Increasing the TRL of an L band Retrodirective array for Type Approved SATCOM applications

ABSTRACT

Retrodirective, self-steering, antennas have the advantage of being able to automatically return a signal back in the direction along from which it originated. The tracking is real time and is carried out in the analogue domain which results in simple circuits which can be accommodated, planar-form, behind the antenna elements. The main objective of this paper is to detail the continuation of the work on L band retrodirective antennas which has the ambition of increasing the TRL such that a minimal viable product can be produced, suitable for type approval as an L band SATCOM user terminal. The focus will be the technical challenges that have arisen as the retrodirective antenna is moved up the TRL chain. Some of these aspects include the ability to track very weak modulated signals (S/N tending to 0dB), TX/RX filter and duplexer specifications, PA and LNA considerations. The resultant retrodirective architecture will be compared against typical specifications of L band satellite ground terminals, showing that the retrodirective antenna offers a simple and effective real time tracking antenna architecture.

1. INTRODUCTION

Satellite communication for on the move has recently attracted a lot of attention, particularly to provide fast data connectivity for moving vehicles in areas where there is no reliable terrestrial infrastructure. The fundamental problem with satellite ground terminals is that they generally need high gain antennas to meet the link budget. The consequence is that high gain antennas are very directional, making them unsuitable for use on a moving vehicle, unless some form of tracking can be employed in the antenna. Mechanical positioning of the antenna is often employed to provide the tracking, although the solutions can be heavy, expensive and unsuitable for portable use. At QUB we have been studying the use of an analogue self tracking antenna (often known as retrodirective antennas) for use within satellite communications on the move. This allows for a potentially low cost tracking antenna, with no moving parts. Three main frequency bands are currently used for satellite broadband on the move, namely L band (1.5-1.6 GHz), Ku Band (10-14 GHz) and Ka Band (20/30 GHz). The higher frequency bands offer higher bandwidth, mainly due to the increased spectrum available, although, due to the smaller wavelength, phased array antennas for the higher frequencies require hundreds of elements, so can be large and complicated. The higher frequency bands are also more susceptible to rain fade. With this in mind L band is an attractive alternative where simpler ground terminal equipment and reliability of the link with regards to rain fade etc are a priority over high bandwidth.

A retrodirective antenna array has the distinct advantage of offering automatic tracking of an incoming signal without a-priori knowledge of its point of origin. This is achieved through its inherent capability to able to automatically return a signal back to its point of origin irrespective of the propagation path characteristics assuming they are lossless and reciprocal [1]. The retrodirective antenna array considered here are those which employ local phase conjugating mixers at each element in the array, Figure 1. Generally these are referred to as “Pon” type structures. An advantage of this structure is that the retrodirective operation is not affected by distance between elements meaning that several sets of subarrays could be placed in different locations. Heterodyne mixing techniques offer a relatively simple method to produce the phase conjugation necessary for the retrodirective antenna. This has been the predominant method of choice for retrodirective arrays since they were first developed in the 1960’s. Despite this apparent simplicity, the mixer based solution alone does not provide sufficient performance (mainly due to the inability to operate with weak satellite signals) to provide a self tracking antenna for satellite ground terminals. These issues have been addressed by QUB in recent ESA projects [Self-Focussing Retro-Reflective Tx/Rx Antennas for Mobile Terminal Applications, AO/1-6168/09/NL/JD. Retrodirective Antenna, ARTES-5.1, 7C.014]. Thus effective architectures need to use more complex mixing strategies, and phase locked loops, to provide a high performance self tracking array, with the ability to track weak signals in real time, re transmit a high power

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signal, and provide the self tracking in full duplex mode.

The L band antenna development at QUB commenced within the ESA project “Self-Focussing Retro-Reflective TX/RX Antennas for Mobile Terminal Applications AO/1-6168/09/NL/JD”. This project produced a 5 element retrodirective antenna prototype raising the TRL at the beginning of the project from TRL2 to TRL4. Looking at the definition of TRL 4 it states that “Component and/or breadboard functional verification in laboratory environment”. This prototype was considered as TRL4, since testing was only possible in laboratory for a number of reasons:

1. The frequency of operation was chosen to be 2.4 GHz TX and 2.2 GHz RX, instead of 1.5 GHz RX, 1.6 GHz TX as used in L band Satcom eg Inmarsat BGAN [3]. This decision was taken so that the breadboard could be readily fabricated with a large choice of Commercial off the shelf components (COTS) for ISM band applications. This meant that it would be impossible to conduct a test in a relevant environment (TRL 5) with a system such as Inmarsat BGAN.

2. The transmit power of the antenna was sufficient to allow technical validation, but would not have provided sufficient EIRP for a link to a satellite. One of the main reasons for the reduced TX power meant that the TX/RX duplexer did not require a high degree of TX/RX isolation, allowing for a less stringent design.

3. The prototype required a CW pilot tone on receive, in addition to the modulated signal. Normally Satcom systems do not include CW beacons for tracking, the antenna must be able to track the modulated signals directly.

4. The ability to transmit to the satellite (if the antenna operated on the correct frequency) would be subject to lengthy type approvals, to ensure the transmit performance meets the specification of the satellite service provider.

