# Development of the ERS-1 Active Radar Calibration Unit

Harry D. Jackson and Alan Woode

*Abstract*—**This paper describes the development of a microwave Active Radar Calibration Unit (ARC) used as a ground calibration reference standard for the European Remote Sensing Satellite ERS-1 imaging Synthetic Aperture Radar. Three such units are placed across the radar swath giving point target returns with a known signal strength and are used to calibrate the radar image. The units have been designed for maximum stability with temperature (<0.1 dB over the temperature range of −15°C to +35°C); for absolute calibration the ARC is referenced to a flat plate using a novel technique of multiple transmission in its self calibration mode, achieving an absolute calibration error of <0.14 dB.**

## I. Introduction

As PART of the verification and calibration plan for the ERS-1 Satellite Active Microwave Instrument (AMI), ground based Active Radar Calibrators (ARC's) are used. Because of the different operating modes of this instrument, Imaging (SAR) and Wind Wave (Scatterometer) two different design of ARC has been built in the ESTEC RF Systems Division. The unit described in this paper has been built for calibration of the Imaging mode SAR having a stability figure of better than (±0.1 dB).

Three calibration units have been built and tested, meeting almost completely the rather demanding specifications for the instrument. These are currently installed on test sites in Flevoland, North Holland, an example is shown in Fig. 1. Other locations will be used later in the life of the satellite.

## II. Design Specification

The overall specification for the ARC has been defined in the ERS-1 Calibration plan but the important parameters are given below.

| | |
|---|---|
| Operating frequency | 5.3 GHz |
| Nominal radar cross section, ($\sigma$) | 65 dBm$^2$ |
| Adjustment | +0, −5 dB |
| Calibration accuracy (absolute) | ±0.5 dB |
| Cross calibration accuracy | ±0.2 dB |
| Stability over 3 years | ±0.1 dB |
| Signal to thermal noise ratio | 20 dB |
| Signal to bi-static clutter ratio | 20 dB |
| Peak signal to multipath ratio | 40 dB |
| Delay | <2.5 $\mu$s |
| Frequency translation | 0 Hz |

Manuscript received May 22, 1991; revised December 4, 1991.
The authors are with the European Space Technology Centre, P.O. Box 299, 2200AG Noordwijk, The Netherlands.
IEEE Log Number 9107464.

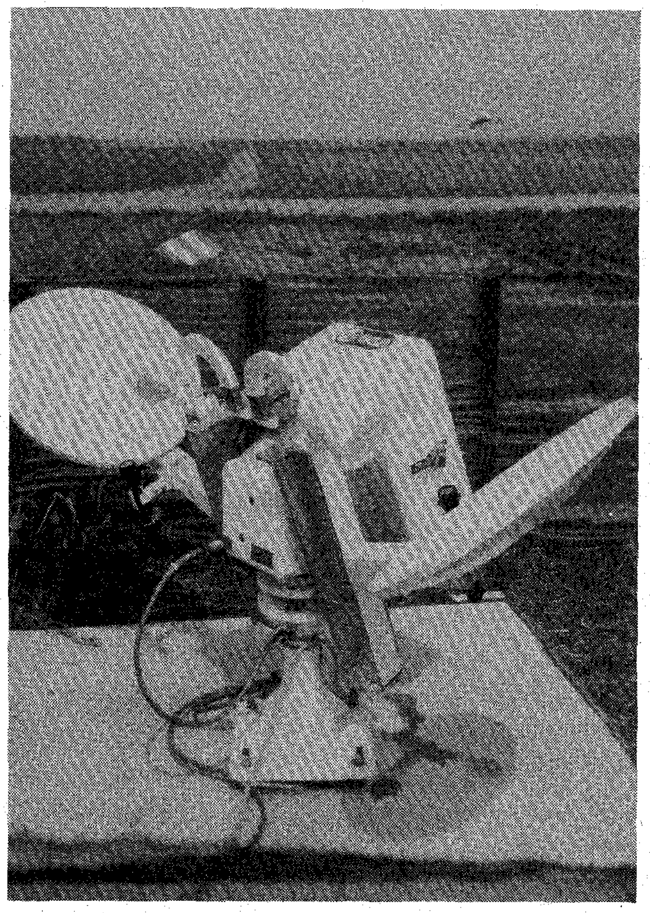


Fig. 1. ERS-1 ARC No. 2. One of three based in North Holland.

