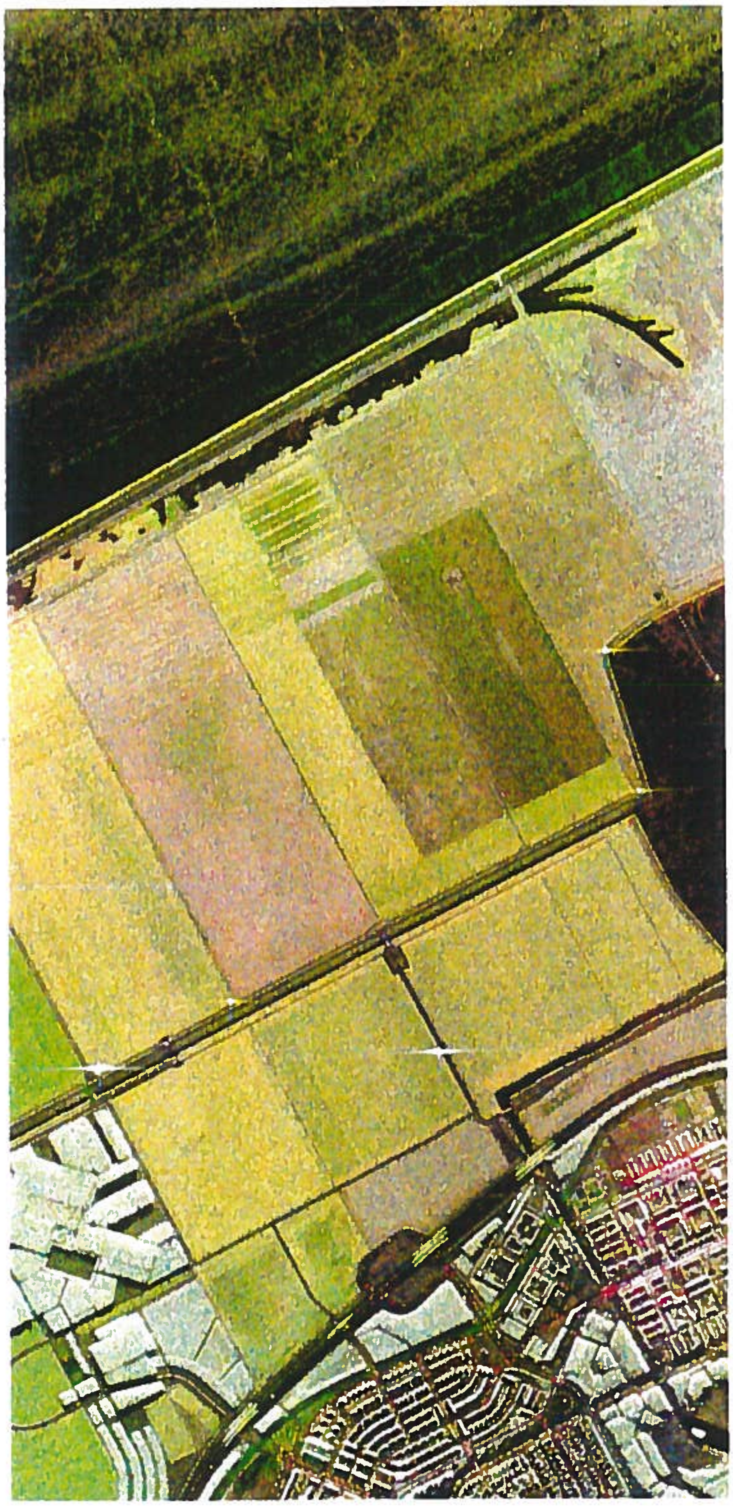
*The **PHARUS** system: an introduction and a collection of images.*

First PHARUS (dual polarisation) SAR image

Scene:	Area near Deil, The Netherlands
Description:	The image mainly shows agricultural fields. In the bottom half some urban areas (orange/grey) can be seen.
Recording date:	September 22, 1995
Altitude:	3000 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	composition of VH and VV channels



PHARUS polarimetric SAR image

Scene:	City of Almere, Flevopolder, The Netherlands
Description:	The image shows agricultural fields, the city of Almere (bottom/right) and water covered with ice (top). The bright reflections in the middle are corner reflectors used for calibrating the SAR image.
Recording date:	January 11, 1996
Altitude:	3000 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

PHARUS polarimetric SAR image

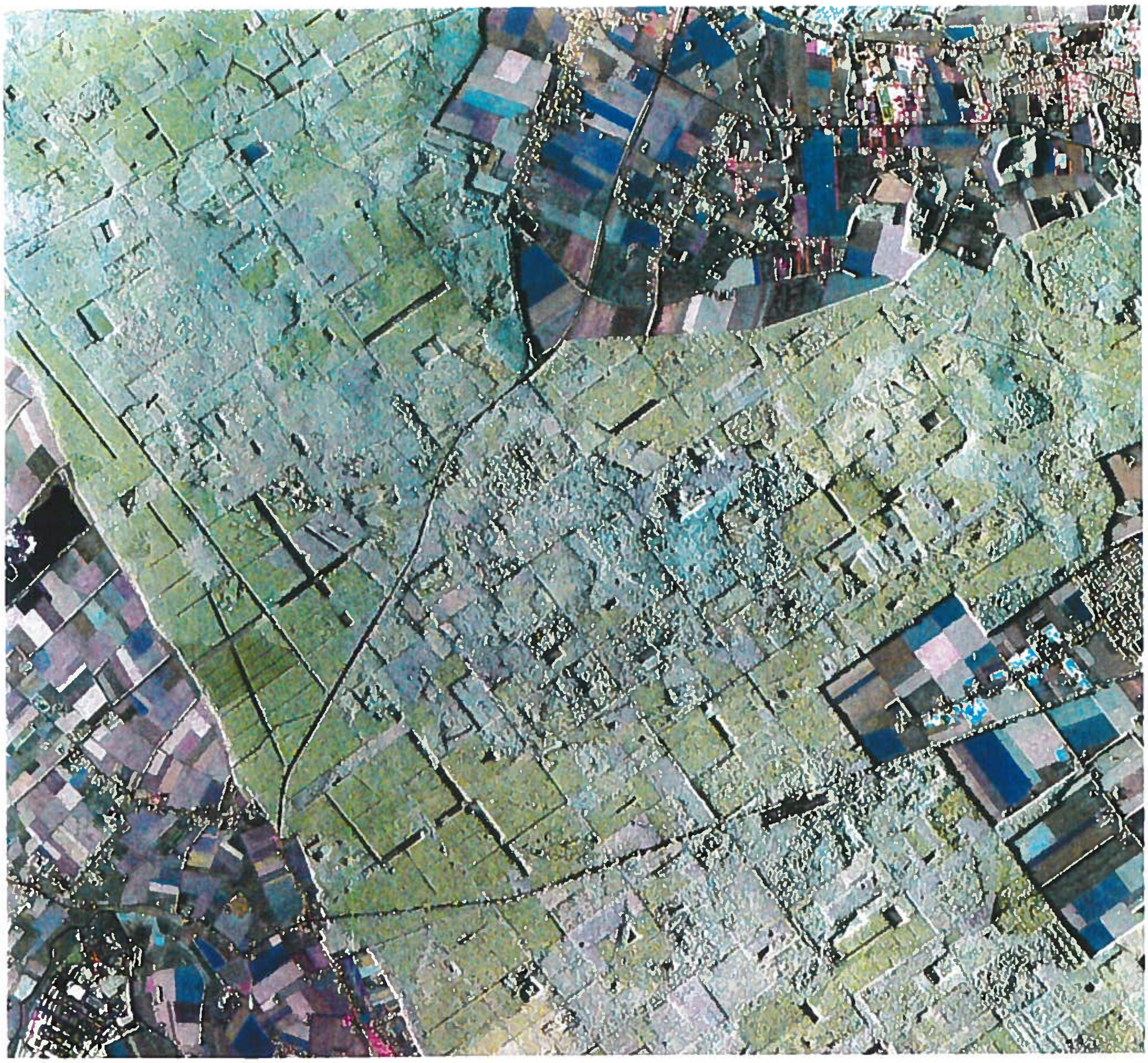
Scene:	Area near Amersfoort, The Netherlands
Description:	This image shows forest (left half) and the city of Amersfoort (right half). The bright reflections on the right come from trains, railways and buildings in a railway station.
Recording date:	April 26, 1996
Altitude:	3000 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

