Design and Performance of the Prototype Advanced SAR Calibration Transponder

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INTRODUCTION

Ground transponders have been used very successfully, by the European Space Agency (ESA) and others, to calibrate satellite Synthetic Aperture Radar (SAR) instruments [1],[2]. Calibration transponders will doubtless play an important role in the characterisation of future SAR instruments, too. In previous studies for ESA and for the British National Space Centre [3]–[5], Systems Engineering & Assessment Ltd (SEA) and QinetiQ developed a design for a calibration transponder for future SARs. Those studies addressed alternative technologies to improve performance and/or reduce costs; transponder coding and other advanced modes; and options for transponders for quad-polarisation SAR systems.

Under a more recent ESA contract, 15088/01/NL/PB, SEA and QinetiQ have built and trialled a Prototype Advanced SAR Calibration Transponder. Full details can be found in the Final Report [6] and the supporting documents referenced therein. This paper summarises the prototype transponder design and outlines future intentions for a possible quad-polarisation transponder.

PROTOTYPE TRANSPONDER DESIGN

A high-level block diagram of the Prototype Advanced SAR Calibration Transponder is shown in Fig. 1 below. It shares many characteristics with the proven architecture of ESA's ERS-1/ERS-2 [1] and ASAR [2] transponders, such as the inclusion of an internal gain stabilisation subsystem. However, there are several novel features, notably the incorporation of a digital base-band subsystem and the use of horn antennas. These aspects are discussed below.

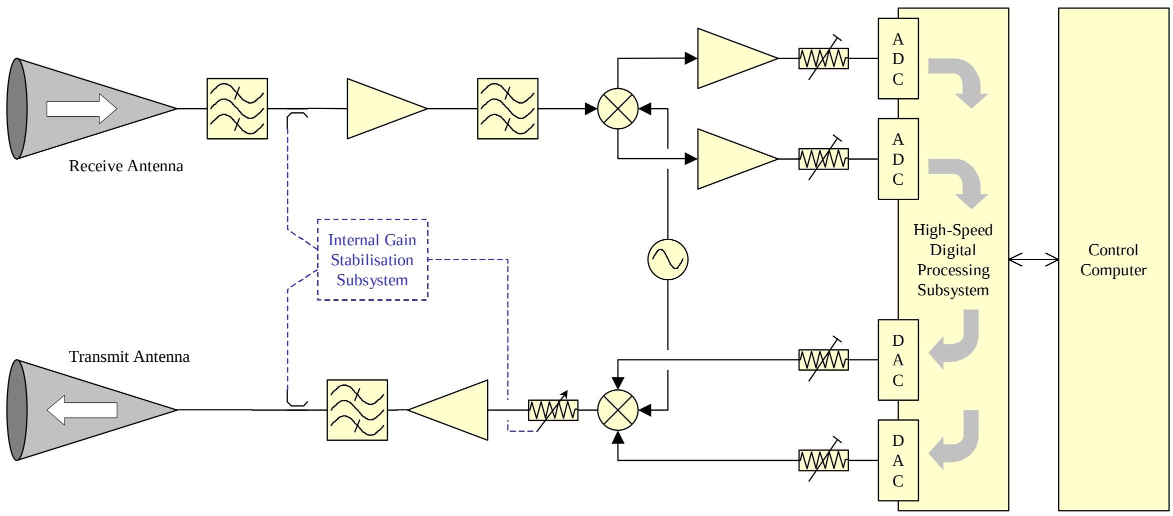

Fig. 1. Top-level block diagram of the Prototype Advanced SAR Calibration Transponder

Fig. 2. View of the transponder weatherproof enclosure and antennas

The prototype transponder has been designed for use with ERS-2, Radarsat-1 and Envisat ASAR. The operational bandwidth of ~60 MHz centred at 5.312 GHz covers all three instruments' bands. The antennas are diagonally polarised, to transpond both V and H polarised pulses from the various SARs without the need for rotation of the antennas. The transponder radar cross-section (RCS) is 66 dBm^2 for diagonal polarisation, corresponding to 60 dBm^2 for H or V polarisation. The key quantitative performance parameters (RCS stability etc.) are similar to those for previous SAR transponders.