The terms used are defined as follows:

*Radar Cross Section:* The RCS or $\sigma$ of the ARC will be imaged as a point target with a brightness given by

$$\sigma = \frac{G_1 \times G_2 \times G_{SYS} \times L^2}{4\pi}$$

where $G_1$ and $G_2$ are the transmit and receive antenna gain, $G_{SYS}$ is the system gain of the electronics module and $L$ is the radar wavelength.

*Adjustment:* The effective $\sigma$ of the ARC must be adjustable within the limits given.

*Calibration Accuracy:* The range of residual uncertainties in the value of $\sigma$ after a calibration routine on the ARC has been carried out.

*Cross Calibration Accuracy:* The residual uncertainty in the relative value of $\sigma$ when cross comparing different ARC's.

0018-9480/92$03.00 

*Overall Stability:* The excursion in the $\sigma$ value as seen by the ERS-1 SAR.

*Signal to Bi-Static Clutter Ratio:* The ratio of signal to incoherent bi-static scattering from the area surrounding the ARC, both for transmission and reception.

*Peak Signal to Multipath:* The ratio of signal to coherent specular reflections from the surrounding area.

*Delay:* The time between reception and re-transmission of the SAR signal at the ARC.

## III. Requirements of the Active Calibrator

To achieve the specifications given above it is necessary to translate them into actual requirements at the equipment level, this is summarized below.

### *Antenna*

To achieve the specified performance for the ARC, two antennas will be required having the following performance:

| | |
|---|---|
| Center Frequency | 5.3 GHz |
| Polarization | vertical |
| Side lobes 34–180 deg off boresight | $< -40$ dB |
| Absolute gain | 27 dBi |
| Cross polar $\pm 2$ deg | $<40$ dB |
| Main lobe gain variation ($\pm 0.35$ deg) | $<0.025$ dB |
| Return loss | $<30$ dB |
| Spill over coupling | $>80$ dB |
| Deflection with 60 km/h wind loading | $<0.01$ deg |
| Misalignment due to thermal variation in sunlight, 60 °C | $<0.01$ deg. |

The side lobe performance is critical both to reduce bi-static clutter and multipath interference, it will also influence cross coupling between the transmit to receive antennas. The antenna gain requirements are a compromise between the gain necessary to achieve an adequate $S/N$ ratio and the gain variations across the main lobe, compatible with the expected pointing accuracy of the positioning system. If the beam is too narrow the errors caused by pointing would be too great.

### *RF and Electronics Unit*

This unit will maintain the standard gain functions of the ARC, the requirements are:

| | |
|---|---|
| Center frequency | 5.3 GHz |
| Bandwidth (3 dB) | $\pm 50$ MHz |
| Gain | 43 dB |
| Gain adjustability | $+2/-7$ dB |
| Gain stability (−15 to +35°C, over a 3 year life) | $<0.1$ dB |
| Signal/noise ratio | $>20$ dB |
| Delay (fixed, $\pm 0.1$ $\mu$s) | 1.5 $\mu$sec |

Gain stability is the most difficult of these specifications to achieve, it requires a gain control circuit with sufficient resolution and accuracy to maintain the overall ARC gain stability requirement. To achieve the specification a digital sampling and gain control loop is used as analogue feedback is unlikely to achieve the performance requirements. Fig. 2 shows the basic configuration for gain control with a delay. A major source of error is double transit caused by antenna leakage, it does not effect the loop gain, because the calibration pulse is shorter than the built in delay, but it will cause an interference pattern on the actual signal returned from the ARC to the satellite as shown diagrammatically in Fig. 2. The overall gain of the R.F. and Electronics unit is determined by the required radar cross section and the antenna gain, bandwidth is limited to reduce the risk of spurious reception.

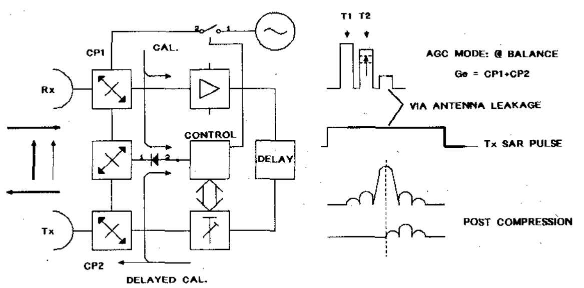


Fig. 2. AGC operation and leakage effects.