PHARUS change detection SAR image (HH channel)

Scene:	Area near Amersfoort, The Netherlands
Description:	Most obvious are the changes detected in the railway station in the top/right quadrant of the image, i.e. trains that have left on April 25 (red) and that have arrived on April 26 (blue).
Recording date:	April 25 and 26, 1996
Altitude:	3000 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red =objects present on April 25 Blue=objects present on next day

PHARUS polarimetric SAR image

Scene:	Area near Delft, The Netherlands
Description:	The bright redish reflections are from the HH channel and are due to the buildings in Delft. Such reflections are often seen in SAR images and occur in the flight direction of the SAR platform.
Recording date:	April 26, 1996
Altitude:	3000 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

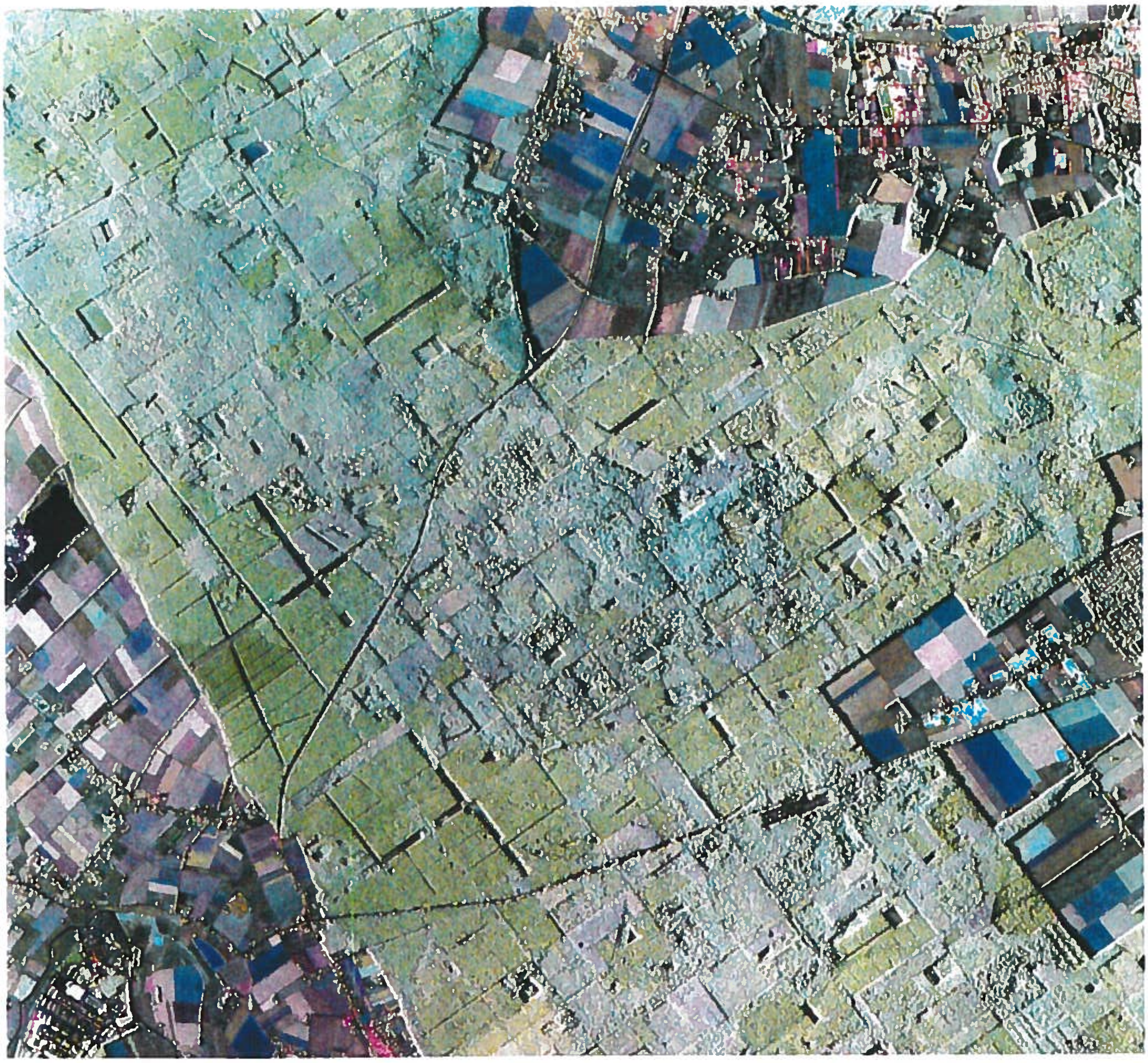


PHARUS polarimetric SAR image

Scene:	Reichswald near the city of Kranenburg, Germany
Description:	Reichswald is the name of the forest in the middle of the image. The Reichswald consists of deciduous forest (lightgreen areas) and pine forest (darkgreen area in the center).
Recording date:	October 22, 1996
Altitude:	4500 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

