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DEVELOPMENT OF AN X-BAND SCATTEROMETER

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Abstract

In this paper a brief description will be given about the structure of scatterometer systems, the main principles on which these instruments are based and the areas where scatterometers can be used. The microwave, analogue and digital circuits of the scatterometer that has been built will be presented. The I/Q detector that is the base of the whole system, the modelling of the detector, theb differences between the ideal and the real detectors and the problems caused by these differences during the measurement are in the scope of the paper. Finally some advantages and possibilities of the computerised data processing will be shown.

Keywords: scatterometer, I/Q detector.

1. Introduction

The reflection capability of a given surface can be measured by microwave scatterometers. The operating principle of this instrument is the same as that of other active remote sensing instruments: an electromagnetic wave with known parameters is transmitted, and a part of this wave, which is reflected by the target, is detected. The schematic blocks [1] of scatterometer systems are shown in *Fig. 1*.

The power received by the receiving antenna is linearly proportional to the transmitted power, to the gain of the transmitting and receiving antenna, to the square of the wavelength and the radar cross-section of the target. The received power is inversely proportional to the fourth power of the distance. If the parameters of the system and the distance of the target are known, the radar cross-section or in the case of distributed targets the differential radar cross-section can be calculated from the received power [2,3].

The oscillator of the transmitter can be a continuous wave (CW) oscillator, a frequency-modulated continuous wave (FM/CW) oscillator or a pulse-modulated oscillator. In the first case an electromagnetic wave with constant amplitude and frequency is transmitted. In the second case the transmitted wave's amplitude is constant, but the frequency is swept periodically over a given frequency band. In the case of a pulse-modulated

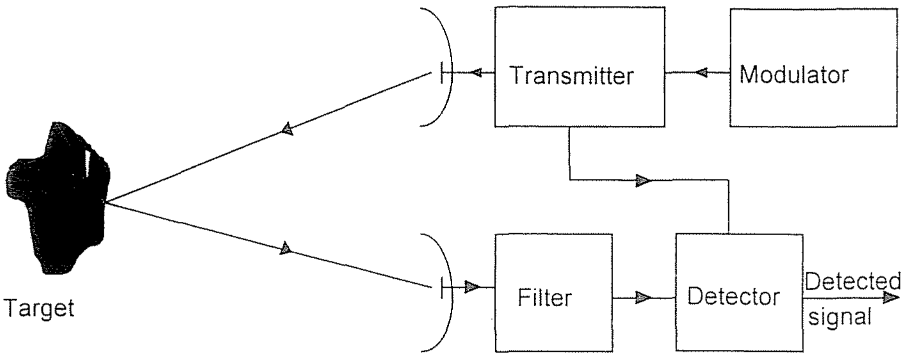

Fig. 1. Schematic blocks of a scatterometer

oscillator the transmitted frequency is constant and the envelope is a periodically repeated pulse.

The scatterometer on which we worked uses an FM/CW oscillator, but the frequency is changing in discrete steps because of the computer controlling.

2. Scatterometer Systems

Fig. 2 shows a complete system [4, 5]. The microwave oscillator (VCO) is a Gunn oscillator which has a central frequency of 10.15 GHz and the sweep bandwidth is 200 MHz. The signal from the oscillator enters the directional coupler, passes through a circulator to the microwave switches, and then to the antenna. The antenna is a two-segment microstrip antenna which can transmit or receive in horizontal and vertical polarization. The system can measure the like- and cross-polarization, too, with the circulator and the switches. The left switch can switch off the transmitting microwave power. The reference and the received signals are both divided by a hybrid. One signal passes through a $\pi/4$ phase-shifter, the other signal without a phase shifter to the hybrid which adds the two signals. Thus the in-phase (I) and the quadrature-phase (Q) signals are detected by the Schottky diodes and the low-pass filters. The I/Q signals get to an analogue multiplexer, then to a 12-bit A/D converter.