## IV. Design Realization

A design fulfilling these specifications has been realized in the R.F. Systems Division Laboratories of ESTEC and is shown in the simplified block diagram Fig. 3. A brief description of its operation is given below.

Approximately one hour before each expected satellite overpass, a lap-top computer commands the positioner to point the antennas and switches dc power to the ARC electronics unit. The electronics unit then operates continuously in a self calibrating mode, achieving initial gain stability in about 3 minutes and reaching thermal stability during the remainder of the period. On receiving the first downlink pulse from the satellite the calibration mode is inhibited and the transponder gain is held constant for the time of the satellite overpass (approximately 1/2 sec, about 800 pulses are received and retransmitted during an overpass). After a short delay the electronics unit is switched off and the antennas moved to a parked position which minimizes the accumulation of debris on reflectors or feed horn window.

When operating in the calibration mode, 1 $\mu$s calibration pulses are injected from the calibration pulse generator into the gain and delay loop via the couplers CP4 and CP1. The amplitude of each injected calibration pulse is monitored in the Control Electronics Unit via CP3, D1 and AM3. After amplification in the main gain/delay loop the amplitude is also monitored in the Control Electronics Unit via the coupler CP2, AT1, and common components in the video sampling circuit.

For such a system to work successfully, timing of the sampling circuit is critical, this is shown pictorially in Fig. 2, the timing pulses being $T_1$ and $T_2$. By choosing the length of the calibration pulse to be shorter than the delay

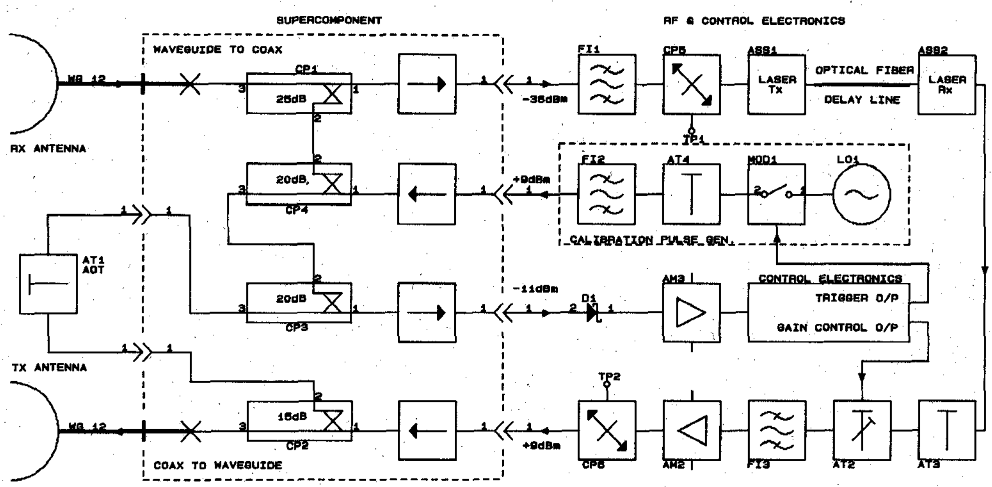



Fig. 3. Simplified block diagram.

time any measurement errors caused by antenna cross coupling or multiple transits of the calibration pulse are minimized.

The overall transponder gain is defined by the value of the couplers CP1, CP2 and the fixed attenuator AT1, an error signal caused by unbalance in the sampled signal amplitudes will cause the digital attenuator to increment or decrement. With such a system the sampling unit is effectively used as a nulling device and changes due to the calibration pulse amplitude, temperature, or ageing are minimized.

The advantages of including a delay in the transponder for both the operational and AGC modes are summarized below:

i) Distortion due to antenna leakage is non-coherent and is suppressed with range compression.

ii) The point target image of each ARC is displaced from it's physical location by about 600 m across swath. As each ARC is located within 50 m of a building, this allows easy separation of images, and with suitable locations can place the ARC image on a uniform background.

iii) AGC stability is improved, coherent distortion of the calibration pulse due to antenna leakage is eliminated and common components can be used for amplitude monitoring which avoids ageing or temperature errors.

