CALIBRATION ASPECTS OF A POLARIMETRIC PHASED ARRAY AIRBORNE SAR
L'ÉTALONNAGE D'UN SAR AÉROPORTÉ POLARIMÉTRIQUE À ANTENNE ACTIVE

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Résumé
Le but de l'étalonnage est d'obtenir un instrument exact et précis. La précision de l'instrument est determinée par l'étalonnage interne alors que l'exactitude l'est par l'étalonnage absolu. L'instrument seul est considéré dans l'étalonnage interne. En général dans ce type d'étalonnage, on ne tient pas compte de l'antenne. Cette séparation n'est plus possible lorsqu'une antenne active est utilisée puisque l'antenna fait alors partie du système. L'étalonnage interne devient difficile dans le cas d'une antenne active consistant en un résea d'émetteurs et de récepteurs.
Dans ce papier, la discussion porte sur les différents aspects de l'étalonnage d'un système SAR polarimétrique et de sa réalisation

Abstract
Purpose of calibration is to get an accurate and precise instrument. The precision of the instrument can be determined using internal calibration, while the accuracy is denoted with absolute calibration. With internal calibration only the instrument is considered. Because of practical considerations the antenna is usually discarded in this type of calibration. When a phased array antenna is used this decoupling is no longer possible, because the antenna is now part of the whole system. Internal calibration becomes quite difficult to perform in the case of a phased array antenna with distributed transmitters and receivers.
This paper will discuss the different calibration aspects in the case of a polarimetric SAR system and the implementation in the system.

Preface

The PHARUS project is carried out in a cooperation between the Physics and Electronics Laboratory of TNO (FEL-TNO), the National Aerospace Laboratory NLR and the Delft University of Technology, Laboratory for Telecommunication and Remote Sensing Technology. Financial support for the project is provided by the Ministry of Defense and by the Netherlands Remote Sensing Board (BCRS). The program management on behalf of these partners is carried out by the Netherlands Agency for Aerospace Programs (NIVR).

Introduction

The advantages of the phased array antenna which are generally not encountered in other antenna types has lead to an increased interest in its application in remote-sensing radar systems. Both beam-direction and gain pattern can electronically be controlled. The possibility of shaping the gain pattern has positive effect on sidelobe levels. The flexibility offered by a phased array system, however, has a few drawbacks: beside the higher cost, the system needs more complex circuitry, and often requires computer control, especially when electronic beam control is implemented. Full testing of a phased array is a cumbersome affair. Since the phase and amplitude of the elements of the phased array are controlled by several phase shifters and power amplifiers, the synthesized gain pattern in particular will become a part of the system. Environmental influences and aging of the electronics will directly yield to a degradation of the antenna gain pattern.

Calibration Aspects

If an airborne SAR is used to produce radar backscatter maps with a certain accuracy, the system must be well calibrated. For systems using passive antennas the calibration problem may be divided in two parts: the external calibration taking care of the antenna pattern, including the antenna gain and polarization cross-talk whereas the amplitude and phase relation in the transmitter-receiver chain is calibrated by an internal loop.
Radiometric calibration of a SAR-image is achieved by monitoring all the relevant parameters of the radar equation. The precision and accuracy of the instrument are limited by the errors made in monitoring these parameters. Whereas most parameters can quite readily and constantly be monitored, monitoring of the array pattern during the flight is a cumbersome and time-consuming affair, and therefore mostly omitted. Variations in the antenna pattern and gain have the greatest influence on the uncertainty of the scattercoefficient estimate. Obvious, the effect of a phased array antenna, of which the antenna pattern is formed by the amplitude and phase of several individual T/R-modules fed to radiating elements, will even be worse.
Like the majority of measurements in physics, remote sensing belongs to the class of, so-called, indirect measurements. An important characteristic of such indirect measurements is that always a graduated scale is needed to reduce the quantity to be measured to the one that is actually measured and de facto the creation of such a scale is the objective of calibration.
In order to systematize this discussion on calibration aspects it is helpful to model the radar observation process by means of a layered structure.
If the object signatures are known, the calibration problem can be reduced to a calibration of the sensor in terms of power relations which seems a technical rather then a physical problem. In this way the radar becomes a measuring instrument in the usual sense, whether this instrument will combine the sensor (layer 3) and processing (layer 4) functions or not, depends on the type of system.
A good measuring instrument must be accurate, precise and stable. "Accurate" implies "conforming to truth", "precise" means "well defined" whereas an instrument is said to be stable if repetition of the same measurement yields

