Defence Research and Development Canada
Recherche et développement pour la défense Canada

DEFENCE R&D DÉFENSE

COASP and CHASP Processors for Strip-map and Moving Target Adaptive Processing of EC CV-580 Synthetic Aperture Radar Data

Algorithms and Software Description

Paris W. Vachon and Marina V. Dragosevic

Defence R&D Canada – Ottawa

TECHNICAL MEMORANDUM
DRDC Ottawa TM 2006-066
May 2006

Canada

COASP and CHASP Processors for Strip-map and Moving Target Adaptive Processing of EC CV-580 Synthetic Aperture Radar Data

Algorithms and Software Description

Paris W. Vachon
Defence R&D Canada – Ottawa

Marina V. Dragošević
TerraBytes Consulting

Defence R&D Canada – Ottawa

Technical Memorandum

DRDC Ottawa TM 2006-066

May 2006

Author

Original signed by Paris W. Vachon

Paris W. Vachon

Approved by

Original signed by Gary W. Geling

Gary W. Geling
Head, Radar Applications and Space Technologies

Approved for release by

Original signed by Cam Boulet

Cam Boulet
Chair, Document Review Panel

Abstract

DRDC Ottawa has been working with data from the Environment Canada (EC) CV-580 C-band polarimetric synthetic aperture radar (SAR) since the late 1990's in support of target detection and classification studies. Until recently, processing of data from this SAR system has been carried out in-house using the Polarimetrc Generalized Airborne SAR Processor (PolGASP) that was developed at the Canada Centre for Remote Sensing. As DRDC Ottawa interests began to focus on moving targets to improve Polar Epsilon maritime and land target detection and classification capabilities, PolGASP-processed data proved to be inadequate to support required downstream analyses. PolGASP uses a simple azimuth-oriented compression algorithm, fixed processing parameters over each flight line, and assumes that the target is static (i.e., not moving). Therefore, the COASP (Configurable Airborne SAR Processor) and CHASP (Chip Adaptive SAR Processor) processors have been developed to replace and augment PolGASP and to provide better focused imagery to support downstream analysis such as polarimetric decomposition of moving ship targets, ship velocity estimation, and to act as a test-bed for phase-based target detection algorithms. In this document, the COASP and CHASP processors are described from an algorithmic and software perspective. Test results for moving ship targets are presented; focus improvements are readily apparent and derived ship velocities are favourably compared with available validation data.

Résumé

RDDC Ottawa utilise les données du radar à synthèse d'ouverture (SAR) polarimétrique en bande C du CV-580 d'Environnement Canada (EC) depuis la fin des années 1990 à l'appui des études de détection et de classification des cibles. Jusqu'à récemment, le traitement des données de ce système SAR était effectué à l'interne à l'aide du processeur SAR polarimétrique généralisé aéroporté (PolGASP) qui a été mis au point au Centre canadien de télédétection. À mesure que RDDC Ottawa a commencé à concentrer ses intérêts sur les cibles mobiles pour améliorer les capacités de détection et de classification des cibles maritimes et terrestres dans le cadre du projet Polar Epsilon, les données traitées par le PolGASP se sont révélées inadéquates pour appuyer les analyses en aval requises. Le PolGASP utilise un algorithme de compression en azimut et des paramètres de traitement fixes sur chaque ligne de vol, et il considère que la cible est statique (c.-à-d. qu'elle ne se déplace pas). Par conséquent, les processeurs COASP (processeur SAR configurable aéroporté) et CHASP (processeur SAR adaptatif orienté bloc) ont été mis au point pour remplacer le PolGASP par un outil plus perfectionné et pour fournir des images avec une meilleure focalisation dans le but d'appuyer l'analyse en aval, par exemple la décomposition polarimétrique des navires cibles mobiles et l'estimation de la vitesse des navires, et pour servir de banc d'essai des algorithmes de détection des cibles basée sur la phase. Le présent document décrit les processeurs COASP et CHASP des points de vue algorithmique et logiciel. Il présente les résultats obtenus dans des essais portant sur des navires cibles mobiles. L'amélioration de la focalisation est tout de suite évidente et la comparaison entre les vitesses des navires qu'on a déduites et les données de validation disponibles donne des résultats positifs.

This page intentionally left blank.

Executive summary

COASP and CHASP Processors for Strip-map and Moving Target Adaptive Processing of EC CV-580 Synthetic Aperture Radar Data: Algorithms and Software Description

Paris W. Vachon, Marina V. Dragošević; DRDC Ottawa TM 2006-066; Defence R&D Canada – Ottawa; May 2006.

The Environment Canada (EC) CV-580 C-band polarimetric synthetic aperture radar (SAR) has been used by DRDC Ottawa in preparation for the polarimetric data that will be available from RADARSAT-2 in the near future. DRDC Ottawa has deployed this radar for several maritime trials and has processed the data from this radar using the Polarimetric Generalized Airborne SAR Processor (PolGASP) that was developed at the Canada Centre for Remote Sensing (CCRS). PolGASP uses several approximations that render its products inadequate to support the production of well-focused imagery of moving ship targets. This has compromised downstream analysis such as polarimetric decomposition for ship classification studies.

To better support polarimetric research activities aimed at improving Polar Epsilon target detection and classification capabilities, DRDC Ottawa has developed two processors to replace and augment the PolGASP functionality. These processors are referred to as COASP (Configurable Airborne SAR Processor) and CHASP (Chip Adaptive SAR Processor). COASP is a flexible strip-map processor that directly replaces PolGASP for EC CV-580 SAR processing. CHASP is normally run after COASP for specific targets of interest in order to adaptively improve their focus and estimate their velocity. In an operational setting, a target detection algorithm could be run on the COASP output products to identify targets of interest. Both COASP and CHASP are block-oriented, use a Range-Doppler processing algorithm, and can produce calibrated products. COASP is a pre-processor for CHASP in that it carries out the required range compression and motion compensation operations.

This document describes the COASP and CHASP algorithms and software, as implemented and run operationally at DRDC Ottawa.

Target adaptation in CHASP is available through several algorithms. Assessment of target focus can be automatic or via an image analyst. Available algorithms permit adjustment of the Doppler centroid (due to target rangeward motion) and the Doppler rate (due to target azimuthal motion) and include ghost (i.e., azimuth ambiguity) balancing, frequency tracking of residual phase, inter-look correlation, and target contrast maximization. Test results for moving ship targets acquired during a trial in September 2004 are presented. The derived ship velocities are favourably compared with available validation data and the improvement in image focus is readily apparent.

CHASP represents a general SAR processing capability for moving targets. As such it is

planned that CHASP will be tested for spaceborne SAR data (RADARSAT-1 in particular). Furthermore, it contains many algorithms for manipulation and analysis of moving target data. In this context, CHASP will be used as a test bed to develop and demonstrate advanced phase-based ship detection algorithms.

Sommaire

COASP and CHASP Processors for Strip-map and Moving Target Adaptive Processing of EC CV-580 Synthetic Aperture Radar Data: Algorithms and Software Description

Paris W. Vachon, Marina V. Dragošević; DRDC Ottawa TM 2006-066; R & D pour la défense Canada – Ottawa; mai 2006.

RDDC Ottawa a utilisé le radar à synthèse d'ouverture (SAR) polarimétrique en bande C du CV-580 d'Environnement Canada (EC) pour se préparer à la réception des données polarimétriques qui seront offertes par RADARSAT-2 dans un proche avenir. Il a mis en place ce radar pour plusieurs essais maritimes et il a traité ses données à l'aide du processeur SAR polarimétrique généralisé aéroporté (PolGASP) qui a été mis au point au Centre canadien de télédétection (CCT). Parce qu'il utilise plusieurs approximations, le PolGASP fournit des données qui sont inadéquates pour appuyer la production d'images bien focalisées des navires cibles mobiles. Cette situation a compromis l'analyse en aval, par exemple la décomposition polarimétrique pour les études de classification des navires.

Afin de mieux appuyer les travaux de recherche polarimétrique visant à améliorer les capacités de détection et de classification des cibles dans le cadre du projet Polar Epsilon, RDDC Ottawa a mis au point deux processeurs destinés à remplacer la fonctionnalité du PolGASP par une fonctionnalité plus perfectionnée. Ces processeurs sont le COASP (processeur SAR configurable aéroporté) et le CHASP (processeur SAR adaptatif orienté bloc). Le COASP est un processeur de cartes-bandes souple qui remplace directement le PolGASP pour le traitement des données du SAR du CV-580 d'EC. Le CHASP est normalement utilisé à la suite du traitement effectué sur le COASP pour des cibles d'intérêt particulières afin d'améliorer de manière adaptive leur focalisation et d'estimer leur vitesse. En milieu opérationnel, un algorithme de détection des cibles pourrait être appliqué aux données fournies par le COASP dans le but d'identifier les cibles d'intérêt. Tant le COASP que le CHASP sont des processeurs orientés bloc, utilisent un algorithme de traitement distance-fréquence Doppler et peuvent fournir des produits étalonnés. Le COASP est un pré-processeur pour le CHASP en ce sens qu'il effectue les opérations requises de compression en distance et de compensation de mouvement.

Le présent document décrit les algorithmes et le logiciel du COASP et du CHASP, tels qu'ils sont mis en œuvre et exécutés en milieu opérationnel à RDDC Ottawa.

L'adaptation des cibles dans le CHASP est offerte par plusieurs algorithmes. L'évaluation de la focalisation des cibles peut se faire automatiquement ou par l'intermédiaire d'un imagiste. Les algorithmes disponibles permettent le réglage du centroïde Doppler (déplacement en distance de la cible) et de la vitesse Doppler (déplacement en azimut de la cible) et ils comprennent l'équilibrage des images fantômes (ambiguïté en azimut), la poursuite en fréquence de phase résiduelle, la corrélation inter-observation et la maximisation de contraste de cible. Les résultats obtenus dans un essai portant sur des navires cibles mobiles effectué en septembre 2004 sont présentés. La comparaison entre les vitesses des navires qu'on a déduites et les données de validation disponibles donne des résultats positifs et l'amélioration de la focalisation est tout de suite évidente.

Le CHASP représente une capacité de traitement SAR général pour les cibles mobiles. À ce titre, on prévoit le mettre à l'essai pour le traitement des données du SAR aéroporté (RADARSAT-1 en particulier). De plus, il contient un grand nombre d'algorithmes pour la manipulation et l'analyse de données relatives aux cibles mobiles. Dans ce contexte, on prévoit que le CHASP sera utilisé comme banc d'essai pour l'élaboration et la démonstration d'algorithmes avancés de détection de navires basée sur la phase.

Table of contents

List of figures

List of tables

Acknowledgements

We thank: Terry Potter for his skill and expertise in EC CV-580 SAR data processing and for his willingness to work with us to develop and adopt new processing methodologies; Bob Hawkins (CCRS), Kevin Murnaghan (CCRS), and Chuck Livingstone (DRDC Ottawa) for their insight to the EC CV-580 SAR system and their willingness to support our processor development efforts; D Space D's Polar Epsilon project for their interest in and support of this project; representatives from D Space D, CFJIC and MCE for participating in Demonstrations of this software and providing helpful feedback; and colleagues at DRDC Ottawa for helpful discussions.

1 Introduction

DRDC Ottawa is carrying out R&D activities in support of the Polar Epsilon project through a Service Level Arrangement (SLA). Polar Epsilon will implement a wide area surveillance capability for the Canadian Arctic and the maritime approaches to Canada by using RADARSAT-2 synthetic aperture radar (SAR) data. One work package in the SLA focuses on advanced ship detection techniques for SAR data. The outcome of this work package could help to improve Polar Epsilon target detection and classification capabilities. Data from the Environment Canada (EC) CV-580 C-band polarimetric SAR [4] has been used as a source of polarimetric data for ship targets in advance of the launch of RADARSAT-2 (which is currently scheduled for late 2006).

The EC CV-580 SAR was developed at the Canada Centre for Remote Sensing (CCRS) starting in the mid 1980's. Its functionality was improved over the years to include radiometric image calibration, polarimetry, and various interferometry modes. Following the transfer of this facility from CCRS to EC in 1996, DRDC Ottawa has deployed this radar to collect polarimetric data of ships during several maritime trials.

Processing of trial data from the EC CV-580 SAR is carried out in-house at DRDC Ottawa. This has involved use of CCRS tools that were transferred to DRDC Ottawa through a software license agreement; DRDC Ottawa staff received training from CCRS on the use of these tools. The CCRS processor is referred to as the Polarimetrc Generalized Airborne SAR Processor (PolGASP) [3], and uses a simple azimuth-oriented compression algorithm, fixed processing parameters over each flight line, and assumes that the target is static (i.e., not moving). As DRDC Ottawa interests began to focus on ships, the design of PolGASP proved to be inadequate to support the production of well-focused imagery of moving ship targets. This has compromised downstream analysis such as polarimetric decomposition for ship classification studies.

To replace and augment the PolGASP functionality, two new processors have been developed at DRDC Ottawa. COASP (Configurable Airborne SAR Processor) is a strip-map synthetic aperture radar (SAR) processor for the EC CV-580 Polarimetric SAR. COASP replaces PolGASP, but could find other uses since it can also process single channel data and because all of the system parameters are configured externally. The main functionality of COASP includes:

- In-phase and quadrature channel conditioning;
- Range compression, if not done in hardware;
- Motion compensation using externally calculated parameters;
- Azimuth compression using the Range-Doppler or the simple PolGASP-style algorithm;
- Radiometric correction and calibration;
- Georeferencing using externally calculated antenna positioning; and

- Some data quality checking.

Most of the above functionality can be controlled using configuration files.

COASP differs from PolGASP in several important ways. First, COASP processing is block oriented. Entire data blocks are read into memory and completely processed before they are saved. Second, processing is organized in modules. When multiple CPUs are available, it is recommended that COASP be run as a parallel application, which is a run-time configuration option. COASP is parallel by design. It forks multiple parallel tasks, as configured. All COASP tasks are identical, but work on different segments of the data. Each module is a unit of processing which can be carried out independently by several tasks. Following each module, the tasks are synchronized.

PolGASP performance for moving targets has been unsatisfactory. Development of COASP was driven by a need to provide better imagery for this important target class. In addition to full strip-map SAR processing, COASP can be configured to serve as a preprocessor for CHASP.

CHASP (Chip Adaptive SAR Processor) is a single data block processor which is intended for data adaptive processing. It requires range compressed and calibrated input. It accepts EC CV-580 SAR auxiliary files, but can be used without them and, in principle, it can process data from various sources, including airborne and spaceborne. The main goal of CHASP processing is to achieve a better focus of moving targets. This goal is accomplished by optimization of a set of processing parameters, which may be defined as one of these two parameter sets:

- Doppler centroid (or, equivalently, relative radial speed) and Doppler rate (or, equivalently, along track velocity adjustment); and
- Doppler centroid and azimuth reference phase polynomial coefficients.

In both cases it is assumed that the target is moving linearly and its observable velocity components are along the radar line of sight (LOS) and along track. The radial or LOS speed is assumed to be constant. The parallel or along track speed is assumed constant in the first approximation, but it may be refined to include variability using higher order polynomial phase coefficients. The estimated parameters are considered constant for the target as a whole, ignoring the effects of target rotation. Hence, CHASP is mainly concerned with the travelling velocity of the target. Other types of target motion, such as heave, would require the inverse SAR (ISAR) approach.

Various effects of target motion on the image are exploited, most importantly target smearing in range and target smearing in azimuth, which can be observed and measured at different levels, including:

- In the final image since target motion causes smearing and loss of contrast;
- Between sub-apertures or “look” images produced from Doppler sub-bands since target motion causes look misregistration; and

- In time-frequency space since target motion causes deviation from the expected time-frequency lock.

The adaptation can be achieved in two modes:

- CHASP can be used as a processing engine, while an external driver varies processing parameters and searches for the best focused image or measures look misregistration; and
- CHASP has its own adaptive algorithms and can produce estimates of the processing parameters, though an external driver might still be used to iteratively improve the results.

COASP and CHASP share the same software architecture and many common libraries.

In this document we review the key features of the implemented algorithms, COASP and CHASP design, external tools, processing procedures and the software organization. Key differences between these processors and PolGASP are pointed out. Processor test results and sample imagery are presented in the Annexes. The development presented in this document assumes familiarity with digital signal processing and with SAR processing concepts [1].

2 SAR Algorithm Review

This section provides a brief summary of the implemented standard SAR algorithms. The specific form of each algorithm is described exactly as implemented.

2.1 Image Formation Algorithms

This is the class of algorithms that work directly on the data samples, processing them from the raw level to a focused image. Some of them are used in COASP, others in CHASP and certain algorithms are available in both processors.

2.1.1 Input Data Conditioning

In-phase (I) and quadrature (Q) components of the raw data are de-biased using the mean values $\langle I \rangle$ and $\langle Q \rangle$ averaged over one data block. In comparison, PolGASP uses a global file average instead.

I and Q are balanced in power and orthogonalized to counter cross-talk. The first correction is present in PolGASP, but the second is not. We have noticed a difference between the degree of co-polarization (channel A) and cross-polarization (channel B) cross talk.

The applied corrections are:

$$\begin{bmatrix} I_{out} \\ Q_{out} \end{bmatrix} = \begin{bmatrix} r_1 & 0 \\ -r_2 & 1 \end{bmatrix} \begin{bmatrix} I - \langle I \rangle \\ Q - \langle Q \rangle \end{bmatrix} \tag{1}$$

where:

$$r_2 = \frac{\langle IQ \rangle - \langle I \rangle \langle Q \rangle}{\langle I^2 \rangle - \langle I \rangle^2} \tag{2}$$

$$r_1^2 = \frac{\langle Q^2 \rangle - \langle Q \rangle^2}{\langle I^2 \rangle - \langle I \rangle^2} - r_2^2 \tag{3}$$

This algorithm is only available in COASP since CHASP starts from pre-processed data.

2.1.2 Range Filtering

Range filtering is done by fast convolution. Range filtering is done if software range compression must be performed (the “SAW OUT” case; the EC CV-580 SAR can perform range compression using a surface acoustic wave (SAW) device, the “SAW IN” case) or if the time delay between channel acquisition must be accounted for in software (usually for the vertical transmitter, i.e. the VV and VH channels). Therefore, three types of range processing have been made available:

- No processing (data copy);

- Range shift (by fast convolution);
- Range compression (by fast convolution); and
- Range compression and shift (by fast convolution).

Filters for fast convolution are computed in the initialization step and are used for all data blocks. Separate filters are created for each of the channels that will be processed (which may be from one to four). For SAW OUT cases the time domain chirp $f(n)$ is read from an auxiliary input file; it may be zero-padded before transformation into the frequency domain via Fast Fourier Transform (FFT). The size of the FFT, N, depends on the length of the range line. PolGASP currently supports only 4K SAW OUT processing; CHASP is more general. The externally provided chirp, shown in Fig. 1, has been generated off-line and includes time domain windowing to suppress aliasing. No additional frequency domain windowing is applied. The range compression filter in the frequency domain, $F(k)$, is calculated using a library FFT function, followed by normalization. Since the library FFT function does not include any normalization, the output FFT($f(n)$) is normalized by:

$$A = N||f(n)|| \tag{4}$$

which assumes that the implementation of a forward and inverse FFT does not include a factor of $1/N$.

The shift filter is generated in the frequency domain according to the formula:

$$S(k) = \begin{cases} \exp(-j\frac{2\pi d}{N}k) & 0 \leq k < M/2 \\ \exp(-j\frac{2\pi d}{N}(k-N)) & N - M/2 \leq k < N \\ 0 & \text{elsewhere} \end{cases} \tag{5}$$

where $M < N$ corresponds to the chirp bandwidth and d is the delay expressed in sample intervals.

Finally, the range filter $H(k)$ can be one of the following:

$$H(k) = \begin{cases} 1 & \text{no processing} \\ S(k)/N & \text{shifting} \\ F(k)/A & \text{compression} \\ S(k)F(k)/A & \text{compression \& shifting} \end{cases} \tag{6}$$

Using the pre-computed filters, range filtering is performed in three steps:

1. FFT of all range lines in the block;
2. Multiplication by the proper filter for all range lines in the block;
3. Inverse FFT of all range lines in the block.

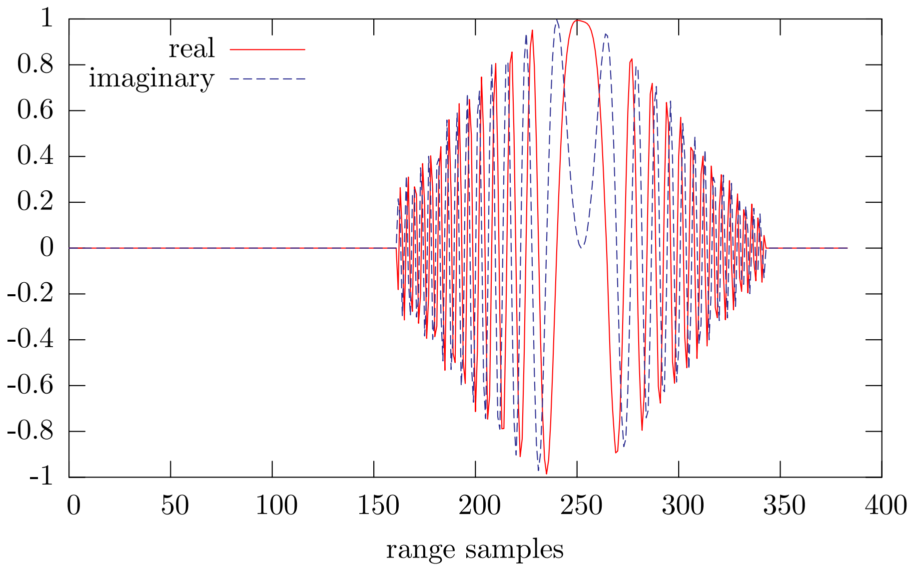


Figure 1: *Time response of the range compression filter.*

Optionally, the initial part of the filtered range line may be discarded if it does not contain valid data. The length of the transition interval is equal to the length of the range filter time response, but the number of discarded samples can be modified by operator input.

This algorithm is only available in COASP and is specific to the EC CV-580. CHASP starts from pre-processed data which must be range compressed.

2.1.3 Motion Compensation

Motion compensation consists of a phase adjustment of each sample in the data block to account for platform motion during data acquisition.

Parameters for motion compensation must be previously calculated, resampled to the rate of the pulse repetition frequency (PRF), formatted according to the Matlab$^{\mathrm{TM}}$ version 4 specifications and saved to a file known as the "PRF file". Traditionally, this operation was done by a suite of CCRS interactive motion compensation (MoComp) programs, that have been replaced by a faster and more accurate program called InQC. Both the CCRS MoComp software and the DRDC InQC software produce PRF files that can be used by PolGASP, COASP and CHASP.

For each range line, the horizontal deviation Δ_h and the vertical deviation Δ_v of the C-band antenna from the reference flight track are known from the PRF file. Also from the PRF file, the position of the C-band antenna is known for each range line. This position is given in the Earth Centred, Earth Fixed (ECEF) reference system. Using this position, the slant range of each sample, as well as the geoid elevation above the reference ellipsoid, the elevation angle can be calculated for each slant range sample of each range line. The algorithm is described in Section 2.2.3.