*Coupler Gain Control Block*

The stability of components outside the control loop are critical, any change reflecting directly on the transponder gain, the four couplers CP1 through CP4, being especially so. As no commercial couplers were available with sufficient capability, they were manufactured as an integrated super-component, to the following specification:

| | |
|---|---|
| Return loss, all ports | $<30$ dB |
| Isolation | $>26$ dB |
| Insertion loss, max | $<0.5$ dB |
| Coupling, nominal values | $\pm 0.5$ dB |
| Stability with aging, over 3 years with temps of 0–70°C | $<0.1$ dB |

The production units, with microstrip couplers, isolators and integrated coaxial to waveguide transitions were manufactured by the Netherlands TNO Laboratories. During stability testing of the completed RF/Electronics unit the performance of the super-component was demonstrated to be completely adequate able to achieve the required microwave performance with good expectations of its long term ageing requirements.

*Optical Delay Unit*

An optical delay Unit was chosen as it had several advantages over the alternative Bulk Acoustic Wave (BAW) or Surface Acoustic Wave (SAW) devices:

No frequency translation was required.
Minimal spurious triple transit signals.
Low loss and wide bandwidth.

As this was the first time an optical delay line had been used for such an application some specific problems arose that required solving. It was unfortunate that little help was available from the supplier and some time was lost during the development phase. Problems that occurred were:

Temperature sensitive distortion due to coherent reflections from discontinuities in the delay line connections (around $\pm 0.2$ dB).
Intermittent performance of optical connectors.

These two problems were cured by fusion splicing at the interface of the laser and optical detector. A third more severe problem only became apparent after the above problems were solved. Randomly occurring small amplitude instabilities were caused by mismatch between the laser transmitter and the optic fibre. Although small ($\pm .07$ dB) these instabilities meant the overall stability specification could not be met.

The solution was to fit optical isolators with a return loss of better than 35 dB close to the laser transmitters again using fusion splicing, performance of these components is now to specification.

*Control Electronics*

As the feedback control circuitry is digital it is important that the video amplifier (AM3) output is sampled at the correct times ($T_1$ and $T_2$) and with sufficient accuracy for storage prior to comparison for gain error correction. To achieve this the control electronics is synchronized to a crystal clock.

To give adequate tracking performance a 12 bit, 10M samples/sec A/D converter was used at the detector output. The monitoring resolution was calculated to be about 0.003 dB/bit. The gain control circuitry latches the A/D converter output at times $T_1$ and $T_2$ (Fig. 2) into registers and a comparator digitally compares their magnitude. The comparator output increments or decrements the control attenuator AT2 via a 12 bit counter driver. To reduce the effects of video and power supply noise, digital averaging of the sampled error signals is carried out before AT2 is incremented. With an injected calibration pulse PRF of 1700 Hz the loop gain/loss can be compensated for at a rate of 0.27 dB/s.

*Loop Components*

Good quality commercial grade components are used within the control loop. The control attenuator AT2 is a digital 12 bit PIN device with a resolution of 0.01 dB. To achieve the correct operating point of the amplifiers a replaceable fixed attenuator AT3 is also included.

*Antennas*

The antennas are a common design to those used on the ESTEC Scatterometer ARC, where more stringent performance requirements apply, they have been manufactured by ERA in the U.K. The design chosen is an offset feed parabola with corrugated feed horn necessary to meet the side lobe and return loss specification. This design meets fully all the specifications listed in Section III. Solid waveguides connect to the RF/electronics unit to minimize changes outside of the control loop.

*Mechanical*

The loop electronics are housed within a proprietary environmental box with breathing desiccator to control humidity, the antenna horns and waveguides vent within the box. Solid state temperature controllers are used to limit the temperature excursion of the critical components, these are operating at temperatures below 10°C. Power supplies, the positioner controller and the control computer are mounted within a free standing transportable rack unit that can be positioned up to 50 m away from the main ARC. The two antennas, and the RF/Electronics box are mounted on a mechanical platform attached to the positioner unit. The antennas are optically aligned on the platform to better than 0.05 deg. Sufficient rigidity is given by the structure to maintain the pointing accuracy.

*Pointing and Control*

An electronically controlled elevation over azimuth positioner is used to point the ARC to the required satellite orbit. With such a positioner it is possible to control it remotely and to make rapid changes if required eg for calibrating ascending and descending orbits.,

Control and monitoring is accomplished by a lap-top computer mounted in the remote rack unit. Control and status monitoring is via an RS232 line selected by the parallel port. A permanently connected modem allows continuous contact with the ARC to be maintained if required.