the same reading. Precision and stability are design objectives, while accuracy is a matter of calibration. This statement is in no way trivial: too many people are thinking that the quality of an instrument may be improved by frequent calibration. With an instrument that fulfills the accuracy, precision and stability requirements the image processing can be based on true σ-values. Needless to say that procedures like filtering, which potentially may interfere with the "truth-principle", have to be applied with great care. Finally, at the interpretation level, the σ-values will have to be combined with the signature data to yield information on the object.
The assumption that the calibration of the radar may be based on power measurements alone is actually an over-simplification. This is caused by the fact that, in remote sensing, the radar is collecting the power scattered by a certain area or volume, the resolution cell. The usual assumption is then that the radar return of each resolution cell can be replaced by that of a distribution of N-point scatterers. Under certain conditions, the radiation of these N scatterers can be added on an incoherent or power basis. Since each point target is seen from the radar location in a different direction however, the power contribution of each individual point scatterer has to be weighted according to the magnitude of the antenna pattern in the direction that applies. Therefore it turns out that the antenna gain and the antenna pattern are of equal importance.
The ultimate consequence of this power-addition requirement would be a preference for, straight-on, system-designs based on the application of e.g. passive antennas. For such systems the calibration problem may be divided in two parts: the external calibration taking care of the antenna pattern, including the antenna gain whereas the power relation in the transmitter-receiver chain is calibrated by an internal loop.
In case of an advanced SAR-system based on the use of a distributed phased-array antenna both calibrations will mix and the internal calibration in particular will become a fiction. Active antennas like this can only be calibrated when they are operational i.e. when all transmitter and receiver modules are active. In fact also in this case one would prefer a system that is as simple as possible since each operational mode (like incidence angle, swath-width or polarization) will ask for an additional calibration. In general two options can be considered to be appropriate for the calibration of active antennas: the use of a homogeneous distributed target, of which the scatter coefficient is known or the use of a point target of known cross-section in combination with antenna pattern measurements for all