2. INCREASED TRL PROTOTYPE

Based on the findings of the TRL4 prototype, the next stage for QUB was to embark on the design of a second prototype to raise the TRL. The aim here was to design a retrodirective antenna element, capable of being configured as an array in “tile” fashion. Within this design very important consideration was given to providing an antenna that was compatible with the Inmarsat BGAN system [3], and meets the requirements for type approval. Type approval considers a number of factors, some of which are available from ETSI [4], and additional requirements can be stipulated from the satellite service providers. Some of the most critical factors that required to be considered in the raised TRL prototype were:

- The transmit signal requires to have an acceptable low distortion (often measured as EVM).
- The spurious levels of transmitted emissions have to be below a certain mask at certain frequency bands.
- Transmit type approval requires a certain EIRP specification from the antenna.
- Receive performance requires a certain G/T
- Radiation pattern requirements for various scan angles (side lobe level, cross polar, axial ratio etc). Being a steerable antenna means that the specification has to be met for all scan angles, and is not as simple as a fixed, non steerable antenna.
- Pointing loss should be below a certain value for all scan angles.

3. DESIGN PROCEDURE

Despite the enormous progress in simulation software, it is still very challenging to produce accurate predictions of all factors of a system such as the retrodirective antenna. Results such as radiation patterns can be easily predicted, although other results, such as transmitted
spurious components, transmitted error vector magnitude (EVM), etc, can be harder to predict with high accuracy. As can be seen from Figure 2, the retrodirective antenna is more than a simple passive device, since it consists of a basic superheterodyne receiver subsystem. Simulations of a wide range of parameters are very challenging since accurate models are required for all components, eg TX PA, duplexer, RX LNA, TX/RX Filters. The component simulation models also need to accurately operate in non linear regions. In addition the effects of the PCB used for the retrodirective system has to be considered, as unwanted effects such as poor grounding could deteriorate the performance of the components, eg the TX/RX isolation of the duplexer can be quite sensitive to the quality of the grounding around the device. With this in mind, it was important to build practical systems as early as possible to verify the accuracy of the simulation results.

The hardware breadboard design to raise the TRL was done in three stages (Figure 3 (a-c)). The first stage involved fabricating the individual system components as separate modules (Figure 3 (a)). This allowed the entire retrodirective system to be tested in a modular fashion, allowing for changes to the system to be readily made until the specification was met. Following this the system was designed on a single PCB (Figure 3(b)), which was fabricated in house. Due to the various effects of designing on a single PCB, such as cross coupling and grounding issues, there was some rework required to this PCB until the desired performance was achieved. The final stage (Figure 3(c)), reflecting all the reworked changes, was to design the final PCB, which would be implemented as a retrodirective array of up to 16 elements. Although this 3 stage hardware process may seem a bit lengthy, it appeared to be essential as it meant that the breadboards, when manufactured as a 16 element array, had very few design issues. If there was considerable problems at this stage it would have required rework of 16 boards, instead of 1, using considerable resource to accomplish.

Figure 2. Retrodirective antenna module block diagram

Figure 3. Three stages of breadboard hardware design

4. RETRODIRECTIVE MODULE TESTING

The testing of the retrodirective antenna reported here is mainly focused on the tests carried out to a single retrodirective module. The performance of the beam scanning of the circular polarised antenna array has also been extensively characterised and is reported in [5]

4.1. Transmitted EIRP

The retrodirective antenna module was measured in a 10M far field anechoic chamber, configured for monostatic retrodirective radiation pattern measurements. The EIRP of the single module was measured by first calibrating the anechoic chamber using a known gain standard (in this case a linear polarised dipole was used). This was then substituted by the retrodirective module, such that the EIRP could be calculated from the received power. The results of the transmitted EIRP Vs TXLO drive power are shown in
Figure 4. From this graph it was calculated that an EIRP of 3.15 dBW was being produced at the P1dB point. Also shown in Figure 4 is the transmitted Error Vector Magnitude (EVM), for a transmitted 16QAM 150kbps signal, typical of what would be used on transmit by an L band satellite ground terminal. An EVM of 5.4% is obtained with an EIRP of 1 dBW (Figure 5). A 5.4% EVM is equivalent to a BER of $<10^{-6}$ [6] and would be acceptable for satellite ground terminal applications, although typically a 6 dB back off from the P1dB point is employed where the available EIRP would be -2.85 dBW, at this point the transmitted EVM is reduced to 1.9%, allowing for error free transmission. Estimating the EIRP of a larger retrodirective array can be calculated as follows:

$$EIRP(\text{Array}) = EIRP(\text{single element}) + 10\log(\text{No of elements}) + 10\log(\text{No of PA’s})$$

From the above, if the retrodirective module was configured as a 16 element array, allowing for a 6 dB back off from P1dB, it would produce an EIRP of -2.85+24 = 21.15 dBW. This is within close agreement for a typical EIRP for a class 1 ground terminal for L band Satcom, which is required to be in the region of 20 dBW.