Three options are implemented. Two of the options are based on the following algorithm:

1. Find the array of elevation angles $\gamma(a, r)$ for each slant range $R_c(r)$ for each sample index r and for a given range line index (azimuth) a, as discussed in Section 2.2.3;

2. Extract deviations $\Delta_h(a)$ and $\Delta_v(a)$ for the azimuth position a and find the deviation $\Delta(a)$ and angle $\theta(a)$ where:

$$\begin{aligned} \Delta(a)^2 &= \Delta_h(a)^2 + \Delta_v(a)^2 && (7) \\ \theta(a) &= \mathrm{atan2}(\Delta_v(a), \Delta_h(a)) && (8) \end{aligned}$$

   where the function atan2 (software standard supported by all math libraries) is defined using the principal value of the function arctangent in four quadrants ($\alpha = \arctan(u) \Leftrightarrow u = \tan(\alpha), -\pi/2 < \alpha < \pi/2$) as follows:

$$\mathrm{atan2}(y, x) = \begin{cases} \arctan(y/x) & x > 0 \\ \arctan(y/x) - \pi & x < 0, y < 0 \\ \arctan(y/x) + \pi & x < 0, y \geq 0 \\ \pi/2 & x = 0, y > 0 \\ -\pi/2 & x = 0, y < 0 \end{cases} \qquad (9)$$

   (for $x = y = 0$ this function is not defined);

3. For each range sample r of the range line a find angle $\beta(a, r)$

$$\beta(a, r) = \theta(a) + \frac{\pi}{2} - s\gamma(a, r) \qquad (10)$$

   where s indicates the look direction, represented as:

$$s = \begin{cases} 1 & \text{starboard (right)} \\ -1 & \text{port (left)} \end{cases} \qquad (11)$$

   and then find the distance $R(a, r)$:

$$R^2(a, r) = R_c^2(r) + \Delta^2(a) - 2R_c(r)\Delta(a)\cos(\beta(a, r)), \qquad (12)$$

   the phase $\varphi(a, r)$:

$$\varphi(a, r) = 4\pi \frac{R_c(r) - R(a, r)}{\lambda}, \qquad (13)$$

   and the phase rotation terms $q(a, r)$:

$$q(a, r) = \exp(j\varphi(a, r)) \qquad (14)$$

   and save them in memory;

4. For each azimuth index a and range index r, multiply the data sample by the complex conjugate of the phase rotation term $q(a, r)$.

The only difference between the two options that use this algorithm is in the rate of along track updates for the array of elevation angles $\gamma(a, r)$. The array can be updated for each azimuth position at the pulse repetition frequency (PRF) or it can be updated once per group of range lines. In the latter case, there may be a small phase discontinuity between groups of lines due to the updating strategy.

This method differs from the one implemented in PolGASP, where a plane Earth surface approximation is used. The PolGASP method is implemented as the third possibility. The algorithm is as follows:

1. Find the antenna elevation above ground H for the first azimuth position of interest based on the calculations explained in Section 2.2.3 and consider this elevation as constant;

2. Extract deviations $\Delta_h(a)$ and $\Delta_v(a)$ for a set of azimuth position a and find the ground distance $x(r)$ for for each slant range $R(r)$ as

$$x(r)^2 = R(r)^2 - H^2; \tag{15}$$

3. Find the corrected horizontal and vertical displacements $p(a, r)$, $q(a, r)$ and the corrected distance $R_c(a, r)$:

$$\begin{aligned} p(a,r) &= x(r) + s\Delta_h(a) & (16) \\ q(a,r) &= H - \Delta_v(a) & (17) \\ R_c^2(a,r) &= p^2(a,r) + q^2(a,r) & (18) \end{aligned}$$

   then find the phase $\varphi(a, r)$:

$$\varphi(a,r) = 4\pi \frac{R_c(a,r) - R(r)}{\lambda} \tag{19}$$

   and the corresponding phase rotation terms $q(a, r)$;

4. For each azimuth index a and range index r, multiply the data sample by the complex conjugate of the phase rotation term $q(a, r)$.

Motion compensation as described above is applied to azimuth uncompressed data. The opposite phase terms are optionally applied to the azimuth compressed data in order to restore the phase of the acquired signal.

This algorithm is only available in COASP and is specific to the EC CV-580. CHASP starts from pre-processed data for which platform motion has already been compensated.

2.1.4 Radiometric Corrections

Three types of radiometric corrections are applied to the EC CV-580 SAR data.

Receiver Gain Application Co-polarization and cross-polarization signal paths are called channel A and B. Coarse attenuation and fine gain is recorded for both channels and made available for each range line via the ancillary file. Interestingly, not all ancillary files carry correct information for the two channels. The HH ancillary file is being used to extract the coarse attenuation and the fine gain. The data are corrected by adding the attenuation value in dB to the signal (or noise) power and subtracting the gain value.

Spread Loss Radiometric Correction Spread loss correction is applied by multiplying data samples with a real factor equal to $(R(r)/R_{ref})^p$, where R_{ref} is the reference range and p is the degree. Unlike PolGASP, R_{ref} and p are not hard-coded. The appropriate degree p depends in principle on the implemented azimuth compression algorithm and azimuth filter normalization. For compatibility with PolGASP $R_{ref} = 1$ and, for the compression method used, $p = 3/2$. These are the default values, which may be modified by the operator.

Antenna Gain Compensation There are four separate antenna gain files for starboard and for port looking, for horizontal and for vertical channels. The proper antenna gains are read during program initialization. They are available for angles $\theta(k) = \theta_{min} + k\delta\theta$, the minimum value θ_{min} and the increments $\delta\theta$ are among the system parameters in the appropriate section of the configuration file, described in Section 3.3. They are not hard-coded as in PolGASP. Upon reading, these values are saved in a table against angles $\theta'(k) = \theta(k) - \theta_{offset} + \pi/2$, where θ_{offset} is an offset angle, different for port and starboard looking, included in the system parameters section of the configuration file. Since interpolation between the tabulated values will be required, the second derivative is constructed and saved to be used later for cubic spline interpolation. The corrected angles $\theta'(k)$, the corresponding antenna gain samples and the second derivative samples are tabulated and kept to be reused in all data blocks. During block processing, the elevation angles $\gamma(a, r)$ are calculated for all data samples. Mapping between slant range and elevation angle is described in Section 2.2.3. Roll angle $\varphi_{roll}(a)$ is obtained from the ancillary data. It is not updated for each range line; the same value is used for a group of adjacent lines. These two angles are used to find the desired angle $\gamma(a, r) + s\varphi_{roll}(a)$ for all samples. Then the antenna gain table and the second derivative table are used to calculate the gain for the desired array of antenna angles. This approach uses the cubic spline method. Finally, the gain is converted from dB to linear scale.

All of these algorithms are available in COASP. Only the spread loss radiometric correction is made available in CHASP. In this way, the power p in $(R(r)/R_{ref})^p$ may be modified even after preprocessing, should it become appropriate for any of the CHASP algorithms.

2.1.5 Calibration

Data calibration consists of applying several scaling and phase rotation factors. The magnitude multiplication factors are [6]:

$$\sqrt{\frac{v_g \sin\alpha}{K_0 K' P_{Tx} P_n}} \tag{20}$$

where:

- v_g ground speed, read from the PRF file;
- α incidence angle, calculated as described in Section 2.2.4;
- K_0 system constant, provided externally;
- K' calibration value for each channel determined as described in Section 4.1;
- P_{Tx} average transmitted power reading from the SAR log sheets;
- P_n the BITE noise image power, measured after processing the BITE noise.

Conversion to linear is necessary for those values that are provided in dB, such as P_{Tx} and K'. Phase correction θ is set externally for each channel and applied via multiplication with the phase term $\exp(j\theta)$ that is derived from the analysis of calibration targets.

This algorithm is only available in COASP. It is assumed that calibrated COASP output is used as CHASP input.

2.1.6 Simple Azimuth Compression

This simple azimuth compression algorithm is a straightforward extension of the algorithm used in PolGASP. Azimuth compression is achieved by fast correlation with a range-variant one-dimensional kernel, the azimuth reference function. Since the Doppler centroid (DC) is expected to be close to zero, no range migration (RM) is performed within this algorithm. The central part of the azimuth compression algorithm is the generation of the correlation kernel. Focusing depends critically on the “PRF over v” parameter (f_p/v_g), available from the PRF file for each azimuth index a, and on the correct slant range value (R) for each range index r. Additionally, unlike in PolGASP, this algorithm can accommodate a small Doppler offset.

A shift in the azimuth direction may be required for the VV and VH channels, which are interleaved with the HH and HV channels. The shift (interpolation) filter is generated in the frequency domain according to the formula:

$$S(k) = \begin{cases} \exp(j2\pi d\frac{k}{N}) & \text{if } 0 \le k < k_c + N_B/2 \\ \exp(j2\pi d(\frac{k}{N} - 1)) & \text{if } k_c + N - N_B/2 \le k < N \\ 0 & \text{elsewhere} \end{cases} \tag{21}$$

where d is the shift in terms of range lines (typically 0.5), N is the FFT length in azimuth, which is also equal to the block size in azimuth and $(k_c - N_B/2, k_c + N_B/2)$ is the domain of Doppler frequency indices about the DC index k_c such that it corresponds to the Doppler band $(f_p k_c/N - f_p N_B/(2N), f_p k_c/N + f_p N_B/(2N))$ of the signal. The DC index k_c may be larger or smaller than 0. Since relative DC, f_c, is provided as an input parameter, the value Nf_c is rounded to the nearest integer and then its value modulo N is used to derive k_c. By doing so, the algorithm is restricted to DC values within the 0 ambiguity. This algorithm is not meant to deal with any significant DC offsets and in particular is not suitable for the case of a non-zero PRF ambiguity.

To create the reference function for each range bin, the following normalized parameters are used:

$$\tilde{R}_0 = \frac{4\pi R_0}{\lambda} \tag{22}$$

$$\Delta\tilde{R} = \frac{4\pi \Delta R}{\lambda} \tag{23}$$

$$\Delta\tilde{a} = \frac{4\pi \Delta a}{\lambda} \tag{24}$$

$$\tilde{f}_c = 2\pi \frac{f_c}{f_p} \tag{25}$$

Here R_0 is the near range and ΔR is the slant range spacing, both determined from the system parameters. The parameter $\Delta a = v_g/f_p$ is the azimuth spacing and its value can be defined in several ways, as discussed in Sections 3.3 and 6.3. The most common situation is that Δa is the inverse of the mean "PRF over v" parameter for a processing block, as read from the PRF file. Finally, f_c/f_p is the relative DC with an ambiguity cycle of 1 that is externally set.

The algorithm to create the reference functions is:

1. Update the normalized slant range at slant range index r:

$$\tilde{R} = \tilde{R}_0 + r\Delta\tilde{R} \tag{26}$$

2. Find the length of the reference function:

$$L = 2\sin\left(\frac{\theta}{2}\right)\frac{\tilde{R}}{\Delta\tilde{a}} \tag{27}$$

   where θ is the beam width in azimuth, also read as a system parameter. L is then forced to be the nearest odd number.

3. Find the offset due to a non-zero DC:

$$L_{\text{off}} = -\frac{\tilde{R}\tilde{f}_c}{\Delta\tilde{a}\sqrt{\Delta\tilde{a}^2 - \tilde{f}_c^2}} \tag{28}$$

   and force it to the nearest integer. Then find non-symmetric interval limits:

$$L_1 = \frac{L-1}{2} + L_{\text{off}} \tag{29}$$

$$L_2 = \frac{L-1}{2} - L_{\text{off}} \tag{30}$$

4. Create the phase function:

$$\phi(k) = \begin{cases} 0 & k = 0 \\ \tilde{R} - \sqrt{\tilde{R}^2 + (k\Delta\tilde{a})^2} & 0 < k \leq L_1 \\ \tilde{R} - \sqrt{\tilde{R}^2 + ((N-k)\Delta\tilde{a})^2} & N - L_2 \leq k < N \end{cases} \tag{31}$$

   where N is the length of the data block along azimuth, also equal to the azimuth FFT length used along azimuth.

5. Create the complex function with phase $\phi(k)$ and amplitude 1 in the given interval; set to 0 outside of this interval.

6. Create the desired window, which is usually Kaiser with the given shape factor, as read from the configuration file, and with length L. Normalize the window to have a power of 1. Multiply the shifted window by the complex function so as to match the interval determined by L_1, L_2 and N. This is the reference function.

7. Take the FFT of the reference function and divide the result by N.

8. Where appropriate (usually the vertical channels), multiply the FFT of the reference function with the shift filter of equation (21).

Separate reference functions are created for all range bins. The radar signal, transformed by FFT, is multiplied by the complex conjugate of the reference function in the frequency domain. The result is transformed back by inverse FFT.

This algorithm is implemented for comparison with PolGASP. It can be used in COASP and in CHASP. Since it ignores the two-dimensional nature of the point target response (PTR), it is not used often.

2.1.7 Range-Doppler Algorithm

It is common to use the Doppler rate (DR) and the Doppler bandwidth (DB) as the parameters for the Range-Doppler algorithm. The DR is related to the azimuth spacing Δa or, inversely, the "PRF over v" parameter, used in the simple azimuth compression algorithm; it also depends on the slant range R. There is a slight difference between the DR at zero Doppler, $b_0(R_0)$, and the DR at the beam centre, $b_c(R_c)$, for the same target. It is appropriate to use a normalized value (for either b_0 or b_c):

$$\tilde{b} = 2\pi \frac{b}{f_p^2} \tag{32}$$

The relationship between spacing, distance and DR, in the normalized form, is;

$$\tilde{b}_0 = -\frac{\Delta\tilde{a}^2}{\tilde{R}_0} \tag{33}$$

$$\tilde{b}_c = -\frac{\Delta\tilde{a}^2}{\tilde{R}_c} + \frac{\tilde{f}_c^2}{\tilde{R}_c} \tag{34}$$

The Doppler bandwidth available for azimuth processing is, in normalized form:

$$\tilde{B}_a = \frac{2\pi B_a}{f_p} = 2\sin\left(\frac{\theta}{2}\right)\Delta\tilde{a} \tag{35}$$

The azimuth shift filter of equation (21) is a special case that is valid only for small values of the DC relative to the PRF. In a more general case, the shift filter depends on the ambiguity number m, which is an integer satisfying $f_c/f_p = m + k_c/N$, $0 \le k_c < 1$. Then:

$$S(k) = \begin{cases} \exp(j2\pi d(m + \frac{k}{N})) & \text{if } k_c - N_B/2 \le k < k_c + N_B/2 \\ \exp(j2\pi d(m + 1 + \frac{k}{N})) & \text{if } 0 \le k < k_c - N + N_B/2 \\ \exp(j2\pi d(m - 1 + \frac{k}{N})) & \text{if } k_c + N - N_B/2 \le k < N \\ 0 & \text{elsewhere} \end{cases} \tag{36}$$

where d is the azimuth shift expressed in terms of range lines and $f_p N_B/N = B_a$ is the Doppler bandwidth. The shift operation can tolerate small DC errors ($|\Delta\tilde{f}_c| < 2\pi - \tilde{B}_a$ or $|\Delta k_c| < N - N_B$). Odd ambiguity errors ($|\Delta\tilde{f}_c| = 2\pi$ or $\Delta m = \pm 1$) cause the shifted samples to have inverted sign. In between these extremes, shifted samples are adversly affected by DC errors.

The Range-Doppler algorithm is implemented as follows:

1. Create the array of the DR values for all range bins using the formula of equation (34) with slant range updates as given by equation (26);

2. FFT the signal along azimuth for all range bins;

3. Resample along range the signal in the range-Doppler domain; this is the range cell migration correction (RCMC);

4. Create the azimuth correlator for all range bins;

5. Multiply the transformed and resampled signal with the complex conjugate of the azimuth correlator for all range bins;

6. Multiply the filtered signal in the Doppler domain by a real window function or by a set of window functions for each range bin; and

7. Do the inverse FFT of the signal along azimuth, optionally with base-banding before applying the transformation.

Resampling in the range-Doppler domain is along the range direction and the amount of the required shift $\delta_r(r,k)$ depends both on range (through the updated values of f_c and b_c) and on the azimuth frequency index k as follows:

$$\delta_r(r,k) = \frac{1}{\Delta\tilde{R}}\left(\frac{\tilde{f}_c^2}{2\tilde{b}_c} - \frac{2\pi}{N}\frac{\tilde{f}_c}{\tilde{b}_c}(k - k_{ref}) - \left(\frac{2\pi}{N}\right)^2 \frac{1}{2\tilde{b}_c}(k - k_{ref})^2\right) \tag{37}$$

The shift is in terms of the slant range sampling. The reference index k_{ref} is not the same for all values of k, due to aliasing and is defined as:

$$k_{ref} = \begin{cases} k_c & \text{if } k_c - N/2 \le k < k_c + N/2 \\ k_c - N & \text{if } 0 \le k < k_c - N/2 \\ k_c + N & \text{if } k_c + N/2 \le k < N \end{cases} \tag{38}$$

The integer part of $\delta_r(r,k)$ is applied by reindexing. The shift by the fractional part of $\delta_r(r,k)$ is implemented via interpolation using a truncated sinc kernel.

The procedure for generating the azimuth correlator functions is as follows:

1. Generate the phase function:

$$\phi(k,r) = \begin{cases} \frac{\tilde{f}_c^2}{2\tilde{b}_c} + \tilde{f}_c k + \frac{1}{2}\tilde{b}_c k^2 & 0 \le k < L/2 \\ \frac{\tilde{f}_c^2}{2\tilde{b}_c} + \tilde{f}_c (k-N) + \frac{1}{2}\tilde{b}_c (k-N)^2 & N - L/2 \le k < N \end{cases} \tag{39}$$

   where $L = \tilde{B}_a/\tilde{b}_c$ and f_c, b_c, B_a all depend on r;

2. Create the complex function with phase $\phi(k,r)$ and amplitude 1 in the given interval, 0 outside of this interval;

3. FFT the reference function and divide by NL;

4. Multiply by the proper azimuth shift filter created according to equation (36).

The azimuth shift d in the azimuth shift filter of equation (36) should be modified for each range bin to include the half-interval delay of the VV and VH channels, as well as the delay $-\tilde{f}_c/\tilde{b}_c$ between the beam centre (acquisition) time and the zero Doppler (closest point of approach) time for ground targets.

The described procedure does not include the so called secondary range compression (SRC). This is because the SRC effect is negligible for the EC CV-580 SAR; furthermore the range chirp, which is non-linear and created using a SAW device, is not known in a closed form. SRC correction may be added if data from other sources are to be processed. However, in such cases, the preprocessed range compressed data may already be SRC corrected by the pre-processor.

This algorithm is included in both COASP and in CHASP. COASP always produces a single complex image, although its Doppler band can be reduced and the position of the processed Doppler band can be controlled. CHASP can produce up to two complex images at a time, each one using a different Doppler band.

2.1.8 Multilooking

Using a reference function truncated in time to perform time correlation in azimuth focusing is often referred to as sub-aperture processing. Similarly, using a frequency band filtered reference is often referred to as sub-band or look processing. In both cases multiple partial correlators can be defined, with or without overlap. Multilooking is the operation of incoherent summation of the processed looks.

Multilooking is only supported in CHASP and only up to two spectral looks can be produced, converted to power and summed together. A single look can also be converted to power in CHASP, but not in COASP.

2.1.9 Spatial Filtering and Pixel Resizing

In this context spatial filtering is the operation of azimuth-wise finite impulse response (FIR) low-pass (LP) filtering intended to smooth out the data and to reduce its bandwidth.

Upon spatial filtering, the data can be down-sampled by an integer factor or, even, by a suitable rational number factor. Down-sampling by a rational factor requires interpolation, which, however, can be incorporated in the spatial FIR filter. The suitable down-sampling or resizing factor is chosen such that the azimuth spacing becomes equal to the range spacing projected on the ground, which is $\Delta R_g = \Delta R/\sin(\alpha_i)$, where ΔR is the slant range spacing and $\sin(\alpha_i)$ is the local sine of the incidence angle. Assuming that only a narrow section of the swath is of interest, the incidence angle can be approximated by its central value. Then it is not necessary to resample the image to ground range. The existing slant range image is equal to the ground range image with ground spacing ΔR_g. Therefore, the azimuth down-sampling factor is $k_{az} = f_p \Delta R/v_g/\sin(\alpha_i)$.

This algorithm is only available in CHASP for either complex or for real (magnitude) data products.

2.2 Algorithms for Calculating the Imaging Geometry

This is the class of algorithms that deal with the imaging geometry using external information on the antenna position as a function of time. As a rule, the ground or ocean surface model is the global ellipsoid model; by default WGS84 is used. Additionally, the geoid hight above the ellipsoid may be specified and used in order to refine the calculations.

Global ellipsoid geometry (as opposed to plain ground geometry) is consistent with the motion calculation software package InQC.

2.2.1 Georeferencing

For a given C-band antenna position in the Earth Centred, Earth Fixed (ECEF) frame (C_x, C_y, C_z) and for the slant range R of interest, the algorithm for finding the ground point of closest approach (PCA) is as follows:

First, get an initial guess. For the first point in a range line the algorithm is:

1. Convert the C-band antenna position from ECEF to geodetic coordinates (latitude ϕ, longitude λ and altitude H) as shown in Section 2.2.2;

2. Find the unit vector pointing geodetically downwards from the sensor:

$$d_x = -\cos\phi\cos\lambda \tag{40}$$
$$d_y = -\cos\phi\sin\lambda \tag{41}$$
$$d_z = -\sin\phi \tag{42}$$

3. Find the C-band antenna velocity (V_x, V_y, V_z) by numerical differentiation of its position and normalize it by its norm V to a unit vector:

$$v_x = V_x/V \tag{43}$$
$$v_y = V_y/V \tag{44}$$
$$v_z = V_z/V \tag{45}$$

4. Find the right looking unit vector as the vector product of two unit vectors (d_x, d_y, d_z) and (v_x, v_y, v_z);

5. Use the plain ground approximation to find the approximate elevation angle γ:

$$\cos\gamma = \frac{H-h}{R} \tag{46}$$

   where H is the sensor altitude and h is the terrain elevation above ellipsoid;

6. Find the point at distance R from the sensor in the direction given by γ and the unit vectors pointing down and right:

$$G_x = C_x + R(d_x\cos\gamma + sd_x\sin\gamma) \tag{47}$$
$$G_y = C_y + R(d_y\cos\gamma + sd_y\sin\gamma) \tag{48}$$
$$G_z = C_z + R(d_z\cos\gamma + sd_z\sin\gamma) \tag{49}$$

   where s is the side indicator (1 for starboard, -1 for port).

When the initial value is available, refine it as follows:

1. Normalize the input coordinates and the global ellipsoid axes R_e, R_p by R:

$$\tilde{C}_x = C_x/R \tag{50}$$
$$\tilde{C}_y = C_y/R \tag{51}$$
$$\tilde{C}_z = C_z/R \tag{52}$$
$$\tilde{G}_x = G_x/R \tag{53}$$
$$\tilde{G}_y = G_y/R \tag{54}$$
$$\tilde{G}_z = G_z/R \tag{55}$$
$$A = R_e^2/R^2 \tag{56}$$
$$B = R_p^2/R^2 \tag{57}$$

2. Find the C-band antenna velocity (V_x, V_y, V_z) by numerical differentiation of its position and normalize it by its norm V to a unit vector:

$$p_1 = -V_x/V \tag{58}$$
$$p_2 = -V_y/V \tag{59}$$
$$p_3 = -V_z/V \tag{60}$$
$$p_4 = \dot{R}/V \tag{61}$$

   The last parameter $p_4 = 0$ for PCA, proportional to the DC in the general case;

3. To find the normalized ground point ($\tilde{G}_x$, $\tilde{G}_y$ and $\tilde{G}_z$), solve the system of nonlinear equations:

$$(\tilde{G}_x - \tilde{C}_x)^2 + (\tilde{G}_y - \tilde{C}_y)^2 + (\tilde{G}_z - \tilde{C}_z)^2 - 1 = e_1 = 0 \tag{62}$$
$$\frac{\tilde{G}_x^2 + \tilde{G}_y^2}{A} + \frac{\tilde{G}_z^2}{B} - 1 = e_2 = 0 \tag{63}$$
$$(\tilde{G}_x - \tilde{C}_x)p_1 + (\tilde{G}_y - \tilde{C}_y)p_2 + (\tilde{G}_z - \tilde{C}_z)p_3 - p_4 = e_3 = 0 \tag{64}$$

   The Jacobian is:

$$\mathbf{J} = \begin{bmatrix} 2(\tilde{G}_x - \tilde{C}_x) & 2(\tilde{G}_y - \tilde{C}_y) & 2(\tilde{G}_z - \tilde{C}_z) \\ \frac{2}{A}\tilde{G}_x & \frac{2}{A}\tilde{G}_y & \frac{2}{B}\tilde{G}_z \\ p_1 & p_2 & p_3 \end{bmatrix} \tag{65}$$

   Thus the correction applied in each iteration to $\tilde{G}_x, \tilde{G}_y, \tilde{G}_z$ is:

$$-\mathbf{J}^{-1} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} \tag{66}$$

   Convergence is checked by means of comparing $e_1^2 + e_2^2 + e_3^2$ to a predefined tolerance and by comparing the total number of executed iterations to a predefined maximum number;

4. De-normalize:

$$G_x = R\tilde{G}_x \tag{67}$$
$$G_y = R\tilde{G}_y \tag{68}$$
$$G_z = R\tilde{G}_z \tag{69}$$

When terrain elevation h is given, corrections are done, since the above derived value is on the global ellipsoid.