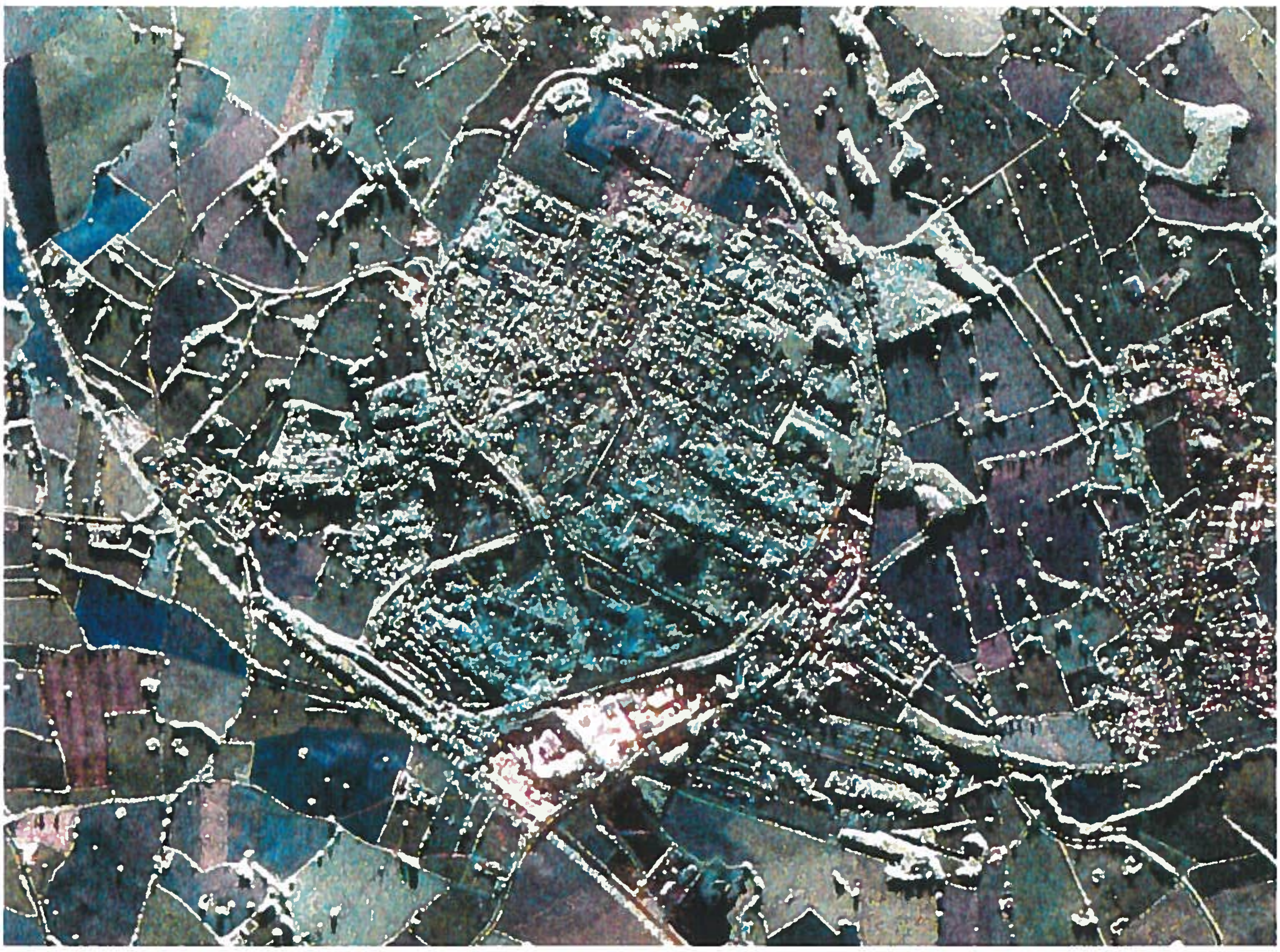
PHARUS polarimetric SAR image

Scene:	Area near Delft, The Netherlands
Description:	The bright redish reflections are from the HH channel and are due to the buildings in Delft. Such reflections are often seen in SAR images and occur in the flight direction of the SAR platform.
Recording date:	April 26, 1996
Altitude:	3000 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV



PHARUS polarimetric SAR image

Scene:	Reichswald near the city of Kranenburg, Germany
Description:	Reichswald is the name of the forest in the middle of the image. The Reichswald consists of deciduous forest (lightgreen areas) and pine forest (darkgreen area in the center).
Recording date:	October 22, 1996
Altitude:	4500 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

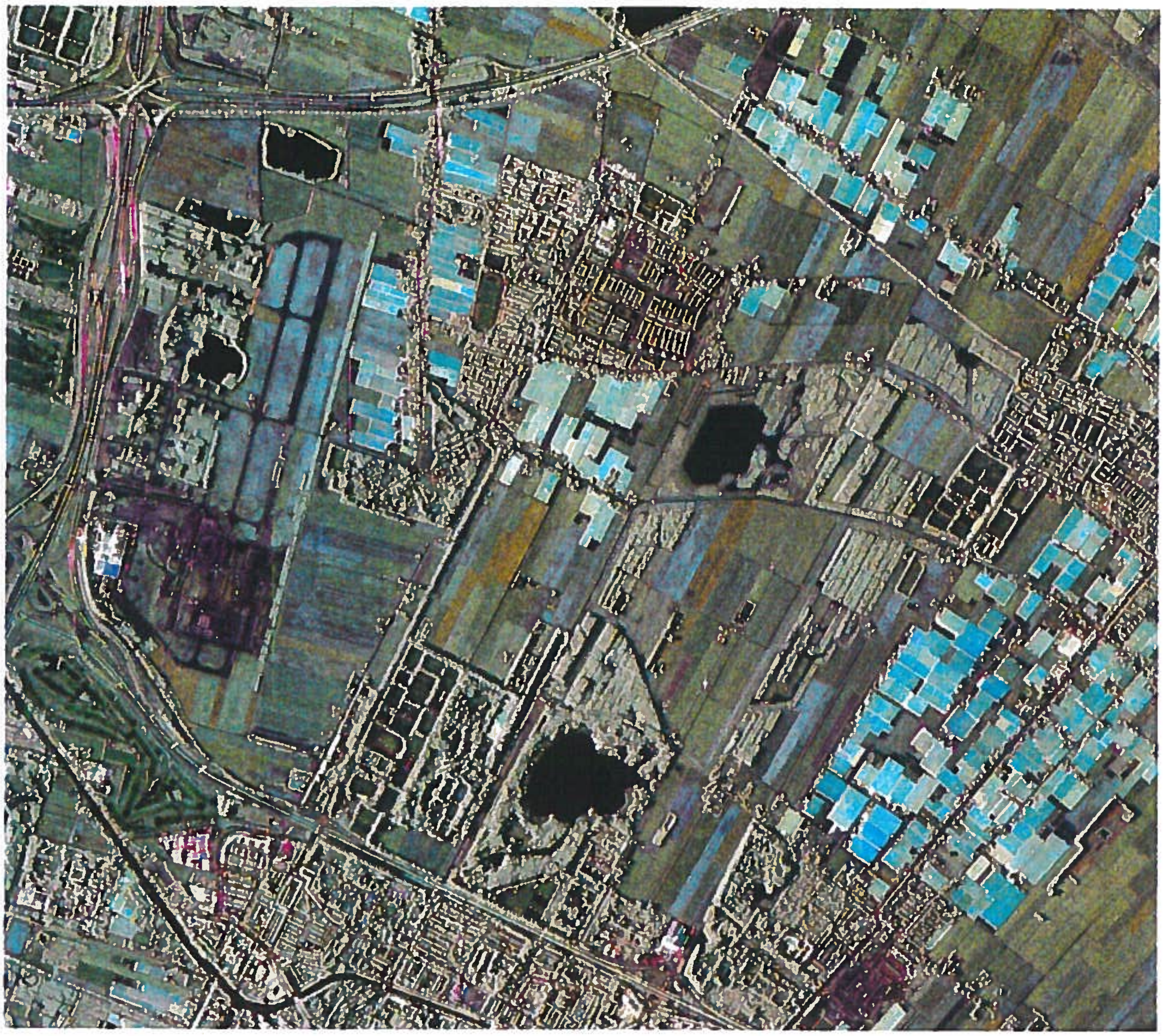


PHARUS polarimetric SAR image

Scene:	Military test area near the city of Swynnerton, United Kingdom
Description:	The military test area measures approximately 2x2 km and can be seen in the middle of the image. The test area consists of grass and forest and is surrounded by agricultural fields.
Recording date:	October 24, 1996
Altitude:	4500 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