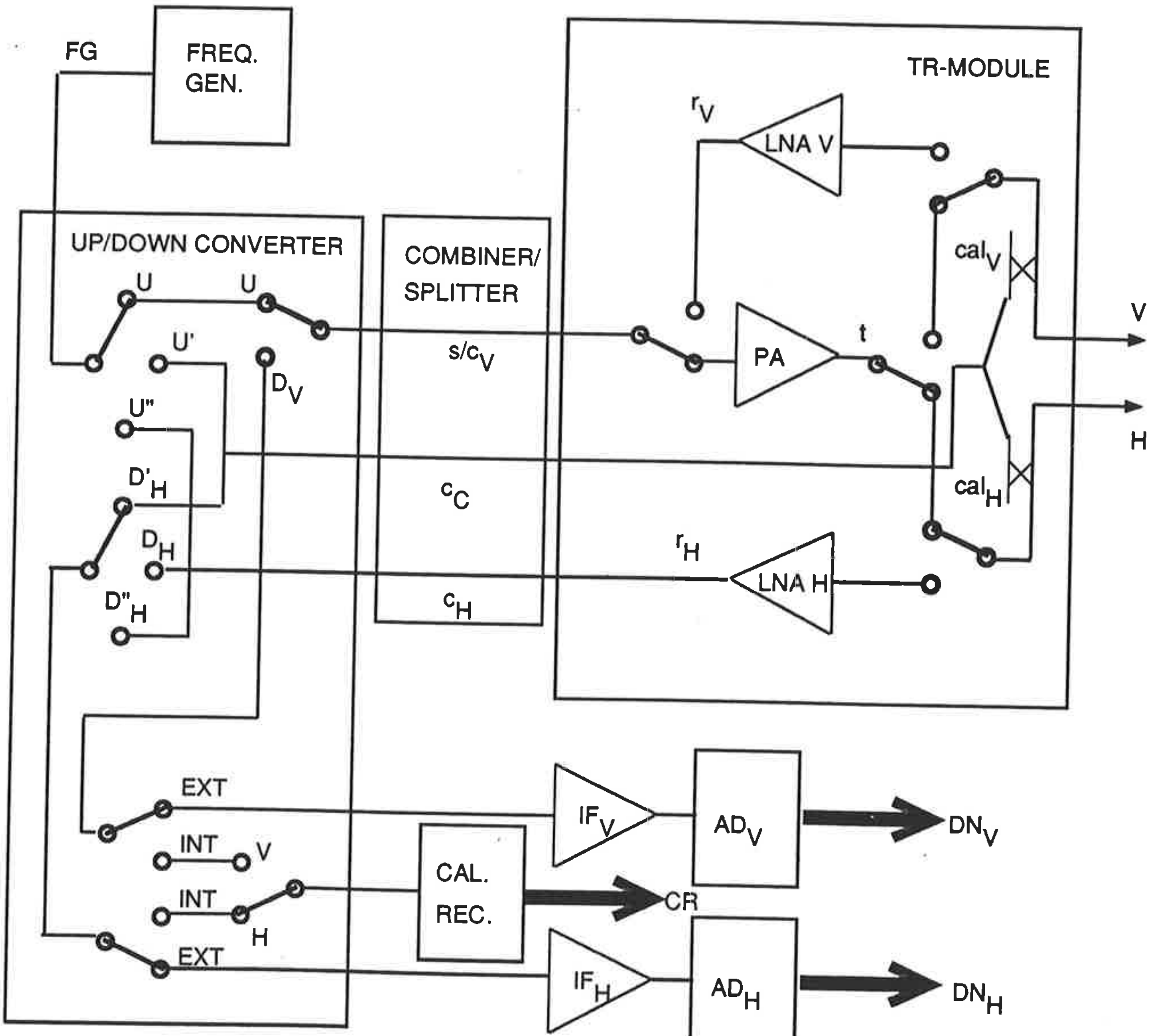

Figure 1. Simplified blockdiagram of the PHARUS system

operational modes and a monitoring of the amplitude and phase behavior of all transmitter-receiver modules. Unnecessary to say that the system stability must be good enough to bridge the time period between two calibrations. In the meantime in fact only the appropriate functioning of the array components can be supervised. The outcome of this book-keeping could be incorporated in the signal processing.

There are two different methods for internal calibration:
1- Separate subsystem calibration : every subsystem is fully characterized and calibrated.
2- Ratio calibration: overall calibration of the total system

The ratio method is superior to the separate method but the actual method to be used depends a lot on the technological possibilities and the measuring time involved. The best calibration method is the ratio method. This method can however not be used in the case of a phased array with distributed transmitters and receivers. Every T/R module has to be calibrated separately.
The internal calibration of the PHARUS system can be accomplished for example by using a attenuated replica of the transmit signal and feeding this into the receiver. There are however some restrictions concerning this simple solution. The power amplifier (PA) and the low-noise amplifier (LNA) needs to be both on during an internal calibration measurement requiring enough isolation between the output of the PA and the input of the LNA. An other possibility is to introduce a separate calibration/monitoring channel. The advantages and implementation of such a separate channel will be discussed in the following section.