This algorithm is applied for all slant range samples at some azimuth position a, so that the previous solution in $\tilde{G}_x, \tilde{G}_y, \tilde{G}_z$ serves as the initial value for the next slant range, except for the very first point. Then very few iterations are needed per slant range.

For selected points on a grid, the ground ECEF position is used to determine latitude and longitude:

$$\phi_g = \operatorname{atan2}\left(G_z, \frac{R_p^2}{R_e^2}\sqrt{G_x^2 + G_y^2}\right) \tag{70}$$

$$\lambda_g = \operatorname{atan2}(G_y, G_x) \tag{71}$$

Longitude is then mapped into the $(-\pi, \pi)$ interval.

Georeferencing is not done at all in PolGASP. Georeferencing is optionally used in COASP. Georeferencing is optionally used in CHASP for the target of interest or for the image chip centre.

2.2.2 Conversion to Geodetic Coordinates

The key point is to find the nadir ground point (N_x, N_y, N_z), given the antenna position (C_x, C_y, C_z) in ECEF. This establishes the local geodetic vertical direction.

For generality, there is a check to determine if the antenna is in the equatorial plane ($C_z = 0$). This not very likely, but if so:

$$N_z = 0 \tag{72}$$

$$N_x = \frac{C_x}{C} R_e \tag{73}$$

$$N_y = \frac{C_y}{C} R_e \tag{74}$$

where C is the norm of the ECEF position vector, $C^2 = C_x^2 + C_y^2 + C_z^2$.

Otherwise, the nadir position is found by numerical methods as follows:

1. Substitute (rotate and normalize):

$$\tilde{C}_z = \frac{C_z}{R_e} \tag{75}$$

$$\tilde{C}_y = \frac{\sqrt{C_x^2 + C_y^2}}{R_e} \tag{76}$$

$$\rho = \frac{R_p}{R_e} \tag{77}$$

2. Initiate:

$$\tilde{N}_z = \rho \left(1 + \rho^2 \frac{\tilde{C}_y^2}{\tilde{C}_z^2}\right)^{-\frac{1}{2}} \frac{\tilde{C}_z}{|\tilde{C}_z|} \tag{78}$$

$$\tilde{N}_y = \tilde{N}_z \frac{\tilde{C}_y}{\tilde{C}_z} \tag{79}$$

3. Solve the nonlinear system of equations in $\tilde{N}_y$ and $\tilde{N}_z$ by an iterative Newton method:

$$\begin{aligned} \rho^2 \tilde{N}_y^2 + \tilde{N}_z^2 - \rho^2 &= e_1 = 0 && (80) \\ \rho^2 \tilde{C}_z \tilde{N}_y - \tilde{C}_y \tilde{N}_z + (1-\rho^2)\tilde{N}_y \tilde{N}_z &= e_2 = 0 && (81) \end{aligned}$$

where the inverse of the Jacobian is:

$$\begin{aligned} \mathbf{J}^{-1} &= \frac{1}{d} \begin{bmatrix} (1-\rho^2)\tilde{N}_y - \tilde{C}_y & -2\tilde{N}_z \\ -(1-\rho^2)\tilde{N}_z - \rho^2 \tilde{C}_z & 2\rho^2 \tilde{N}_y \end{bmatrix} && (82) \\ d &= ((1-\rho^2)\tilde{N}_y - \tilde{C}_y) 2\rho^2 \tilde{N}_y - ((1-\rho^2)\tilde{N}_z - \rho^2 \tilde{C}_z) 2\tilde{N}_z && (83) \end{aligned}$$

Thus the correction applied to $[\tilde{N}_y \tilde{N}_z]^T$ in each iteration is:

$$-\mathbf{J}^{-1} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \tag{84}$$

Convergence is checked by means of comparing $e_1^2 + e_2^2$ to a predefined tolerance factor and by comparing the total number of executed iterations to a predefined maximum number;

4. Substitute back (de-normalize and rotate back):

$$\begin{aligned} N_z &= \tilde{N}_z R_e && (85) \\ N_x &= \frac{C_x}{\sqrt{C_x^2 + C_y^2}} |\tilde{N}_y| R_e && (86) \\ N_y &= \frac{C_y}{\sqrt{C_x^2 + C_y^2}} |\tilde{N}_y| R_e && (87) \end{aligned}$$

When nadir is known, find its latitude and longitude and distance from the sensor:

$$\begin{aligned} \phi &= \operatorname{atan2}(N_z, \frac{R_p^2}{R_e^2} \sqrt{N_x^2 + N_y^2}) && (88) \\ \lambda &= \operatorname{atan2}(N_y, N_x) && (89) \\ H &= \sqrt{C_x^2 + C_y^2 + C_z^2} - \sqrt{N_x^2 + N_y^2 + N_z^2} && (90) \end{aligned}$$

2.2.3 Elevation Angle Calculation

Given the sensor ECEF position $\mathbf{C}$, Sections 2.2.1 and 2.2.2 show how to find the ground target position $\mathbf{G}$ at distance R at PCA. Their difference is the slant range vector $\mathbf{R} = \mathbf{C} - \mathbf{G}$. In Section 2.2.1 the unity downwards vector $\mathbf{d}$ was also computed. Then the elevation angle is found as the angle between vectors $-\mathbf{d}$ and $\mathbf{R}$,

$$\cos\gamma = \frac{\mathbf{R}^T(-\mathbf{d})}{||\mathbf{R}||} \tag{91}$$

When terrain elevation h is given, corrections are done, since the above derived value is on the global ellipsoid.

$$\delta = \frac{h \sin \alpha}{R} \tag{92}$$

where α is the incidence angle (see Section 2.2.4), is the value to be added to γ.

This algorithm is needed in COASP in support of many other functions (e.g. georeferencing, antenna gain compensation). It is not strictly needed in CHASP, but it may be used to provide positional information on a selected target.

2.2.4 Incidence Angle Calculation

Given the sensor ECEF position $\mathbf{C}$, Sections 2.2.1 and 2.2.2 show how to find the ground target position $\mathbf{G}$ at distance R at PCA. Then the incidence angle is:

$$\mathbf{R} = \mathbf{C} - \mathbf{G} \tag{93}$$

$$\bar{\mathbf{G}} = \begin{bmatrix} G_x \\ G_y \\ G_z R_e^2 / R_p^2 \end{bmatrix} \tag{94}$$

$$\cos \alpha = \frac{\mathbf{R}^T \bar{\mathbf{G}}}{||\mathbf{R}|| || \bar{\mathbf{G}} ||} \tag{95}$$

Then $\sin \alpha$ is chosen to be non-negative.

This algorithm is needed in COASP in support of other functions (e.g. calibration). It is not strictly needed in CHASP, but it may be used to provide information on a selected target. It can also be used in CHASP to calculate the ground pixel size corresponding to the slant range pixel size.

2.2.5 Nadir Computation

Algorithms described in Sections 2.2.1 and 2.2.3 are accompanied by a check to see if the computed distance between the sensor and the geoid is less than the slant range for the given range index. All of the algorithms described in Sections 2.2.1, 2.2.3, and 2.2.4 are actually applied only if that condition is satisfied. The first range index when it becomes satisfied is recorded as the computed nadir index.

2.3 Statistical Algorithms Used for Quality Control

This is the class of algorithms that are used on the signal or image samples at different stages of processing in order to extract information about the data acquisition process. These algorithms do not affect the data directly.

2.3.1 Input Dynamic Range

A histogram of the raw input samples is calculated over suitably defined rectangular image regions. The number of extreme values is then found using the extreme histogram bins for the current EC CV-580 SAR 6-bit analogue-to-digital (A/D) converter. This count includes all clipped samples. This is a simple, although not very precise, indicator of signal data saturation. In a similar way, the count of very small values is taken from the histogram bins at and around zero. This is taken as an indication of underflow.

This algorithm is only applicable to COASP.

2.3.2 Coarse Doppler Centroid Estimation

The first step is to find the average:

$$P_0 = \langle u(a,r)u^*(a,r)\rangle \tag{96}$$

$$P_1 = \langle u(a,r)u^*(a-1,r)\rangle \tag{97}$$

within a segment of range r and azimuth a where $u(a,r)$ is a range compressed sample. The angle of P_1 in the complex plane is normalized by 2π and is the ambiguous estimate of the relative Doppler centroid (DC) for that segment. The estimate is calculated with a user specified density over the image; it serves for quality checking purposes. Ideally it should be 0 or nearly so and it should not have a trend with respect to either range or azimuth.

Similar information is not provided by PolGASP. This algorithm is optionally used in both COASP and CHASP.

2.3.3 Refined Doppler Centroid Estimation

The same algorithm described in Section 2.3.2 can be applied to the image samples that have already been compressed in azimuth. The averaging is done only on the valid pixels, while the transient samples must be left out. Since the influence of partially exposed targets is suppressed in the compressed image, the DC estimates are refined. The applied azimuth window may affect the DC estimates and best results are obtained if a rectangular window is used. If the true DC is very far from the initial estimate, several iterations may be required. Because of this limitation, this algorithm is used only in CHASP.

This method, just like the coarse one, cannot resolve the PRF ambiguity.

2.4 Algorithms for Data Manipulation

This is the set of algorithms that prepare data for processing and store the processed data. They conform to the naming conventions of the input and output files. They are EC CV-580 SAR specific in the case of COASP. They are much more general in the case of CHASP.

2.4.1 Raw Data Ingest

Raw data are ingested form disk in blocks consisting of many range lines. Entire range lines are always read. This differs from PolGASP.

At the beginning of the raw data file, some lines may be skipped in order to make the channels with the horizontal transmitter occur first. Then, channel alignment is no longer needed as a special pre-processing step.

Blocks may overlap. First the overlap parameter is used to reposition the file pointer and then a block of range lines is read from file into memory. The size of the overlap depends on the length of the synthetic aperture, i.e. the length of the azimuth reference function, which depends on the slant range and the azimuth spacing, as indicated by equation (27). As the "PRF over v" parameter varies, the spacing and the length of the reference function may vary within the same pass. Care is taken to use the same overlap throughout the pass in spite of possible changes of the reference function.

COASP can hold one or more polarimetric channels simultaneously in memory. Typically only one block of one channel is read at a time, looping through the channels and then looping through the blocks. Should there be a need to combine different channels, they could be read in pairs or quartets at a time.

COASP can only read full blocks of data. If the desired end line is reached before completing a block, more lines will be read and processed. If the end of file occurs before a block is completed, the remaining lines are zeroed. The number of zeroed lines is saved for use in further processing to prevent undesirable edge effects.

This function is used in COASP.

2.4.2 Nadir Detection

For SAW IN cases, range compression is done in hardware. Some passes are nadir passes meaning that the range gate starts before the actual returns arrive. Nadir detection for SAW IN data is done on a small block of range lines read as soon as the signal files are opened. The mean power of this block is found by averaging over all samples in range and over a certain number of lines in azimuth. This value is taken as the threshold. Sample power is tested against the threshold starting from the nearest sample. Nadir is detected if two successive samples exceed the threshold. This method usually works because the nadir return is usually very strong.

The detected nadir index should be in agreement with the computed nadir index discussed in Section 2.2.5.

This function is used in COASP.

2.4.3 Conversion to Floating Point

Conversion to floating point is done using a look-up table (LUT) of length 2^8. The LUT can be addressed by 8-bit raw values to read out the floating point value. The input numerical format is assumed to be the 2's complement signed integer. The raw EC CV-580 polarimetric SAR samples are actually 6-bit signed integers; therefore, a portion of this LUT is not used.

In each data block, a histogram of the converted data is computed for selected bins to support the function mentioned in Section 2.3.1. Bins corresponding to values in the range of -32.0 to 31.0 (represented by 20 hex and 1F hex) are evaluated and used as an indication of saturation. Bins corresponding to values 0, ± 1 are also evaluated and used as an indication of weak signal condition. Such indication is not available in PolGASP.

This function is only used in COASP, while CHASP uses only floating point input data.

2.4.4 Ingest of COASP Products

CHASP reads COASP products from the first desired line to the last specified line, inclusive, or until the completion of a full processing block and from the first desired sample to the last desired sample, inclusive. The data are always assumed to be complex and in the IEEE standard floating point numeric format. The COASP data header is used to navigate through the input flat raster file.

If range compressed and calibrated data from any other source are available in this format, CHASP can read them; it requires very little additional information for its processing. It suffices to create a suitable configuration file with the radar wavelength, slant range spacing, "PRF over v" and a suitable COASP-like header with the near slant range and input sample size.

CHASP is designed to process only one image chip in a single processing block. One or more channels can be read simultaneously.

2.4.5 Ingest of Auxiliary Data

The following files contain auxiliary information:

- Ancillary files;
- PRF file;
- Antenna gain files; and the
- Range chirp file.

The ancillary files are always required for COASP processing. They are not used in CHASP. The ancillary files are structured binary files. Depending on the platform on which COASP runs, their bytes may need to be swapped. Another possible problem is related to the memory alignments on different systems. The latest version of the ancillary data structure definition in C language resolves the alignment problem simply by adding a 32-bit spare field at the end. All ancillary files created on SGI workstations have now become readable on the platforms under Linux.

The PRF file is conditionally used in COASP and CHASP. It is a Matlab™ format file and it can be read properly regardless of its endianess. Only the required components of the PRF file are read, depending on the configuration. The PRF file information is essential in COASP for motion compensation, antenna gain compensation and georeferencing. It is also the primary source of the "PRF over v" parameter used in focusing. However, it is possible to provide a constant value for this parameter through the configuration file. CHASP is less dependent on the PRF file and the intention is that it can be used for SAR data other than just the EC CV-580 SAR. CHASP typically uses the "PRF over v" parameter from the PRF file when available; otherwise it gets it from the configuration file. Some CHASP functions need the position of the antenna to calculate the incidence angle and other geometric parameters, but they can also use the corresponding parameters set in the configuration file.

Antenna gain files are ASCII files in a very simple format; they are an array of gains in dB for the various channels and look directions and they can be used only with the help of the configuration parameters, which associate them with the elevation angles. These parameters are hard-coded in PolGASP. This file is ingested by COASP.

The range chirp file is an ASCII file containing simple array of values. These values are the time response of the range compression filter. This differs from the PolGASP case. This file is ingested by COASP in the "SAW OUT" case.

2.4.6 Saving the Image

The image is saved as it is being processed. The first and the last processing block are saved together with leading or trailing invalid data. Blocks other than the first or last are saved, discarding the transient invalid data. The valid portion of the image is in the centre and there are invalid transient pixels on both sides. This style is used for compatibility with PolGASP and it insures that there is no time offset between the raw signal and the processed output image.

Data saved from COASP are always complex, floating point and are not transposed (relative to the raw input). Data saved from CHASP may be complex or magnitude images. Normally they are in floating point flat raster format, with the exception of Portable Gray Map (PGM) format products, which are saved as unsigned integers, preceded by some ASCII fields according to the PGM format specification. CHASP output images may be transposed or not. There can be one or two output images per channel. The output format depends on the applied processing methods, which is all reflected in the header file.

3 COASP

COASP is a program which efficiently implements the strip-map SAR processing algorithms discussed in Section 2.

3.1 Modules

COASP modules are listed in Table 1 in the order in which they appear. Module names are in the left column and their functionality is in the middle column. The last column shows the control options. Some of the modules are automatic, which means that they are not controlled directly by the user. For example, ingest, I and Q correction and data storage are executed always and unconditionally, while transposition is executed as required and is needed if any type of azimuth processing is requested. All of these modules are labeled as automatic. Other modules can be turned on or off and they can be controlled by various configuration flags. If this is the case, the names of the associated configuration flags are shown in the last column. For example, FFT in azimuth is activated if azimuth focus is required or if channel alignment in azimuth is required, which is expressed by configuration flags "azimuth_focus" and "azimuth_align". Some of the modules are exclusive. For example, azimuth focusing can be done by the Range-Doppler algorithm, involving several modules, or by the simpler PolGASP-style algorithm.

Modules are executed in a loop over channels or groups of channels read together (unless all channels are read together). Also, one level higher, modules are executed repeatedly over processing blocks.

Module names appear in the log file. Whenever a module is completed, a progress message is logged for that module. If a module fails, an error message is logged indicating the failed module.

3.2 Interfaces

All interfaces are via files. There are no interactive steps.

3.2.1 Input

The setup is done by editing the configuration file. A summary of the input files is presented in Fig. 2. Input files are grouped according to various criteria.

Static data files are a set of auxiliary files which do not change from one processing run to another. They characterize the system in a static manner (although they might be updated as the system evolves). These are the antenna gain files for both sides and for both polarizations and the range chirp file as estimated upon certain measurements (depicted in Fig. 1). These files are in a simple ASCII format, given as an array of numbers with no annotations. In particular, the antenna gain files are just lists of dB values. The corresponding antenna angles are implicit and hard-coded in PolGASP; they are defined

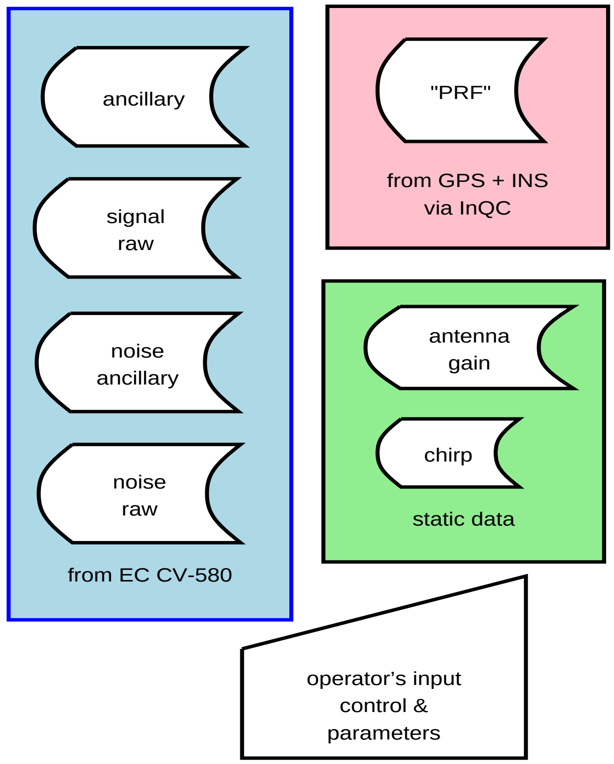


Figure 2: *Input files for COASP.*

via the configuration file for COASP. The chirp file is a time series for COASP with spacing equal to the sampling interval. PolGASP uses a different chirp, which is in the frequency domain with sampling equal to 1/4096 of the sampling frequency.

All other data files are dynamic; they differ from pass to pass. They are grouped according to their origin and nature. The "PRF" file is a result of previous processing steps (using the program InQC) and it combines the information obtained from the differential global positioning (dGPS) system and the information obtained from the inertial navigation system (INS), resampled to the pulse repetition frequency (PRF). The "PRF" file is in Matlab$^{\text{TM}}$ version 4 format for compatibility with PolGASP. All values are saved as double precision real vectors and they are named. The naming is compatible with the previous EC CV-580 SAR processing software. COASP may use the following quantities from the "PRF" file:

Xant	C-band antenna position in ECEF system
Yant	C-band antenna position in ECEF system
Zant	C-band antenna position in ECEF system
delh_main	horizontal deviation from reference path Δ_h
delv_main	vertical deviation from reference path Δ_v
best_prfoverv	estimated f_p/v_g
gps_vg	estimated ground speed

Only the required parameters are read. For example, if motion compensation is requested, then the deviation parameters delh_main and delv_main are read and used. If focusing is requested, but the value of f_p/v_g is not provided as an external parameter, then it is read from the "PRF" file. The ground speed is required only for calibration. Antenna position is needed for many different modules, including motion compensation, antenna gain correction and incidence angle correction.

Raw signal and ancillary data are a set of files recorded on-board EC CV-580 and then extracted and saved as disk files. Headers are produced as separate files during this operation. There are altogether 24 files organized as signal and noise files. The signal files for line number L and pass number P are named as follows:

lLpPhh.sig	signed byte signal samples, HH channel
lLpPhv.sig	signed byte signal samples, HV channel
lLpPvv.sig	signed byte signal samples, VV channel
lLpPvh.sig	signed byte signal samples, VH channel
lLpPhh.hdr	ASCII signal header, HH channel
lLpPhv.hdr	ASCII signal header, HV channel
lLpPvv.hdr	ASCII signal header, VV channel
lLpPvh.hdr	ASCII signal header, VH channel
lLpPhh.anc	structured binary signal ancillary, HH channel
lLpPhv.anc	structured binary signal ancillary, HV channel
lLpPvv.anc	structured binary signal ancillary, VV channel
lLpPvh.anc	structured binary signal ancillary, VH channel

The noise files for line number L and pass number P are named as follows:

lLpPhhn.sig	signed byte noise samples, HH channel
lLpPhvn.sig	signed byte noise samples, HV channel
lLpPvvn.sig	signed byte noise samples, VV channel
lLpPvhn.sig	signed byte noise samples, VH channel
lLpPhhn.hdr	ASCII noise header, HH channel
lLpPhvn.hdr	ASCII noise header, HV channel
lLpPvvn.hdr	ASCII noise header, VV channel
lLpPvhn.hdr	ASCII noise header, VH channel
lLpPhhn.anc	structured binary noise ancillary, HH channel
lLpPhvn.anc	structured binary noise ancillary, HV channel
lLpPvvn.anc	structured binary noise ancillary, VV channel
lLpPvhn.anc	structured binary noise ancillary, VH channel

Signal and noise files can be of any duration, but they are always aligned with the corresponding ancillary files. Separation into the signal and noise part is a result of a processing operation and is somewhat arbitrary. Noise files are meant to capture the calibration noise, but they are usually longer than necessary and include parts that are not usable.

The configuration file, as discussed further in Section 3.3, is an ASCII file that uses the simplest possible syntax taken from PolGASP.

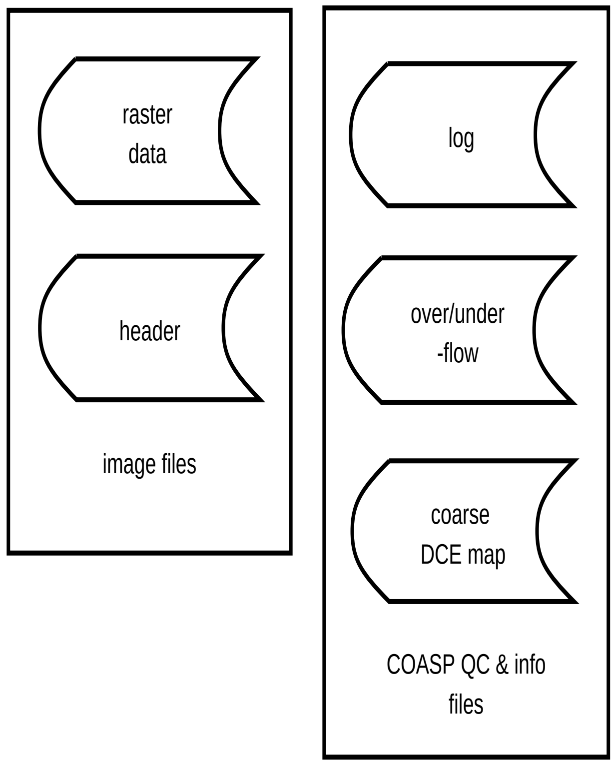


Figure 3: *Output files from COASP.*

3.2.2 Output

The main output is the set of image files and the corresponding header files. In the case of signal data processing their names are:

lLpPhh.rc	binary processed signal samples, HH channel
lLpPhv.rc	binary processed signal samples, HV channel
lLpPvv.rc	binary processed signal samples, VV channel
lLpPvh.rc	binary processed signal samples, VH channel
lLpPhhrc.hdr	ASCII signal header, HH channel
lLpPhvrc.hdr	ASCII signal header, HV channel
lLpPvvrc.hdr	ASCII signal header, VV channel
lLpPvhrc.hdr	ASCII signal header, VH channel

For noise processing the names of the files are according to the following convention:

1$Lp$$P$hhn.rc	binary processed signal samples, HH channel
1$Lp$$P$hvn.rc	binary processed signal samples, HV channel
1$Lp$$P$vvn.rc	binary processed signal samples, VV channel
1$Lp$$P$vhn.rc	binary processed signal samples, VH channel
1$Lp$$P$hhrcn.hdr	ASCII signal header, HH channel
1$Lp$$P$hvrcn.hdr	ASCII signal header, HV channel
1$Lp$$P$vvrcn.hdr	ASCII signal header, VV channel
1$Lp$$P$vhrcn.hdr	ASCII signal header, VH channel

The header files are not exactly the same as the PolGASP header files, but they are reasonably similar. They explain the size and data type of the output and the orientation, which is not transposed with respect to the input. They give the list of the all input files, start and end pulses, as well as the time of acquisition. They also carry status information that explains which processing modules have been applied. The four corners of the image are given in terms of their geodetic latitude and longitude, as well as a georeferenced grid across the image.