PHARUS polarimetric SAR image

Scene:	Amsterdam, The Netherlands
Description:	In the top/left quadrant of the image, the Amsterdam Canals can be seen whereas the river on the left is the Amstel. The bright reflections are due to buildings that are aligned in the flight direction of the SAR platform.
Recording date:	May 29, 1997
Altitude:	4500 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

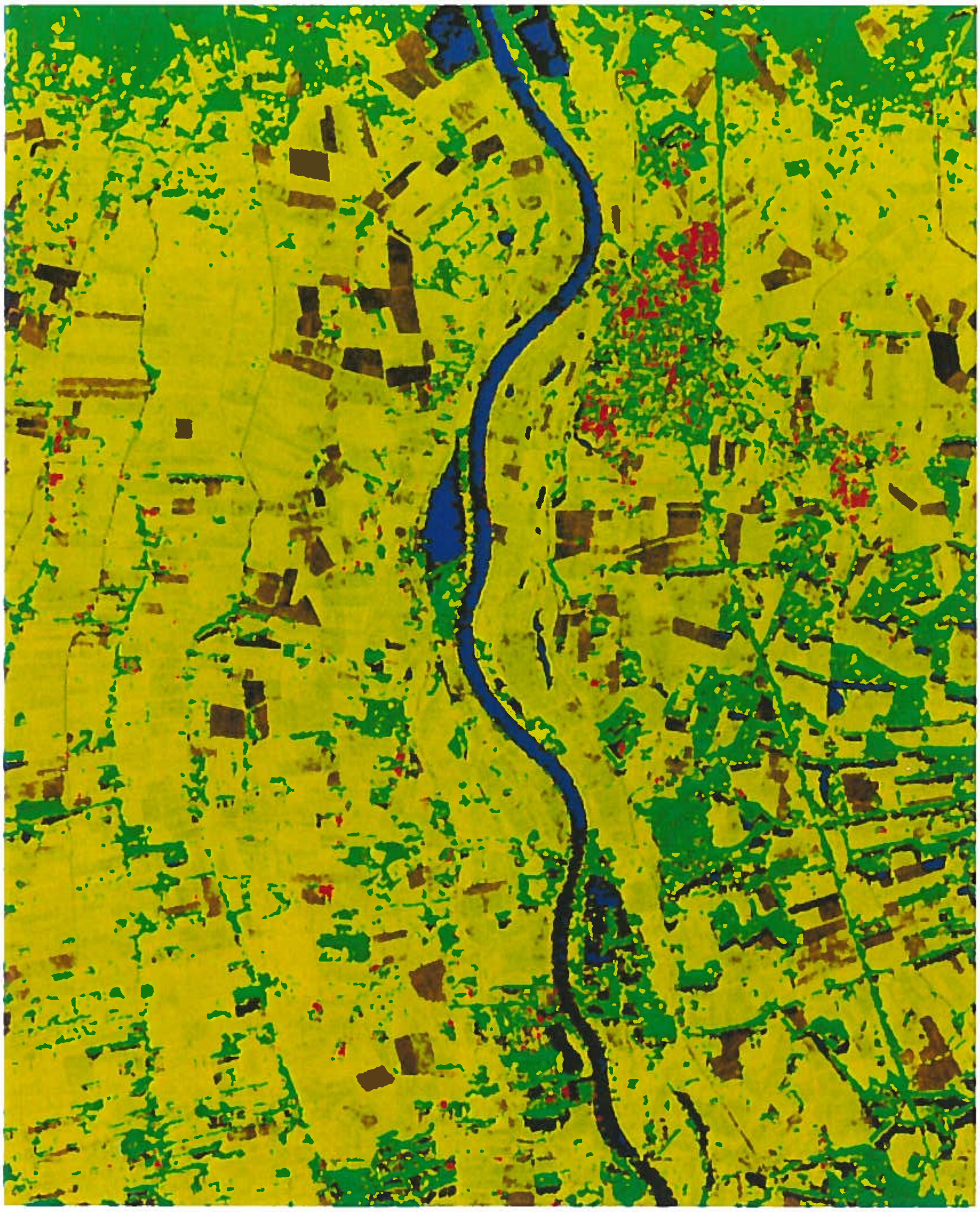


PHARUS polarimetric SAR image

Scene:	Former airbase near the city of Delft, The Netherlands
Description:	The left part of the image shows the former airbase Ypenburg. The runways appear in black and roughly align with the vertical direction of the image. The right part of the image shows areas with greenhouses which appear as blue.
Recording date:	May 29, 1997
Altitude:	4500 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

PHARUS polarimetric SAR image

Scene:	Area near the city of Olst, The Netherlands
Description:	The image shows a large variety of agricultural fields, forest and grass. In the middle we can see the river IJssel and the red area in the top half is the city of Olst.
Recording date:	June 2, 1997
Altitude:	4500 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

