

DESIGN AND CALIBRATION OF THE PHARUS POLARIMETRIC AIRBORNE SAR *

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ABSTRACT

The PHARUS system uses a phased array antenna with solid state amplifiers. The project consisted of two phases, a definition phase and a realization phase. The definition phase consisted of the actual realization of a SAR research system called PHARS, which made its first successful testflight in November 1990. The research system is based on the concept of a wide beamwidth antenna, rigidly fixed to the aircraft. Pulse compression and a high PRF ensure sufficient sensitivity in this system, which is equipped with a 160 Watt peak pulse power solid state transmitter. The processing is done off-line. In the realization phase the polarimetric PHARUS system has been developed. The design is based on the experience gained with the PHARS system. The system uses a phased array with dual polarized patch radiators and is equipped with solid state amplifiers. This paper will give an overview of the PHARUS design and operational use. Apart from the use as an advanced polarimetric airborne SAR, there is the perspective of using PHARUS as a demonstrator for ESA's future ASAR system.

PREFACE

The PHARUS project (Hooeboom, 1992) is carried out in a cooperation between the Physics and Electronics Laboratory of 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).

1.0 INTRODUCTION

After several years of development, PHARUS, the Phased Array Universal SAR, performed its first test flight on September 22nd. 1995. That event almost completed the development of the polarimetric imaging Synthetic Aperture Radar. It was conducted by the Physics and Electronics Laboratory TNO, the National Aerospace Laboratory NLR and the Delft University of Technology. Aimed at dual use in both Defense and Civil applications, the project was sponsored by the Dutch Ministry of Defense, the National Remote Sensing Program and the institutes themselves. The National Institute for Aerospace Programs coordinated this high risk and costly program. The PHARUS team is proud of presenting today services with this system in the interest of the user community in The Netherlands and elsewhere. It is believed that the novel design of this C-band SAR (5.6 cm wavelength) will enable many new applications. As will be explained in this paper the system combines high resolution with accurate calibration, polarimetry and a high degree of freedom in imaging modes. The frequency choice relates directly to the

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successful space based SAR programs of this and next decade. It enables the user to prepare for future missions with realistic simulations and to enhance datasets obtained from today's satellites. Especially the preparation for ESA's ASAR mission is mentioned here.

PHARUS is an experimental system. It is meant for remote sensing research in many application area's, both civil and military, maritime and on land. Furthermore the developers of the system hope to enhance in the future the systems capabilities. Potential growth was built into the system as recommended by the sponsors. As a result of the approach followed, PHARUS is not a small, dedicated easy to operate system but rather a complex instrument requiring trained personnel to plan and execute missions.

Meanwhile the team hopes to keep the system up to date with modern requirement. Like higher resolution, cross-track interferometry (3D imaging for elevation maps) and along-track interferometry (Moving Target Indication or velocity measurements). Also real time on-board processing is envisaged in the interest of military users and for quick look products. The team is preparing plans to guarantee operation of the system into the next century through a continuous program for maintenance, spare parts and product improvement. It is foreseen that PHARUS will grow from its current experimental stadium into a reliable, quasi operational sensor. Along with the system's growth, the users experience with polarimetric SAR imagery will also grow. Not only the radar is described, but also the digitization and data recording systems, the aircraft carrying the sensor and the off-line SAR processing software used to correlate the data into images. Next the main features and the first results of PHARUS are described.

2.0 THE PHARUS SYSTEM

The PHARUS imaging airborne radar system is divided into three main subsystems:

- the radar in the pod outside the aircraft
- the on-board digitizing and data-reduction and recording inside the aircraft
- the ground-based flight and radar data handling and SAR processing

Each of these main subsystems is described in the following sections in more detail. In addition the system consists of a Radar Power Supply (RAPPS), an Operator Control Panel (OCP) and the Citation Measurement System (ADC/GPS/IRS/TIME) for registration of the system time and flight trajectory. Figure 1 illustrates the PHARUS overall system configuration.