PHARUS internal monitoring

In figure 1 a simplified blockdiagram of the PHARUS system [1] is given pointing out the system calibration aspects. In the equations given in this paper uppercase letters are used for system parameters, while lower-case letters are used for parameters specific for T/R modules. A different setting of a switch in the Up/down converter is denoted with a single (') or double (") quote. In the following the digital number measured during different settings of the system will be given and it will be pointed out how these measurements can be incorporated in the signal processing to compensate for drift in components. In table 1 the used symbols are given.

FG	frequency generator output
U	up converter
D_H	down converter horizontal channel
D_V	down converter vertical channel
s	transmit splitter
c_H	combiner horizontal receive channel
c_V	combiner vertical receive channel
c_C	combiner calibration channel
t_H	TR-module horizontal transmit channel
t_V	TR-module vertical transmit channel
g_H	gain patch antenna horizontal port
g_V	gain patch antenna vertical port
r_H	TR-module horizontal receive channel
r_V	TR-module vertical receive channel
cal_H	TR-module horizontal channel calibration coupler
cal_V	TR-module vertical channel calibration coupler
IF_H	IF amplifier horizontal channel
IF_V	IF amplifier vertical channel
AD_H	A/D converter horizontal channel
AD_V	A/D converter vertical channel
CR_H	calibration receiver horizontal channel
CR_V	calibration receiver vertical channel
DN_M	digital number measurement target
DN_{ST}	digital number system calibration transmit
DN_{SR}	digital number system calibration receive
DN_{SS}	digital number system calibration source
DN_{At}	digital number autocalibration transmit
DN_{Ar}	digital number autocalibration receive
DN_{AS}	digital number autocalibration source
Σ	sommation over all active TR modules

Table 1. Used symbols for the transfer function of components or subsystem.

Target measurement

For the digital numbers which are output of the analog to digital converters during the measurement of a target yields, for the horizontal transmitted polarization:

$$DN_{M,HH} = FG.U.\sum\left(s.t_H.g_H^2.r_H.c_H\right).\ D_H.IF_H.AD_H.\frac{\sigma_{HH}}{(4\pi)^3 R^4/\lambda^2} \quad (1)$$

$$DN_{M,HV} = FG.U.\sum\left(s.t_H.g_H.g_V.r_V.c_V\right).\ D_V.IF_V.AD_V.\frac{\sigma_{HV}}{(4\pi)^3 R^4/\lambda^2} \quad (2)$$

and for vertical transmitted polarization:

$$DN_{M,VH} = FG.U.\sum\left(s.t_V.g_V.g_H.r_H.c_H\right).\ D_H.IF_H.AD_H.\frac{\sigma_{VH}}{(4\pi)^3 R^4/\lambda^2} \quad (3)$$

$$DN_{M,VV} = FG.U.\sum\left(s.t_V.g_V^2.r_V.c_V\right).\ D_V.IF_V.AD_V.\frac{\sigma_{VV}}{(4\pi)^3 R^4/\lambda^2} \quad (4)$$

It will be clear that using the equations with a perfectly stable radar and a target with known radar cross section is sufficient to determine the radar system constant. In practice one have to account for variations in almost all of the components and subsystems so additional measurements are necessary.

Systemcalibration during transmission

During every transmitted pulse a attenuated replica is send to the horizontal receiver chain using the calibration channel. The measurement of the transmitted pulse allows to compensate for drift in a number of components. For the measurement of the attenuated replica of the transmitted pulse in horizontal or vertical polarization the following relations can be given:

$$DN_{ST,H} = FG.U.\sum\left(s.t_H.cal_H.c_C\right).D_{H'}.IF_H.AD_H \tag{5}$$

$$DN_{ST,V} = FG.U.\sum\left(s.t_V.cal_V.c_C\right).D_{H'}.IF_H.AD_H \tag{6}$$

Notice that one polarization is measured at the same time (according to the transmitted polarization) and both measurements uses the horizontal downconverter and IF section. Using the ratio method ($DN_{M,pol}/DN_{ST,pol}$) for internal calibration from (5) and (6) the common elements FG and U can be eliminated from (1) to (4). From (1) and (3) also IF_H and AD_H are eliminated. Within the contribution of the T/R modules some common elements can be found but it will be clear that especially no compensation is found for drift in the elements r_H and r_V. For these parameters additional measurements will be necessary for the receiver chain.