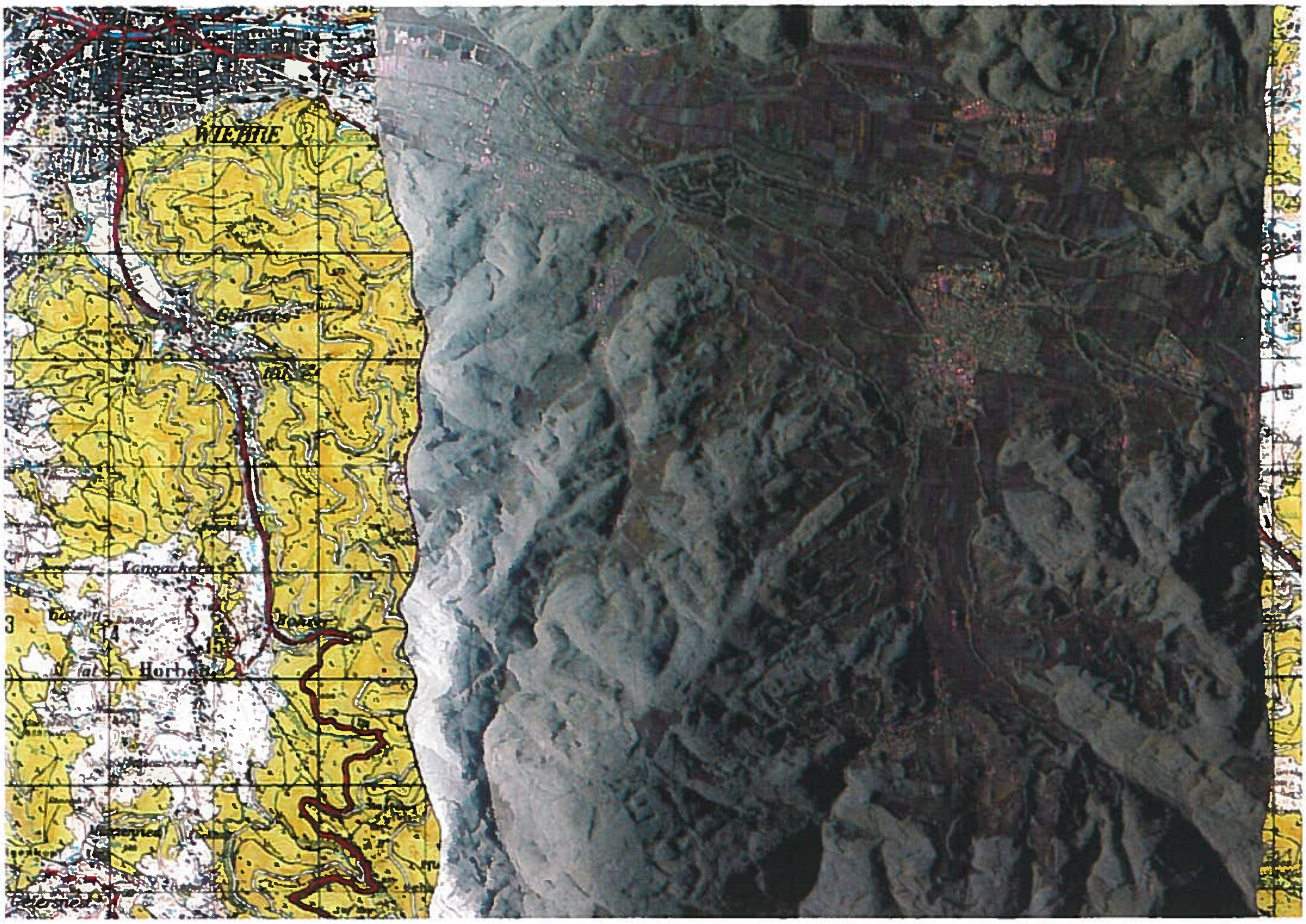


Landuse classification based on PHARUS polarimetric SAR image

Scene:	Area near the city of Olst, The Netherlands
Description:	For terrain analysis purposes, the area has been classified in water (blue), urban areas (red), grass (lightgreen), forest (darkgreen), bare soil (brown) and shadow areas (grey).
Recording date:	June 2, 1997
Altitude:	4500 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Blue=water, red=urban areas, lightgreen=grass, darkgreen=forest, brown=bare soil, grey=shadow areas

PHARUS Moving Target Indication SAR image (HH channel)

Scene:	Highway near the city of Zoetermeer, The Netherlands
Description:	Operating PHARUS in MTI mode makes it possible to derive the velocity of vehicles on the highway. The numbers in the image give the velocities in km/hr.
Recording date:	June 2, 1997
Altitude:	4500 m
Geometric resolution:	approx. 3 x 3 m
Processing mode:	single look
Colour composition:	Grey scale



PHARUS geocoded polarimetric SAR image

Scene:	Black Forest near the city of Freiburg, Germany
Description:	The SAR image shows the Black Forest which mainly consists of mountainous areas grown with forest. The SAR image has been geocoded to landmap coordinates so that the polarimetric information can be used in Geographic Information Systems.
Recording date:	October 21, 1997
Altitude:	4500 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

PHARUS polarimetric SAR image

Scene:	Zoetermeer, The Netherlands
Description:	The image shows the city of Zoetermeer (bottom/left) and a variety of agricultural fields.
Recording date:	January 27, 1998
Altitude:	4500 m
Geometric resolution:	approx. 4 x 4 m
Processing mode:	5 looks
Colour composition:	Red=HH, Green=HV, Blue=VV

PHARUS polarimetric SAR image

Scene: The Hague, The Netherlands
Description: The image shows a part of the city of The Hague. In the top/right quadrant the building of the TNO Physics and Electronics Laboratory can be seen. The inlay is an aerial photograph of the building.
Recording date: January 27, 1998
Altitude: 4500 m
Geometric resolution: approx. 4 x 4 m
Processing mode: 5 looks
Colour composition: Red=HH, Green=HV, Blue=VV

An introduction to the

PHARUS

system

Extracted from the "PHARUS User Manual"

Contents

1. Introduction

After several years of research and development, PHARUS, the phased array universal SAR performed its first test flight on September 22nd, 1995. That event marked the beginning of the use of PHARUS and thus constituted a major milestone in the development of the phased array, polarimetric imaging Synthetic Aperture Radar. The system has been developed by the TNO Physics and Electronics Laboratory in cooperation with the National Aerospace Laboratory NLR and the Delft University of Technology.

The PHARUS team is proud of presenting today services with this system in the interest of the user community in The Netherlands and elsewhere. The novel design of this C-band SAR (5.7 cm wavelength) enables many new applications of SAR. 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 successful space based SAR programs of this and the next decade. It enables the user to prepare for future missions with realistic simulations and to enhance data sets 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 areas, both civil and military, maritime and on land. Furthermore, potential growth was built into the system, allowing enhancement of the system's capabilities in the future. 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.

The system will be kept up to date with modern user requirements like higher resolution, cross-track interferometry (three-dimensional imaging for elevation maps) and along track interferometry (Moving Target Indication -MTI- or velocity measurements). Real time on-board processing is also envisaged both for quick look products and in the interest of military users. Operation of the system into the next century is to be guaranteed 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.

In the course of this explanatory memorandum on the PHARUS system, attention will be paid to (polarimetric) SAR imaging in order to give the reader more insight into the specific subjects. Next, the PHARUS system will be described, including possible imaging modes, followed by a discussion on the generic SAR processor (GSP) which has been developed by TNO-FEL in cooperation with ICT. This SAR processor is capable of handling SAR data from various SAR sytems, both air- and spaceborne Finally, some remarks are made on available image data formats as an output of the GSP.

2. SAR and polarimetry

2.1 Principle of SAR

SAR (synthetic aperture radar) is a sidelooking imaging radar on a moving platform (e.g. aircraft, satellite). The characteristic feature of SAR is the high resolution in the direction of motion, obtained by aperture synthesis. The result is an image, consisting of pixels, resembling an aerial photograph. SAR is in the category of coherent pulse radars, i.e., it transmits pulses (as opposed to a continuous wave) and measures both amplitude and phase of the received echo signal.

The radar illuminates -with its antenna beam- a patch on the ground, to the side of the platform. By the motion of the platform, an illuminated continuous strip is formed, called the swath, see

Figure 2.1. After processing, the strip is resolved into resolution cells, one of which is depicted in Figure 2.1.