In RAPPS the Citation's DC Power is converted to ± 150 V for the radar. This is done to reduce the requirements on the EMI-filters and on cables and connectors, while allowing sufficient buffering of the radar power to overcome dips in the Citation's DC Power. The OCP is used to control the PHARUS system, in particular the radar, the digitizer and the data recorder and to present the actual system status. It is implemented using a portable Personal Computer connected to the digitizer and to the recorder through standard RS422 datalinks; the digitizer in turn is connected to the radar. The actual system status is displayed on the OCP screen, and the operator's commands (typically 10 characters long) are logged for post-flight analysis. Also, all subsystems store their settings in a so called Most Recent Parameter Base (MRPB); the OCP can log these (OCP-retrieved) MRPB-page in binary form. The PHARUS system has a modular architecture, enabling easy operation to specific requirements and a user oriented configuration.

The system is capable of realizing high resolutions (3 x 3 m) over relatively long ranges in single polarization mode. In dual and quad polarization (polarimetric) mode the range is reduced. Alternatively, the resolution can be reduced in any of the modes. Basic radar parameters like transmit and receive polarization, pulse length, chirp bandwidth, pulse repetition frequency and receiver gain are programmable

on-flight, as are data-handling parameters like range window and offset, decimation, filtering, presumming and scaling. The PHARUS system is mounted on the Cessna Citation II owned by NLR and TU Delft, enabling maximum altitude of 14 km and a speed of 150 to 250 m/s. The pulse repetition frequency of the system can be set to compensate for variations in the flight speed, enabling equidistant sampling of the terrain.

