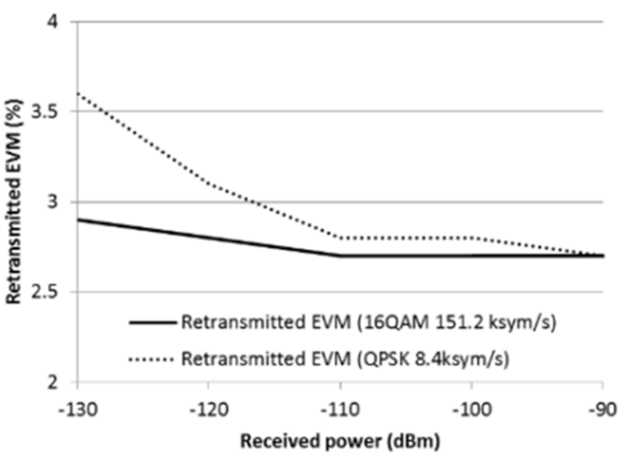



Fig. 3. Measured retransmit EVM Vs received signal strength.

### C. *Effect of TX/RX Frequency Offset on Beam Pointing*

It was shown in [18] that for a frequency offset retrodirective array that there is a difference in the received signal angle of arrival, $\theta_{in}$, compared to the retransmitted beam direction, $\theta_s$, (4)

$$\frac{sin\theta_{in}}{sin\theta_s} = \frac{f_{in} - f_\Delta}{f_{in}} \quad (4)$$

BGAN via INMARSAT uses TX/RX 1.65/1.55 GHz frequency operation. If we assume an array size of 3x3 elements, and the commonly used approximation for the shape of the central region of the main beam of an antenna [19] as being:

$$G(\theta) = G - 12\,(\theta/\alpha)^2 \quad (5)$$

where $G$ is the boresight gain (dB) and the half power beamwidth is $\alpha$, and we assume the half power beamwidth of a 3x3 element array at 0.45λ element spacing to be 40°, then from (4) the maximum beam pointing error is 3.2°, and (5) pointing loss is 0.075 dB at ±40° which is the maximum azimuth/elevation coverage achievable using the array of planar antennas reported here.

## III. Retrodirective Satcom PLL Phase Conjugator

The aim of this section is to describe a high performance retrodirective array, which has been tailored for SATCOM applications such as Inmarsat BGAN [2]. There are some significant step changes to the retrodirective array to make this possible, which will be discussed in detail.

Inmarsat BGAN [2] ground terminals receive and transmit respectively in the frequency range 1525 to 1559 MHz and 1626 to 1660 MHz. To facilitate initial pointing of the user ground terminal the BGAN system transmits an ‘always on’ global beam at 1537 MHz which is modulated with QPSK at 8 kbps. The global beam produces approximately -130 dBm received signal strength at a ground terminal with an omnidirectional antenna. The BGAN system’s three satellites also support 256 spot beams per satellite, which are service activated from the user terminal. For current land portable ground terminal operation the user is required to first manually align the terminal. The initial direction can be determined via the use of information fed from a GPS receiver. Final alignment is then carried through manually peaking a $C/N_0$ display of the received global beam strength. Only after this alignment does user terminal transmission occur which then initiates a spot beam signal response from the satellite.

The challenge of tracking Inmarsat BGAN with a retrodirective array is that the array must be capable of initially acquiring the weak global beam signal, which is typically 20 dB lower in signal strength than a spot beam. In current systems the global beam is intended to be received with an accurately aligned relatively high gain 12-20 dBi user terminal antenna. The challenge with the retrodirective array is that for zero manual alignment each individual low gain element in the RDA must be able to track the global beam signal phase independently. For a wide field of view RDA each element may only have a gain in the region of 4-5 dBi resulting in a -130 dBm received signal strength at each antenna element output.