Antennas

The Prototype Advanced SAR Calibration Transponder employs a pair of high-performance Potter horn antennas (Fig. 2). These were designed and built by Microwave Antennas and Systems Ltd against a mask specified by QinetiQ. They are also used for the ASCAT Ground Transponders, which SEA and QinetiQ are building under contract to Astrium, ultimately for EUMETSAT. The horns are about 0.8 m long and 0.4 m in diameter. They produce a gain of about 23 dBi, with a relatively wide main-lobe (which greatly eases pointing requirements) but very low far side-lobe levels (for multipath suppression), see Fig. 3. They are also physically robust and cost-effective for a SAR transponder.

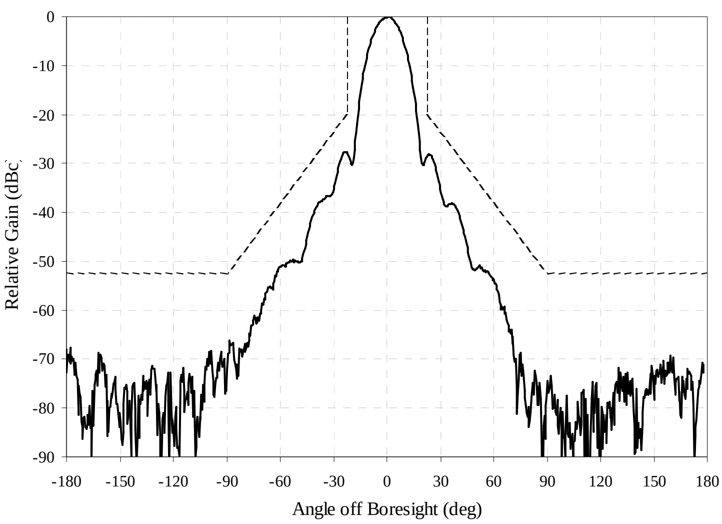

Fig. 3. Example of measured antenna gain (solid line) against the mask (broken line)

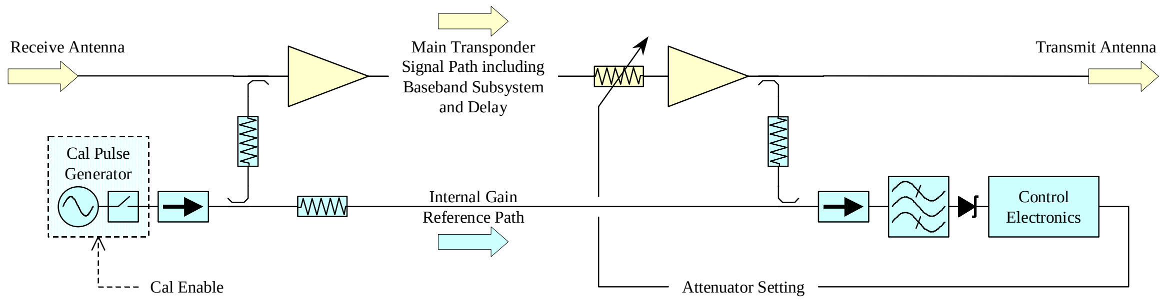

Fig. 4. Schematic of the internal gain stabilisation electronics

Radio-Frequency Subsystem (RFS)

The Radio-Frequency Subsystem, shown in Fig. 1 earlier, incorporates down- and up-converters to the base-band digital subsystem. It is housed in a weatherproof enclosure, maintained at 40 ± 1 °C. An internal gain stabilisation subsystem, similar in concept to that in previous SAR transponders, ensures the stability of the complete (RF and base-band) signal path. The operation of the gain stabilisation subsystem, shown schematically in Fig. 4, is as follows:

When enabled, a calibration pulse generator outputs a short continuous-wave (CW) pulse, which is split and passed round the system via two paths. Part of the calibration signal passes through precision attenuators direct to an amplitude detector. The other part is coupled into the main signal path, just after the receive antenna. It passes round the system and is then taken, via a coupler just before the transmit antenna, to the same detector. A delay in the main signal path ensures that the signals via the two parts are received separately a short time apart. The relative levels of the two signals are used to set a fine-resolution (< 0.01 dB) programmable attenuator, which is iteratively adjusted over a series of pulses until the levels are equal. In this way, the gain of the main transponder path (which includes a number of inherently rather unstable active components) is tied to the gain of a reference path including only highly-stable passive components. Measurements of the system performance show that this technique converges quickly (<< 1 s) and achieves an internal gain stability of ± 0.04 dB for ± 5 °C temperature excursions.