The azimuth and elevation angles are regulated by the control computer through a DA converter.

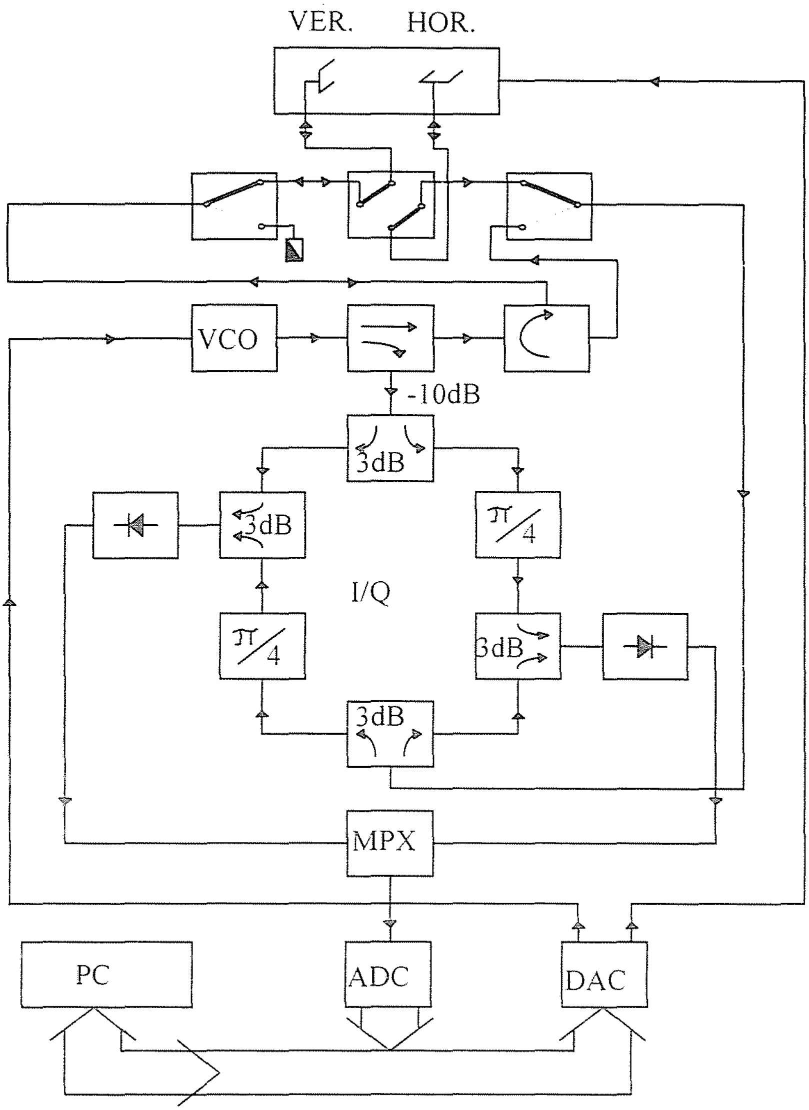

Fig. 2. The 10.15 GHz system

3. Calibration of the System

3.1. Model of the I/Q detector

The model of the I/Q detector should account for the following effects:

- non-linear detector-characteristics,
- asymmetry of the two detectors,

- not exact $\pi/4$ phase shifting (2 cm wavelength),
- internal reflections.

In *Fig. 3* the detector scheme follows the next description. The sampling over frequency is always taken at a fixed frequency value to which the D/A converter is set so that the analysis of the detector is always regarded at this value. The difference between the two detectors is in the values of parameters a, b, α and β. The amplitude of the reference signal is A, and the phase of this can be 0, because only the difference of the two phases is interesting. The amplitude of the reflected signal is B, and its phase is ϕ. $(\alpha - \beta)$ is approximately $\pi/4$. The signals at the input of the detector are shown in *Fig. 4*.