An additional challenge is that the signals to be tracked are phase modulated with either QPSK or 16 QAM. The classical PLL (Fig. 4(a)), configured as a phase lock receiver [20] is unsuitable for tracking phase modulated signals, and can track only CW or AM signals. Hence, they can only operate with systems that have a separate CW pilot signal on a different frequency to the modulated signal. Unfortunately, using an analogue phase locked loop, it is very difficult to track the phase of these modulated signals, particularly if they contain phase modulation. This is due to the phase detector comparing the incoming phase modulated signal with a stable, CW reference signal supplied locally at the retrodirective antenna. With a phase modulated signal the output of the phase detector will not be a stable dc voltage to control the VCXO, instead it will fluctuate according to the phase modulation of the signal. This prevents the PLL from stably locking.

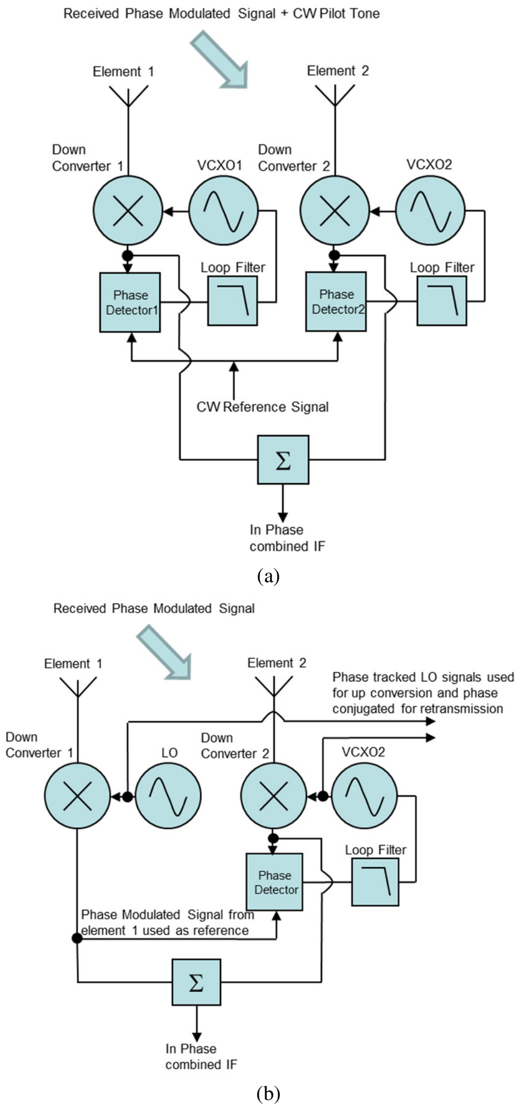



Fig. 4. Tracking PLL configurations. (a) Tracking PLL configured as phaselock receiver, (b) New configuration of tracking PLL for tracking phase modulated signals.

To counteract this problem the architecture of Fig. 4(b) is used, shown here in a simplified form. The basic principle is that the signal from element 1 is used as the phase reference, so that the phase detector is presented with two identically modulated signals. This allows for a constant dc voltage to be available at the phase detector output thus making the self tracking architecture completely independent of the modulation type used. The first channel has a fixed LO frequency, and the second uses a Voltage Controlled Crystal Oscillator (VCXO) as the LO, which has its control voltage derived from the phase detector. The idea of using a narrow band VCXO is that the jitter and phase noise of the signal is very low, allowing for a high quality spectrally pure signal for retransmission. It is shown in [21], when phase tracking a received signal of -130 dBm, the phase jitter performance of the VCXO is only degraded by 3° in comparison to the classical phase lock receiver configuration of [20].

The architecture of Fig. 4(b) results in the two down converted outputs always being in phase and can therefore be optimally combined regardless of input phase of the input signals. The relative phase difference of the LO and VCXO track the phase of the incoming signals and can be used for retransmission, back in the same direction, if they are up converted using a phase conjugating mixer. The representation in Fig. 4(b) is a simplified single conversion architecture, in reality dual stage downconversion is required to allow the removal of image frequencies on receive mode. Larger arrays can be accommodated by using element 1 (Fig. 5) as the phase reference and adding additional elements and phase conjugation circuits.