## V. The Test Program

*Testing The RF/Electronics Unit*

A rigorous test program on the RF/Electronics units has been carried out to demonstrate compliance with the specification (Section II). The most demanding of these tests is the gain stability with temperature and a dedicated temperature controlled test set has been built up specifically for this test. The complete unit is mounted within a temperature controlled chamber which is programmed to cycle between the required limits. Measurement of the gain stability relies totally on a HP438A dual power meter with HP8481A heads for monitoring the input and output power via calibrated waveguide couplers. These are mounted outside the temperature chamber with thermal breaks to the main chamber and are individually temperature stabilized. Logging and averaging of the measured data is carried out within a control computer.

For the prototype unit many iterations were made to optimize the performance of the RF/Electronics unit. A plot of the stability obtained for one of the production units is given in Fig. 4, the uncompensated gain variation is seen to be better than 0.03 dB. Specifications on gain flatness, compression and spurious are also all met.

*Absolute Calibration*

An absolute calibration of the individual ARC's was carried out on an outside test range using a metal plate with a known radar cross section as depicted in Fig. 5. With the ARC in its calibration mode a test pulse is transmitted from the transponder, reflected by the plate, then received by the ARC and retransmitted once more after the 1.5 $\mu$s delay. By balancing the transmission path loss, the $\sigma$ of the plate and the ARC gain a series of decaying pulses can be monitored within the RF loop from which the absolute ARC gain can be extracted. The pulse amplitude decay was measured over four pulses resulting in high measurement accuracy and repeatability (.05 dB):

$$\sigma_t = \frac{4\pi \cdot \lambda^2 \cdot R^4 \cdot G_{(\text{delta})}}{A^2}$$

where

| | |
|---|---|
| $\sigma_t$ | transponder gain |
| $G_{(\text{delta})}$ | gain difference between pulses |
| $A$ | calibration plate diameter |
| $\lambda$ | free space wavelength |
| $R$ | transponder target separation. |

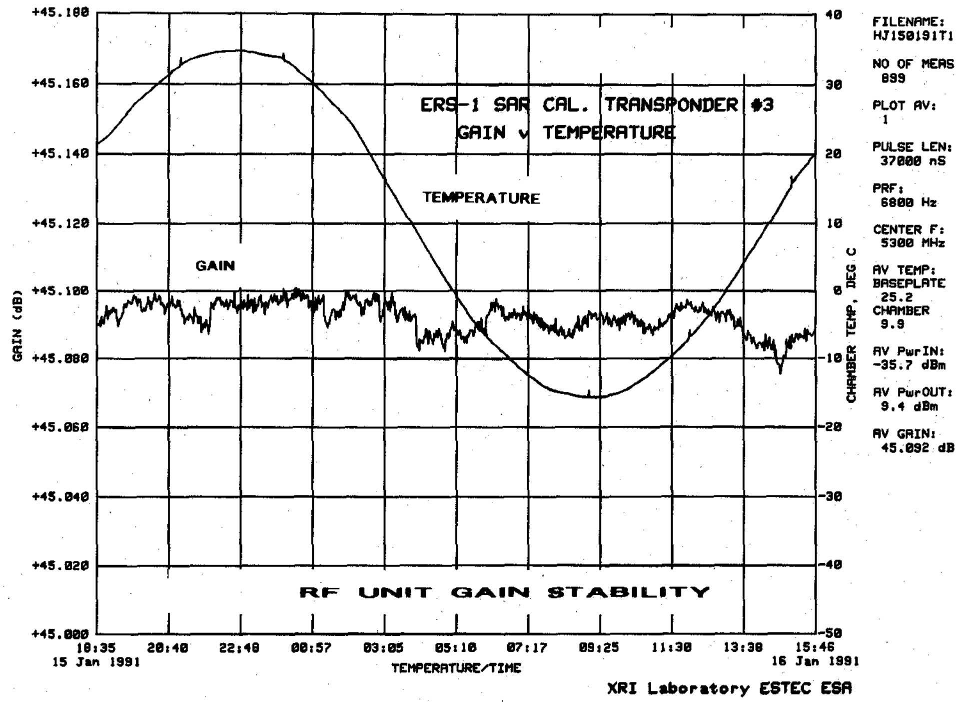



Fig. 4. RF unit gain stability.