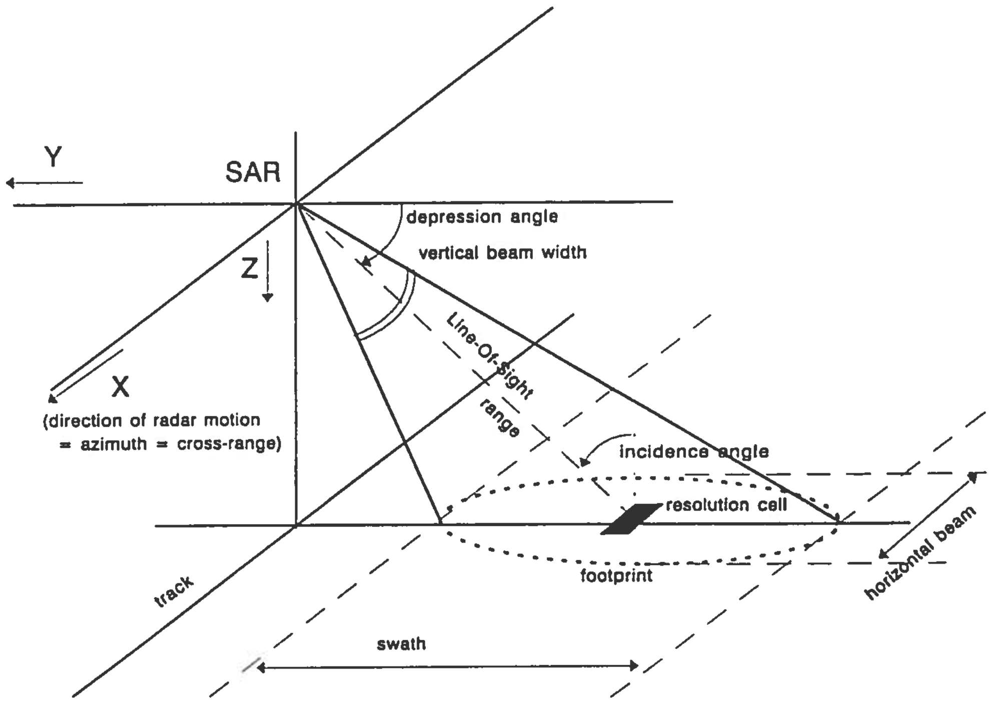


Figure 2.1 Airborne SAR Geometry

To achieve high resolution in the range direction, a short pulse is required. Instead of transmitting a very short pulse with very high peak power, a long time coded pulse with lower peak power, but equal energy is transmitted. The modulation allows compression of the received pulse, thus gathering the total pulse energy into a short pulse. This process is referred to as pulse compression or range compression. The most widely used form of coding is a linear frequency modulation (*chirp*).

To achieve high resolution in the cross-range, or azimuth direction, a very narrow antenna beam would be needed for classical SLAR systems, requiring a very large antenna aperture. The principle of SAR is to extend the small physical antenna aperture to a many times larger 'synthetic aperture' by coherent integration of echoes received over a certain distance travelled by the moving platform. In the case of PHARUS, for instance, the real antenna is 1 meter long, while the synthetic aperture may be several hundred meters long.

Coherent integration is mathematically analogous to pulse compression, and is called azimuth compression. This equivalence can be understood by considering that the frequency modulation in the transmitted pulse is similar to the Doppler frequency modulation induced by the motion of the platform. Hence, the Doppler modulation that exists in a series of received pulses, due to motion, is used in a way similar to the frequency modulation within a pulse, which is intentionally generated by the radar.

A characteristic feature of SAR is that azimuth resolution is independent of range. In radars that do not employ the synthetic aperture principle (therefore sometimes called real aperture radars), cross-range resolution is determined by the antenna beam width and is therefore an *angular* resolution. The resulting geometric resolution gets worse as the distance increases. In SAR, the larger antenna footprint at longer range allows longer observation of an object (longer synthetic aperture), so that the resulting geometric resolution remains the same in the end. In practice, range is limited by the amount of transmit power available.

Another basic property of a coherent imaging radar, such as SAR, is the phenomenon of 'speckle'. This is a type of noisiness that can be reduced by an averaging technique called multi-looking.

After SAR processing, a SAR image consists of an array of pixels, where each pixel value is a measure of the radar reflectivity of the corresponding area, i.e., a resolution cell, on the ground. The image is therefore basically a reflectivity map. The measured value in each pixel is commonly referred to as the backscattering coefficient. For display purposes, it is common practice to display this map using a black and white intensity coding: dark for low backscatter, bright for high backscatter. This greyscale map constitutes the 'image'.

2.2 Principle of polarimetry

Early SAR systems used a single polarisation antenna for transmitting pulses and receiving their echoes and are therefore called non-polarimetric systems. For instance, if the antenna was linearly horizontally polarised, the system was a HH polarised system, that is, it used horizontal polarisation for both transmission and reception. Analyses of non-polarimetric SAR images always left questions unanswered like:

- what would the image have been if another system had been used, for example a VV or a HV or a differently polarised system?
- is the polarisation used optimal for the application?

These questions are answered completely by the use of polarimetric systems. The subject of polarimetry is the interpretation of polarimetric data.

In a non-polarimetric SAR image the reflectivity of a single resolution cell is measured as a single number: the backscattering coefficient (usually HH or VV), which can be displayed using intensity coding (black and white). In a fully polarimetric SAR image, such as generated by PHARUS, four polarisation combinations of the backscatter coefficients are available for imaging, e.g. by using both intensity and colour coding. Furthermore, using these four polarisation channels, any other polarisation can be generated, e.g. for reasons of calibration or contrast optimisation.

The polarimetric generalisation of the backscattering coefficient is called the scattering matrix S. The matrix consists of 4 complex numbers, representing the complex backscattering coefficients for all four polarisation combinations:

$$S = \begin{pmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{pmatrix}$$

PHARUS is capable of measuring the full scattering matrix rather than the backscatter coefficient for one polarisation setting only. It is measured as follows. The PHARUS polarimetric SAR in full polarisation mode uses a single phased array antenna which can be electronically switched between horizontal and vertical polarisation. In full polarimetric mode, it first transmits a horizontally polarised pulse and then records the horizontally and vertically received echoes (both amplitude and phase) simultaneously, using two receive channels. The generated complex numbers correspond to S_{hh} and S_{vh}, respectively. It then repeats this step for a vertically polarised transmitted pulse; both polarisations are interleaved on Transmit. This completes the 2x2 matrix.

Since the scattering matrix contains many independent variables, there are many ways in which a polarimetric image could be displayed. One way of doing this is to assign colours to the matrix elements, and thus create a colour image. However, it is not possible to convey all information contained in the scattering matrices in a single colour image.