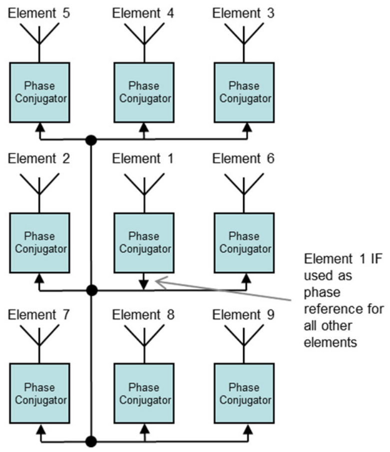
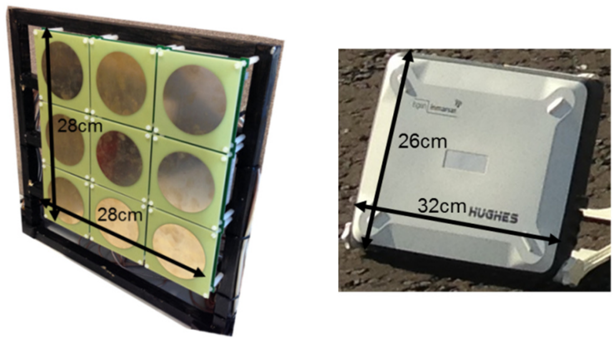


Fig. 5. Accommodation of reference element on a larger 3x3 array.

To allow the tracking PLL to operate with the challenging link budgets found in systems such as Inmarsat BGAN, some improvements, in addition to the above, are required to the retrodirective antenna phase conjugating PLL architecture. These are: (1) An active PLL loop filter has been added, which is 2nd Order with a cutoff frequency of 100 Hz providing the best compromise between PLL stability and locking performance to signals of low S/N ratio. (2) The transmit and receive filters use a low loss commercial BGAN duplexer (0.8dB loss on RX path, >60dB TX/RX isolation). (3) The IF filter prior to the phase detector is a 10 KHz bandwidth optimized for the 8.4 kbps global beam signal. (4) The low noise amplifier uses two cascaded LNAS to give a combined gain of 30 dB and noise figure of 1.2 dB. (5) Power amplifiers were added to allow transmitted EIRPs in the region of 10 dBW for a 3x3 element array. The new block diagram, incorporating these changes, is shown in Fig. 7.

## IV. Retrodirective SATCOM Proof of Concept Array

A 3x3 element retrodirective proof of concept array has been constructed, Fig. 6(a), according to the block diagram of Fig. 7. The array elements are approximately λ/2 spaced to prevent grating lobes. Power consumption was measured at <100mW per element on receive tracking mode. The size of the 3x3 array is 28cm x 28cm, c.f. 26cm x 32cm for a commercial conventional terminal (Hughes 9201), Fig. 6(b).



(a) (b)

Fig. 6 (a) 1.5/1.6 GHz retrodirective array configured as 3x3, (b) Hughes 9201 commercial BGAN user terminal.

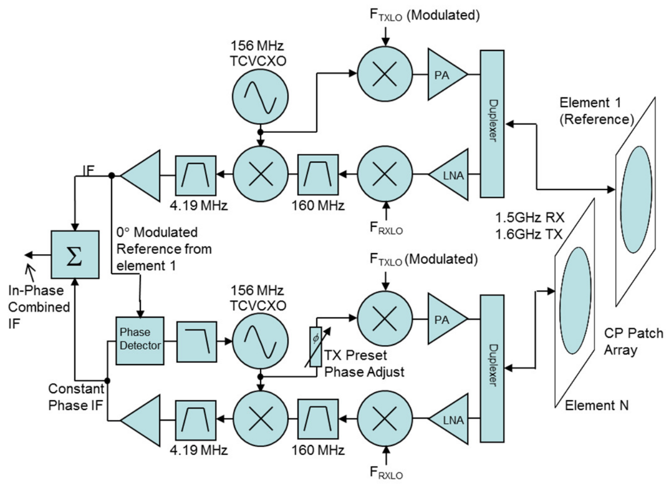


Fig. 7. Block diagram showing two elements of the retrodirective array for BGAN tracking applications.