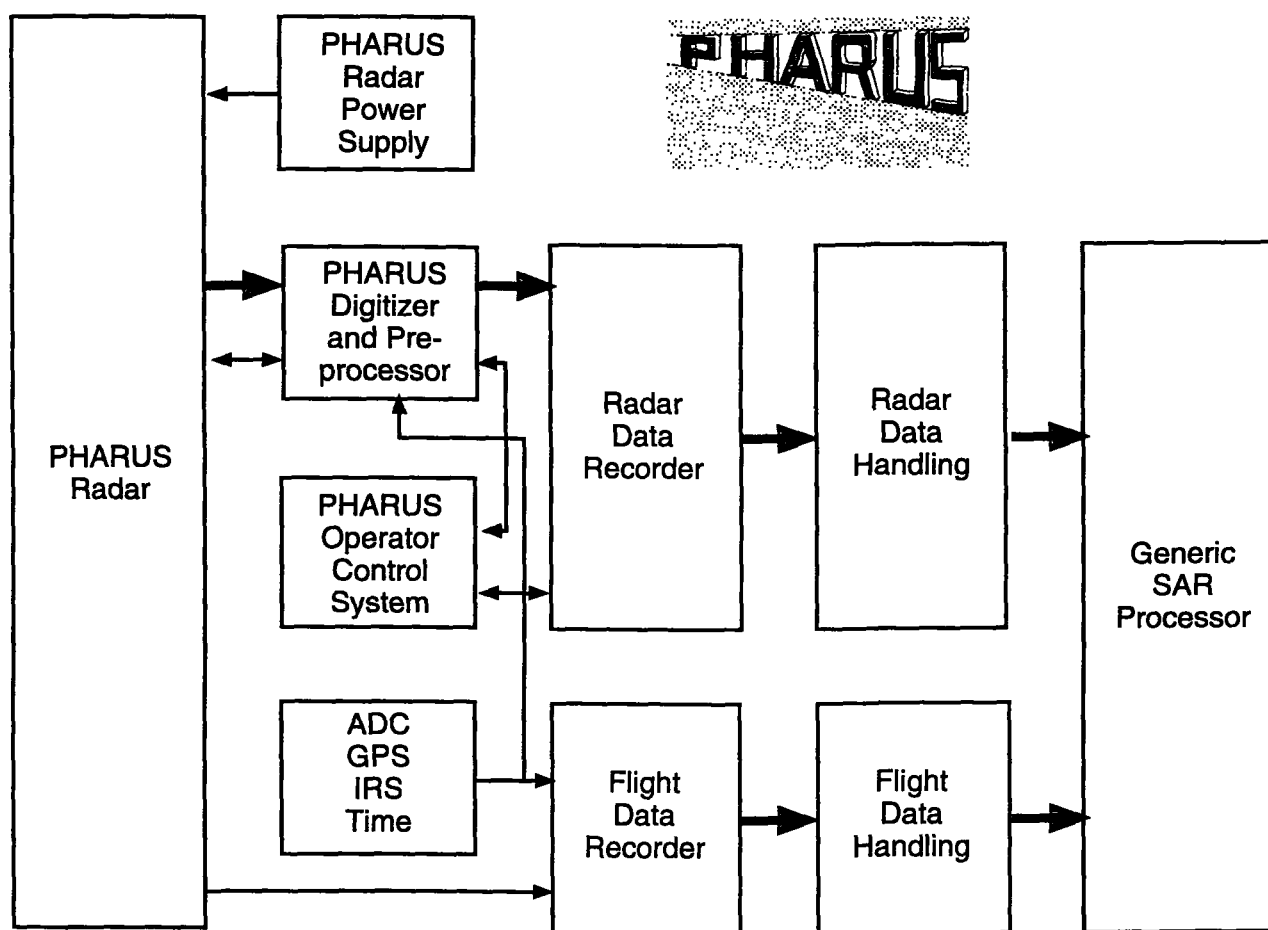


Figure 1. PHARUS overall system configuration

2.1 THE RADAR

Since PHARUS is a coherent radar system, a key role is played by the frequency generator, generating from a single reference source all the required frequencies in the system in a fixed time frame. From this the timing generator initiates transmission of a radar pulse by switching the radar system to transmit mode and triggering the chirp generator to generate the required radar pulse. This pulse is converted up to 5.3 GHz by the up/down converter and transmitted by the active phased array antenna. When the radar pulse has been transmitted, the timing generator switches the radar to receive mode, opening the two receiver channels (one for each polarization). Received signals are downconverted back to a fixed IF by the up/down converter and the IF Amplifiers with a user controlled gain, and fed to digitizer, along with a

frequency reference signal for digitization and recording. The settings of the most of the subsystems are controlled by the operator through the OCP: pulse length, pulse repetition frequency, chirp type (pre-set or user defined), IF amplifier gain. One of the most prominent features of the radar is its active array antenna. It is presently configured as an 2 x 24 array of active TR-modules. Each TR-module generates up to 20 W output power. The antenna can be upgraded to an 4 x 24 array for increased power and reduced elevation beamwidth. The use of a phased array enables electronic control of the beam direction and shape, thus allowing compensation of the drift angle of the aircraft with the radar itself mounted rigidly on the aircraft. The PHARUS active array features good polarization decoupling, dual polarization operation (interleaved on transmit, simultaneous on receive), beam shaping (uniform or tapered excitation) and, through the use of a separate calibration channel, internal calibration. The radar can toggle between two modes by interleaving them (dual pulse mode), giving each mode half the repetition frequency. Each mode has its own set of values for beam direction, chirp pattern, gain setting and transmit polarization. Finally, the radar can be switched to several specific system calibration modes, through which the behavior of the system at the time of the measurement can be recorded, and an autocalibration mode through which the active phased array antenna is recalibrated to its original state.

2.2 SARDIG

SARDIG is the digitizing and pre-processing unit of the PHARUS system on-board the aircraft. SARDIG has 3 main functions:

- 1 - digitizing, processing in-line, processing across-line, formatting of radar data
- 2a- communications centre for the commanding of PHARUS by the Operator Control Panel (OCP)
- 2b- communications centre for the reporting of PHARUS to the OCP
- 3 - collecting aircraft data to be added to radardata for general information.

Sardig receives three signals from the Radar:

- Horizontal polarization receiver signal,
- Vertical polarization receiver signal,
- Timing reference signal.

Sardig communicates with the Radar and with the OCP via a RS422 datalink, which is a standard computer interconnection for harsh environment. Sardig receives information from a number of aircraft systems via typical aircraft standard signals:

- Time code Generator,
- Flight Management System,
- Global Positioning System,
- Inertial Reference System,
- Antenna Reference Assembly.

In the Timing reference signal the transmit time of the radar pulse is exactly marked and the differentiation between the first and second pulse (in double pulse mode) is indicated. Four different types of

data can be generated (e. g. HH, HV, VH and VV) with the two signals (H-/V-receiver) and two types of radarpulse. Each type of data represents one channel of data. One line of data can consist of one, two, three or four channels of data.