Depending on the settings, COASP can generate other files for quality checking purposes. If requested, some information is extracted from the input histograms according to Section 2.3.1 and saved in files:

extreme_0
extreme_1
extreme_2
extreme_3

Up to four such files are created, one for each of the input channels.

If requested, coarse DC estimates are saved on a grid. There are up to four files, one for each channel:

doppler_0
doppler_1
doppler_2
doppler_3

Finally, COASP creates a log file. The information logged can be of one of the following types:

- Error;
- Warning;
- Progress;
- Info; and
- Debug.

Each logged item contains the date, time, type, and message. During program execution, or after completion of the processing, it is recommended that the grep function be used to search for any Error or Warning messages. It is also useful to use grep to monitor the processing Progress and to get a list of all completed operations.

3.3 Program Configuration

The COASP configuration file has a very simple format, which consists of a token and a value. Some values are static and should not be changed, others are dynamic. A leading semicolon is used for comments. Values may be logical flags (to select one of the possible options), character strings (for filenames and mission names) or numeric values (for various parameters). For most of the selections the recognized logical flags are "Yes" and "No".

One section of the configuration file contains the system parameters. It is shown below together with typical values:

```
; System parameters
;
wavelength              0.0565646000
range_shift_hh          0
range_shift_hv          0
range_shift_vv          1.25
range_shift_vh          1.25
azimuth_shift_hh        0
azimuth_shift_hv        0
azimuth_shift_vv        0.5
azimuth_shift_vh        0.5
range_slant_spacing     4.0
saw_delay               13.289e-06
boresight_offset_hs     -1.585
boresight_offset_vs     -1.585
boresight_offset_hp     -3.330
boresight_offset_vp     -3.330
azimuth_beamwidth       3.03
antenna_ang_min         -73.0
antenna_ang_inc         1.0
CalConstant             19.0
```

The shifts are in terms of range or azimuth spacing, all angles are in degrees and all other values are in SI units. In PolGASP many of these parameters are hard-coded.

There are some configuration parameters related to the platform. They are:

```
; Processor parameters
```

```
;
processors              2
block_lines             8192
parts                   4
channels_together       1
change_anc_endian       Yes
change_output_endian    No
interp_size             11
interp_fractions        16
; possibilities for mocomp_type are Flat, Part, Each
mocomp_type             Flat
```

The values shown above serve only as an example. They are suitable for processing on a dual CPU machine with plentiful memory. In the example, it is assumed that the byte order is different from the byte order of the machine on which the ancillary files were created. It is possible to choose the number of processes to run concurrently, usually the same as the number of CPUs. The size of the blocks in azimuth is related to the available memory. It is more efficient to process in larger blocks whenever possible. Some parameters are updated once for each processing block. The "PRF over v" is a typical example. IQ correction is based on processing blocks. Also, the coarse DC mapping, if requested, is performed based on processing blocks. The length of the block should be suitable for FFT if azimuth compression is requested. There is a minimum block size if azimuth compression is requested, because a certain number of lines must be discarded. Each block is internally divided into sub-blocks. Different sub-blocks may be processed by different CPUs. Therefore the number of sub-blocks, defined as the value of parts, should be a multiple of the number of processors available. The size of each sub-block or part defines the frequency of updates for various output or processing parameters. For example, parts define the density of the georeference grid in azimuth. If the motion compensation type is set to "Part", then the elevation angle used in motion compensation is updated for each part. The incidence angle and velocity used in calibration also work in this way. Hence, the choice may have some influence on the final result.

It is possible to control the processing of the various different channels. For example, when processing four polarimetric channels, it is possible to load a data block of each kind to memory and to process them simultaneously. To select this option, the value of channels_together should be 4. There are currently no functions in COASP which require the simultaneous presence of all four polarimetric channels. The option is provided for possible future extensions and for generality. Channels can be processed two by two, but this method has no foreseeable usage or advantage. Channels can be processed one at a time within a loop over data blocks. Then one block of one kind is loaded into memory and completely processed and saved. All four kinds of blocks are processed before moving on to the next block. In this case, channels_together is 1 although the number of channels is 4. If the total number of channels is 1, then channels_together should also be 1. In this way, COASP can be run four times instead of once to process all four channels in separate runs.

Since ancillary data are in a binary format, their endianess may be an issue. It is foreseen that COASP may run on the same type of platform as the program which created the ancillary file, or on a different type of platform. For now, ancillary files are always created on SGI machines; for now COASP may run either on SGI or on an Intel based platform. In the latter case, ancillary files must be read with byte swapping. When COASP runs on SGI they must not be swapped.

Byte swapping of the output image is optional and depends on the processing platform and the destination and the eventual use of the resulting imagery.

The Range-Doppler algorithm requires interpolation. It is possible to select the size of the interpolation kernel, which is a trade-off between speed and accuracy. On a fast machine, there is no reason to compromise accuracy and a value of 11 should be chosen for interp_size. The value of interp_fractions defines the granularity of the interpolation since a set of interpolation kernels is pre-calculated. A sub-pixel resolution of 1/16 is usually acceptable. This parameter has no effect on the throughput. Finally, mocomp_type is another parameter which is directly related to the processing algorithms. As discussed in Section 2.1.3, the fastest option is "Flat" and the slowest, most accurate one is "Each". The option "Flat" produces a smoother, though less correct phase than "Part".

The rest of the configuration file can be regarded as a work order, because it expresses what the user wants to do. The work order part is quite long, although not all entries are required. The list of keys recognized by COASP is:

```
; WorkOrder
;
mission_id
input_data_file
noise_data_file
channels
SAW
chirp_file
prf_file
first_line
last_line
geoid_over_ellipsoid
georef_grid_rg
doppler_grid_rg
satur_grid_rg
channel_align
range_discard
auto_nadir
skip_nadir
motion_compensation
motion_restore
```

```
azimuth_focus
RangeDoppler
ZD_frame
azimuth_align
window_shape
full_bandwidth
prf_over_v
use_mean_prf_over_v
relative_dc_offset
relative_v_offset
; radiometry:
antenna_gain
antenna_hp
antenna_vp
antenna_hs
antenna_vs
spread_loss
reference_range
calibration
; calibration:
; from the sheet in dB
AvTx_power
; from GenCal in dB
K_prime_hh
K_prime_hv
K_prime_vv
K_prime_vh
; from GenCal in degrees
Phase_corr_hh
Phase_corr_hv
Phase_corr_vv
Phase_corr_vh
; power (from PowerBite not in dB)
AvBITE_hh
AvBITE_hv
AvBITE_vv
AvBITE_vh
```

Mission identification is optional using any string.

For all four channels to be processed, input_data_file must be the base of the names of the files which contain the raw data; the value for channels must then be 4. When only one data file is to be processed, that filename must be specified complete with the extension. If processing the signal data, then noise_data_file may be omitted or left blank. When noise is processed, then this key is used to specify the name of the noise file (the base or the full name); in this case input_data_file is not used.

The recognized values for SAW are "IN" and "OUT". It is important to correctly declare the status of the SAW, IN or OUT, indicating that range compression is done by hardware or software, respectively. The entry for chirp_file is required in the SAW OUT case. If not specified, range compression will not be performed.

The name of the "PRF" file must be given in almost all cases because the most important processing modules depend on the information from the "PRF" file.

The first and last line are specified to select the part of the signal file which is to be processed. If first_line is not specified, processing starts from the start of file. If last_line is not specified, then data are processed until the end of file. COASP will read up to the specified last line and, possibly, beyond. It will read and process less if and only if the end of file occurs before the specified line is reached.

The entry for geoid_over_ellipsoid is used for geometric corrections. It may be positive or negative (in meters). When data are acquired over the ocean, the geoid surface is below the global ellipsoid and then a negative number is entered.

Georeferencing is optionally done along with motion compensation. Georeferencing is activated by choosing a positive number for georef_grid_rg. A value of 1 is interpreted as mid-swath georeferencing and 2 as near and far edge georeferencing. In all other cases the grid is uniform in slant range. Azimuth intervals cannot be chosen independently of processing blocks and parts. Coarse DC estimation and mapping is controlled in the same way using doppler_grid_rg. A value of 0 suppresses this option and positive values define the density of the estimates in range. The same is applied to the saturation check via satur_grid_rg, which defines slant range segmentation for the purpose of histogram evaluation.

The alignment of channels gives the possibility to skip range lines in such a way that horizontally transmitted pulses lead. Possibilities are Yes and No.

The value for discard_range can be Yes or No. If No is selected, then all samples are saved in the output image even though some may be invalid. Nadir passes and SAW OUT passes have some number of invalid pixels at the start of each range line. These can be discarded, which changes the format of the output. For SAW OUT passes, the number of initial invalid samples equals the length of the range chirp. For SAW IN nadir passes, the invalid samples are pre-nadir. Their position is estimated if auto_nadir is set to Yes. It is possible to discard additional samples by choosing a non-zero value for skip_nadir. If this value is positive, then more samples are discarded, but if this value is negative, some of the invalid samples will be kept. The value of skip_nadir is effective only if discard_range is set to Yes. The actual output format is always written into the output header. All other saved information, such as near slant range, are also adjusted and reflect the actual output.

Motion compensation can be done or skipped. Even if selected, but the PRF file is not specified, it will not be done. Motion compensation changes the phase of the signal to look like the acquisition was taken from the reference path. Since some applications may expect the phase to be compatible with the actual antenna position, the motion_restore option can be used.

Azimuth focus can be done or skipped. If selected, then there are several options regarding the focusing algorithm. It is possible to select Yes or No for RangeDoppler, thus choosing to apply the Range-Doppler algorithm or the simpler PolGASP algorithm. For the recommended case of Range-Doppler there are many more options. The first one is to select the zero-Doppler output geometry by entering Yes for ZD_frame or the beam-centre output geometry by entering No.

Polarimetric acquisition is not simultaneous for all channels. Channels are interleaved in pairs. The choice of azimuth_align Yes interpolates two channels (VV and VH) to find the values which coincide in time with the other two channels (HH and HV). This operation is straightforward if DC is known, otherwise it may not be easy to provide good interpolation. Therefore, alignment of channels in azimuth may be selected or deferred until later. Numerically, the most convenient approach is to do azimuth interpolation simultaneously with azimuth compression. However, azimuth shifting to align the channels may be carried out independent of the azimuth focus settings.

In azimuth compression a window is used to control the side-lobes. The shape factor for the Kaiser window is given by the value of window_shape. 0 corresponds to a rectangular window; 2.8 is the PolGASP hard-coded value.

For the Range-Doppler algorithm, the processed Doppler bandwidth can be specified. If not specified, then the total available bandwidth will be used and it will be determined based on the beam width, the aircraft position, and the ground speed parameters. The parameter full_bandwidth has no effect on the alternative focusing algorithm. This parameter is expressed in terms of the PRF.

Both azimuth focusing algorithms use the "PRF over v" parameter. It can be specified as an external parameter or not. The key prf_over_v is mostly used for noise processing. In this case the parameter is set to the average value of the "PRF over v" used for signal processing. Either the PRF file must be given or the value of prf_over_v must be given. If neither is present, there will be no azimuth compression. Usually, prf_over_v is not specified for signal focusing. If specified, then it will override the values read from the "PRF" file. Since the parameter f_p/v_g varies slowly in the "PRF" file, it may sometimes be desirable to use its mean value for the processed data segment. This is an option behind the use_mean_prf_over_v key. This parameter is always expressed in SI units (m^{-1}).

It is generally assumed that the EC CV-580 SAR is well steered to zero-Doppler. If this is not the case, then the value of the DC can be entered to correct the problem. At this time, only a single value is acceptable for the whole swath. The value of relative_dc_offset is interpreted as a fraction of the PRF. It is generally assumed that the "PRF over v" value from the "PRF" file is good. The value of relative_v_offset is a modifier of the f_p/v_g parameter. For example the value 0.01 modifies v_g and, hence, the spacing v_g/f_p by 1%.

Antenna gain correction can be selected. Antenna gain correction requires the antenna gain files. If they are not present, the correction will be not be carried out. There is a separate antenna gain file for the four cases: HH port, VV port, HH starboard and VV starboard. The cross-polarization cases are derived from these four.

Power spread loss can be selected. An integer number is expected to specify the degree of compensation applied to the ratio of the range and the reference range.

Calibration can be selected, in which case K', phase correction, average transmitted power and BITE power will be used. Also, ground speed and incidence angle will be used based on the PRF file.

Table 1: *COASP modules.*

module	*functionality*	*control*
Ingest	get a block of raw data	automatic
Conversion	convert to floating point	automatic
Truncate	eliminate invalid range samples	SAW, range_discard
IQMeasure	find bias, power, cross-talk	automatic
IQCorrect	debias and balance	automatic
RGfilter	compress, shift	SAW, range_shift_*pol*
Truncate	eliminate pre-nadir range samples	SAW, range_discard
Mocomp	generate track deviation phase	motion_compensation
Mocomp2	apply motion compensation	motion_compensation
RFGain	apply RF gains	automatic
Radio	correct for spread loss	spread_loss
AntGain	correct for antenna gain	antenna_gain
Calib	calibrate	calibration
Sigma	correct for incidence angle	calibration
Xcorrel	coarse DC estimation	doppler_grid_rg
Trim	adjust length for transposition	automatic
Transpose	transpose for azimuth access	automatic
AzFFT	FFT in azimuth	azimuth_focus, azimuth_align
Skew	resample for RCMC	azimuth_focus, RangeDoppler
RefRD	calculate filter for RDA	azimuth_focus, RangeDoppler
AzRef	calculate simple filter	azimuth_focus, RangeDoppler
AZfilter	apply azimuth filter	azimuth_focus
AZshift	just shift in azimuth	azimuth_align, azimuth_focus
LookRD	multiply by spectral window	azimuth_focus, RangeDoppler
AzFFT	inverse FFT in azimuth	azimuth_focus, azimuth_align
Transpose	transpose for range access	automatic
Mocomp	generate track deviation phase	motion_restore
undoMocomp2	restore track deviation phase	motion_restore
Store	save processed data block	automatic

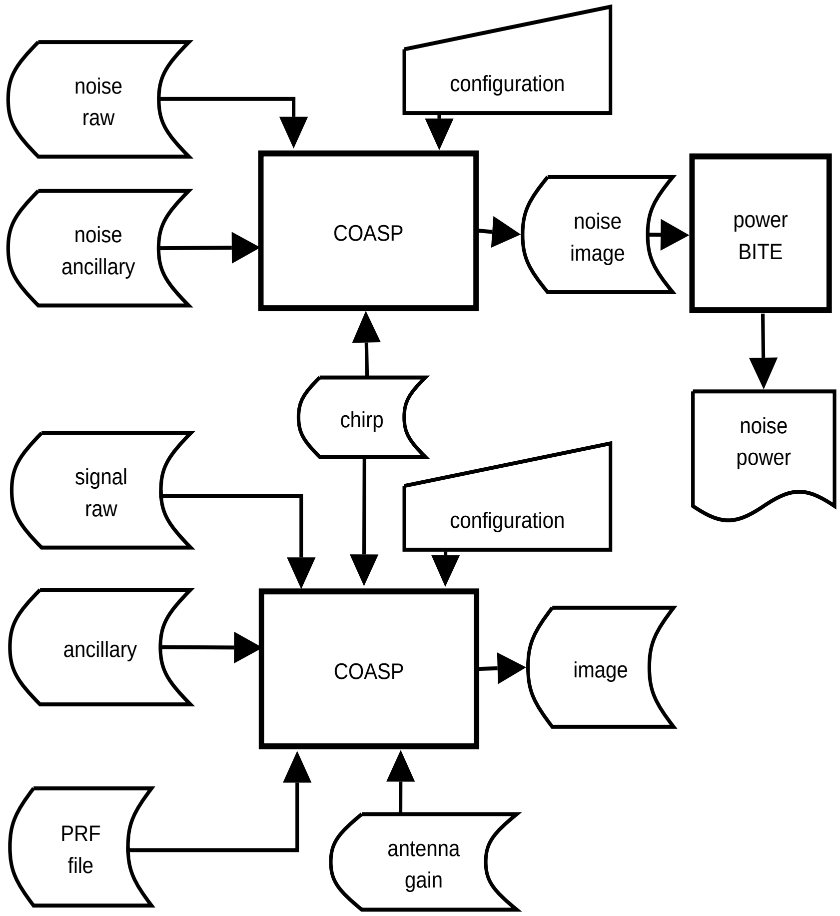


Figure 4: *COASP processing.*

4 COASP Procedures

COASP is part of the EC CV-580 processing chain. Unlike PolGASP, COASP generates calibrated images. COASP uses the same external tools, Targanal and GenCal, which are used for PolGASP calibration with ComplexCAL, but the calibration procedure differs. Since Targanal and GenCal were designed for PolGASP, they cannot support some COASP options. As a result, some parts of the procedure are not as efficient nor as accurate as they could be.

4.1 Creating Calibrated Images with COASP

There is a difference between processing non-calibration passes and processing calibration passes. In both cases the signal and the noise must be processed using the same processing algorithms and the same processing parameters. This is depicted in Fig. 4.

4.1.1 Non-calibration Passes

If a non-calibration pass is being processed, it is best to start with the noise processing. Assuming that the position of the good BITE noise is known, the configuration file may be edited. Many operations are skipped in noise processing and the “PRF” file is not used. Instead, the value of prf_over_v must be provided in the configuration file. This value can be determined in several ways using the “PRF” file for the signal part. Since the value of this parameter (called best_prfoverv in the PRF file) is variable, the mean should be used. There are several ways to find the mean:

- As a part of motion calculation (InQC) the estimated f_p/v_g values are displayed and even an approximate visual estimation may suffice;
- If a small section of the signal data is processed first, then the average value for that signal section will be written in the output header file; and
- The “PRF” file can be loaded into Matlab^{TM} and best_prfoverv averaged over the interval of interest.

After processing the noise section, it is recommended that the result be inspected and the log file checked (`grep Progress chasp1.log`) to ensure that all operations have executed as expected. Processed noise images should be smooth and evenly grey with no gradients in brightness or discontinuities. However, some noise images near their start and end may not have this property. This situation has occurred in several SAW OUT passes and it affects a small portion of the full range. The first valid and last valid azimuth line are shown in the output noise header. Between these lines, the image should have the expected features. The noise power must then be measured using a script called `PowerBite.sh`. Using this script, averaging is automatically done between the first valid and the last valid line in azimuth and across all samples. It is possible to restrict averaging in range should there be any anomalies appearing at near or far ranges. The BITE noise power will be written to the standard output.

The user must then edit the configuration file for the signal processing. The BITE noise power values are entered as Av_BITE_hh, Av_BITE_hv, Av_BITE_vv and Av_BITE_vh parameters. The user should select all radiometric corrections, antenna compensation and calibration options and use the same focusing algorithm and the same window_shape that was used for noise processing.

```
antenna_gain            Yes
calibration             Yes
azimuth_focus           Yes
RangeDoppler            Yes
window_shape            2.8
reference_range         1
spread_loss             3
```

The user should also make sure that the antenna files are specified and available as specified. The average transmitted power, K' values and phase corrections must also be correctly entered. The value of `AvTx_power` is available from the flight log sheets. The calibration constants are taken from a suitable calibration pass (ideally acquired during the same flight).

4.1.2 Calibration Passes

In the case of calibration lines it may be better to process the part of the signal data taken over the calibration site before processing the noise. It is also recommended that only that part be processed, simply because the rest will have to be reprocessed anyway. In this case radiometric, antenna and calibration corrections should be turned off, but azimuth focusing should be normal.

```
antenna_gain            No
calibration             No
azimuth_focus           Yes
RangeDoppler            Yes
window_shape            2.8
reference_range         1
spread_loss             0
```

This is because the existing software (Targanal and GenCal) expects the output to be uncompensated for the spread loss and antenna gain. The procedures used to calculate K' apply these compensations because PolGASP does not. It would be straightforward to modify and simplify these procedures to accept data which are already compensated for the effects of the range spread loss and the antenna gain. Compensation done in COASP is more accurate due to the more precise geometric calculations and due to a better estimate of the f_p/v_g parameter than the compensation applied in GenCal. However, at present time, this is not available. The calibration site should be processed without such compensations.

After processing the signal data containing the calibration devices, the output image and the output header should be examined. The value of the the f_p/v_g parameter can be found in the output header with the keyword "PRF over v"; it can be used for noise processing. Log file can also be examined by searching for Warning, Error and Progress keywords.

Noise processing is the next operation. It is the same as for the non-calibration lines. The same script `PowBite.sh` can be used to measure the mean noise power. The purpose of noise averaging is to find values for the following parameters:

- Az_BITE_*Pol* to be inserted into the signal configuration file which is used for generating calibrated images; and
- mean_S_noise_rf_gain to be added to the signal image header file which is used in calibration.

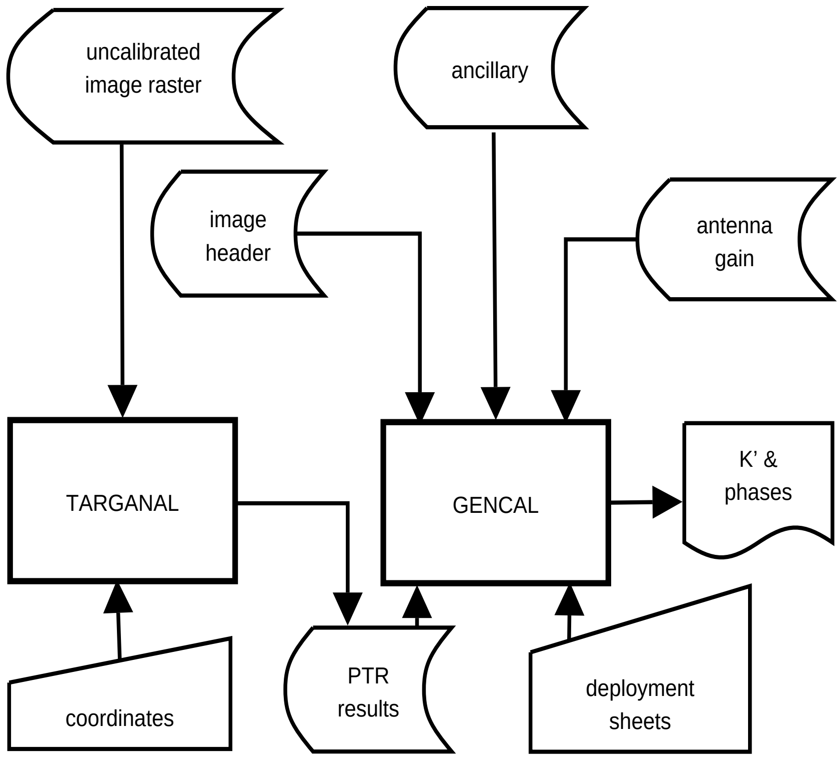


Figure 5: *Calibration software.*

If the script `PowerBite.sh` is used to measure noise power; it will attempt to append the measured noise power to the appropriate image header file. Since the calibrators are already processed, their header file should exist and the script will try to insert the BITE power measurements there. If this fails, then the calibrator header file must be edited by appending the BITE noise power to it. Other procedures expect these values to be in the header file because PolGASP places them there. This is the main reason for this step in the calibration procedure.

When this is complete, some conversions and name changes are needed to make the COASP header file look like a PolGASP header file. Most of these steps are automated. When this is done, the regular calibration procedures, including Targanal and GenCal, can be executed, as shown in Fig. 5. These procedures should produce the K' and the phase correction values.