Systemcalibration receive

The advantage of a separate monitoring channel is the possibility besides the measurement of the transmitted pulse to inject signals directly into the receiver. The measured signals during this injection are a reference for the behavior of the r_H and r_V elements. But the measurement needs to be corrected for source, downconverter and IF differences. An additional source measurement is also needed. The measured numbers during the systemcalibration receive are given by:

$$DN_{SR,H} = FG.U'.\sum\left(c_C.cal_H.r_H.c_H\right).D_H.IF_H.AD_H \tag{7}$$

$$DN_{SR,V} = FG.U'.\sum\left(c_C.cal_V.r_V.c_V\right).D_V.IF_V.AD_V \tag{8}$$

Notice that both polarizations can be measured at the same time, using the normal receiver chain.

Systemcalibration Source

The systemcalibration measurement in receive mode needs to be corrected for the influences of the measurement chain (source and receiver) without the device under test (T/R modules). This can be accomplished with a measurement of the source. The digital number which will be output during the source measurement are given by:

$$DN_{SS} = FG.U''.D_{H''}.IF_H.AD_H \tag{9}$$

In the ratio of the systemcalibration receive and systemcalibration source $DN_{SR,H}/DN_{SS}$ resp. $DN_{SR,V}/DN_{SS}$ the parameter FG can be eliminated for both polarizations and IF_H and AD_H for only the horizontal channel.

Dataprocessing

Using the above described measurements it is possible to normalize the target measurements by combining the systemcalibration measurements in such a way that all potential drift sensitive elements will be eliminated from the result. The following relation can be found for the HH measurement of a target.

$$DN_{M,HH} = \frac{DN_{ST,H}DN_{SR,H}}{DN_{SS}}.\frac{\sum\left(s.t_H.g_H^2.r_H.c_H\right)}{\sum\left(s.t_H.cal_H.c_C\right).\sum\left(c_C.cal_H.r_H.c_H\right)}.\frac{U''D_{H''}}{U'D_{H'}}.\frac{\sigma_{HH}}{(4\pi)^3R^4/\lambda^2} \tag{10}$$

Similar relations can be found for the other three polarimetric measurements. The wanted form of this expression is

$$DN_{M,HH} = Systemconstant.\sigma_{HH} \tag{11}$$

The relation given in (10) contains a number of parameters which are constant or known:

- the parameters s, c_H, c_V and c_C describe the behavior of the combiner/splitter, this are passive elements which can be thought to be constant during all measurements.
- the parameters g_H, g_V, cal_H and cal_V are related to the antenna and the coupling between the antenna and calibration port of the T/R module. These parameters are determined by passive elements and are constant during all measurements.
- the parameters U"/U' and $D_{H''}/D_{H'}$ describe the difference between the measurement of systemcalibration receive and systemcalibration source. This difference is caused by passive elements in the Up/down converter. These parameters will also nominally be constant during all measurements.
- the parameters DN_{ST}, DN_{SR} and DN_{SS} are known quantities which will be measured at the beginning of each measurement session and can be regarded as constant during a session.
- the last parameters are related to the used frequency and the measurement range which are all known.

The only parameters not yet covered are the parameters which describe to behavior of the T/R modules (t_H, t_V, r_H and r_V). The correction of these parameters to there nominal values is the purpose of the autocalibration which will be described in a separate paper in this proceedings [2]. After the autocalibration the parameters are known and can be taken constant during a measurement. It depends on the stability of the T/R module how often an autocalibration have to be performed. In normal operation it seems useful to perform an autocalibration before a series af measurements.

Conclusion

Using the three systemcalibration modes in combination with the autocalibration of the T/R modules the measured signals can directly be interpreted as a function of the radar cross section.

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PARIS

3 - 6 Mai 1994

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