Each analog radar signal is digitized at a sample rate of 100 MHz into 8 bits. For each channel a window can be defined in terms of range offset (meters) and window length (meters) of which the samples are stored in a temporarily data buffer. There are two range buffers in parallel (for each analog input one). The stored data has to be transferred from the range buffers before the data of the next pulse will be written, otherwise the data is lost.

The data of the windows stored in the range buffers are processed by the pixelprocessor. The pixelprocessor treats each line, and within each line each channel likewise. The main function of the pixelprocessor is to convert the real samples representing the offset modulated signal of a channel into complex samples representing a base band signal. The second function is "range decimation" which is to recalculate the base band signals to a lower bandwidth and a lower sample frequency, thus reducing the crosstrack resolution for the benefit of less data or longer windows to record. For research and testing other features are available. The pixelprocessor takes the data from the range buffers channel by channel in parallel groups of four real samples at a rate of 12.5 MHz and transfers the results in pairs of complex pixels to the presummers as $2 \times (9+9)$ bits data.

A minimum pulse repetition frequency (PRF) is required for a given azimuth resolution and aircraft speed. However, in order to transmit as much power as possible, it is desirable to transmit more pulses than strictly required, thus producing more echo lines. In order to reduce the amount of data to record, the number of lines is then reduced by lowpass filtering and subsampling of all series of corresponding pixels of successive lines. This way, the advantage of increased power is retained, while the data rate remains acceptable. There are four presummer units available. The filter characteristics can be defined in filter files to be loaded via the OCP. Up to 256 taps filters, with 12 bit coefficients can be defined. While operating all four presummerboards the line reduction factor is equal to the number of taps divided by four. The system automatically positions the presummer filters to generate outputs that are equally spaced in time. The presummers operate in parallel on complex pixel pairs generated by the pixelprocessor. The process frequency is the output frequency of the pixelprocessor: 12.5 MHz or reduced if selected. Presummer outputs for the recording interface are available as complex pixelpairs in $2 \times (10+10)$ bits data at burst rates equal to the presummer input frequency.

Radar data processed by the pixelprocessor and by the presummers is recorded line by line. Each line of radardata is preceded by a header consisting of a sync pattern, a precise time tag, full status information of PHARUS and a selection of aircraft data. The header takes 256 bytes and the $2 \times (10+10) = 40$ bits of data per complex pixel pair of the presummers is packed in groups of 5 bytes, all data to the recorder is transferred at 12.5 Mbyte/sec.

2.3 THE SAR PROCESSOR

Data from the on-board recorder is processed into SAR images with the Generic SAR Processor (GSP) at FEL. This is a workstation with software developed by FEL in cooperation with ICT Automatisering that can perform all required SAR processing tasks for a generic SAR system, both airborne and spaceborne. The operations that are performed on PHARUS data are: tape reading, data format conversion, raw data quality analysis & improvement, pulse compression, azimuth compression, motion compensation, radiometric correction, geometric transformation (i.e. projection to a flat surface), and calibration. Azimuth compression with motion compensation is the most complex, and also the most computational intensive task. A full polarimetric image requires in the order of a few hours of processing

time. Polarimetric calibration using corners and polarimetric transponders is done interactively, and the time required depends on the level of calibration (e.g., how many calibration objects are used) and the quantity of the data. The SAR processor is an important factor in the final image quality. The GSP can be configured to process fast with reduced quality, or process slow with very high quality. Fast processing may be useful to obtain an overview of recorded image data while accurate processing can be applied to the final area of interest.

3.0 MAIN FEATURES OF THE PHARUS SYSTEM

Some key features of the PHARUS system are:

- Solid state radar technology
- Modular, upgradeable system architecture
- Programmable radar characteristics
- Programmable data-reduction and recording characteristics
- Internal calibration
- Capable of simulating satellite modes (ASAR)
- Programmable resolution, swath width
- Polarimetric

PHARUS is capable of generating radar images in several resolutions, depending on the required application. Since the amount of generated data is directly related to the requirements for resolution (determined by bandwidth), polarimetry (single, dual, full, sets the number of channels to be recorded) and the limitations of the platform (ground speed, maximum pulse repetition frequency) the resulting range and swath width are determined by the recording capacity (100 Mbit/s) in a complex manner. In table 1 an example is given of some of the different modes in which the system can operate.