Finally, the K', phase correction, noise power and transmitter power must be correctly entered into the COASP configuration file and the calibration, antenna_gain and spread_loss options must be enabled. The calibrated image can then be produced.

4.2 Using COASP as a Pre-processor for CHASP

The original motivation for developing COASP was to prepare CV-580 C-band polarimetric SAR data for target adaptive processing. The required functionality for that purpose is not the full set of SAR processor operations. The main functionality which is the prerequisite for further adaptive processing comprises:

- Conversion to floating point;
- Input data conditioning;
- Range compression when not done in hardware;
- Channel alignment in range;
- Motion compensation;
- Relative calibration; and
- Quality checking.

All of these functions are supported by COASP. As opposed to regular processing, the following selections should be made in the configuration file:

```
azimuth_focus No
azimuth_align No
motion_restore No
```

Azimuth focus is skipped because it would be done in CHASP using data adaptive processing parameters. Azimuth alignment should be avoided because this operation assumes some value for the DC and for the Doppler bandwidth. These values may not be known in advance and may be estimated later. Therefore, the following adaptive processing should also take care of the proper alignment between channels in azimuth.

Antenna gain compensation and spread loss compensation should be enabled. If the constants are known, calibration should also be enabled. The output will be relatively calibrated so that the four channels can be used in polarimetric decompositions. Absolute calibration will not be achieved if COASP calibration constants are determined using the simple focusing algorithm or if PolGASP calibration constants are used. If the Range-Doppler algorithm is used for calibration processing, then a well calibrated output is expected after CHASP processing.

5 Moving Targets

Imaging moving targets implies knowing the state of their motion. Since this information is usually not available *a priori*, it is necessary to estimate the speed of the target in two dimensions. In principle, simultaneous estimation of the position and the velocity of a target is one of the most difficult problems in radar theory. In SAR this problem is especially challenging when only a single synthetic aperture is available.

CHASP is designed to work robustly for the special case of bright targets against a low clutter background, in particular for ships on the ocean.

5.1 Models

Generally speaking, a ship exhibits two kinds of motion: linear motion at its travelling speed and rotational motion due to waves. CHASP copes well with the linear motion of the ships, but is not very effective in dealing with the rotational motion. ISAR techniques would be more appropriate in the latter case.

In any case CHASP is concerned only with the surface motion and it estimates the velocity in two dimensions. The velocity of the target is decomposed into two components, one in the cross track direction (v_x) and the other along track (v_a).

The cross-track component is related to the radar line-of-sight (LOS) projection of the velocity simply via the sine of the incidence angle

$$v_x = \frac{v_{los}}{\sin\alpha} \tag{98}$$

The LOS projection is derived from the DC estimate to which it is directly related:

$$f_c = \frac{-2}{\lambda} v_{los} \tag{99}$$

The along-track component modifies the DR so that

$$\frac{\Delta b}{b} \approx 2\frac{v_a}{v_g} \tag{100}$$

Therefore, the so called auto focusing techniques can be applied.

If the target motion is uniformly linear, then the two velocity components v_x and v_a are observable separately through DC and DR. However, cross-track acceleration modifies the DR. Furthermore, the along track speed v_a may be time varying. This assumption leads to higher order terms in the target phase history, which can be estimated by parametric or non-parametric methods. CHASP is designed to estimate DR deviations Δa as an unknown variable using some non-parametric methods. After such estimation, for the purpose of making the results usable in image focusing, the variations are modelled by a polynomial. The fitted polynomial coefficients are then used to construct a modified azimuth chirp and to create the compression filter. They can also be used to evaluate the relative speed and to assess its variability during the exposure (dwell or integration) time.

5.2 Adaptive Algorithms

Different approaches to velocity estimation are used in CHASP. CHASP estimation algorithms are related to various effects of motion on the image focus. A specific algorithm is associated with each one of these effects. A brief summary of the basic underlying principles is as follows:

- An incorrect DC may cause ghosts in the image. Ghost minimization is a search method which finds the DC value for which the ghost-to-target power ratio reaches the minimum.

- If two Doppler looks are produced, incorrect DC causes their misregistration in range. Look cross-correlation methods reveal the amount of misregistration and serve as the basis for estimating the DC error.

- If two Doppler looks are produced, incorrect DR causes their misregistration in azimuth. Look cross-correlation methods reveal the amount of misregistration and serve as the basis for estimating the DR error.

- If several Doppler looks are produced around the presumed DC value, the integrated target response of each look will depend on the corresponding antenna gain. If DC is incorrect the integrated response in some lateral looks may be significantly lower than expected. Look integrated response checking is a method to assess the accuracy of the initial DC estimate.

- Using an incorrect DR cannot fully compensate the frequency modulation. Tracking the residual Doppler frequency is an adaptive technique which reveals the residual modulation.

- Due to an uncompensated DC the target is displaced in the image relative to the central position of the uncompressed target response. The correlation of the antenna pattern and the magnitude of the uncompressed target response peaks at the beam centre. The correlation between the presumed azimuth chirp and the uncompressed complex target response peaks at the beam centre if the DC is correct and incorporated into the presumed chirp. In the case of a DC error there is a shift between the peak positions of the two correlation sequences. Locating the uncompressed response and comparing it to the location of the compressed response is the method which reveals the DC error.

- Doppler parameter error cause smearing in the image. Contrast maximization is a search method which finds the parameters such that the contrast is optimized.

- The Doppler spectrum of a moving target is shifted relative to the Doppler spectrum of the ocean. Under favorable conditions the estimated shift is mainly due to the motion of the target.

5.2.1 Target Localization and Evaluation of the Integrated Response

This auxiliary algorithm is used in support of other algorithms that zoom-in on the desired target. If the location of the desired target is not externally set, then the brightest pixel is found. The complete procedure for quantifying such a target is as follows:

1. Find the pixel of maximum intensity in the entire chip, in a restricted portion of the chip or initiate the procedure using externally set pixel coordinates;
2. Examine the region around the maximum iteratively: The pixels bordering the target region are examined to see if their inclusion would or would not contribute significantly to the integrated power response. The threshold is set relative to the previously established integrated response, not relative to the background (since it is not available). The surrounding pixels are examined along the parallel sides of a rectangle; range and azimuth sides are tested alternatively. Whenever the test is positive, the bounding rectangle grows in that direction. The process stops when the contribution of a new line of pixels is below a threshold related to the integrated power response;
3. The centre of mass is found using the image samples within the target bounds;
4. The moments about the centre of mass are found. They indicate the effective extent of the target in the range and azimuth dimension and the skewness of the target.

Within this algorithm the integrated response (IR) of the target is evaluated without really having a reliable estimate of the clutter. Target response estimates obtained from different azimuth looks must be interpreted accordingly.

This algorithm is only available in CHASP.

5.2.2 Measuring Ghost-to-target Ratio

This algorithm is used as part of the search method to find the optimal DC which minimized the ghost to target ratio.

1. At the azimuth distance of $\pm d_G$ from the target's centre of mass is the position of the azimuth ambiguity (i.e. possible ghosts) in the image. The azimuth ambiguity (target-to-ghost) distance can be expressed using the DR or the azimuth spacing (or, equivalently, the "PRF over v" parameter):

   $$\begin{aligned} d_G &= -\frac{f_p^2}{b} = -\frac{2\pi}{\tilde{b}} && (101) \\ &= \frac{\lambda R}{2}\left(\frac{f_p}{v_g}\right)^2 = \frac{2\pi \tilde{R}}{\Delta \tilde{a}^2} && (102) \end{aligned}$$

   The integrated power of the ghost targets is determined;
2. The ratio of the integrated ghost responses and the target response is formed. The largest of the two ghost responses is used for this measure.

The method assumes that there are no other targets present at the d_G distance from the target of interest. The method may not be very sensitive to the ambiguities. Therefore, the interval of the searched DC values is limited to the baseband and other methods must be used to detect ambiguities.

Ghost-to-target ratio is minimized when ghosts are symmetric around the target. However, in the case of a low target-to-clutter ratio, this method is not sensitive enough. Ghosts are not noticeable for small DC errors. The interval of DC values which do not exhibit any ghosting may be quite broad.

This algorithm is only available in CHASP.

5.2.3 Azimuth Multi-look Cross-correlation

Two azimuth looks are generated using non-overlapping, but immediately adjacent, spectral bands. Zero overlap is chosen as the most convenient, although a different value may be chosen. Each look image is converted to power, creating two real images $I_1(a,r)$ and $I_2(a,r)$. Next the cross-correlation $P(d)$ for lag $-d_{max} \leq d \leq d_{max}$ is computed as:

$$P(d) = \frac{\langle I_1(a,r) I_2(a-d,r)\rangle}{\sqrt{\langle I_1(a,r) I_1(a-d,r)\rangle \langle I_2(a,r) I_2(a-d,r)\rangle}} \tag{103}$$

where averaging is over all N_r range indices r and over $N_a - 2d_{max}$ azimuth indices a. The position of the maximum of $P(d)$ indicates the misregistration between the two azimuth looks. The level and the width of the peak can be taken as a measure of confidence.

CHASP provides the sequence $P(d)$ for a given (configurable) length $2d_{max} + 1$ for all processed channels. Peak assessment can only be done externally. Conversion of the peak position to along-track velocity and DR adjustment is supported internally by CHASP.

When two azimuth looks are used with Doppler spectral distance (centre-to-centre) f_Δ, normalized according to previous normalizations:

$$\tilde{f}_\Delta = \frac{2\pi f_\Delta}{f_p} \tag{104}$$

the relative velocity error can be estimated as:

$$\frac{\Delta v}{v_g} = \frac{\Delta b}{2b} = \frac{\tilde{b}}{2\tilde{f}_\Delta} d = -\frac{\Delta \tilde{a}^2}{2\tilde{R}\tilde{f}_\Delta} d \tag{105}$$

The conversion factor from the misregistration d to the relative velocity compensation $\Delta v / v_g$ is expressed in terms of the normalized DR, as well as in terms of the normalize spacing (or the "PRF over v" parameter) and the normalized slant range. The latter may be more convenient in the case of EC CV-580 SAR. The relative DR adjustment $\Delta b / b$ is just another way of viewing the influence of the along track motion on the target focus.

The position of the azimuth look pairs can be varied by changing the frequency offset parameter $f^{(off)}$, while keeping the same DC and the same look bandwidths. In this way, several pairs of azimuth cross-correlation estimates can be generated, each associated with a triplet of values, as shown for the k-th pair:

$n_k = f_p f_k^{(off)}/b = \tilde{f}_k^{(off)}/\tilde{b}$	relative position in the aperture
$\Delta b_k/b$	relative DR mismatch
$\Delta v_k/v_g$	relative along-track speed

Next, the polynomial fit of $\Delta\tilde{b}_k$ against n_k is performed, as discussed in Section 5.2.8. After two integrations the phase polynomial coefficients are obtained.

CHASP does not perform two-dimensional look cross-correlation. It is assumed that the DC is adjusted such that there is no significant misregistration in range. However, CHASP does provide a means of monitoring the DC adjustment because it estimates the integrated response for each look using the algorithm described in Section 5.2.1. Should the integrated target response be low in any of the looks, the DC estimate would have to be corrected. The correction should be made to the effect that the weak look be left out. As a result a new look would be introduced at the opposite side of the Doppler spectrum. In the case that both out-most looks are weak, a reduction of the processed bandwidth must be considered.

This functionality is only available in CHASP.

5.2.4 Target Doppler History Tracking

This method has some conceptual similarity with the Phase Gradient Method, but it has many important differences.

First the data are de-chirped along azimuth using the expected or nominal DR. After this operation small targets become represented by narrow-band signals with frequency proportional to their position and duration equal to the synthetic aperture. Many such signals may be superposed and the clutter contributes to a certain noise level. A small target, represented by a narrow-band signal, may have some frequency modulation if the DR is incorrect, presumably due to target motion. There is also some amplitude modulation due to the antenna gain azimuthal pattern and, possibly, due to many other effects occurring during the synthetic aperture.

There is a class of adaptive recursive filters which can lock onto one or more narrow-band components and track the frequency variation. The adaptation principle is to recursively adjust filter parameters trying to minimize the output power of the filter [2]. The filter has a given constrained form and several free parameters. In this particular case, an adaptive first order infinite impulse response (IIR) notch filter is used and its parameters are the central frequency $\omega \in (-\pi, \pi)$ and the width $1 - \alpha$. The filter, expressed using the z transorm, is in the form

$$H(z) = \frac{1 - \exp(j\omega)z^{-1}}{1 - \alpha\exp(j\omega)z^{-1}} \tag{106}$$

The filter may have more than one cascade of the same form if multiple targets are expected at the same range. The output power of the filter is recursively minimized using a gradient type stochastic algorithm. The filter operates on several azimuth lines simultaneously, trying to minimize the combined filtered output power. This allows the filter to track targets which have a certain range width and which may have some amount of range migration. The range migration information is also made available as an optional output. The filter runs recursively forward and than backwards through the data forming arrays $\omega_f(i)$, $\alpha_f(i)$ and $\omega_b(i)$, $\alpha_b(i)$, respectively.

It is very important to have good initial conditions for tracking. The initial value for the frequency ω is established by running the FFT on the de-chirped signal and finding the maximum. This operation is very similar to the SPECAN algorithm, followed by target detection and estimation of its position, as explained in Section 5.2.1. The initial value for the filter width α is constant, but configurable. The tracking interval is the full aperture and its position is estimated as described in Section 5.2.5.

This algorithm is only available in CHASP.

5.2.5 Estimating Position of Uncompressed Target Response

The purpose of this algorithm is to detect the azimuth bins within the data matrix which are occupied by the target response at the processing level when the data are range compressed but azimuth uncompressed. The algorithm is based on correlation between the antenna gain pattern and the data magnitude. The antenna azimuth pattern is not exactly known, but is estimated by a raised cosine function of the proper length, derived from the azimuth beamwidth and the slant range and the azimuth spacing. The data magnitude is averaged in range so that range migration does not play a role. Averaging is over several range bins, depending on the estimated size of the compressed target.

Location of the target cannot be estimated very precisely using this algorithm because the correlation function has a very broad peak.

This algorithm is used as an auxiliary algorithm for frequency tracking described in Section 5.2.4. It sets the time window for tracking.

This algorithm is also used within the DC estimation method described in Section 5.2.6.

This algorithm is only available in CHASP.

5.2.6 Estimating Target Azimuth Offset Due to DC Error

This algorithm is designed to compare the azimuth position of a target in the uncompressed and in the compressed image. Beam centre (acquisition geometry) output image frame is used to facilitate comparison. The central position a_{acq} of the uncompressed target response is estimated by the algorithm described in Section 5.2.5. The compressed target position a_{img} in beam centre geometry is available from the tracking algorithm discussed in section 5.2.4. One possibility is to use the position obtained by SPECAN, which is also used to initiate tracking. The other possibility is to use the mean of the estimated instantaneous frequency. The offset $a_{acq} - a_{img}$, expressed in azimuth pixels, is due to the DC error

$$\Delta\tilde{f}_c = \tilde{b}(a_{acq} - a_{img}) \tag{107}$$

and $\Delta\tilde{f}_c$ should be added to the original estimate of the normalized DC.

This algorithm cannot be used to resolve the PRF ambiguity. It can be used to refine the initial DC estimate. It should be kept in mind that the variance of $\Delta\tilde{f}_c$ is large, mostly because the location of the uncompressed target cannot be estimated very precisely using the algorithm described in section 5.2.5. With this exception, the offset algorithm is very similar to the DC estimation method based on moving target displacement from known land features (such as trucks and roads).

This algorithm is only available in CHASP.

5.2.7 Measuring Image Contrast

When target bounds are determined using the algorithm described in Section 5.2.1, the image contrast within these bounds is estimated. The contrast measure is simply the ratio of the variance over the mean squared of the imaged target

$$C = \frac{\langle p^2\rangle - \langle p\rangle^2}{\langle p\rangle^2} \tag{108}$$

where $p = ||I(a,r)||$ is the magnitude squared of the pixels in the target area.

This algorithm is used in search procedures in which contrast is the optimization criterion. Using this criterion is effective in PRF ambiguity resolution and in DR adjustment. It can also be used for DC refinement around an initial value.

This algorithm is only available in CHASP.

5.2.8 Polynomial Fitting of Phase History

The polynomial phase of the PTR is constructed based on estimates of the instantaneous frequency or frequency rate during the synthetic aperture formation. The general form of the polynomial model is:

$$y_i = \sum_{m=0}^{p} g_m x_i^m + e_i \tag{109}$$

where p is the order, x_i is the aperture time or the sample index, y_i is the measured (estimated) quantity (DR error $\Delta\tilde{b}$ or the normalized Doppler frequency excursion from the nominal) and e_i is the equation error which is to be minimized in the least squares sense.

Fitting consists of forming and solving the system of equations $Y = XG$, where the elements of the vector Y are $\langle x_i^m y_i\rangle$ for $m = 0, \ldots, p$ and the elements of the symmetric matrix X

are $\langle x_i^m \rangle$ for $m = 0, \ldots, 2p$. A numerical method (Gauss-Jordan) is used to solve the linear system of equations. The coefficients G pertain to the y_i expansion. The polynomial needs to be integrated once or twice with respect to x_i (depending on the nature of y_i) to form the phase coefficients. As long as x_i is in terms of sample indices and the quantities y_i are normalized, the integration is straightforward, leading directly to the phase coefficients in radians.

When there are more channels (four polarimetric channels), then the common polynomial coefficients are sought.

This algorithm is only available in CHASP.

5.2.9 Inter-look Coherence

A special product is defined to represent the coherence between two azimuth looks. It is defined for complex looks as follows:

$$C(a,r) = \frac{\langle I_1(a,r) I_2^*(a,r) \rangle_w}{\sqrt{\langle |I_1(a,r)|^2 \rangle_w \langle |I_2(a,r)|^2 \rangle_w}} \tag{110}$$

where weighted averaging is done in azimuth in such a way that square pixels are produced. The coherence product can also be computed on real (i.e. detected) looks. The same type of moving weighted averaging is used.

This algorithm is only available in CHASP.

5.2.10 RCS

The total radar cross section (RCS) is estimated for the target of interest by assuming that the target is the only bright feature in the image chip. First, the background clutter power (p_0^2) is estimated from the four corners of the valid image surface. Transient portions of the image may appear along the chip borders due to azimuth compression and due to RCMC resampling and are excluded from the averaging. The four corners are positioned at equal distances from the pixel of maximum return power. The RCS integration is performed over the entire valid part of the image, accounting for the slant to ground projection in range and possible downsampling in azimuth:

$$P = \Sigma_a \Sigma_r (|I(a,r)|^2 - p_0^2) \frac{\Delta R}{\sin(\alpha_i)} k_{az} \Delta a \tag{111}$$

Range and azimuth spacing is described in Section 2.1.9; if the natural azimuth spacing is preserved, $k_{az} = 1$. Both clutter power and RCS are converted to dB units (i.e. $\sigma^0 = 20 \log_{10}(p_0)$, $\sigma = 10 \log_{10}(P)$).

This algorithm is only available in CHASP.

Table 2: CHASP modules shared with COASP.

module	*functionality*	*control*
Radio	correct for spread loss	spread_loss
Xcorrel	coarse or fine DC estimation	doppler_grid_rg
Trim	adjust length for transposition	automatic
Transpose	transpose for azimuth access	automatic
AzFFT	FFT in azimuth	azimuth_focus, azimuth_align
Skew	resample for RCMC	azimuth_focus, RangeDoppler
RefRD	calculate filter for RDA	azimuth_focus, RangeDoppler
AzRef	calculate simple filter	azimuth_focus, RangeDoppler
AZfilter	apply azimuth filter	azimuth_focus
AZshift	just shift in azimuth	azimuth_align, azimuth_focus
LookRD	multiply by spectral window	azimuth_focus, RangeDoppler
AzFFT	inverse FFT in azimuth	azimuth_focus, azimuth_align
Transpose	transpose for range access	automatic
Store	save processed data block	automatic

6 CHASP

CHASP is a program which implements the same azimuth focusing and geometry algorithms as COASP, described in Section 2 and it also includes the adaptive algorithms described in Section 5.2.

CHASP runs only on range compressed and motion compensated input data. In the case of polarimetric data, the channels should at least be relatively calibrated.

6.1 Modules

Some modules that are present in COASP are also included in CHASP, see Table 2.

CHASP specific modules are listed in Table 3. Some of these modules are mutually exclusive. For example frequency tracking cannot be done together with Range-Doppler focusing or look correlation.

Table 3: *CHASP specific modules.*

module	*functionality*	*control*
Load	get a block of range compressed data	automatic
Phase0	correct phase of “late” channels	compensate_radial
Pow	convert to power	multi_look correlate_looks_len, auto_focus
Locate	quantify target [+ghost]	locate, correlate_looks_len, auto_focus
Cross	azimuth look cross-correlation	correlate_looks_len
Coher	azimuth look coherence	coherence, mag_coherence
Fit	fit multi-look results	auto_fit
AzChirp	create chirps for deramping	auto_focus
Test	track frequency, find azimuth offset	auto_focus
Track2	smooth out tracking results	auto_focus
Sum	azimuth look summation	multi_look
Contrast	find target contrast	measure_contrast
Spat0	compute square spacing	spatial_size
Spat	resample azimuth to square pixels	spatial_size
SQRTscale	nonlinear scaling	multi_look, pgm_out

6.2 Interfaces

All interfaces are via files. CHASP is configured using a configuration file. It writes all relevant results to the header files. It also produces some diagnostic files. As a rule, CHASP must be launched multiple times during the analysis of a given target. In between the runs the configuration is changed so that a different algorithm can be used or different parameters are used. Various scenarios are possible. They are all based on:

- Changing the configuration files; and
- Inspection of the header file and/or the diagnostic files (plots).

These different scenarios can be executed in several ways:

- Manually, involving an image analyst in the loop;
- Semi-automatically, using scripts for iterative runs; and
- Automatically, involving a wrapper and a higher order algorithm.

6.2.1 Input

CHASP uses the COASP output files, the "PRF file" and the configuration file as its input. It can process all four channels that have been pre-processed by COASP or only one of them. A summary of input files is depicted in Fig. 6.

CHASP can work without a "PRF file", but in this case some basic parameters must be defined via the configuration file. As a rule, the "PRF file" should be used when EC CV-580 data are being analyzed. CHASP can take and process other range compressed data in flat raster format, as long as the minimum information is made available through a COASP-like header. For example, RADARSAT-1 or ENVISAT ASAR data may be processed if suitably pre-processed. They must be range compressed, floating point and properly formatted. Doppler estimates must be known and set in their proper places in the configuration file.

6.2.2 Output

CHASP output is similar to COASP output. It includes the image files with the headers, possibly some diagnostic files and the log file. A summary of output files is depicted in Fig. 7. In one of its modes, CHASP generates two image files per channel, each representing a separate azimuth look. In all other modes it produces one image file per channel.