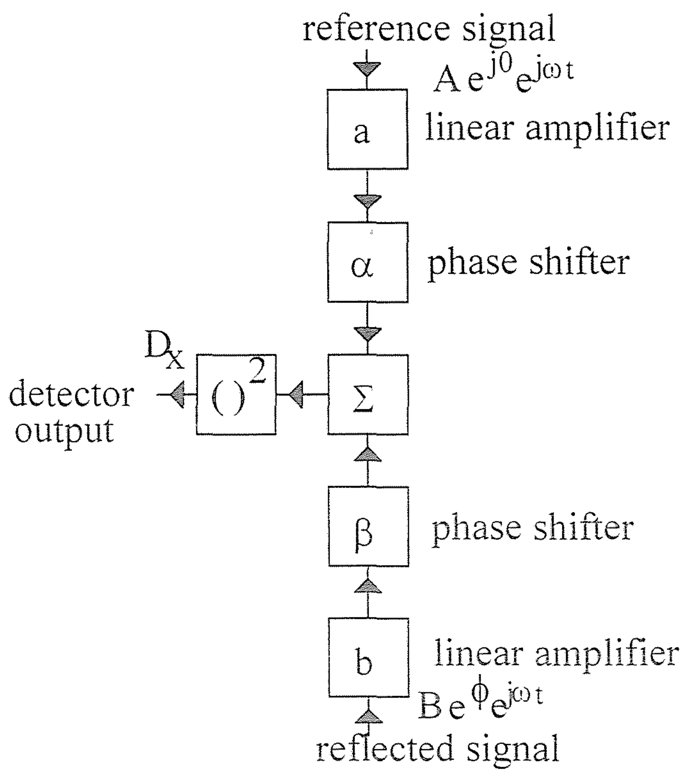

Fig. 3. The detector model

The phasors are rotating with the same frequency, i.e. the VCO CW signal frequency at the moment of sampling. The complex sum of the reference and the reflected signal appears at the detector. Only the amplitude of this signal is important, the phase can be ignored. This amplitude can be calculated with the help of the cosine theorem:

$$D=\sqrt{(a|A|)^2+(b|B|)^2-2a|A|b|B|\cos\{\pi-[\phi-(\beta-\alpha)]\}}. \qquad (1)$$

Using the $\beta-\alpha=\gamma$ and the $\Gamma=B/A$ notations, and if the amplitude of the reference signal is unit, we get:

$$D_x=a_x^2+b_x^2\cdot|\Gamma|^2+2\cdot a_x\cdot b_x\cdot|\Gamma|\cdot\cos(\phi-\gamma_x), \qquad X\in I,Q. \qquad (2)$$

The solution of the equations:

To describe the measured surface reflection we have to get Γ and ϕ from the signals appearing at the output of the detectors. This gives a system of trigonometric-quadratic equations with two unknown quantities, so the iteration is the easiest way to solve it.

Using the notation

$$\Gamma_x\equiv|\Gamma|\cdot\cos(\phi-\gamma_x)=\frac{D_x-a_x^2-b_x^2\cdot|\Gamma|^2}{2\cdot a_x\cdot b_x} \qquad x\in I,Q \qquad (3)$$

the connection between $|\Gamma|,\Gamma_I,\Gamma_Q$, can be seen in *Fig. 5*, where the circle is the Thales circle that can be drawn around γ.

Using the cosine and the sine theorem for the ABC triangle:

$$|\Gamma|=\frac{\sqrt{\Gamma_I^2+\Gamma_Q^2-2\Gamma_I\Gamma_Q\cos(\gamma_I-\gamma_Q)}}{\sin(\gamma_I-\gamma_Q)}. \qquad (4)$$