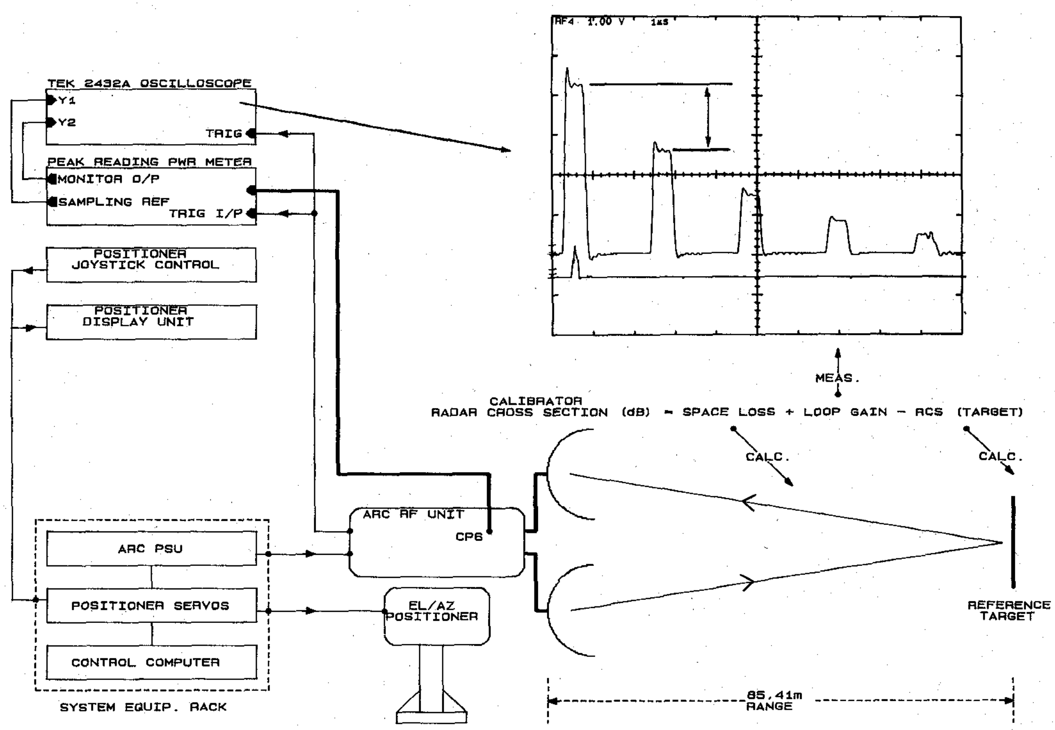



Fig. 5. RCS calibration.

Although in the far field some parallax error exists due to the spacing of the receive and transmit antennas. This was estimated by re-aligning both boresights of a spare equipment to the reflector center and noting the increase in return signal. Multipath effects were estimated by incrementing the range $R$ and recording variations in RCS, subsequent analysis then yields a correction value. This is shown in Fig. 6, a linear regression of the measured data fits well with the theoretical RCS slope due to changes in range.