SATCOM systems such as Inmarsat BGAN [2] require circular polarised antennas operating over a wide range of scan angles. The array elements used in Fig. 6(a) are circular patches with dual linear polarisation and are described in detail in [22]. By feeding the dual linear ports with 0° and 90°, circular polarisation can be generated over sufficient bandwidth for this application. Sequential rotation of the antenna elements [23] was deployed in order to reduce mutual coupling effect and improve axial ratio, which was determined by the methods of [22] to be most favourable for retrodirective circular polarised array use.

The patch element gain was measured as 6.65 dBi. This reasonably high gain for a single element helps to achieve the boresight G/T and EIRP, although is a compromise in terms of the pointing loss obtained at other scanning angles when deployed as a retrodirective array, since the element gain reduces by at least 2 dB for ±40° azimuth/elevation angle, which means that the overall monostatic response of these elements, configured as a retrodirective array, will have a similar pointing loss. This pointing loss is comparable to other SATCOM proof of concept scanning antennas [24].

To correct for phase inaccuracies in the transmit local oscillator beam forming network a preset phase adjust is used (shown in Fig. 7). This phase shifting arrangement is used as a one-off calibration adjustment to achieve coherent transmission at boresight. After this adjustment the array will phase-conjugate correctly over the required azimuth range.

The 3x3 array was measured in a 10m far field anechoic chamber facility configured for retrodirective monostatic radiation pattern measurements. In addition, the retrodirective array had the ability to selectively switch on individual elements, allowing active radiation patterns to be measured. The methods of [25] were then used to calculate the bistatic radation patterns, which account for the real effects of the individual elements in the array, rather than the less accurate method of using a generic element, multiplied by the array factor.

Within the anechoic chamber the signal was transmitted to the antenna under test at 1.54 GHz, using a dual polarised horn antenna which was configured to transmit circular polarisation. The retrodirective return signal retransmitted from the antenna under test was then received in the far field by a linear polarised horn antenna. Both vertical and horizontal components of the retransmitted signal are measured, and post processed to form circular polarised radiation patterns.

The resulting radiation patterns are shown in Fig. 8. These patterns were measured using a received boresight power level at each antenna element of -112 dBm. The received signal was also modulated with QPSK at 8.4 ksym/s, similar to the global beam signal from Inmarsat BGAN. The results show that the monostatic pattern tracks accurately over the desired scanning range of ±40° with a reduction in monostatic gain of around 2 dB at these points. At wider scan angles of ±80° the PLL circuits lose lock of the received signal, this is to be expected since it is beyond the designed scanning range of the array. From a practical point of view, the PLL circuits incorporate a lock detect circuit, used to alert a user of this condition, requiring them to move the antenna back to the ±40° coverage cone.

Also shown on the graph of Fig. 8 is the calculated monostatic pattern based on the active element measurements. This shows the theoretical maximum monostatic gain that can be obtained, assuming perfectly accurate and lossless phase conjugation and spatial power combining occur. The practical monostatic results do not deviate more than -0.5 dB from the active pattern calculation for ±40° scan angles.

The bistatic patterns, calculated from the individually measured active patterns of each element show a sidelobe reduction of >9dB, referenced to boresight. Also superimposed is the measured radiation pattern of the commercial (fixed, non beam steered, array) SATCOM terminal (Hughes 9201) which shows that the retrodirective array is achieving a similar beamwidth, and sidelobe rejection, to the commercial terminal, at each bistatic scan angle. The bistatic results have a slightly broader beamwidth than other reported retrodirective arrays, e.g. the 10x1 reported in [6]. This is due to the 3x3 configuration which was optimised for a coverage of ±40° in both azimuth and elevation, in comparison to a linear array of elements which is only capable of scanning in azimuth.