![Figure 4. EIRP and transmitted EVM of retrodirective module](image)

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<thead>
<tr>
<th>SR</th>
<th>151.2 kHz</th>
<th>16QAM</th>
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<tbody>
<tr>
<td>CF</td>
<td>1.64 GHz</td>
<td>Mean Signal ConstDiag</td>
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Figure 5. Transmitted 16QAM constellation diagram for module EIRP of 1 dBW (EVM = 5.4%)

### 4.2. Transmitted Spectrum

The transmit spectral purity is based on the specification provided by ETSI [4] which typically requires the EIRP of unwanted spurious products outside the band 1625 MHz to 1661 MHz to be less than 50 dBpW (or -70 dBW). If we assume the EIRP of a class I user terminal to be 20 dBw, then this would equate to a 90 dB suppression of unwanted spurious products. To carry out this measurement the transmitted signal from the retrodirective module was received via a spectrum analyser. The result of Figure 6 shows that most spurious products are supressed by >70 dB over the frequency range of 1.59 to 1.69 GHz. This specification was challenging to meet, given that heterodyne mixing was employed on the transmit stage, and was largely achieved by use of the TX filter and TX IF filter (Figure 2).
4.3. G/T Measurement

The G/T of the retrodirective module front end was measured in the anechoic chamber by calibrating the received carrier power density using a known gain standard antenna, and then substituting the retrodirective module. The C/N\textsuperscript{0} of the received carrier was measured by connecting a spectrum analyser to the output of the two cascaded LNAs, shown in block diagram of Figure 2. It was important to ensure that the noise floor of the antenna front end was higher than the internal noise floor of the spectrum analyser, so a 55 dB gain block was added prior to the spectrum analyser, allowing for a sufficient margin. The G/T was then calculated from:

\[ G/T (dB/K) = \text{Carrier power density (dBm)} + \text{Boltzmann constant (dB)} + C/N_0 (dBHz) \]

From the above the retrodirective module yielded a measured G/T of -18.85 dB/K.

To compare the measured G/T result with theoretical calculations, the G/T calculation [7] was used as follows:

\[ T_R = T_{\text{ANT}} + T(1 - 1/G_{\text{FEED}}) + \frac{T(F_{\text{LNA1}} - 1)}{G_{\text{FEED}}} + \frac{T(F_{\text{LNA1}} - 1)}{G_{\text{FEED}}G_{\text{LNA1}}} \]

here: \( G/T = G_{\text{ANT}}/T_R \).

The results of the G/T calculation for the retrodirective module, is shown in Table 1. Here a G/T is calculated of -18.25 dB/K, allowing for an antenna feed loss of 2 dB (0.8 dB for duplexer, 1.2 dB for 90° combiner and feed losses), which agrees favourably with the measured result. If we were to scale the measure G/T by the array factor of a 16 element array (12 dB), it would indicate that a G/T of -6.8dB/K would be possible for a 16 element array. Typically a class 1 user terminal for L band Satcom requires a G/T of &gt;-10.5 dB/k which would be achievable with 7 elements (assuming an ideal array factor).

<table>
<thead>
<tr>
<th>Table 1 G/T calculation of single retrodirective module</th>
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<tr>
<td><strong>Te</strong></td>
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<tr>
<td>Antenna Gain (dB)</td>
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<td>Antenna Noise Temperature (K)</td>
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<td>Antenna feed Loss (dB)</td>
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<td>LNA1 Noise Figure (dB)</td>
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<td>LNA 2 noise figure (dB)</td>
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<td>LNA Gain (dB)</td>
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<td>Noise Temp ((\Sigma T_e))</td>
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<td>G/T (dB) ((G_{\text{ANT}}(dB)-10Log\Sigma T_e))</td>
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4.4. Receive on air performance

The retrodirective antenna was setup outdoors (Figure 7), such that tests could be carried out when receiving an actual global beam signal from Inmarsat BGAN. Figure 8, shows that at the output of the dual cascaded 16dB LNA’s the global beam signal has a level of -102 dBm. Allowing for 2 dB cable loss to the spectrum analyser, this makes the received global beam at the antenna element to be -130 dBm. When the received signal was optimally combined (retrodirective tracking) the received S/N ratio showed an increase of 9 dB for a 9 element array, close to the theoretical array factor of 9.5dB.
have been discussed. The ambition has been to raise the TRL to allow the retrodirective antenna to meet certain key specifications to allow it to have the potential for type approval for L band Satcom ground terminal applications. For a 16 element array a transmit EIRP of 21.15 dBW was possible. This is within close agreement for a typical EIRP for a class 1 ground terminal for L band Satcom, which is required to be in the region of 20 dBW. Receive G/T was calculated to be -6.8 dB/K for a 16 element array, meeting the specification for a typical class 1 user terminal for L band Satcom, requiring a G/T of >-10.5 dB/k. On transmit most spurious products are suppressed by >70 dB over the frequency range of 1.59 to 1.69 GHz.

6. REFERENCES


4. ETSI EN 301 444 V1.2.0 (2011-02) “Satellite Earth Stations and Systems (SES)”.


5. CONCLUSIONS

In this paper the several key factors relating to increasing the TRL of the L band retrodirective array