Some elements of the CHASP header file are shown below:

```
mission_id              326_l1p8_sep2304_CoCoNaut
mission                 21
line                    1
```

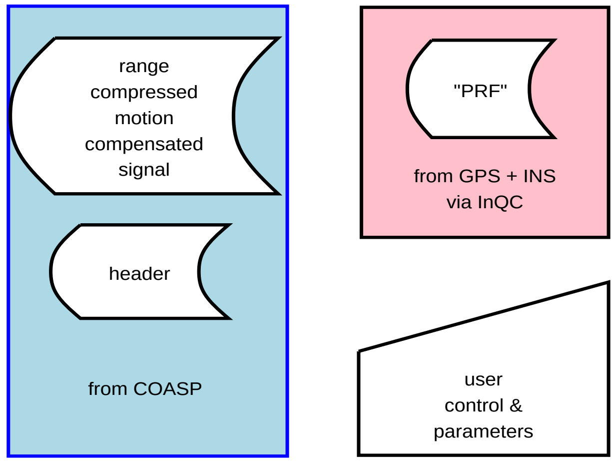


Figure 6: *Input files for CHASP.*

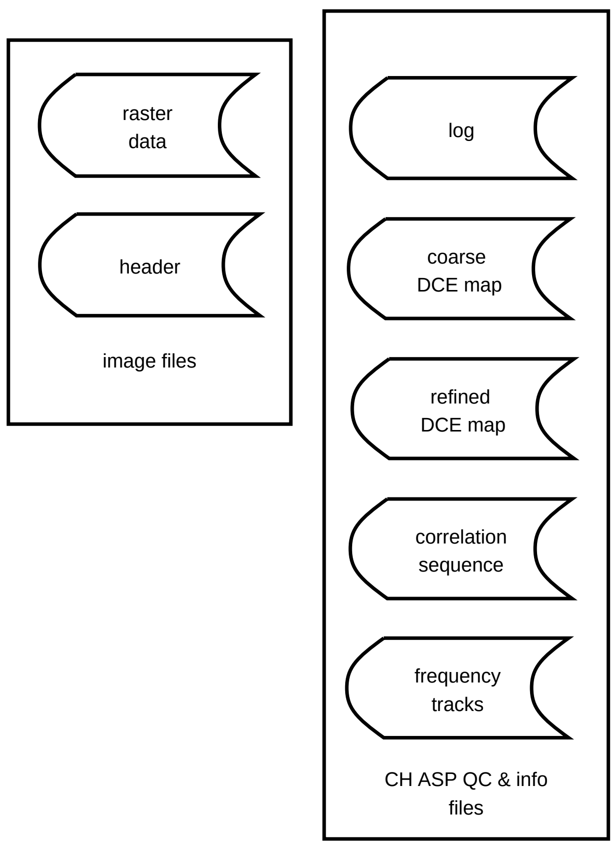


Figure 7: *Output files from CHASP.*

```
pass                    8
antenna_look_direction  Port
swath_mode              Nadir
altitude                6930.9423828125
groundspeed             139.5191955566
Tx_polarization         Horizontal
Rx_polarization         Horizontal
SAW                     out
in_status               +RC+MOC+RAD(3)+ANT+CAL
out_status              +SHIFT+FOCUS_RD+MLOOK
signal_data_file        l1p8hh.sig
signal_header_file      l1p8hh.hdr
COASP_file              l1p8hh.rc
COASP_header_file       l1p8hhrc.hdr
polgasp_image_file      l1p8hh.chasp
look2_image_file        N/A
moc_prf_file            l1p8prf.mat
replica_file            marina_2.tmp
```

This part of the header file provides some general information. Certain information is just copied from the COASP header file. File names (other than the replica_file) are taken from the configuration file. The in_status information is copied from the COASP header file, while the the out_status information is written according to the configured CHASP processing. In this particular case, the input data were range compressed (RC), motion compensated (MOC), radiometricly corrected using range cubed (RAD(3)), corrected for the antenna gain pattern (ANT) and calibrated (CAL). CHASP operations included channel alignment (SHIFT), azimuth compression by the Range-Doppler algorithm (FOCUS_RD) and multi-looking (MLOOK). In some other cases out_status may indicate coherence (COH), spatial resizing (SPAT), frequency tracking (TRACK), look correlation (LOOK_CORR) and fitting (LOOK_FIT) or application of the adaptive phase coefficients (AUTO_CHIRP). Altitude and ground speed are added for convenience, though thay are not used in CHASP. They are in SI units.

The image chip format and its relative position are described in the following way:

```
transposed              0
datatype                1
complex_flag            0
first_line_ext          1
first_line              184242
number_lines            4096
start_sample            1565
number_samples          256
near_srd                14029.7685546875
```

```
sample_size          4.0000000000
sample_size_az       0.4312970042
```

This image is real (owing to multi-looking) and has preserved the original orientation (not transposed). The first line and start sample are relative to the signal data as extracted from the tapes. The image dimensions are given by number_lines and number_samples. The pixel size in range and azimuth is given by sample_size and sample_size_az, respectively. Near slant range, given by near_srd, is the slant range of the first range pixel in the product. Upon CHASP execution, these parameters always reflect the current values. All physical values are in SI units.

Much more information is made available through the header file as CHASP processing progresses. The main results from various adaptive algorithms are written in a cumulative fashion. Examples of processing numerical results can be found in Section 7.

Target attributes may be calculated and written into the header file. In addition to the target image position, these attributes include the slant range (in meters), the elevation angle (in degrees), the sine of the incidence angle, geograpihic coordinates (in degrees), the azimuth shift between the beam center and the PCA (in terms of the azimuth spacing), the azimuth distance of the ambiguities (in terms of the azimuth spacing), the RCS (dB) and the estimated clutter power (dB). An example is shown below:

```
target_az_max          2441
target_rg_max          106
target_az_cent         2449.746582
target_rg_cent         109.508110
target_az_ext          19.043644
target_rg_ext          8.161801
target_skew            0.823403
target_slant_range     14453.768555
target_elev_angle      61.226273
target_sin_inc_angle   0.877925
target_latitude        48.563366
target_longitude       -125.751979
target_az_shift        1606.022674
target_ghost_distance  2203.115967
target_RCS             47.822350
clutter_sigma0         -46.105431
```

The applied processing parameters are also written to the header file. They include the following parameters: f_p/v_g, b/f_p^2 and f_c/f_p:

```
proc_prf_over_v        2.321511
```

```
proc_normalized_DR     -0.000436
proc_normalized_DC     -0.700000
```

6.3 Program Configuration

CHASP uses a configuration file which is very similar to the COASP configuration file.

The section of the configuration file which contains the system parameters is the same as for COASP. Some parts of this section may be omitted since they are not used. This includes the parameters related to the SAW delay, antenna boresight offset and antenna elevation aperture.

The processor section is almost identical to the COASP processor section. However, certain algorithms do not support data partition or they have not been tested enough for such a configuration. Therefore, the number of parts is set to 1 and, as a consequence, the number of processors is set to 1. This is not a major drawback since the data chips are small and CHASP is fast. There is one additional parameter, which is the initial relative width for the frequency tracking algorithm. The ancillary data are not even used, so the corresponding line may be omitted. The size of the block is usually 4096 for near ranges and 8192 for far ranges. This is because the aperture increases with range. An example is shown below:

```
; Processor parameters
;
processors              1
block_lines             8192
parts                   1
channels_together       1
interp_size             11
interp_fractions        16
alpha                   0.85
change_anc_endian       Yes
change_output_endian    No
change_input_endian     No
```

One section plays the role of the work order and is shorter than in COASP. An example is as follows:

```
; WorkOrder
;
input_data_file         l1p8
channels                4
prf_file                l1p8prf.mat
first_line              16191
```

```
last_line               24382
first_sample            1181
last_sample             1436
geoid_over_ellipsoid    -15.27
reference_range         1
spread_loss             0
georef_grid_rg          0
doppler_grid_rg         64
azimuth_focus           Yes
azimuth_align           Yes
ZD_frame                Yes
compensate_radial       No
window_shape            2.8
multi_look              No
coherence               No
mag_coherence           No
spatial_size            No
pgm_out                 No
pgm_floor               -50
```

The same rules apply as for COASP. It is possible to process four channels, specifying only the base part of the filename. The "hh", "hv", "vv" and "vh" suffixes and the extension ".rc" are implicit. Alternatively, a single, fully named file may be processed. Under normal conditions, the "PRF" file will be used and must be specified. Exceptionally, it may be omitted, but then the basic processing parameters must be specified in the proper places. The domain of processing can be specified both in azimuth and in range and is relative to the COASP output. It is commonly assumed that the range spread loss is accounted for in COASP. However, in the case that it was inadequate (wrong power of R/R_{ref}), it can be modified. Normally channel alignment in azimuth should be done in CHASP. If channel algnment was done in COASP, it should be turned off in CHASP. The compensate_radial flag indicates that a phase adjustment should be made to account for the DC (target approaching or receding) which was unknown during COASP processing. This may not always be successful. If DC is large, the interpolation done in COASP may be quite bad. The multi_look flag really stands for conversion to magnitude or power (often called "detection", a term which is avoided here to avoid possible confusion with the process of target detection in a SAR image). This flag may be used for single look and for double look processing. The coherence flag may be used to create cohernce products, which represent the phase coherence between azimuth looks. To compute the complex coherence, it is necessary to set the number of looks to 2 and multi_look to No, while spatial_size should be set to Yes. The mag_coherence flag is similar to the coherence flag, except that it applies to the magnitude and ignores the phase of the two azimuth looks. The spatial_size flag, if set, causes azimuth smoothing and down-sampling to produce the square sized pixels. The azimuth spacing is then adjusted to the ground projected range spacing. This operation is available for magnitude and for complex images and can be used for generating coherence products. In the first two cases, weighted azimuth moving average is used to smoothen the image and to reduce its azimuth bandwidth. In the case of coherence products, weighted azimuth averaging is used to compute the coherence. Finally, the pgm_out flag, if set, causes a conversion to 8-bit unsigned integer through nonlinear (logarithmic) scaling and a cut-off threshold. The threshold is called pgm_floor and is expressed in dB relative to the maximum intensity.

There is a section that is used especially to configure the adaptive algorithms. The options are shown below:

```
; Adaptive algorithm
;
auto_focus
auto_fit
track_range
track_azim
bunch_azim
phase_order
auto_correct
prf_over_v
relative_dc_offset
relative_v_offset
doppler_looks
full_bandwidth
look_bandwidth
look_offset
look_overlap
correlate_looks_len
locate
measure_contrast
```

The auto_focus flag is used to activate the tracking algorithm. The auto_fit flag is used for phase polynomial fitting and is used after multi-look analysis when several pairs of looks have been cross-correlated. The values of track_range and track_azim may be used to indicate the position of the target of interest. Often, only track_range is set, but track_azim is not. In this case, CHASP finds the brightest target at the given range. This is useful when there are no other brighter targets at the same range and if DC estimates are being changed, causing the target position to vary in the image. The value of bunch_azim refers to the range width of the zone where the target is expected to be and is used to limit the search for the brightest target. It is also used as an upper bound for the target zone for the calculation of the integrated response (IR). When CHASP is in the tracking mode, this parameter determines how many range bins are included in tracking of a single target. The value assigned to phase_order is used for polynomial phase fitting for the multi-look and for the tracking algorithm. It must not be greater than 4. The auto_correct flag controls the higher order adjustment of the azimuth reference function. If it is on, CHASP uses the provided phase polynomial coefficients to modify the reference function for azimuth compression. The field prf_over_v is rarely used for EC CV-580 SAR processing, because the PRF file is available. If the PRF file is unreliable or missing or if other SAR data are being processed, this method can be used. The parameter relative_dc_offset is the value of the DC in fractions of PRF that is to be used in processing. It may be varied to search for the optimum value. The parameter relative_v_offset is the adjustment of the along track speed in fractions of the aircraft ground speed. Varying this parameter modifies the initial value of the "PRF over v" read from the PRF file or read from the prf_over_v field. In the case of spaceborne SAR, the effective speed is used instead of the ground speed in all expressions and parameters. CHASP can only process one or two azimuth looks at a time, as specified by the doppler_looks parameter. The full Doppler bandwidth and the Doppler bandwidth of one look must be specified in terms of the PRF. In order to create different pairs of looks, the parameter look_offset can be used. It is expressed in fractions of the PRF and specifies the offset from the DC. In the case of two looks the offset is the difference between their median and the DC. Usually, the two looks are created with no overlap, but the parameter look_overlap can have a non-zero value, measured in fractions of the PRF. CHASP does not allow such a combination of these parameters that would attempt to create looks outside of the spectral band defined by the DC and the full bandwidth. CHASP creates magnitude looks if multi_look option is selected. The cross correlation between these looks is computed if the parameter correlate_looks_len is greater than zero. The value specifies the maximum azimuth lag that is considered for computing the cross-correlation. The locate flag controls whether or not CHASP should look for a target. If requested, the target size is measured and various parameters, such as incidence angle, georeferencing etc., are computed for the target of interest. The measure_contrast flag controls whether or not CHASP should estimate the contrast in the region occupied by a target.

One section of the CHASP configuration file is dedicated to certain results of adaptive processing that need to be passed on to the next instance of CHASP. The initial content of this section is as follows:

```
; Exchange parameters
;
phase_term_0           0.000000e+00
phase_term_1           0.000000e+00
phase_term_2
phase_term_3
phase_term_4
multilook_f_hh_1        -0.2
multilook_f_hh_2        -0.1
multilook_f_hh_3        0.0
multilook_f_hh_4        0.1
multilook_f_hh_5        0.2
multilook_f_hv_1        -0.2
multilook_f_hv_2        -0.1
```

```
multilook_f_hv_3        0.0
multilook_f_hv_4        0.1
multilook_f_hv_5        0.2
multilook_f_vv_1        -0.2
multilook_f_vv_2        -0.1
multilook_f_vv_3        0.0
multilook_f_vv_4        0.1
multilook_f_vv_5        0.2
multilook_f_vh_1        -0.2
multilook_f_vh_2        -0.1
multilook_f_vh_3        0.0
multilook_f_vh_4        0.1
multilook_f_vh_5        0.2
```

This section is used when CHASP does Doppler history analysis, which is in the multi-look mode and in the tracking mode. In the tracking mode, one single run is sufficient to estimate the residual azimuth frequency modulation and to fit a phase polynomial of the desired order. The polynomial coefficients are then written to the configuration file so that they may be used in a subsequent run if the auto_correct option is on. In the multi-look mode, the interaction is more complicated. CHASP must be run several times to produce several pairs of looks and to measure their respective azimuth misregistration. The configuration file contains initially a list of azimuth look offsets for each polarimetric channel that should be registered. The offset is always set by the look_offset parameter; however, only the results listed in this section are registered. In the case shown above, 5 different pairs of looks are specified for all polarimetric channels. It would take at least 5 runs of CHASP to fill the configuration file with the results. As CHASP runs, it writes the results for the specified look pairs into the configuration file. At the end, the lines appended to this section might look something like this:

```
multilook_t_hh_1        441.678131
multilook_t_hv_1        441.800354
multilook_t_vv_1        441.678131
multilook_t_vh_1        441.800354
multilook_b_hh_1        0.000058
multilook_b_hv_1        0.000058
multilook_b_vv_1        0.000064
multilook_b_vh_1        0.000058
multilook_v_hh_1        -0.010188
multilook_v_hv_1        -0.010186
multilook_v_vv_1        -0.011320
multilook_v_vh_1        -0.010186
multilook_t_hh_2        220.839066
multilook_t_hv_2        220.839066
multilook_t_vv_2        220.839066
```

```
multilook_t_vh_2         220.839066
multilook_b_hh_2         0.000084
multilook_b_hv_2         0.000077
multilook_b_vv_2         0.000090
multilook_b_vh_2         0.000077
multilook_v_hh_2         -0.014717
multilook_v_hv_2         -0.013585
multilook_v_vv_2         -0.015849
multilook_v_vh_2         -0.013585
multilook_t_hh_3        -0.000000
multilook_t_hv_3        -0.000000
multilook_t_vv_3        -0.000000
multilook_t_vh_3        -0.000000
multilook_b_hh_3        0.000135
multilook_b_hv_3        0.000045
multilook_b_vv_3        0.000122
multilook_b_vh_3        0.000045
multilook_v_hh_3        -0.023773
multilook_v_hv_3        -0.007922
multilook_v_vv_3        -0.021509
multilook_v_vh_3        -0.007922
multilook_t_hh_4         -220.777969
multilook_t_hv_4         -220.839066
multilook_t_vv_4         -220.839066
multilook_t_vh_4         -220.839066
multilook_b_hh_4         0.000110
multilook_b_hv_4         0.000135
multilook_b_vv_4         0.000174
multilook_b_vh_4         0.000135
multilook_v_hh_4         -0.019250
multilook_v_hv_4         -0.023773
multilook_v_vv_4         -0.030565
multilook_v_vh_4         -0.023773
multilook_t_hh_5         -441.555939
multilook_t_hv_5         -441.678131
multilook_t_vv_5         -441.555939
multilook_t_vh_5         -441.678131
multilook_b_hh_5         0.000135
multilook_b_hv_5         0.000116
multilook_b_vv_5         0.000129
multilook_b_vh_5         0.000116
multilook_v_hh_5         -0.023780
multilook_v_hv_5         -0.020377
multilook_v_vv_5         -0.022647
multilook_v_vh_5         -0.020377
```

These are the results obtained by analyzing different pairs of adjacent looks in all four polarimetric channels. Entries starting with "multilook_t" refer to the time position in the aperture in terms of pulses; entries starting with "multilook_b" refer to the DR adjustment and entries starting with "multilook_v" pertain to the relative along-track velocity adjustments. Each line corresponds to one pair of azimuth looks and one polarimetric channel. When CHASP runs with the auto_fit flag set on, it reads all these entries and does an overall polynomial fit of the proper order. The outcome is then placed in the configuration file so that it can be applied (controlled by the the auto_correct flag). The outcome may look like this:

```
phase_term_0            0.000000e+00
phase_term_1            0.000000e+00
phase_term_2            5.100321e-05
phase_term_3            -1.399908e-08
phase_term_4            -3.292814e-12
```

This is the phase polynomial for phase_order set to 4. The internally used fitting order for the DR deviation is actually 2, since two subsequent integrations are needed. Integration constants are always set to 0. The polynomial is in terms of azimuth samples (pulse indices). A similar set of polynomial coefficients is produce when running the tracking algorithm (auto_focus flag on). In that case, the phase coefficients are the only exported parameters and they may look as follows:

```
phase_term_0            0.000000e+00
phase_term_1            5.076659e-01
phase_term_2            5.383605e-05
phase_term_3            -1.864142e-08
phase_term_4            -1.383054e-12
```

In this case, the estimated phase gradient (residual frequency modulation) is the input to the fitting procedure. The internally used order is 3 in this case, because only one integration is needed to model the phase history (set to be of order 4). Thus, the linear term also appears in the polynomial, reflecting the target position (relative to the chip centre), combined with the DC error.

7 CHASP Procedures

CHASP is very flexible and versatile and can be used in different ways. Basically, CHASP does the signal processing tasks, while the procedures that can use various CHASP results should be organized at a higher level. CHASP can be used to iteratively improve focus, assuming an image analyst in the loop. More efficiently, procedures can be streamlined to run CHASP in a semiautomatic mode. It would be possible to design a fully automated end-to-end processing chain with no human interaction by integrating different procedures.

At the time of writing this document, several procedures have been streamlined using shell scripts and some external tools. The external tools are used mostly for diagnostics. These tools have played a larger role during CHASP development. They are described in more detail in Section 8.

Fig. 8 shows schematically one group of procedures, along with the external tools (shown in blue) and the estimation results (shown as yellow oval objects). This is a set of search procedures; they search a domain of DC and DR values to optimize various criteria. This set of methods is designed to estimate DC and DR, assumed constant. External drivers are used to change the processing parameters in the configuration file and to invoke CHASP as many times as needed. CHASP produces and analyzes an image for each set of processing parameters. Image features, measured from multiple runs, accumulate in the header files and can be assessed later to choose the optimal combination of the DC and DR. This is the core part of these search procedures. Additionally, external tools are used to extract some statistics from the products and/or to plot the results.

Fig. 9 shows another family of procedures, also accompanied by some external tools. These procedures are designed to analyze the phase history, which may have higher order terms. The implemented techniques are based on statistical signal processing applied to intermediate or special CHASP products, such as sub-aperture images or signal domain data. The results coming out of CHASP are the estimated parameters in an explicit form. The velocity estimates are written to the header file, while the fitted polynomial coefficients are written into the "exchange" portion of the configuration file (and can be applied using the auto_correct flag). The external tools used in this case serve mainly for plotting the diagnostic output.

7.1 Optimizing the Doppler Centroid

The DC, being one of the most critical parameters, is estimated first. Subsequently it may be refined in many iterations.

7.1.1 Background DC

COASP and CHASP produce Doppler centroid estimates as a function of range for every processed block. The density of estimates in range is configurable. It is expected that these estimates will be close to zero for the scene, with larger fluctuations in the regions of high

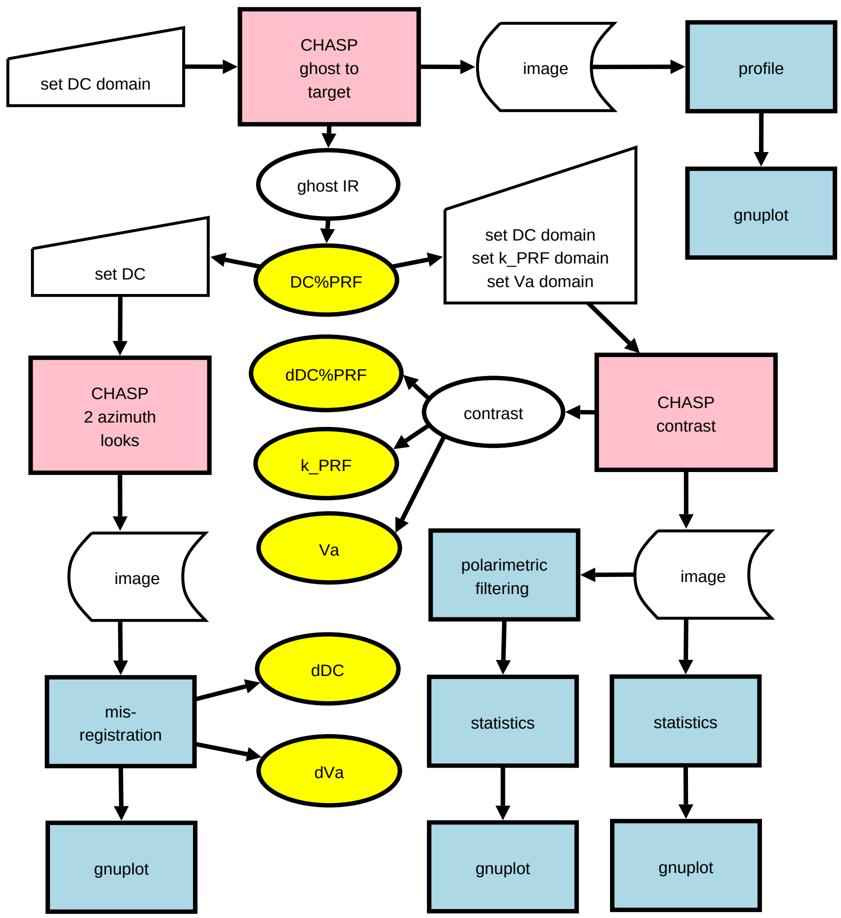


Figure 8: *CHASP DC and DR search procedures.*

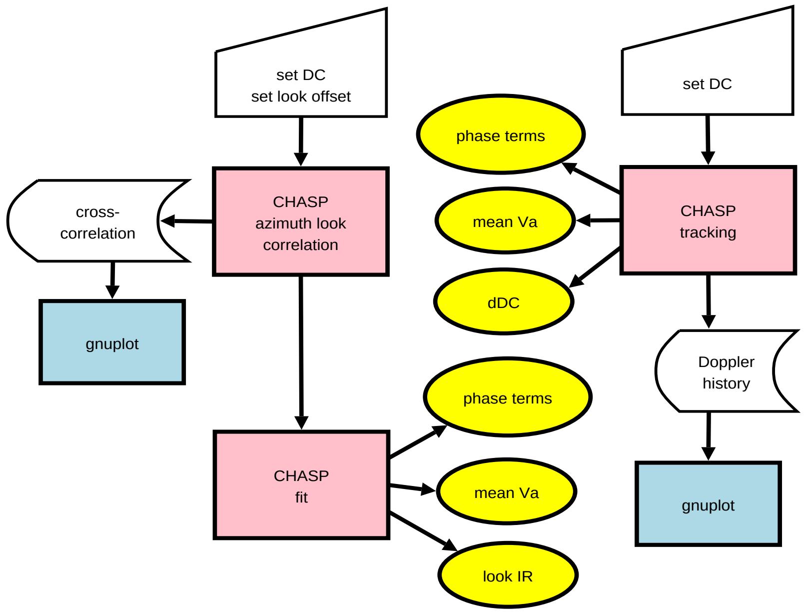


Figure 9: *CHASP procedures for phase history estimation.*

contrast. As part of routine processing, the expected zero Doppler of the background should always be checked. If the clutter DC is not zero, the estimate of the target cross-track speed should be corrected accordingly.