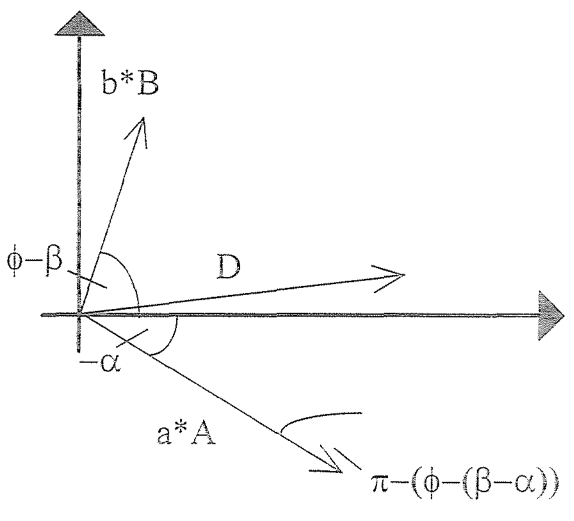

Fig. 4. Phasor-diagram of the detectors

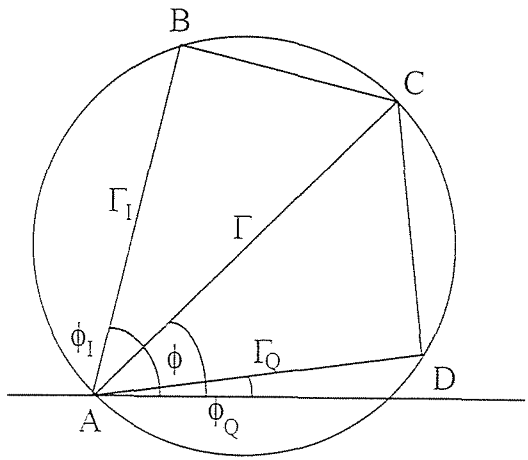

Fig. 5. The relationship of Γ, Γ_I and Γ_Q

If $\Gamma = 0$ is substituted after several iterations, the solution can be obtained. The usage of this formula does not cause problems, because the difference between the two γ is approximately $\pi/2$. If Γ is known, ϕ can be calculated from both equations.

3.2. System Calibration

To solve *Eqs.* (3) and (4) the values for a, b and γ are needed. The number of the unknown quantities is six, therefore three measurements are needed with three different targets with known radar cross-section and phase. To simplify the calibration, one measurement can be done without any target. In this case the antenna is turned to the sky, and the real detector linear multiplicative factors can be calculated simply. The other parameters can be calculated based on the additional two measurements.

The unknown quantities of *Eq.* (2) are a_x, b_x and γ_x. To find the set of six unknown parameters for the two channels of I and Q, three known external reflections should be measured by the system, e.g. the measurement of three different radar targets with known radar cross-section placed at various distances from the scatterometer antenna.

The first, simplest measurement can use the system's internal reflections, as calibrating reflection, while the external reflection is set to zero, i.e. the antenna is pointed towards the sky. For this case *Eq.* (5) defines the extraction of the real linear detector parameters for the reference signal:

$$D_x^{(1)} = a_x^2 \quad \Rightarrow \quad a_x = \sqrt{D_x^{(1)}}\,, \qquad x \in \{I, Q\}\,. \tag{5}$$

The second target produces the reflection given by *Eq.* (6):

$$\Gamma = \Gamma_0 = |\Gamma_0| e^{j\phi_0} . \tag{6}$$

The I and Q signals will be those of *Eq.* (7):

$$D_x^{(2)} = a_x^2 + b_x^2 \, |\Gamma_0|^2 + 2a_x b_x \, |\Gamma_0| \cos{(\phi_0 - \gamma_x)} \ , \quad x \in \{I, Q\} \ . \tag{7}$$

For the third calibration target *Eq.* (8) gives the reflection:

$$\Gamma = ce^{j\delta}\Gamma_0 = c|\Gamma_0| e^{j(\phi_0 + \delta)} . \tag{8}$$

In the latter case the same reflector can be displaced to another distance from the antenna, so c and δ can be expressed from this measurement. The I and Q channel signals of the detector are given by *Eq.* (9):

$$D_x^{(3)} = a_x^2 + b_x^2 c^2 \, |\Gamma_0|^2 + 2a_x b_x c \, |\Gamma_0| \cos{(\phi_0 + \delta - \gamma_x)} \ , \quad x \in \{I, Q\} \ . \tag{9}$$