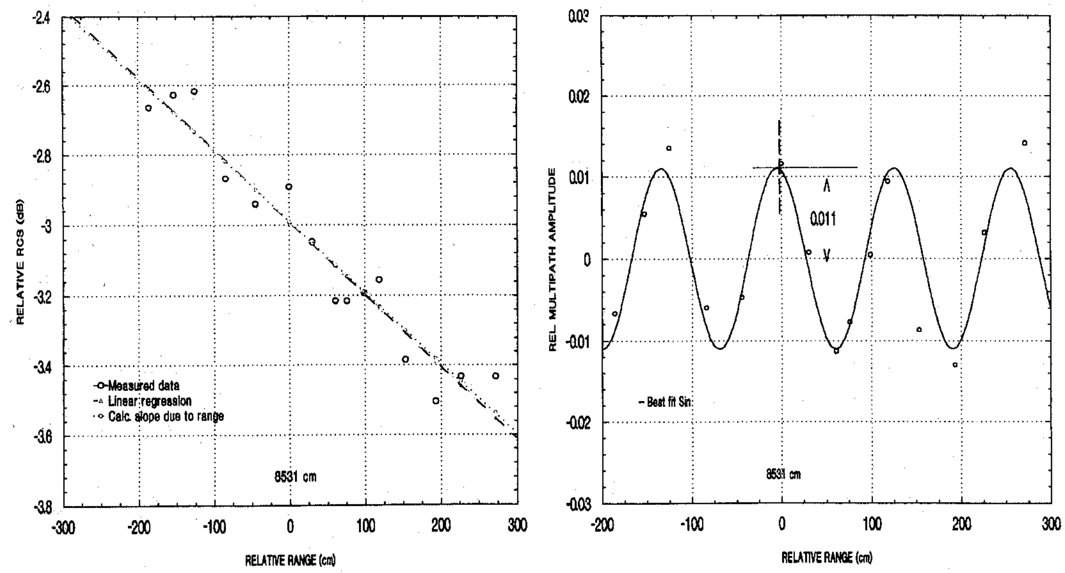



Fig. 6. Calibration multipath correction.

TABLE I
ERS-1 SAR Active Radar Calibrator: Stability and Calibration Error Budgets

| Source | Stability | Cross Calibration Error | Absolute Calibration Error |
|---|---|---|---|
| 1) Antenna Pointing | (pk-pk. dB) | (pk-pk. dB) | (pk-pk. dB) |
| with ERS track error ±0 Km | | 0.015 | |
| ±1 Km | 0.009 | | 0.018 |
| ±2 Km | 0.018 | | 0.024 |
| ±5 Km | 0.840 | | 0.900 |
| 2) Antenna Thermal | 0.010 | 0.010 | 0.010 |
| 3) Electronics Thermal Stability | 0.080 | 0.080 | 0.080 |
| 4) Impulse Distortion | 0.010 | 0.010 | 0.010 |
| 5) Calibration | | | |
| Target plate flatness | | | 0.006 |
| Clutter | | | 0.050 |
| Multipath correction (−0.095 dB measured) | | | 0.040 |
| 2 * Antenna far-field correction (+0.161 dB measured) | | | 0.060 |
| Range measurement | | | 0.020 |
| Loop gain measurement resolution | | 0.050 | 0.050 |
| Column RSS values | | | |
| with ERS track error of ±1 Km | 0.08 | 0.10 | 0.13 |
| ±2 Km | 0.08 | — | 0.13 |
| ±5 Km | 0.84 | — | 0.90 |

| | |
|---|---|
| Stability | Variation in RCS of a single, deployed ARC with multiple observations. |
| Cross Calibration Error | Non-systematic error in the quoted RCS for any deployed ARC. |
| Absolute Calibration Error | Error in the quoted RCS for any deployed ARC. |

## VI. Error Budgets

After completion of the absolute calibration an error budget has been compiled and is given in Table I (RSS). Although not exhaustive it is believed that all significant errors have been included, a brief description of these is given below.

*Antenna Pointing Errors:* The errors from various sources were combined using a probability density function based on the quadratic form of the measured ARC RCS polar diagram.

*Antenna Gain Instability:* These are due to thermal expansion, calculations were made using the manufacturers supplied data.

*Electronics Thermal Stability:* The figure used is the worst case for the four RF units tested.

*Impulse Distortion:* This represents the interference effect of a retransmitted echo caused by worst case antenna leakage.

*Target Plate Flatness and Range Measurements:* Measurements were performed by the ESTEC metrology section, the plate flatness was 0.1 mm p.p. and the range measurement, using laser range finding techniques, accurate to ±50 mm.

*Far Field and Multipath Errors:* are estimates based on the measured corrections described in Section V above.

The above errors do not all contribute to the stability and cross calibration requirements for instance calibration errors do not effect stability and only non-systematic errors effect cross calibration. Several other error sources were evaluated and considered to be insignificant.

Although strictly not part of the ARC specification, the effect of ERS-1 track errors are included for completeness, but should the orbit stability deteriorate pointing coordinates can be remotely updated to avoid additional errors.

## VII. Deployment

Three locations in Flevoland, a province of the Netherlands were identified by ESA as suitable sites for the ARCs. Requirements for the locations were:

- ERS-1 SAR coverage during commissioning and operational phases.
- Image location (approx 650 m down range) on a suitable background.
- Prime power availability, easy access and some degree of security.