7.1.2 Ghost Minimization

The very first CHASP procedure is to estimate the target DC by a search procedure. The first estimate need not be very accurate and may be ambiguous (by multiples of PRF), but it must be sufficiently good to allow proper positioning of the processed Doppler band. All other algorithms depend on it. The first DC estimation procedure is very simple. An external driver is used to edit the configuration file so as to vary the DC value for processing (relative_dc_offset). The DR (or the relative_v_offset) may be left at the nominal (0) value. Flags multi_look and locate should be turned on. The range of interest may optionally be specified (based on detection results) using the fields track_range and bunch_azim (if not, the brightest point is chosen). The external driver should take the candidate DC values from a predefined set covering the baseband only. A typical search domain for DC is from -0.5 to 0.5 of the PRF, but it may be shifted if the background DC is not 0. The typical steps are 0.1 of the PRF. CHASP measures the ghost-to-target ratio, which is the ratio of the integrated responses (IR) and it registers the results in the header file for each polarimetric channel. The results appear in the following form, converted to dB:

```
ghost_to_target_-0.50  -24.429785
ghost_to_target_-0.40  -14.364273
ghost_to_target_-0.30  -7.147068
```

```
ghost_to_target_-0.20  -11.108494
ghost_to_target_-0.10  -15.816446
ghost_to_target_0.00   -19.328917
ghost_to_target_0.10   -26.459095
ghost_to_target_0.20   -33.800874
ghost_to_target_0.30   -39.209541
ghost_to_target_0.40   -27.704741
ghost_to_target_0.50   -26.502129
```

The subscript indicates the DC/PRF value to which the ghost-to-target ratio refers. The best value and the initial DC estimate in this case would be 0.3.

Additionally, a script has been developed to create image profiles and to plot them, so that ghost minimization can be visualized. For large ships, the best result is represented by a profile with symmetric ghosts. For small ships, there is usually an interval of DC values for which no ghosts are visible. The best guess is then the central point of that interval or, conversely, the opposite of the worst case (two peaks of equal magnitude).

7.1.3 PRF Ambiguity Resolution via Contrast Improvement

An initial DC estimate must be available. A contrast metric cannot be used for a global DC search, but it can be used for PRF ambiguity resolution. An external driver should be used to find the first DC estimate f_c; it should then test three hypotheses:

H_0**:** f_c is correct;

H_{-1}**:** $f_c - f_p$ is correct;

H_{+1}**:** $f_c + f_p$ is correct.

Actually, the external driver sets the corresponding values of the DC and lets CHASP measure the contrast. The flags multi_look and locate and measure_contrast should all be on. At the same time, it is recommended that the along track velocity parameter be varied. Contrast is higher for the right ambiguity number than for the other two hypotheses. The scores for each test are written in the header file:

```
contrast_-0.70_-0.0250 91.853935
contrast_-0.70_-0.0200 152.875870
contrast_-0.70_-0.0150 154.498505
contrast_-0.70_-0.0100 69.981544
contrast_-0.70_-0.0500 32.899227
contrast_0.30_-0.0250  81.000061
contrast_0.30_-0.0200  80.679070
contrast_0.30_-0.0150  66.814659
contrast_0.30_-0.0100  64.353661
```

```
contrast_0.30_-0.0500  30.610451
contrast_1.30_-0.0250  43.837189
contrast_1.30_-0.0200  51.074425
contrast_1.30_-0.0150  57.648361
contrast_1.30_-0.0100  65.502968
contrast_1.30_-0.0500  25.539270
```

For each score there are two subscripts, one defining the DC/PRF ratio f_c/f_p and the other defining the relative along-track speed adjustment $\Delta v/v_g$, normalized by the ground speed. The final part of the procedure is to look up the highest contrast.

7.1.4 Multilook Test

An initial DC estimate must be available. Multilook processing (described in Section 7.2) is not specifically designed for DC estimation, but it does provide an opportunity to validate the presumed value. While doing the multilook analysis for various look offsets, the IR measured in each look is saved in the header file. The locate option must be on. The check consists of simply examining if all of the processed looks present a high IR. Due to a possible DC error, the looks with the largest offset might have a low IR. Under ideal conditions, an algorithm could be designed to correlate the look IR with the integrated antenna gain for the corresponding band. Such an algorithm would work well for point targets and for uniform (or well averaged) clutter, but is not likely to be very precise for complex targets like ships. The output has the following form, expressed in dB:

```
look_mass_-0.80        48.017757
look_mass_-1.00        47.198250
look_mass_-0.70        46.294056
look_mass_-0.90        46.758781
look_mass_-0.60        47.809086
look_mass_-0.50        47.972179
look_mass_-0.40        45.993084
```

Here, again, the subscript stands for the DC/PRF value. In this case, none of the looks appears to be out of the presumed band, although the IR distribution does not look symmetric. Within an end-to-end scenario, this test could be formalized to provide a confidence measure for the DC estimate. The above values may be compared to the target RCS, estimated for the full bandwidth. In this particular case the estimated RCS for the same polarization (HH) was 47.8 dB.

7.1.5 Displacement Test

Target displacement, due to its LOS speed, is relatively easy to measure against known ground features (such as roads for moving ground vehicles). A similar approach is not suitable for moving vessels, since there is no static reference. However, a very similar approach is possible, based on the estimated central position of the uncompressed target response and the estimated position in the image. An algorithm for locating the uncompressed target response is built into the tracking technique (part of the techniques described in Section 7.3). The tracking algorithm is not designed specifically for DC estimation; it estimates the position of the uncompressed response for another purpose. It also estimates the image position of the target as obtained by a rudimentary SPECAN method. Therefore, whenever the tracking algorithm is used, the DC consistency test is also applied. The resulting correction is put in the header file, together with the other results of this algorithm. An example of the result is as follows:

```
track_dc_corr          0.0387084410
```

The result is the suggested correction of the DC expressed in terms of the PRF.

It should be mentioned that the error variance of the position estimates is rather high for uncompressed targets. As a comparison, this is comparable to estimating the DC in spectral domain for a single target in clutter. In both cases, the accuracy of the estimate depends strongly on the signal to clutter ratio, but it also depends on the slope of the antenna gain pattern in the used region.

An initial estimate is assumed, but its accuracy is not critical, since no band processing is involved. The result is ambiguous with respect to the PRF.

7.1.6 Range Misregistration Effects

This is one of the oldest methods for PRF ambiguity resolution. It is usually not precise enough to provide a good estimate of the fractional part of the DC. CHASP does not have this algorithm available internally. An external algorithm can be applied if two complex looks are produced and output from CHASP, as discussed in Section 8.

7.2 Adjusting the Along-track Speed and Doppler Rate

Along track velocity estimation starts after DC (i.e. radial velocity) estimation. The choice of the procedure depends on whether the available DC estimate is unambiguous (PRF ambiguity resolved) or ambiguous (PRF ambiguity not yet resolved).

All of the procedures in this category overlap with the other procedures described in Sections 7.1 and 7.3.

7.2.1 Azimuth Look Misregistration

This is probably the best starting point for along track velocity estimation. It can be used as soon as a DC estimate exists, even if the estimate is ambiguous, but it is recommened that the procedure be repeated if a refined DC estimate becomes available.

The same external tool that estimates misregistration in range (referred to in Section 7.1.6), also estimates misregistration in azimuth, since it does oversampling and 2D cross-correlation of two azimuth looks. This method can provide an initial velocity estimate together with PRF ambiguity resolution, but the velocity estimate must be further refined.

7.2.2 Contrast Improvement

As explained in Section 7.1, a search method for PRF ambiguity resolution can and should be combined with along track velocity estimation. If no previous velocity estimates exist, the domain of search should cover all reasonable values for vessels of interest. If a previous estimate is available, the search interval can be narrowed down.

7.2.3 Evaluation of the Phase Polynomial

When higher order phase terms are estimated (described in Section 7.3), it may still be of interest to have a single value for the along track velocity estimate.

If multilook method is applied with more than two looks, or if tracking is applied, second order coefficients may still be fitted, but usually a higher order is chosen, as discussed in Section 7.3.

An algorithm is implemented in CHASP to use such higher order polynomial coefficients, to derive the corresponding velocity polynomial coefficients, to evaluate velocity as a function of aperture time and then to find its central and mean value, as well as the standard deviation. The results are written into the header file in fractions of the ground speed. The output format is as follows:

```
vel_a_cenM            -0.0167134032
vel_a_meanM           -0.0169953499
vel_a_stdM            0.0057592499
vel_a_cenT            -0.0192909129
vel_a_meanT           -0.0189229604
vel_a_stdT            0.0071107792
```

The first three lines come from the multilook method, the following three lines come from the tracking method. This method is applied whenever multilook or tracking is used. After estimating the phase coefficients, along track velocity is estimated. Clearly, there are cases when the mean value is quite sufficient for good focusing.

7.3 Determining Higher Order Phase Coefficients

An attempt is made to assess the variability of the target speed over the exposure time.

7.3.1 Multilook Method

The multilook method, supported by CHASP itself, can be applied, using two or more looks. This approach requires that a good unambiguous DC estimate be known, because the method is based on 1D cross-correlation, assuming that the so-called range walk (RW) has been compensated properly. When only two looks are used they can each have a larger bandwidth, but it is possible to estimate just the second term of the phase polynomial, corresponding to a constant DR bias or a constant along-track velocity. Therefore, a small look bandwidth is used and look offset is changed to sweep through the available Doppler bandwidth.

An external driver changes the look offset, so that CHASP creates several pairs of looks each time it is launched. The results are stored in the proper section of the configuration file. An external tool must then set the auto_fit flag and let CHASP fit the polynomial coefficients for the phase. The coefficients are written back to the configuration file (usually a temporary configuration file is used). In this way, the coefficients become available for focusing.

Additionally, the method described in Section 7.2.3 is applied, making it possible to assess the appropriateness of the constant speed assumption. Also, the IR values are provided automatically, allowing for yet another assessment of the DC estimate, as explained in Section 7.1.

The diagnostic plots include the cross-correlation sequences for each pair of Doppler looks and for all polarimetric channels. The user can visualize the sharpness of the peaks to get an idea on how successful the process was.

7.3.2 Tracking

The tracking method is self sufficient; it requires only one run of CHASP to do tracking and to fit the phase polynomial. Conceptually, it does a similar task as the multilook method, but it does it in a continuous, recursive way.

This mode also includes the method described in Section 7.2.3. In addition to that, it also provides an estimate of the DC error, as discussed in Section 7.1.

Some diagnostic plots are also made available. The plots include the instantaneous frequency, scaled to represent the motion in terms of azimuth pixel spacing. The power at the input of the tracking filter is shown, as well as the power notched out by that filter.

8 External Support Tools

There is a set of stand-alone programs and a set of shell scripts which are used to view or to analyze COASP and CHASP products as part of the processing procedure.

The viewers use share-ware programs such as `Gnuplot` for the graphics and `xv` for image visualization. It is assumed that these programs are available on every platform on which COASP and CHASP may be run.

The analyzers are stand-alone, simple programs which do not themselves have any graphical capabilities.

8.1 Basic Data Quality Control

This is a script that creates some plots containing the following information saved by COASP:

- Georeference grid from the COASP header;
- Spatial distribution of the strongest input raw samples from the `extreme_?` files;
- Spatial distribution of the weakest input raw samples from the `extreme_?` files; and
- Spatial distribution of the coarse Doppler centroid estimates (aliased to base band).

These plots offer a quick assessment of the geographical coverage of the processed pass or part of a pass, an indication of potential raw data saturation and underflow, and an indication of potential Doppler problems.

The script is called `CHASPQC.sh`; it uses `Gnuplot`. Another script called `Gnu2PS.sh` is available for generating a post-script version of the plots.

8.2 Viewing the Image

Very basic tools are provided for viewing the image using `xv`. If a PGM option is used in CHASP, the product can be displayed directly by `xv`. In all other cases a conversion operation is necessary before using `xv`. One possibility is based on the program `float2chip`, which converts floating point raster images to some standard image formats. There is a script called `ShowImg.sh` which reads the COASP or CHASP header and then sets the parameters for `float2chip`, which does conversion to the PGM format and then uses `xv` to display the image. PGM is the simplest possible standard format recognized by most viewers. It is limited to single channel images. If composite, multi-channel images are to be created, the same standard tools that are used for PolGASP can be applied to COASP and CHASP.

8.3 Measuring Image Statistics

A program called `statis` is used to partition the data matrix into tiles and to extract some basic statistics based from the tiles. The program can read various numeric formats of the input data and it creates an ASCII file with the extracted statistics for each tile. The statistics include the minimum, maximum, power, mean-squared over variance and kurtosis, as well as some measures of the spatial correlation, if requested. The program can also be invoked to do the analysis only on one defined tile of interest. This program is used to measure the contrast in the CHASP output after each reprocessing stage. The tile of interest is selected around the target. In general, this tile differs from the internal spatial window that CHASP places around the target. Because of this difference, the level of contrast measured by CHASP internally and externally are not necessarily the same. However, the contrast dependence on the processing parameters shows the same trends and are not strongly affected by the choice of window.

8.4 Measuring Misregistration

A program called `statis2D` is used to measure the two-dimensional cross-correlation between two images, each representing one azimuth look. Like `statis`, this program partitions the images into tiles and computes tile-based statistics for the pairs of tiles, assuming that one is a shifted and noise corrupted version of the other. This program has initially been developed for master-slave co-registration, but is more general in nature. This program has various options; the one which is used does the following steps:

- Debias and scale each complex image to have mean 0 and variance 1;
- Oversample each image in any one or in both dimensions, as desired;
- For the oversampled complex images $A(p, l)$ and $B(p, l)$ compute the ratio:

$$g(\Delta p, \Delta l) = \frac{\langle |A(p,l)|^2 |B(p-\Delta p, l-\Delta l)|^2 \rangle}{\langle |A(p,l)|^2 \rangle \langle |B(p,l)|^2 \rangle} \tag{112}$$

  for the preset interval of values Δp and Δl and find the maximum of $g(\Delta p, \Delta l)$, which determines the misregistration; and

- Save the maximum and save the values of $g(\Delta p, \Delta l)$.

This program is used to estimate misregistration between two azimuth looks both in range and in azimuth. If DC is known, this program has no advantage over the 1D inter-look cross-correlation algorithm implemented in CHASP. In the case that DC is ambiguous, this method is better; it reveals the RW effect directly. The 1D method would have to be used under different hypothesized ambiguity numbers and then the strategy would be to choose the ambiguity number and the DR with the largest cross-correlation. 2D inter-look cross-correlation could also be used to refine the fractional part of the DC estimate. The purpose of oversampling is to be able to estimate the RW effects on a finer scale. According to the obtained results, however, this method is not very precise at estimating the fractional part of the DC. For EC CV-580 azimuth oversampling is not applied, because the natural spacing is sufficiently small to measure the inter-look displacement (drift). This may not be the case for spaceborne SAR; azimuth oversampling is necessary in that case.

8.5 Manipulating Polarimetric Channels

Several stand-alone programs are provided:

Transformation to Pauli basis The transformation matrix is

$$\mathbf{T} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & -j & 0 & j \end{bmatrix} \tag{113}$$

It transforms the ordered set of HH, HV, VV, VH values (the scattering vector) into the corresponding set of values in the Pauli basis. The program is called `pauli`.

Construction of a synthetic channel A program called `synthetic` performs a linear combination of the input polarimetric channel, given the complex weights.

Polarimetric filter for contrast improvement Given pure ocean polarimetric samples $\mathbf{S}_o(p,l)$ and several polarimetric samples $\mathbf{S}_n$, presumed to belong to the target, a set of weights $\mathbf{q}$ is sought such that the target to ocean contrast in the filtered image is maximized. The problem is to find the maximum of $\mathbf{q}^H \mathbf{T}_n \mathbf{q}$ subject to $\mathbf{q}^H \mathbf{R} \mathbf{q} = 1$, where $\mathbf{T}_n = \langle \mathbf{S}_n \mathbf{S}_n^H \rangle$ and $\mathbf{R} = \langle \mathbf{S}_o(p,l) \mathbf{S}_o^H(p,l) \rangle$. The solution to this problem is:

$$\mathbf{q} = \mathbf{R}^{-1/2} \mathbf{u}_{max} \tag{114}$$

where $\mathbf{u}_{max}$ is the most significant eigenvector of $\mathbf{R}^{-1/2} \mathbf{T}_n \mathbf{R}^{-1/2}$. The program is called `pfilt` and it needs as input one quad channel image with pure ocean and one quad channel image with a target. Target samples are selected as a given number of the brightest pixels in the target image.

Cross-polarimetric balancing The objective is to find a single constant complex factor q_x such that minimizes the quadratic norm of the difference $s_{hv} - q_x s_{vh}$. If the image is calibrated and if it is processed with the correct DC, the solution should be $q_x \approx 1$. This program is called `balance` and it can be applied to image chips to check channel reciprocity in calibrated images.

8.6 CHASP Drivers

CHASP drivers are used to automate some of the procedures for routine processing. CHASP drivers are used for two purposes:

- To automate parameter variation and to launch CHASP recursively; and
- To collect and present diagnostic plots for various CHASP algorithms.

Some CHASP drivers are used to perform other operations, such as:

- To position a window and extract a smaller image clip;
- To do some polarimetric channel manipulations; and
- To estimate some statistical features on produced image chips.

CHASP drivers are implemented as shell scripts, a fast and flexible way of creating a processing chain. A tighter and more automated processing chain can be designed and implemented as an intelligent wrapper for CHASP. It could encompass those procedures which are proven to be more successful upon more extensive testing.

The external CHASP drivers need a support file called GO.chasp. This file defines how to setup CHASP iterations. The content of this file is described below:

`SEARCH_DC` and `SEARCH_V` These are the lists of f_c/f_p and $\Delta v/v_g$ values to be searched in order to determine the combination with the least ghosting in the image. There are procedures to select the best parameters from the list.

`REFINE_DC` and `REFINE_V` These are the lists of f_c/f_p and $\Delta v/v_g$ values to be applied when trying to improve the contrast. There are procedures to select the best parameters from the list.

`STICK_DC` and `STICK_V` These are the values of f_c/f_p and $\Delta v/v_g$ to be applied when measuring azimuth look misregistration. The results must be interpreted as relative to the set values.

`PROFILE_LEN` A power profile is formed to help visually find the ghosts. This is the desired length of the profiles. If the length is less than the image chip azimuth dimension, then azimuth averaging is applied.

`CORRELATE_RG` and `CORRELATE_AZ` These are the maximum values for $|\Delta p|$ and $|\Delta l|$ when checking azimuth look misregistration by 2D correlation method described in Section 8.4.

`LOOKS_BW` and `LOOKS_OFFSET` These parameters are used to select the bandwidth and the position of a pair of azimuth looks which are then produced and compared in CHASP as discussed in Section 5.2.3. By varying the `LOOKS_OFFSET` parameter, several pairs of looks can be analyzed one after another.

`SEARCH_AT_MAX` This is a flag to indicate how to choose a window in the image for the contrast measure. It makes sense to restrict the area so that the target contrast, rather than the background contrast, is maximized. One of the possibilities is to zoom onto the brightest pixel; this is often the best way for large ships or single ships in the ocean.

`SEARCH_AT_PIX` **and** `SEARCH_AT_LIN` This are the image positions where the target is known or expected to show up. They may be used instead of the maximum to centre the position of the window in which the statistics are measured. Usually, they are not precisely known, but they are useful when other bright targets need to be eliminated.

`SEARCH_FRAC_PIX` **and** `SEARCH_FRAC_LIN` These are the reduction factors which define the size of the analysis window relative to the image chip size. The contrast measures are then taken within the window, ignoring the rest of the image.

`ZOOM_AT_MAX` This is another flag to indicate how to choose a window in the image for the contrast measure. If set, it allows the user to find the maximum within the already restricted window and to further zoom onto the corresponding pixel. Two step zooming may be useful if a part of the image is land or if there are multiple targets. The first window can then be defined in terms of the pixel position, thus excluding very bright targets which are not of interest.

`ZOOM_FRAC_PIX` **and** `ZOOM_FRAC_LIN` These are the reduction factors for the second window, if used.

`POLAR_NUM` **and** `POLAR_TYPE` These are the parameters which tell how to control optimization of the polarimetric filter for contrast improvement. As discussed in Section 8.5, it is possible to choose how many bright scattering pixels will be taken to represent the target. It is also possible to choose the channel in which such pixels are picked. It can be any of the original channels, any of the scattering elements in the Pauli basis, or a set taken from all polarimetric channels.

`SAVE_TO_DIR` This is the name of the directory where the results should be stored, including the configuration file with which CHASP was invoked, the produced header files and any plots or text files created as additional information or diagnostics.

The following is a list of the existing scripts with a brief description:

ProfGO.sh Basic operation: Loop through the list of `SEARCH_DC` and `SEARCH_V` values, launch CHASP, save CHASP header in the specified directory; Diagnostic operation: When each product is completed by CHASP, create power profile plots.

SearchGO.sh Basic operation: Loop through the list of `REFINE_DC` and `REFINE_V` values, launch CHASP, save CHASP header in the specified directory; Diagnostic operation: When each product is completed by CHASP, extract a smaller tile, measure its contrast and generate contrast plots.

SearchZoomGO.sh Basic operation: Loop through the list of `REFINE_DC` and `REFINE_V` values, launch CHASP; Diagnostic operation: When each product is completed by CHASP, extract a smaller tile, measure its contrast in each channel, convert to Pauli basis and measure contrast of all components and generate contrast plots for all cases.

SearchPGO.sh Basic operation: Loop through the list of `REFINE_DC` and `REFINE_V` values, launch CHASP for the given ship chip and for the given pure ocean chip; Diagnostic operation: When each product is completed by CHASP, extract a smaller tile, perform polarimetric filtering to improve contrast with respect to the ocean, measure contrast in the synthetic channel and generate contrast plots.

CorrelGO.sh Basic operation: Use `STICK_DC` and `STICK_V` values and other look related specifications and execute CHASP to create two complex looks; Diagnostic operation: When the two looks are formed, extract a smaller segment from each one, optionally compute a Pauli component, find the 2D inter-look cross-correlation on the requested channel or Pauli component, prepare the plots and convert peak location to DC and velocity adjustments.

LooksGO.sh Basic operation: Use `STICK_DC` and `STICK_V` values and other look related specifications and loop through the list of `LOOKS_OFFSET` values and execute CHASP to create two complex looks, then change CHASP mode to auto_fit and run it, save the header, the configuration and the correlation sequence to the requested directory.

9 Software Organization

COASP and CHASP have much in common in terms of software architecture and style. They are widely portable because they are written in standard C programming language and they use only standard Unix system facilities.

9.1 Libraries

This software contains a number of libraries. The following is the list of libraries statically linked into COASP or CHASP or both:

```
lib1D.a
lib3D.a
libada.a
libbasic.a
libgetpos.a
libingest.a
libinput.a
libio.a
liblarge.a
liblog.a
libmodules.a
libpixels.a
libshmap.a
```

On a Linux platform, the share-ware library `libfftw.a` is also added. On an SGI platform, this library is not used in favour of the commercial SGI environment.

The functionality of each library is now briefly outlined.

Library 1D has a set of functions for processing along range and along azimuth and for matrix transposition. Typical functions of this library are 1D transforms and filtering.

Library 3D has a set of functions for geometry calculations and operations with 3D vectors. Georeferencing and related functions are placed here.

Library ada has a set of functions used for adaptive processing. This is the only library that is not needed for COASP.

Library basic contains functions for vector arithmetic, waveform generation and some rudimentary uunctions required for the numerical methods. They are used by a variety of other functions.

Library getpos contains functions for reading the ancillary file, for reading and writing the Matlab™ formatted files and for time conversions.

Library ingest has the set of functions for reading input data files.

Library input has a collection of low-level functions for manipulating ASCII files in the token-value format and a set of utilities for manipulating filenames. These functions are taken from the PolGASP source code and archived into a library.

Library io contains a set of functions for reading and writing header files, configuration and other auxiliary files.

Library large contains only one function and it is used to provide means for using files larger than 2GB on 32 bit machines under Linux. It is not used on SGI platforms.

Library log contains functions for opening and writing log messages. Opening a log file redirects standard error to that file so that all error messaging is affected. Writing a log using this library automatically prepends the date and message type indicator.

Library pixels contains more functions used in image formation, but not 1D in nature.

Library shmap contains functions which support multitasking by forking, shared memory, synchronization mechanisms based on semaphores and utilities for managing parallel execution and shared memory organization.