As the first measurement (no external reflection) gives the a_x parameters it is only b_x and γ_x which are unknown, and these are defined by the latter two measurements, using the detector signals of *Eq.* (10):

$$\left.\begin{aligned} D_x^{(2)} &= a_x^2 + b_x^2 |\Gamma_0|^2 + 2a_x b_x |\Gamma_0| \cos(\phi_0 - \gamma_x) \\ D_x^{(3)} &= a_x^2 + b_x^2 c^2 |\Gamma_0|^2 + 2a_x b_x c |\Gamma_0| \cos(\phi_0 + \delta - \gamma_x) \end{aligned}\right\} \Rightarrow b_x, \gamma_x \ x \in \{I, Q\}. \tag{10}$$

The solution of *Eq.* (10) results in absolute calibration of the system, where all six parameters defining the amplitude and phase difference of the detectors are known.

3.3. Solution for Absolute Calibration

Eq. (10) can be rewritten in a symmetric form, using the substitutions of $c_1 = 1$, $c_2 = c$, $v_1 = \phi_0$ and $v_2 = \phi_0 + \delta$, which yields *Eq.* (11):

$$\begin{aligned} D^{(2)} &= a^2 + (bc_1|\Gamma|)^2 + 2abc_1 \, |\Gamma| \cos{(\vartheta_1 - \gamma)} \, , \\ D^{(3)} &= a^2 + (bc_2|\Gamma|)^2 + 2abc_2 \, |\Gamma| \cos{(\vartheta_2 - \gamma)} \, , \end{aligned} \tag{11}$$

where the unknown real scalars are $|\Gamma|$ and γ. This is a second-order trigonometric equation, to solve it for the two unknowns iteration is a handy method.

We denote the two auxiliary parameters for the iterations as given by *Eq.* (12):

$$b_1 \equiv b\cos(\vartheta_1 - \gamma) = \frac{D^{(2)} - a^2 - (bc_1|\Gamma|)^2}{2ac_1|\Gamma|},$$
$$b_2 \equiv b\cos(\vartheta_2 - \gamma) = \frac{D^{(3)} - a^2 - (bc_2|\Gamma|)^2}{2ac_2|\Gamma|}. \tag{12}$$

Fig. 6 shows the relationship of b and the two iteration parameters: b_1 and b_2.

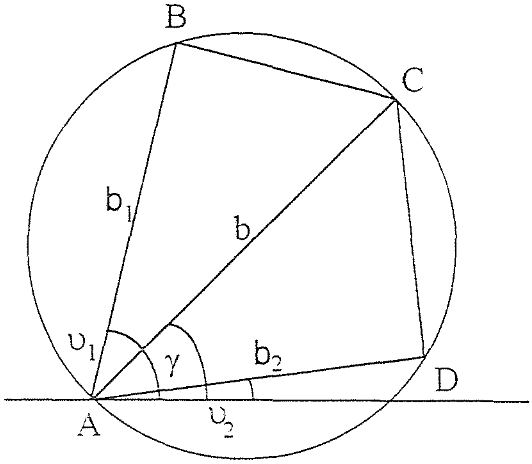

Fig. 6. The relationship of the iteration parameters

The two iteration parameters define b as given by *Eq.* (13):

$$b = \frac{\sqrt{b_1^2 + b_2^2 - 2b_1b_2\cos(\vartheta_1 - \vartheta_2)}}{\sin(\vartheta_1 - \vartheta_2)}. \tag{13}$$

The two *Eqs.* (12) and (13) serve as the to iterative steps for the calculation, starting with $b = 0$. One restriction is that the condition of $\sin(\vartheta_1 - \vartheta_2) \neq 0$ always should be satisfied, which can be kept by placing the targets at a specified distance.