Digital Signal Modulator (DSM)

A schematic block diagram of the base-band digital subsystem, the Digital Signal Modulator or DSM, is shown in Fig. 5. The DSM samples the base-banded I&Q signals from the RFS at 100 MHz rate, digitally processes them in a field-programmable gate array (FPGA), and converts them back to analogue for retransmission. The DSM is controlled and configured over a serial link from a Windows control program running on a laptop personal computer (PC).

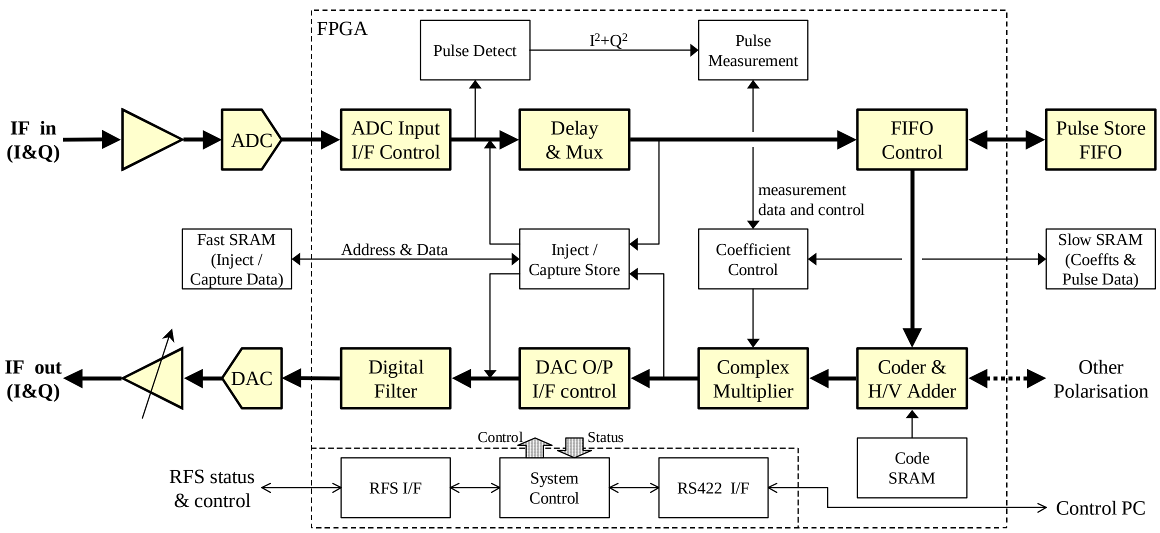

Fig. 5. Schematic of the Digital Signal Modulator (main signal path shown in bold)

The Digital SAR Modulator provides a number of important signal processing and control functions, for both the operational transponding mode and the supporting calibration modes, as described below.

Azimuth Coding

The DSM includes an azimuth coding function, whereby the phase of selected pulses can be inverted (simply by changing the sign of the digital data). The coding sequence is downloaded as a list of multiplying coefficients from the PC. Typical codes include feedback shift register sequences (see [4]) or a simple alternating-sign sequence. Azimuth-coded transponders will not focus in normally processed SAR images. However, the transponder signal can be focused by applying the appropriate synchronised decoding sequence during the SAR processing, in which case the background return (clutter) is defocused instead. For azimuth sign codes, the decoding is very easy and robust, and can provide a processing gain against clutter of up to about 5 dB. Azimuth coding also identifies the transponder unambiguously, because only the transponder signal is focused in the decoded image. If multiple transponders are deployed, orthogonal codes can be used to distinguish each transponder individually. The ability to identify a transponder reliably is clearly particularly valuable if the calibration campaign is automated, or if calibration is performed on board the spacecraft. The DSM can also be used to shift the transponder return in azimuth in the SAR image, by configuring the multiplying coefficients with a complex phase ramp. If required, azimuth shifting and azimuth coding can be combined.

Delays

In a digital subsystem, signals can be delayed for a long period with no degradation, using a first-in-first-out (FIFO) buffer. A small delay through a transponder is useful, because it shifts "ring-around" (i.e. transponder output signals which leak back into the transponder input) down-range of the wanted transponder return, thereby avoiding a potential error contribution. Furthermore, the DSM can transmit each received pulse several times, producing multiple transponder echoes in the SAR image. With suitable allowances in the processing, independent gain measurements can be obtained from each echo, and these can be averaged to improve the calibration performance.