Preparation of the sites was the responsibility of FEL/TNO under a separate contract. This included prime power and telephone connections, placement of a concrete base, provision of a suitable wind-break and obtaining a transmission license from the Dutch PTT. Subsequent, differential GPS measurements resulted in absolute positional data for the ARCs and, more importantly, accurate orientation measurements of a local pointing reference at each site. Each positioner azimuth axis was adjusted to vertical using a precision spirit level and rotating the ARC. Optically aligning the antennas with the pointing reference and programming the positioner control electronics then permits pointing with the desired accuracy.

## VIII. Provisional Results

An illustration of SAR image quality analysis is shown in Fig. 7, the interpolated impulse response function in amplitude and ground range of ARC 2 [1].

## IX. Conclusion

ESTEC has successfully designed an Active Radar Calibrator for calibrating the Synthetic Aperture Radar of its ERS-1 satellite. Although more complex than some alternative designs, the calibration unit easily fulfills the very tight specification placed upon it with estimated stability and calibration errors of $\pm 0.04$ dB and $\pm 0.07$ dB, respectively. Although the 0.1 dB 3 year stability figure will require careful monitoring of all those items outside of the AGC loop.

In order to achieve a stability greater than that expected from the ERS-1 SAR, the design of the equipment is, of necessity, rather complex. Even with the benefit of experience gained, the authors could not recommend economies by removal of any of the main features, such as the custom antennas, delay or AGC, without compromising compliance with the ERS-1 requirements. The fundamental, absolute calibration technique used is also dependent on the antenna performance and internal delay.

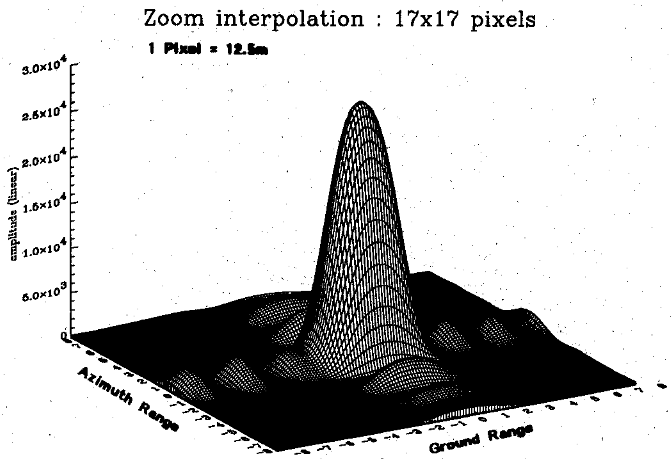


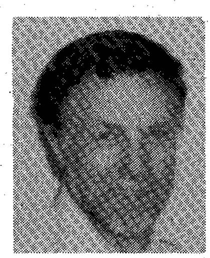

Fig. 7. ARC 2, impulse response.

These units will be used as the prime calibration standards during the ERS-1 verification and operational phases. It is hoped that the AGC and calibration techniques developed will be regarded as adequate to provide standards for cross calibrating between the different remote sensing radars available in the 1990's.

## References

[1] Y. L. Desnos, F. M. Seifert, and M. Loiselet, ESTEC, ESA, "A workstation for ERS1/JPL/JERS1 SAR calibration and quality analysis," submitted to IGARSS'92.

**Harry Jackson** began his professional career when he joined the test equipment division of Thorn-EMI working on the design of high voltage modulators and power supplies for microwave tubes, he later moved within the company to a department evaluating ECM equipment. During this period he obtained an HND from Slough Technical College. In 1986 he joined SERCO SPACE Ltd. as both an Area Manager and Senior Engineer and moved to The Netherlands under a technical support contract to ESTEC, since then he has been involved with the development of scatterometer and SAR calibration equipment for the ERS-1 satellite.



**Alan Woode** obtained the electrical engineering degree from Hatfield Polytechnic in 1962.

His professional career started with the Standard Telecommunication Laboratories, in Harlow, UK, where he worked on early Gunn Device technology and microwave systems. He then moved to Scotland, working for Microwave Electronic Systems Ltd., where he developed a bistatic perimeter protection radar. In 1976 he joined the European Space Agency Technology Centre (ESTEC) in The Netherlands. At present he is Principal Engineer in charge of a laboratory dealing with the technology of microwave Remote Sensing Instrumentation from space, which he started in 1981. Many activities of the Laboratory have been associated with the technology of the successful European Remote Sensing satellite ERS-1, the subject of the paper being one of them.

Mr. Woode is a Fellow of the Institute of Electrical Engineers in London.