3.4. Correct Placement of Targets

According to *Fig. 7* the same radar calibration reflector is used in the cases 2 and 3. In the case 2 the distance from the antenna is x_0, then in the case 3 it is set to a displacement of Δx.

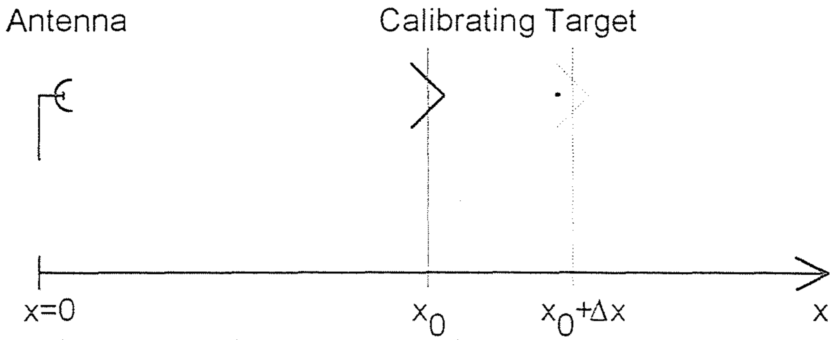

Fig. 7. Positioning of targets 2 and 3 as same target displaced

Examining *Eq.* (12), it turns out that only the ratio of the two reflections is required, i.e. using the square-law distance dependency of the detector voltages this ratio can be calculated as *Eq.* (14) shows:

$$c = \left(\frac{x_0}{x_0 + \Delta x}\right)^2 . \tag{14}$$

The limitation for the sine term in *Eq.* (13) gives a limitation for the maximum displacement of the target from position 2 to position 3. A practical value could be set to the symmetric values around $\pi/2$, e.g. $\pm\pi/4$. This condition for the phase difference should be kept in the whole modulation bandwidth of the radar, which results in the condition of *Eq.* (15) for the maximum displacement.

$$\Delta x = \left(\frac{1}{8} + \frac{n}{4}\right)\frac{c}{f_0}; \qquad |n| \leq \frac{1}{2}\left(\frac{f_0}{\Delta f} - 1\right), \qquad \text{where } n \text{ is an integer.} \tag{15}$$

4. Laboratory Testing

Laboratory tests have been carried out to investigate the stability of the calibration. First the warm-up period was determined, by sampling the detector output signals at the same frequency settings of 100 and 200, which correspond to fixed frequency values in the modulation bandwidth of 200 MHz, around 10.15 GHz centre frequency. *Fig. 8* shows the digital reading versus frequency counts, if there is no external reflection, and *Fig. 9* gives the warm-up period changes of the detected digital I and Q values at frequency settings 100 and 200.

Fig. 9 suggests that the first 25 minutes of the warm-up period is very instable, so the system needs at least this time to get into a stable state.