In the Prototype Advanced SAR Calibration Transponder, the DSM also provides the delay required by the internal gain stabilisation system (see above). In the ESA transponders [1], this delay was implemented by a fibre-optic delay line. A digital delay is simpler and inherently more flexible, e.g. the delay for the internal gain stabilisation mode can be set different from the delay for the transponder operational mode.

Other Benefits of a Digital Subsystem

The digital subsystem measures the power, duration and pulse repetition interval of all observed pulses. Selected pulses can be captured in their entirety and transferred to the control computer for off-line analysis.

The DSM also supports transponder testing and external calibration (i.e. determination of the transponder's effective radar cross-section). In the transponder external calibration procedure, calibration pulse data samples are loaded into the DSM inject/capture store. The calibration pulse is transmitted through the DACs and transmit-chain towards a suitable calibration target (actually a circular flat plate mounted on a tower). The echo from the plate is captured through the receive chain and ADCs. The transponder effective radar cross-section is then calculated from the relative levels of the transmitted and received pulses, the target cross-section and the range.

TRANSPONDER TRIALS

Trials of the Prototype Advanced SAR Calibration Transponder were conducted with Envisat ASAR. The trials successfully demonstrated the operation of the complete transponder, including the pulse coding, multiple-repeats and azimuth-shifting modes. Some results are shown in Fig. 6.

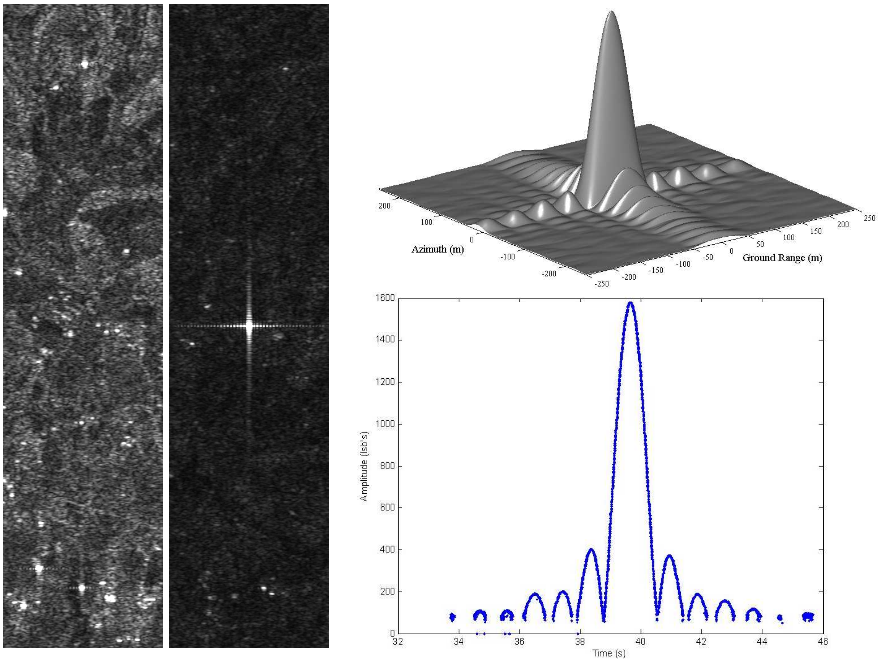

Fig. 6. Results from the Prototype Advanced SAR Calibration Transponder trials. These figures show (i) co-registered normally-processed and decoded images of a coded transponder; (ii) the point-spread function of the decoded transponder return; and (iii) the azimuth transmit beam pattern of ASAR, as measured by the transponder.

FUTURE DEVELOPMENT

Quad-Polarisation Transponder Concept

This ESA contract represents a step towards the Quad-Polarisation Transponder Concept proposed in [3]. Complete characterisation and calibration of quad-polarisation SAR is a challenging requirement: There are four scattered polarisations to be calibrated, and the relative phase differences are of interest in addition to the amplitudes. Also, the various polarisation channels may be significantly contaminated by imperfections in the SAR instrument, such as antenna cross-talk and alignment errors. (For lower-frequency SARs the situation would be further complicated by Faraday rotation. This changes the plane of polarisation so that the polarisation at the ground is significantly different from that transmitted or received by the spacecraft. In that case, the transponder effectively calibrates the *scattered polarisation* component rather than the SAR *instrument polarisation* channel.)