The monostatic cross polar isolation of the 3x3 retrodirective array is better than 15 dB over the ±40° scanning range. The axial ratio of the array, from the monostatic response, Fig. 9, is extremely low at <1.3 dB for the scanning range of ±40° and remains below 3 dB over the entire ±90° coverage. The excellent axial ratio and cross polar results are contributed to by using the element sequential rotations of [22].

On transmit mode the EIRP was measured at boresight, whilst simultaneously locking to a signal on receive. The result of Fig. 10 shows the transmitted EIRP Vs the power level applied at the $F_{TXLO}$ port, Fig. 7. An EIRP of 14.1 dBW was obtained at the P1dB point. Typically, for low distortion transmission using phase modulation such as 16QAM, a back off of up to 6 dB is required from the P1dB point, providing a useable EIRP for 16QAM of at least 8.1 dBW.

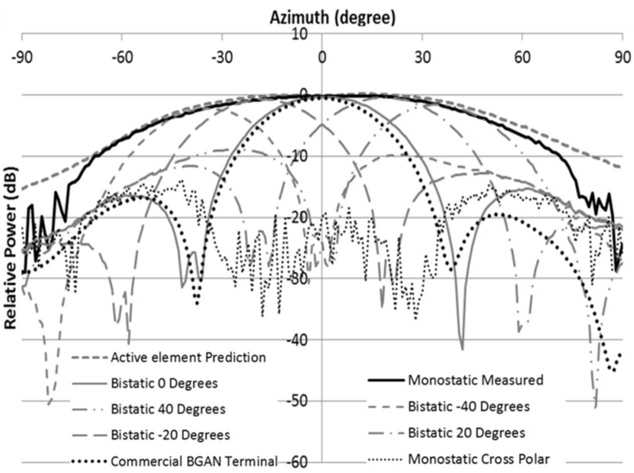


Fig. 8. Normalised transmitted monostatic/bistatic responses for 3x3 array.

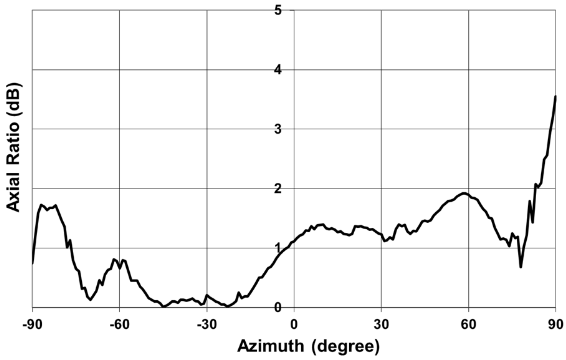



Fig. 9. Measured monostatic Axial Ratio for 3x3 array

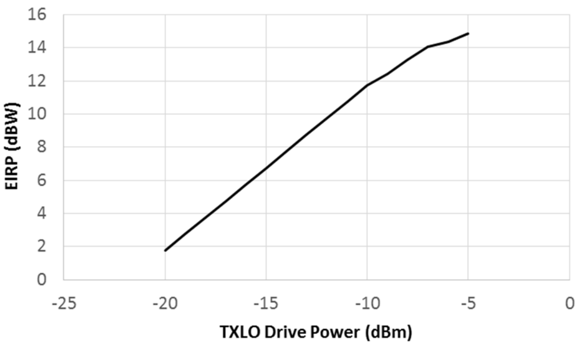



Fig. 10. Measured boresight EIRP Vs TX LO drive power for 3x3 array.

## V. On Air Inmarsat BGAN Measurements

To measure the system with actual Inmarsat signals the 3x3 array, (Fig. 6(a)) was placed outdoors. It was configured for receive operation, with the measured $C/N_0$ taken from the in phase combined IF port, as per Fig. 7. For comparison, the results were benchmarked against a commercial BGAN user terminal antenna (Hughes 9201), Fig. 6(b). On-air results for receive mode are presented in order to show that accurate phase tracking of the BGAN global beam was possible. It was confirmed, at the time of the measurement, that the BGAN global beam was producing a power level in the region of -130 dBm at each antenna element.