Table 1. An Example Of The Different Modes Of PHARUS

mode	resolution (m)	number of looks	swath (km)	range (km)	altitude (km)
single polarization ($\gamma \geq -30$ dB)	4	4	11.2	16	6.0
	8	8	14.6	20	6.0
	16	20	20.0	26	6.0
ASAR mode dual polarization ($\gamma \geq -25$ dB)	24	4 (max. 25)	9.8	20	14.0
polarimetric ($\gamma \geq -40$ dB)	4	4	4.4	8	4.5
	8	8	6.5	11	5.0
	16	20	7.9	13	6.0

The aircraft which will be used for the PHARUS system is a Cessna Citation II, a twin jet engine business plane, and used as a laboratory aircraft by the NLR and TU Delft. The aircraft is equipped with various sensors to acquire aircraft attitude and position. Among others an inertial navigation system, using lasergyro's and GPS will be available. This aircraft is well suited for high resolution SAR imagery

due to the high speed, between 150 and 250 m/s, and the maximum altitude of 14 km, which allows large swath widths to be recorded.

4.0 USE OF THE PHARUS SYSTEM

It is to be expected that, at least in the next decade, priority will be given to the monitoring function of spaceborne sensors, which implies global coverage as the key-issue. On the other hand there is a growing interest in high spatial resolution images of limited areas. A major characteristic of the agricultural practice in Europe is the relative small size of the holdings (Krul, 1990).



Figure 2. PHARUS image (right) recorded during the first testflight on 22 September 1995. The image shows the Betuwe area in The Netherlands. It is a composite image of the HH and VH channels. Resolution 3 meter, flight altitude 5 km. On the left a part of a topographic map is given, showing the same area.

In general the holdings will include a number of crop fields, which means that resolutions of 10 m or better are highly desirable. The operational demands for spaceborne sensors with high spatial resolution are interfering with short revisit times. Due to technological problems polarimetric spaceborne sensors are not to be expected before the next century. It is obvious that aircraft sensors give important complementary support with respect to improved spatial resolution, reduced revisit times and additional wave

parameters (polarization and wavelength).

The PHARS system and since 1995 the PHARUS system are examples of high resolution aircraft sensors. Specially the PHARUS system, due to the flexibility of the operating modes, is a candidate to be used complementary with present and planned spaceborne systems. The PHARUS system can also be used as a demonstration system for future spaceborne systems such as ESA's ASAR.

5.0 CONCLUSIONS

By using a high degree of MMIC integration it is possible to miniaturize the active components of a phased array radar. By integrating the microstrip patch antenna in the module too it is possible to have a complete modular set-up of the system. Every module can be replaced in case of malfunctioning without disassembling a major part of the radar. The single patch antenna is dual polarized with a reduced crosspolarization performance by using symmetrical feeding. A ratrace turns out to be a very useful feeding network since it solves several problems at the same time. Finally it has been possible to implement a channel for monitoring and internal calibration to generate correction numbers to come to the specified antenna pattern.

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

The construction of the PHARUS polarimetric SAR has been finalized. The system uses a dual polarized microstrip patch antenna with 48 radiators (expandable to 96). Each radiator has its own T/R module with a total transmitted power of 475 W. The values for resolution (4/8/16 meter, 3-20 looks) in both azimuth and range are user selectable. The system offers the possibility to select the number of polarizations (1/2/4). The latter choice leads to polarimetric observations. The maximum range and the swath width depends on the selected mode and vary between 7 and 26 km for the range and between 3 and 20 km for the swath width. The number of looks is also dependent on the mode and varies between 3 and 20. The system will have an active phased array antenna, which can be steered in one axis, to compensate aircraft yaw and drift. The system is operational since 1995. The PHARUS system is complementary to present and future spaceborne sensors from an operational point of view.

The PHARS system and the PHARUS system are examples of high resolution aircraft sensors. Specially the PHARUS system, due to the flexibility of the operating modes, is a candidate to be used complementary with present and planned spaceborne systems. The PHARUS system can also be used as a demonstration system for future spaceborne systems such as ESA's ASAR.

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