Four independent transponders with different combinations of antenna polarisations could calibrate all four polarisation components (or, equivalently, the overall sensitivity and the three relative amplitude imbalances). However, calibrating the relative channel phases would be very difficult, because that would rely on accurate (<< wavelength) knowledge of the relative positions of all the antenna phase-centres. Many single-polarisation transponders would be required for an effective calibration campaign. Even with cost reductions, such as the use of horn antennas rather than large reflectors, this would represent a significant investment.

Given a cluster of four transponders each with differently-polarised pairs of antennas and their own ancillary subsystems (e.g. positioners), the next logical step is to combine them into a single integrated system, Fig. 7. The signals from both receive antennas are retransmitted by both of the transmit antennas, so only four antennas (H + V receive and H + V transmit) would be required. Clearly, this could save a lot of hardware relative to four single-polarisation transponders. In particular, the total number of antennas is halved and four positioners are replaced by one. There are performance advantages in an integrated quad-polarisation transponder, too. For example, the different polarisation paths can be better matched, by sharing common critical elements (power amplifiers etc.) and by incorporating a sophisticated, integrated internal gain stabilisation methodology. Moreover, with the antennas on a single assembly, a quad-polarisation transponder would be able to calibrate relative channel phases precisely.

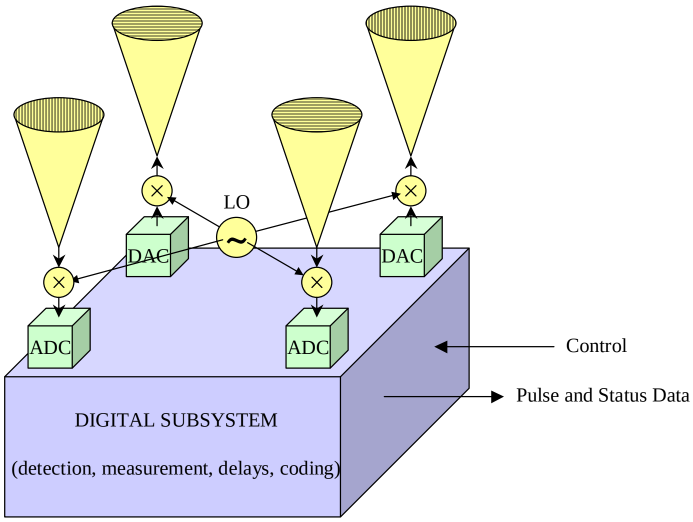

Fig. 7. Quad-Polarisation Transponder Concept based on a digital subsystem

Implementation of the quad-polarisation transponder concept requires that one must be able to distinguish the different transponder polarisation components in the processed SAR imagery. This can be achieved using different delays, azimuth shifts and/or orthogonal codes for each polarisation component. The Prototype Advanced SAR Calibration Transponder has demonstrated all three of these methods. In practice, different delays would be sufficient and relatively simple, but pulse coding (and multiple pulse repeats) also provides some gain against clutter. Incorporating a digital subsystem also provides a very effective way to implement the splitters and combiners necessary to produce the different channels, with precisely (digitally) controlled amplitudes and no path-length issues to upset the phases.

The Potter horn antennas in the prototype transponder provide better than –40 dBc polarisation cross-talk, so the transponder polarisations can be considered as effectively pure H and V. An integrated quad-polarisation transponder can use pulse detections on one polarisation to trigger retransmission of both receive polarisations, even if the second polarisation is not actually detectable on the ground. The resultant images could then provide information on the instrument cross-talk, as well as the amplitudes and phases of each polarisation component. If instrument cross-talk is found to be significant, it may be possible to compensate for its effects in the processing. Even if the instrument cross-talk levels are low or non-observable, the transponder results still have value for verification purposes. (For lower frequency SARs, e.g. L-band, Faraday Rotation would also be present and may well dominate instrument cross-talk. Separating these effects would be more complicated. If the instrument cross-talk is low, the transponder could measure the Faraday rotation directly, by comparing the amplitudes of the H and V signals on the ground for H or V polarisation transmitted by the instrument.)