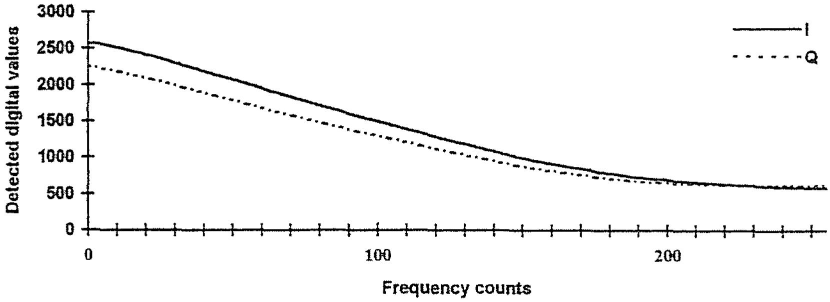

Fig. 8. I and Q digital values versus frequency setting, no external reflection

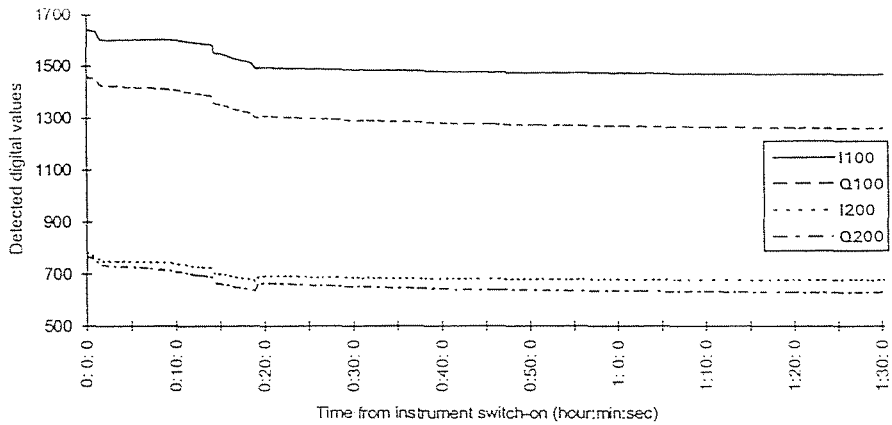

Fig. 9. Detected digital I and Q values at frequency settings 100 and 200

After this time adequate frequency to registrate the no external reflection values is needed.

The final measurement accuracy is shown in *Fig. 10*, which is an evaluation of a measurement of the same target of known radar cross-section at a fixed distance. The error to the nominal radar cross-section is shown versus time in two different cases, i.e. the no reflection registration is done at the 50th and 90th minute measured from the instrument switch-on. The radar cross-section was 7.45 m^2 and the distance was 5 m.

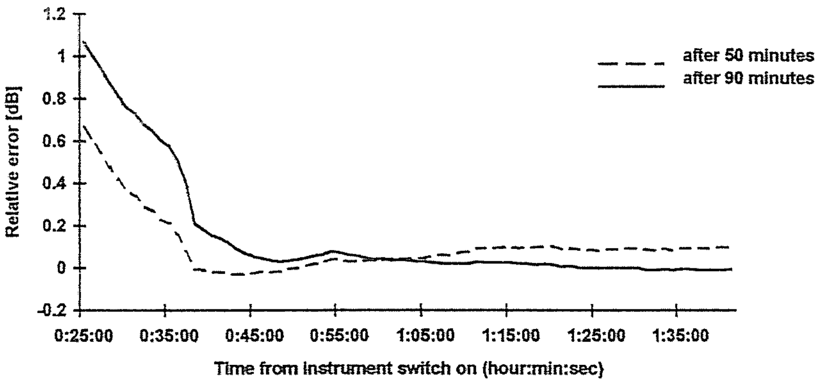

Fig. 10. Measured radar cross-section of metal plate ($\sigma = 7.45\ \text{m}^2$, distance $= 5$ m)

5. Interface Circuits

The interface circuits were designed to the given I/Q detector. There is quite a long distance between the computer and the scatterometer because of the height needed by the antenna, so one of the most important considerations was minimizing the number of wires between them. For this reason serial data transport is used, although this kind of transport needs more additional circuits (the output of the A/D converter is transformed to serial form at the antenna and transformed back to parallel form at the computer). The control cables have more functions depending on the status of the measurement. The computer can communicate with the measurement system with the help of an I/O card based on a 8255PIO IC, which has three eight-bit parallel ports.

In this phase of the development experimental measurements are made to test the reliability of the circuits and the controlling algorithms.

6. Summary

The scatterometer presented uses an FM/CW oscillator which has a central frequency of 10.15 GHz and the sweep bandwidth is 200 MHz, but the frequency is changing in discrete steps. The system can measure the like- and cross-polarized differential radar cross-section. It has been shown that by using a not reflecting calibration case and two additional targets with known radar cross-section the system can be absolutely calibrated and the amplitude and phase errors can be eliminated.

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