The basic use of a polarimetric image is the synthesis of images with arbitrary transmit and receive polarisations. From the scattering matrix map, images can be created representing arbitrary transmit and receive polarisations, even arbitrary elliptical ones. Until now the following advantages of polarimetry have been demonstrated:

- contrasts between targets and backgrounds can be maximised by choosing the correct transmit and receive polarisations
- the accuracy of crop type and land use classification results increases
- the estimation accuracy of soil and vegetation parameters (like forest biomass) increases

The polarimetric analogue of multi-looking (for speckle reduction) is not performed by averaging scattering matrices, because information would be lost by simply adding these complex matrices. An intermediate processing step is necessary: the conversion of the scattering matrices to 4×4 real symmetric Stokes matrices (see section 4.3). These are subsequently averaged. The Stokes matrix consists of real numbers only, but still contains the information of the complex scattering matrix, even redundantly. When Stokes matrices have been averaged, a transformation back to scattering matrices is generally not possible.

3. Main features of PHARUS

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.

Generally, there is a trade-off between resolution, swath width and radar-parameters.

The nominal specifications of the PHARUS system are presented in Table 3.1.

Table 3.1: PHARUS System Technical Specifications

Parameter	Value	Remarks
Radar type	Coherent pulse radar	
RF carrier frequency	5.3 GHz	
pulse repetition frequency	2000 - 5000 Hz	can be locked to ground speed
pulse length	3.2 - 25.6 µs	preferred value 12.8 µs
waveform type	arbitrary	pre-programmed linear FM sweeps for low, medium and high resolution
bandwidth	programmable	45 MHz for high resolution 24 MHz for medium resolution 12 MHz for low resolution upgradeable to 100 MHz
resolution	3 x 3 m max.	in high resolution mode 1m in azimuth for single look
transmit peak power	960 W max.	reduces to 540 W with antenna tapering
polarisation	transmit: H or V receive: H and V	interleaved on transmit optional simultaneous on receive optional
azimuth beamwidth	2.3° (uniform) 3.0° (tapered)	
azimuth scan angle	-20° to +20° in 0.5° steps	
elevation	24°	
elevation scan angle	-15° to 15° in 0.5° steps	
elevation pointing angle	57.5°	reference plane is horizontal
range	26 km	single polarisation, uniform actual range depends on radar-mode
range sampling frequency	100 MHz	8 bits
data storage rate	100 Mbit/s	
platform	Cessna Citation II	PH-LAB
altitude	max. 12 km	
groundspeed	90 - 150 m/s	excluding wind, altitude dependent
flight path registration	IRS, ARA, GPS, FMS	

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

- the radar (RADAR) in the pod outside the aircraft
- the on-board digitising and data-reduction (SARDIG) and recording (DCRSi) inside the aircraft
- the ground-based flight and radar data handling and SAR processing

Figure 3.1 illustrates the PHARUS overall system configuration.

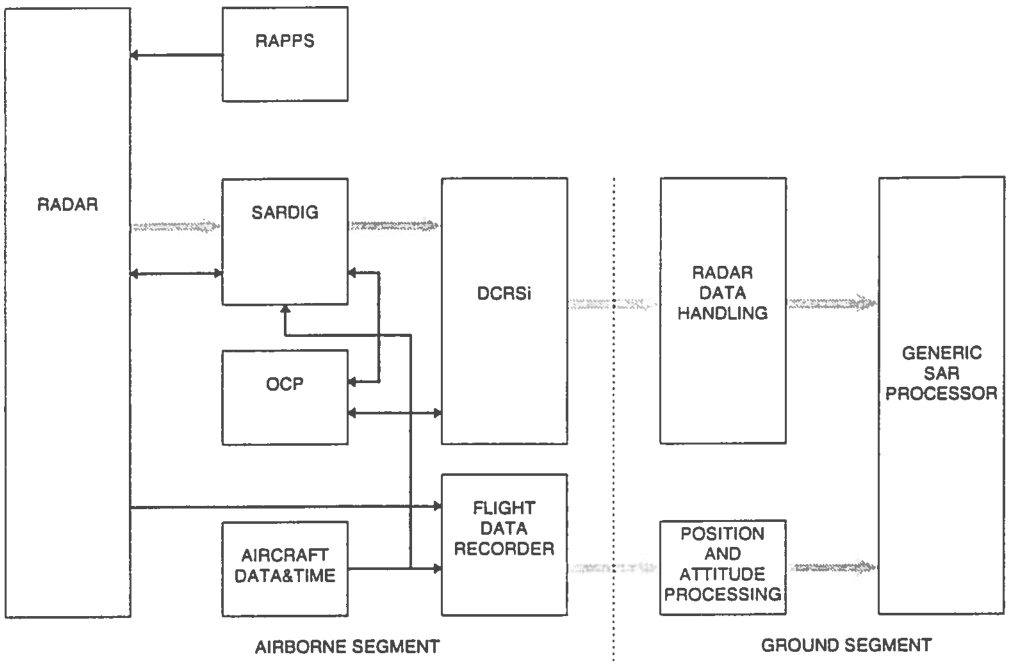


Figure 3.1 PHARUS System Configuration

In RAPPS the Citation's DC Power is converted to +/- 150 V for the radar. The operator control panel (OCP) is used to control the PHARUS system, in particular RADAR, SARDIG and DCRSi, and to present the actual system status.

The PHARUS system has a modular architecture, enabling easy adaptation to specific requirements and a user oriented configuration. The system is capable of realising high resolutions (up to 1 x 3 m) over relatively long ranges in single polarisation mode. The range is reduced in dual and quad polarisation (polarimetric) mode. Alternatively, the resolution can be reduced in any of the modes.

Basic radar parameters like transmit and receive polarisation, pulse length, chirp bandwidth, pulse repetition frequency and receiver gain are in-flight programmable, 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 research aircraft owned by NLR and DUT, enabling an altitude of 12 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 groundspeed, enabling equidistant sampling of the terrain.

One of the most prominent features of the radar is its active array antenna. It is presently configured as a 2 x 24 array of active Transmit/Receive modules (T/R-Modules). Each T/R-Module generates up to 20 W output power. The antenna can be upgraded to a 4 x 24 array for increased power and reduced elevation beamwidth. The use of a phased array enables electronic control of the beam's 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 polarisation decoupling, full polarisation 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 pulse repetition frequency. Each mode has its own set of values for beam direction, chirp pattern, gain setting and transmit polarisation.

Finally, the radar can be switched to several specific system calibration modes, through which the behaviour 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.

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

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

4. PHARUS modes

A number of basic PHARUS modes are presented in Table 4.1. Other modes are possible, but require calculations to determine which PHARUS settings approach the desired mode best.

The table lists mostly non-polarimetric and fully-polarimetric modes. One example of a *dual* polarisation mode is included. This is the so-called ASAR-mode, which was designed to simulate the future space-borne radar of the Envisat satellite. The parameters listed are also depicted in Figure 2.1 on page 4.

Table 4.1: Basic PHARUS modes

resolution (m)	# pol.	# looks	sensitivity (dB)	swath (km)	altitude (km)	max. range (km)
4	4	4	-40	4.4	4.5	8.0
4	4	4	-30	8.0	4.5	14.5
8	4	4	-40	6.5	5.0	11.0
16	4	16	-40	7.9	6.0	13.0
4	1	4	-30	11.2	6.0	16.0
8	1	8	-30	14.6	6.0	20.0
16	1	16	-30	20.0	6.0	26.0
4	1	4	-20	9.9	12.0	18.0
16	1	20	-30	14.9	12.0	22.0
24	2	4	-25	9.8	14.0	20.0

Other parameters such as incidence angles, and minimum range are easily derived from the above table and from the imaging geometry.