A quad-polarisation transponder as outlined would provide a total of up to 40 measurements (if one measurement is taken as an amplitude or a phase). These are:

- ◊ The amplitudes of each of the four transponder polarisations (HH, HV, VH and VV) in each of the four nominal image polarisations (16 values)
- ◊ The corresponding phases (16 values)
- ◊ The amplitudes of the satellite nominal H and V transmissions as observed on the transponder H and V receive antennas (4 values)
- ◊ The corresponding phases (4 values)

These are not all completely independent, some may not be observed in practice and only phase differences (rather than absolute phases) are meaningful. Nevertheless, a quad-polarisation transponder could provide a very large amount of information. The effective exploitation of this information still requires detailed study.

The Prototype Transponder and the Quad-Polarisation Concept

The Prototype Advanced SAR Calibration Transponder actually implements one channel (one transmit polarisation and one receive polarisation) of the Quad-Polarisation Transponder Concept. One half of the transponded signal path is essentially implemented in its entirety, as illustrated schematically in Fig. 8.

Some additional components would be required for the quad-polarisation version. In particular, the internal gain calibration subsystem would need to be developed further to ensure that all polarisation channels are accurately stabilised and matched. The internal gain calibration principles used in the Prototype Advanced SAR Calibration Transponder can be extended to the quad-polarisation case. For example, a calibration pulse could be coupled into both receive chains simultaneously and the resultant signal levels in both transmit chains could be compared with the injected signal level, using four distinct delays provided by the digital subsystem. Some further complexity would be required to stabilise the relative phases – reference [2] describes a possible method.

SUMMARY CONCLUSIONS AND RECOMMENDATIONS

A Prototype Advanced SAR Calibration Transponder has been developed and successfully trialled. It incorporates additional functionality (e.g. pulse coding and pulse repeats) that offers clear operational benefits. Trials indicate that the prototype transponder operates as expected. Its basic performance is similar to existing transponders, but it incorporates many novel design features:

- ◊ The Potter horn antennas used are a good alternative to offset reflectors in transponders.
- ◊ The Digital Signal Modulator has clear operational advantages (coding, multiple pulse repeats, pulse parameter measurements) and practical advantages for the transponder itself (no separate delay-line for the internal gain stabilisation subsystem, support to external calibration).

The Prototype Advanced SAR Calibration Transponder is useful in its own right, but is also a stepping-stone towards an advanced Quad-Polarisation Transponder Concept. The Quad-Polarisation Transponder promises to be a powerful tool for calibrating and characterising future quad-polarisation instruments. The prototype transponder has proved much of the technology, although a few areas merit further work.

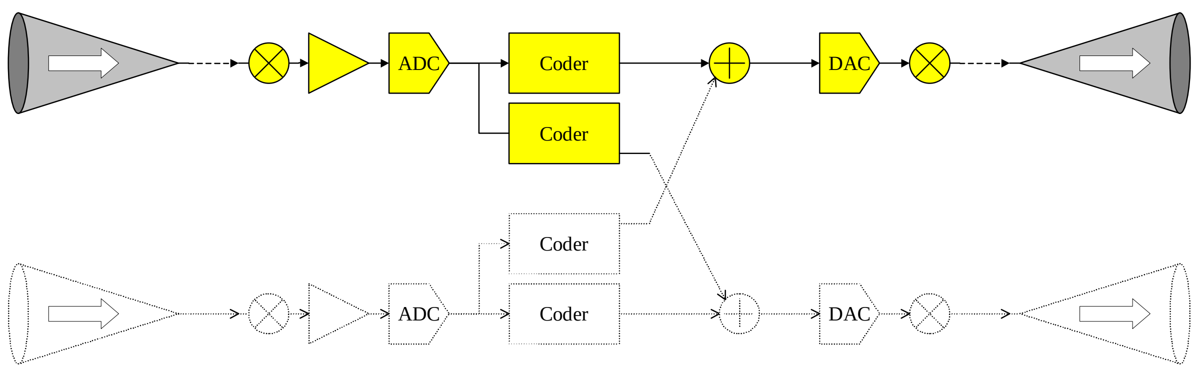

Fig. 8. Relationship of the Prototype Transponder (solid) to the Quad-Polarisation Transponder Concept (dotted)

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