The results are shown in Fig. 11 where the retrodirective array demonstrates an almost flat response over the steering range of ±40°, with an amplitude variation of <1 dB over the steering range -35° to 30°. The commercial BGAN terminal, which is not self-steering, maintains a 1 dB flatness over ±10° azimuth range. The commercial terminal is able to receive a $C/N_0$ of 51 dBHz at boresight, whereas the 3x3 retrodirective array, with a similar aperture area receives 48 dBHz. With regard to Table 2 when antenna gain is reduced by 1 dB, and antenna feed loss increased by 1 dB, G/T reduces by 3 dB, thus suggesting the likely differences between retrodirective and commercial terminal receive performance.

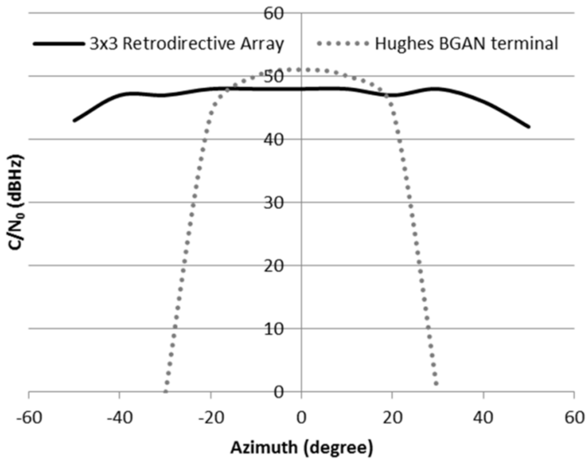



Fig. 11. $C/N_0$ Vs azimuth angle of 3x3 retrodirective array, Vs Commerical BGAN terminal (Hughes 9201) receiving a live Inmarsat global beam signal.

To further confirm that the retrodirective antenna is tracking the phase of the global beam signal accurately results were taken of the phase relationship between two of the 156 MHz TCVCXO signals [21] (Fig. 7), since these track the phase of the incoming signal. This result in Fig. 12 shows that phase is being recovered with sufficient accuracy so that post conjugation an accurate self-pointing high quality signal could be retransmitted back to the satellite.

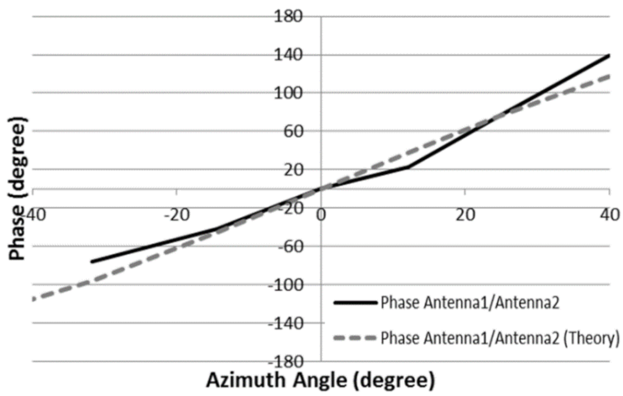



Fig. 12. Phase tracking ability of two elements of retrodirective array receiving a live Inmarsat global beam signal.

## VI. Conclusions

This paper has presented the first in depth look at the challenges involved in using analogue retrodirective arrays for use with an actual BGAN satellite communications system. It was shown that it is possible to construct a retrodirective array that can detect received signal power levels as low as -130 dBm and recover phase sufficiently accurately such that simultaneously self-tracking retransmission is possible. Practical results have been shown for a 3x3 element array tracking signals from Inmarsat BGAN. These showed a significant increase in the beam steering range, from -35° to 30° being achieved as compared to ±10° from a commercial fixed user terminal.

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