The resolution as given in Table 4.1 is the approximate *geometric resolution*. As explained above, the ground range resolution always varies over range, due to the projection effect. The number of looks determines the *radiometric resolution*. The sensitivity also varies over range, and should be at least as good as the number given in the table.

5. The Generic SAR Processor

Data from the on-board recorder is processed into SAR images with the Generic SAR Processor (GSP). Presently the GSP software is running on a UNIX based SUN Sparc station with additional external vector processing supercard. The GSP 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. slant-to-ground range)
- calibration

Azimuth compression with motion compensation is the most complex, and also the most computationally intensive task. A full polarimetric image, such as a high resolution 5 km^2 image, requires several 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 quality of the data. The GSP also contains tools that can operate on data at different levels, such as a display facility (Image Viewer) and a tool for statistic and spectral analysis (Analyzer), as shown in Figure 5.2. Not shown are the data archiving tools and the extensive man-machine interface.

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.

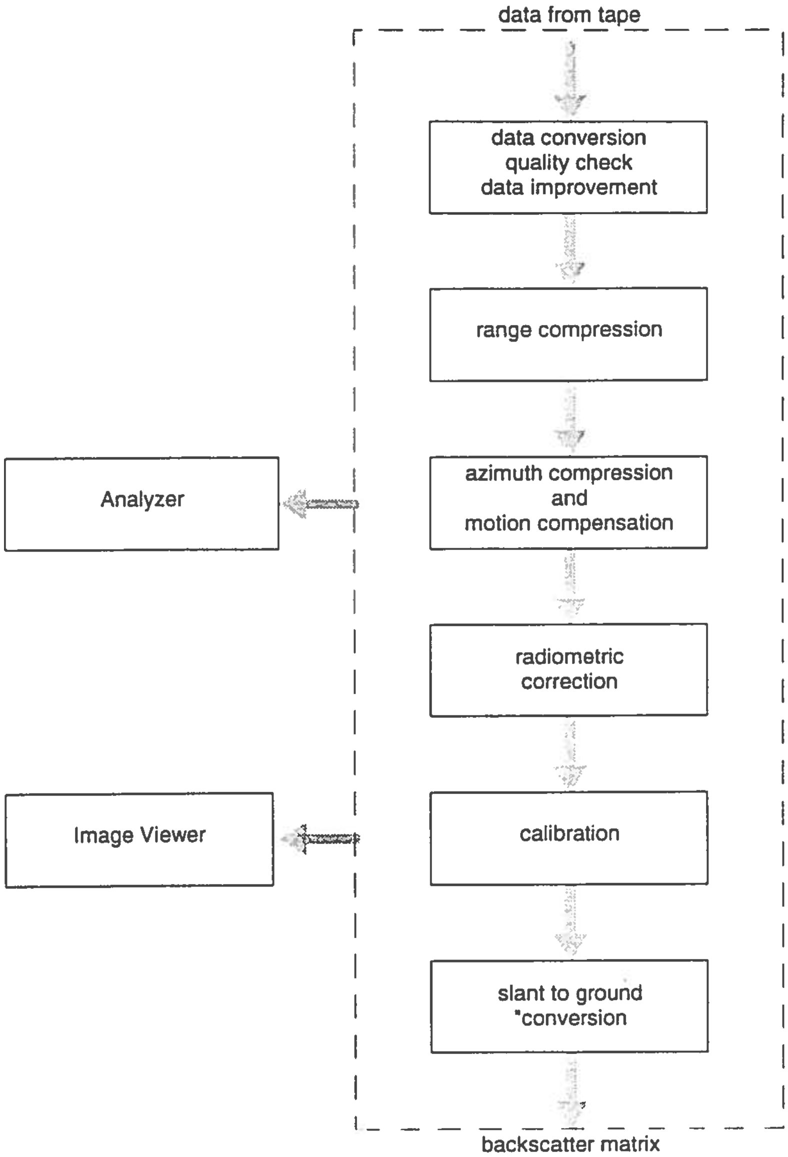


Figure 5.2: GSP Main Functional Blocks

6. Image products

Processing of SAR data with the GSP consists of several stages, resulting in several data products and formats. Of interest to the user are the products produced after basic processing , i.e. data conversion and 'cleaning', range compression, and azimuth compression with motion compensation. The image is then in slant range projection. Next steps that can be performed are ground range projection and calibration.

Initially the compressed image data is in complex format, unless multi-looking has been applied. In most applications, the phase information is not required, so that a real number format, representing pixel intensity is adequate. These pixel values are logarithmically scaled to fit the very large dynamic range into a single byte per pixel. Interpolation operations, such as slant-to-ground range projection are very difficult on complex airborne SAR data, due to the varying spectral characteristics. Therefore, these are done only on real data.

Polarimetric data formats, can be represented either in scattering matrix format (complex) or Stokes matrix format (real).

Note that the data products are essentially reflectivity maps, with several independent variables in the case of polarimetric data. These data products can be used for further analysis by the user. If these products are to be *displayed*, this will generally require a transformation, such as colour coding.

The available data formats are:

single-polarisation:

- complex, slant range, single look[1]
- real, slant range, multi-look
- real (logarithmic) ground range

polarimetric:

- Scattering Matrix (complex), slant range
- Stokes Matrix (real), slant range
- Stokes Matrix, ground range

It is also possible to obtain separate channels from a polarimetric measurement in single-polarisation formats. PHARUS can also record dual polarisation data: in this case, only two of the four scattering matrix elements are provided.

All of the above products can be delivered fully calibrated, except for the Scattering Matrix format. Calibration in the GSP takes place on Stokes Matrix data, which in general cannot be converted back to scattering ma-

[1] A multilook product can also be delivered as a set of complex single look products

trix format. Scattering matrix data can be delivered with associated calibration data, if available.

The above data formats are GSP-specific formats, but are relatively simple, well documented and therefore easy to use or convert.

Single channel real data can be delivered also in widely accepted image formats such as GIF, TIFF, Sun Raster, JPEG etc.. When polarimetric data must be delivered as displayable images, a colour coding scheme must first be determined.

When complex imagery is required, the user should consult the PHARUS team to discuss the processing strategy for phase preservation; although the processor is in principle 'phase preserving', perfect phase preservation may not be possible under aircraft motion conditions. How this should be handled depends on the application.

Ground range images are processed in a rectangular co-ordinate system linked to the aircraft track. A geographical reference can be provided, fixing the image position geographically. If desired, images can be processed to a particular co-ordinate system. Since this requires interpolations, it may affect image quality. In such cases, it must be clear which aspects of image quality are most essential, such as geometric resolution, radiometric resolution, geometric accuracy, etc.. This information is used to guide the choice of interpolation methods.