Library modules has the set of all interface functions between the main program and the processing functions. The processing functions are written without any regard for the multitasking and parallel processing mechanisms. This library contains three functions for every SAR processing module, one to set the parameters for all processes, one to execute the principal processing operation of that module and one to conclude the operation, collect results, update status and data layout in memory. This library uses the utilities provided by the library shmap and is the only library which knows about the parallel execution.

9.2 Parallel Processing Mechanisms

When Symmetric Multiprocessing (SMP) hardware is used the most efficient method of parallelization is to assign different chunks of stored data to different processes. The parent process is forked to create clone processes, which all do the same operations, but act on different portions of the data. Optimally, but not necessarily, the number of processes should be equal to the number of available CPUs.

Processing modules are defined as units of processing which can work independently and asynchronously. At certain points, it is necessary to exchange the information between the processes. This is done within the module synchronization steps. The Inter-Process Communication (IPC) mechanism used for module synchronization in COASP and CHASP is the semaphore array.

Should any of the processes encounter a processing error or exception, it must signal to other processes before exiting. COASP and CHASP have signal handlers to capture various signals and to act accordingly. Most signals are acted upon in the following way: an error message is logged, the process then proceeds to the exiting function in which it sends a similar signal to all other active COASP or CHASP processes. The interrupt signal (signal 2) is processed in a different way. The signal handler sets some flags, but then COASP or CHASP are allowed to complete the current module. In the next synchronization step all processes become aware of the raised flag and they all exit cleanly and orderly. In this way, COASP processing can be interrupted at any point, still saving the work done up to that point. In case of processing errors, a similar logic is applied. The process which detected an error sets a flag for all other processes to see. In the following synchronization step, all processes exit cleanly.

9.3 Memory Organization

A large memory is required for processing SAR data blocks. In the case of parallel processing, this is best done using shared memory partitioned into sub-blocks.

Shared memory is obtained from the system in the initialization step. It has two memory banks, each of the size matching the data block dimensions. All operations can be performed out-of-place, such that the two memory banks serve as input and output in alteration. A third shared memory segment is also created that is structured and contains all relevant information about the current status and layout of the data block.

The dimension (range and azimuth length) of the data, the orientation (range fast index or azimuth fast index), type (real, complex) change during the course processing. Each module is responsible for maintaining the status information through its set and end part. The end part is also responsible for toggling the in/out flag whenever out-of-place operations are performed. This way modules can be skipped without disturbing other modules. Also it is much simpler to insert new modules or to replace existing ones.

In the case of single CPU processing, the same principles are used, but memory is locally allocated, rather than shared.

9.4 Software Modules

The main program controls the flow and the order of processing operations. It first completes the initialization in which all configuration and auxiliary files are read, FFT tables and static filters created, memory is sized-up and the multi-processing environment is created. Then the loop over all processing blocks and channels is started. Everything within the loop is done in a sequence of modules.

Each module has a set up part executed by the parent process. All parameters are set up in this step. When they are set, the parent process allows the second part of the module to commence. The set up step is followed by the do part executed by all processes. Since the forked processes are the clones of the parent process, they all perform the same operations, but each on its own chunk of the data block. As each process finishes the work it lets the parent process know and goes into the wait state. When all processes have completed the work, the parent process executes the end part of the module. It may collect and average all partial results, update the data status, toggle the in/out memory flag, log a proper message and so on. When this is completed, the parent process allows everyone to go to the next module. This pattern repeats for all operations from ingest to saving the processed block on disk.

9.5 Directory Structure

COASP and CHASP directory structure is shown below:

```
-rw-r--r--    MasterMakefile
drwxr-xr-x    bin
drwxr-xr-x    include
drwxr-xr-x    lib
drwxr-xr-x    src1D
drwxr-xr-x    src3D
drwxr-xr-x    srcada
drwxr-xr-x    srcbasic
drwxr-xr-x    srcgetpos
drwxr-xr-x    srcingest
drwxr-xr-x    srcinput
drwxr-xr-x    srcio
drwxr-xr-x    srclarge
drwxr-xr-x    srclog
drwxr-xr-x    srcmain
drwxr-xr-x    srcpixels
drwxr-xr-x    srcshmap
drwxr-xr-x    srcstore
drwxr-xr-x    test
```

Source code to build a library is inside a directory whose name starts with “src”. All header files are kept in the include directory. Libraries are built into the directory named lib. The executables are built into the directory called bin. The directory called test contains sample configuration files, various chirp files and the scripts.

9.6 Software Installation

The software is under Concurrent Version System (CVS) and can be checked out using the following command:

```
cvs co marina/chasp
```

The COASP and CHASP directory structure will be created.

The file called MasterMakefile must be examined. It contains the line which specifies the type of platform on which the software is being installed. It can be one of:

```
MACHINE = L
```

which applies to Linux or

```
MACHINE = I
```

which applies to IRIX. This line must be checked to make sure that the correct platform is specified. After that the executable is built simply using:

```
make -f MasterMakefile clean chasp1
```

for COASP and

```
make -f MasterMakefile clean chasp2
```

for CHASP, or

```
make -f MasterMakefile clean all
```

for both. It is a good idea to make it "clean", though not necessary. The executables `chasp1` and `chasp2` should appear in the bin directory.

The command:

```
make -f MasterMakefile clean
```

removes all object files, libraries and executables.

If needed for whatever reason, the libraries can be built separately. For example the command:

```
make -f MasterMakefile 3D
```

builds the library lib3D.a into the lib directory using the sources in src3D directory. All source directories correspond to a valid target which can be created by MasterMakefile. Other possible targets are chasp1, chasp2, test, clean and all.

Sample configuration files can be found in the test directory and then adapted for the processing of interest.

10 Summary

In this document we have reviewed the algorithms and software that implement the COASP and CHASP processors for processing moving target data from the EC CV-580 SAR. This functionality replaces and augments the PolGASP processor. PolGASP was not developed for moving targets.

COASP is a strip map processor that is block-oriented and uses a Range-Doppler algorithm. COASP is a pre-processor for CHASP and is now used operationally at DRDC Ottawa for processing EC CV-580 SAR data.

CHASP is a single block processor that contains several automatic and interactive algorithms to estimate and adapt to the target Doppler centroid and Doppler rate. This provides estimates of the target velocity and improved image focus. CHASP will be used as a pre-processor for downstream polarimetric target decomposition analysis. This will provide insight to target detection and calibration, which will aid preparation for RADARSAT-2 polarimetric modes of operation and will improve Polar Epsilon target detection and classification capabilities.

References

[1] Cumming, I.G., and Wong, F.H. (2005), *Digital Processing of Synthetic Aperture Radar Data*, Artech House.

[2] Dragošević, M.V., and Stanković, S.S. (1995), *An Adaptive Notch Filter with Improved Tracking Properties*, IEEE Trans. Sig. Proc., Vol. 43 No. 9, pp. 2068-2078.

[3] Hawkins, R.K., Wind, A., Murnaghan, K.P., Gibson, J.R., Nedeclu, S., and Brown, C.E. (2003), *Processing of the C-band Polarimeter on the Environment Canada CV-580 – A Review*, Adv. Space Res., Vol. 32, No. 11, pp. 2319-2328.

[4] Livingstone, C.E., Gray, A.L., Hawkins, R.K., Vachon, P.W., Lukowski, T.I., and Lalonde, M. (1996), *The CCRS Airborne SAR systems: Radar for Remote Sensing Research*, Can. J. Rem. Sens., Vol. 21, No. 4, pp. 468-491.

[5] Rosich Tell, B., and Laur, H. (1996), *Phase Preservation in SAR Processing: The Interferometric Offset Test*, Proc. IGARSS'96, Lincoln, Nebraska, pp. 477-480.

[6] Ulander, L.M.H., Hawkins, R.K., Livingstone, C.E., and Lukowski, T.I. (1991), *Absolute Radiometric Calibration of the CCRS SAR*, IEEE Trans. Geoscience Rem. Sens., Vol. 29 No. 6, pp. 922-933.

[7] Vachon, P.W., Campbell, J.W.M., Bjerkelund, C.A., Dobson, F.W., and Rey, M.T. (1997), *Ship Detection by the RADARSAT SAR: Validation of Detection Model Predictions*, Can. J. Rem. Sens., Vol. 23, No. 1, pp. 48-59.

Annex A: COASP Test Results

COASP has replaced PolGASP upon successful testing.

Data sets summarized in Table A.1 have been used for initial COASP testing. These are all calibration passes.

Several types of tests were conducted, including comparison with PolGASP in terms of calibration, PTR resolution analysis based on Targanal, channel co-registration tests and phase preservation tests. In addition, a repeat pass interferometric product was generated using the data sets 277 and 275 and it was found to have a higher coherence than the corresponding product that had been generated using PolGASP. However, the improvement should probably be attributed to the improved motion calculation software (InQC instead of MoComp).

Several tests have become part of the standard processing procedure. In particular, the PTR 3dB peak width and channel co-registration are routinely checked.

Calibration Tests

Calibration constants based on COASP and PolGASP processing were compared. The results are presented in Tables A.2, A.3, A.4 and A.5 for the four calibration channels. Both the magnitude constant, K', and the phase corrections are in good agreement. There is a discrepancy in the case of dataset 320 (CoCoNaut trial), . A number of data sets from the CoCoNaut trial had a problem because the corner reflectors were placed too close to a high-RCS object. Therefore, some of the results are not reliable. In this case, the COASP result is in line with the other, regular, cases; the PolGASP results seems to be off.

Focus Tests

A typical example of focus test results is shown for a SAW IN case in Table A.6 and for a SAW OUT case in Table A.7. The results are based on the PTR of the corner reflectors as analyzed by Targanal. The 3dB peak width is expressed in terms of range or azimuth spacing.

Table A.1: *Data sets used for COASP testing.*

id	*line&pass*	*date*	*trial*	*SAW*
277	l1p8	24-Sept.-2002	Ottawa	IN
275	l1p6	24-Sept.-2002	Ottawa	IN
295	l7p8	07-Oct.-2003	Quest	IN
320	l1p2	23-Sept.-2005	CoCoNaut	IN
330	l1p12	23-Sept.-2005	CoCoNaut	OUT
294	l7p7	07-Oct.-2003	Quest	OUT
298	l2p2	22-March-2004	MarCo-Pola	IN

Table A.2: *HH channel calibration comparison.*

		K' [dB]		*phase* [deg]	
	id	*PolGASP*	*COASP*	*PolGASP*	*COASP*
SAW IN	277	115.79	115.53	0.00	0.00
	275	115.78	115.58	0.00	0.00
	295	116.38	115.08	0.00	0.00
	320	127.00	116.47	0.00	0.00
	298	116.37	115.73	0.00	0.00
SAW OUT	330	117.38	116.95	0.00	0.00
	294	119.85	119.17	0.00	0.00

Table A.3: *HV channel calibration comparison.*

		K' [dB]		*phase* [deg]	
	id	*PolGASP*	*COASP*	*PolGASP*	*COASP*
SAW IN	277	129.69	129.65	49.90	48.93
	275	129.74	129.63	49.45	49.22
	295	132.52	131.21	299.06	299.24
	320	141.50	131.03	282.78	283.22
	298	132.79	132.20	293.87	293.06
SAW OUT	330	132.60	132.27	36.76	36.48
	294	133.29	133.04	36.91	42.10

Table A.4: *VV channel calibration comparison.*

		K' [dB]		*phase* [deg]	
	id	*PolGASP*	*COASP*	*PolGASP*	*COASP*
SAW IN	277	118.38	118.38	291.23	293.03
	275	118.36	118.37	288.53	289.80
	295	119.32	118.15	285.82	286.05
	320	129.00	118.74	185.18	282.88
	298	118.63	117.83	281.25	282.72
SAW OUT	330	120.24	119.56	287.97	286.92
	294	122.16	121.46	278.69	279.04

Table A.5: *VH channel calibration comparison.*

		K' [dB]		*phase* [deg]	
	id	*PolGASP*	*COASP*	*PolGASP*	*COASP*
SAW IN	277	130.33	130.24	32.65	30.76
	275	130.34	130.17	30.82	28.96
	295	133.07	131.77	307.94	306.63
	320	142.20	131.80	284.61	283.74
	298	134.46	133.67	299.71	297.35
SAW OUT	330	133.73	133.14	45.70	46.91
	294	134.18	133.65	34.01	37.90

Table A.6: *PTR 3dB width for 277.*

	azimuth [pixels]			*range* [pixels]		
calibrator	*COASP InQC*	*PolGASP InQC*	*PolGASP MoComp*	*COASP InQC*	*PolGASP InQC*	*PolGASP MoComp*
S3 HH	1.62	1.75	3.75	1.62	1.50	1.50
VV	1.62	1.62	3.62	1.62	1.50	1.50
S4 HH	1.62	1.62	3.62	1.50	1.50	1.50
VV	1.62	1.62	3.50	1.62	1.50	1.50
S5 HH	1.88	2.00	3.62	1.62	1.62	1.50
VV	1.88	1.88	3.50	1.50	1.50	1.62
S6 HH	2.00	1.88	3.50	1.50	1.50	1.38
VV	1.88	2.00	3.75	1.62	1.62	1.50
S7 HH	1.88	2.00	3.38	1.50	1.50	1.50
VV	1.88	1.88	3.62	1.50	1.50	1.62
S8 HH	1.62	1.62	3.25	1.50	1.50	1.50
VV	1.75	1.75	3.62	1.50	1.50	1.50

Table A.7: *PTR 3dB width for 330.*

	azimuth [pixels]		*range* [pixels]	
calibrator	*COASP InQC*	*PolGASP InQC*	*COASP InQC*	*PolGASP InQC*
DREV HH	1.75	1.75	2.00	2.50
VV	1.75	1.75	2.00	2.50

This example is one of the better-focused PolGASP cases. It is clear that InQC plays a major role in achieving good image resolution. In comparison with PolGASP, COASP resolution is as good as or, in some cases, slightly better.

Co-registration Tests

These tests have now become standard procedures for all COASP processing. A typical example is shown in Table A.8 for a SAW IN case and in Table A.9 for a SAW OUT case. The results are based on Targanal PTR analysis for different channels. The peak positions in the oversampled image chips are compared and the difference is expressed in terms of the original range and azimuth spacing. Channels which are compared are HH and VV for all calibrators, as well as HV and VH for the ARC calibrators. In all of the compared pairs one of the channels had to be interpolated and shifted for alignment with the other channel.

Phase Preservation Tests

Phase preservation tests were conducted using a modified CEOS offset processing test [5]. As in the CEOS test, the same raw data are processed twice, but an offset in both azimuth and in range is introduced when the data are processed for the second time. Then an interferogram is formed for the overlapping part and the phase statistics is examined.

Table A.8: *Channel co-registration for 277.*

	azimuth [pixels]		*range* [pixels]	
calibrator	*COASP*	*PolGASP*	*COASP*	*PolGASP*
Powerhog VV-HH	0.000	-0.125	-0.125	0.000
HV-VH	0.000	0.000	0.000	0.000
Serafina VV-HH	0.000	-0.125	-0.125	-0.125
HV-VH	0.125	-0.125	0.000	0.125
S3 VV-HH	0.000	0.000	-0.125	-0.125
S4 VV-HH	0.000	0.000	0.000	0.000
S5 VV-HH	-0.125	0.000	0.875	-0.875
S6 VV-HH	-0.125	0.000	-0.125	-0125
S7 VV-HH	1.000	-1.000	0.000	0.000
S8 VV-HH	0.000	0.000	0.875	-1.000

Table A.9: *Channel co-registration for 330.*

	azimuth [pixels]		*range* [pixels]	
calibrator	*COASP*	*PolGASP*	*COASP*	*PolGASP*
Powerhog VV-HH	0.000	0.000	0.000	0.375
HV-VH	0.000	-0.375	0.000	0.500
DREV VV-HH	0.125	0.000	-0.625	1.125

According to the standard CEOS offset processing test, the processing parameters should be kept unchanged for the two products. On condition that the processing parameters are identical, the bias and the variance of the interferometric phase should be below some very low thresholds. The recommended bias threshold is some fraction of a degree and the threshold for the standard deviation is 5 degrees. This test can be used to detect some obvious flaws in the design or in the implementation.

In our case, we have modified the test to include the updates which naturally occur in azimuth. Two kinds of updates are considered. Firstly, the focusing parameter "PRF over v" varies slightly and COASP can do block-to-block updates or use the mean value for the processing interval or use an externally set value. Secondly, the geometry varies slowly in azimuth. COASP can update the elevation angle once in a sub-block or for each pulse. The updated geometry is used during motion compensation. Alternatively, COASP can use the same motion compensation algorithm as PolGASP, in which case there are no updates; the altitude is considered to be constant and the Earth is approximated by a plane. Both kinds of updates, "PRF over v" and geometry, require a compromise between two artifacts, namely phase discontinuities and accumulation of phase errors.

Several plots are included to illustrate the main results. The examples show the effects related to the size of the processing block and to the updating strategy. In all plots, the position of the block borders is marked by "A" for one product and by "B" for the other. The azimuth offset is 500 range lines in all examples. The range offset is 100 range bins. Interferometric phase bias and standard deviation are estimated by averaging in range. The full slant range is divided into four segments and the results for the first (near) and last (far) segments are shown. In the example shown in Fig. A.1, the block size is 8192 and is divided into four sub-blocks. The elevation angle is updated once in each sub-block and "PRF over v" is updated once in a block. Geometry updates cause excessive discontinuities at near ranges (close to nadir). At far ranges they become less pronounced, while the "PRF over v" discontinuities show more. In the next example, shown in Fig. A.2, geometry is recalculated for each range line. The results are almost identical to the ones obtained with no geometry updates (not shown). However, if no geometry updates are made, the absolute phase errors accumulate; the trend is the same in both products so that it cancels out. The only discontinuity noticeable in Fig. A.2 is due to the "PRF over v" updates at the block borders. In each block, the mean "PRF over v" value for that block is used. Most of the time, such mean values are only slightly different for the two offset products. However, when a new block is started in one product and not yet in the other, the averaging intervals differ more significantly and the difference in "PRF over v" becomes larger. A similar situation is seen in Fig. A.3, except that the block size is 4096 and block borders occur more frequently. Finally, the smoothest results are shown in Fig. A.4. In this case the average "PRF over v" value for the processed interval is used in each of the two products. The "PRF over v" values are slightly different for the two products, due to the offset of 500 lines. In this particular case, the values are 2.330045 and 2.330122. Hence, there is a non-zero bias in the interferogram phase. This bias increases from near to far range, creating a slight ramp. This behavior is in complete agreement with the theoretical results. The interferometric phase variance increases with range as the SNR decreases, as expected.

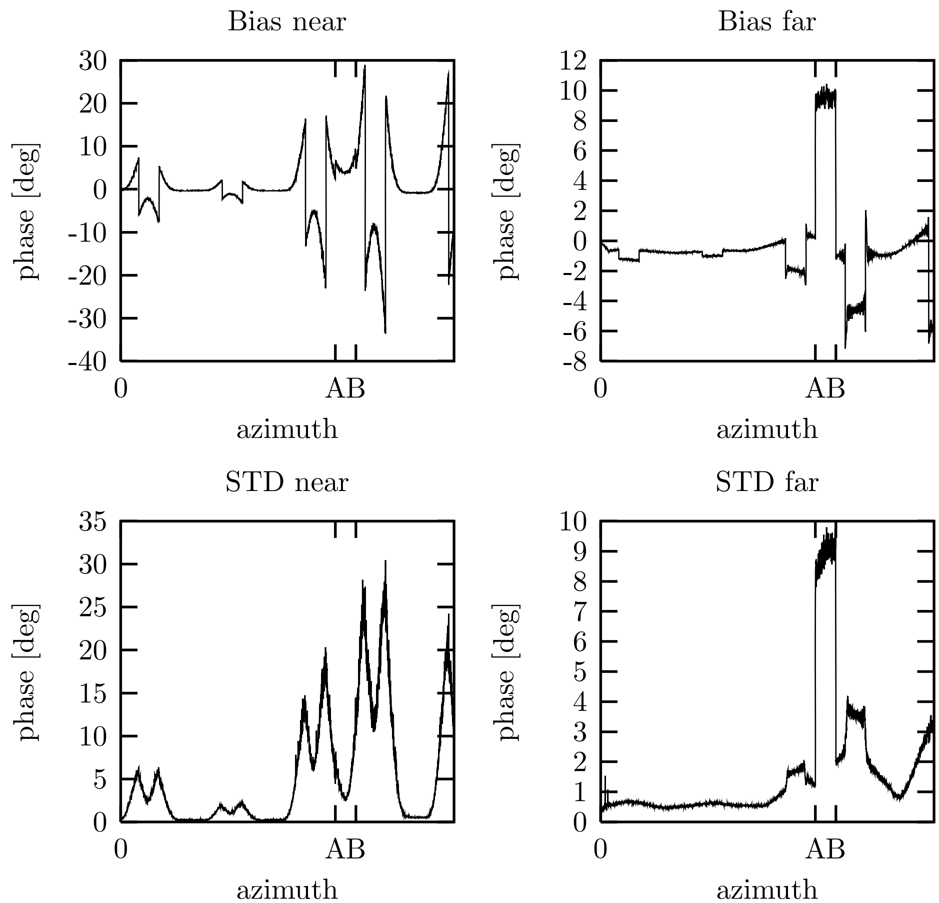


Figure A.1: *Phase preservation test 1 for 277. Block size 8192; "PRF over v" updated for each block; elevation angle updated four times per block.*

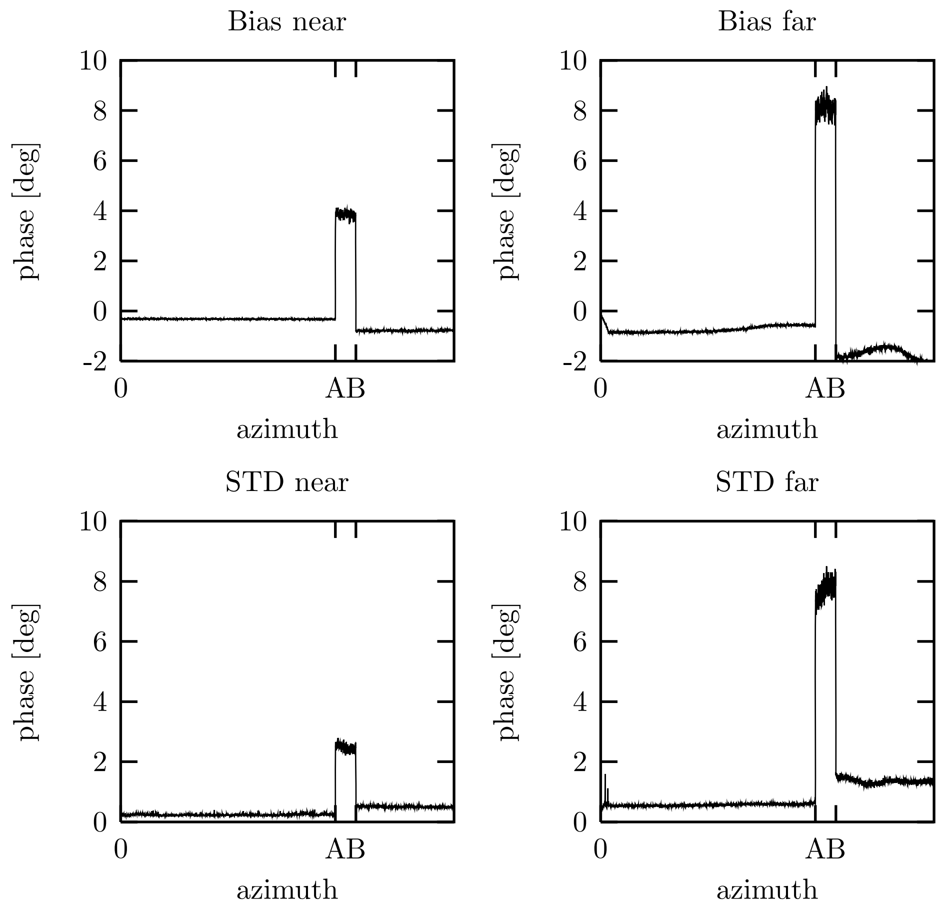


Figure A.2: *Phase preservation test 2 for 277. Block size 8192; "PRF over v" updated for each block; elevation angle updated for each pulse.*

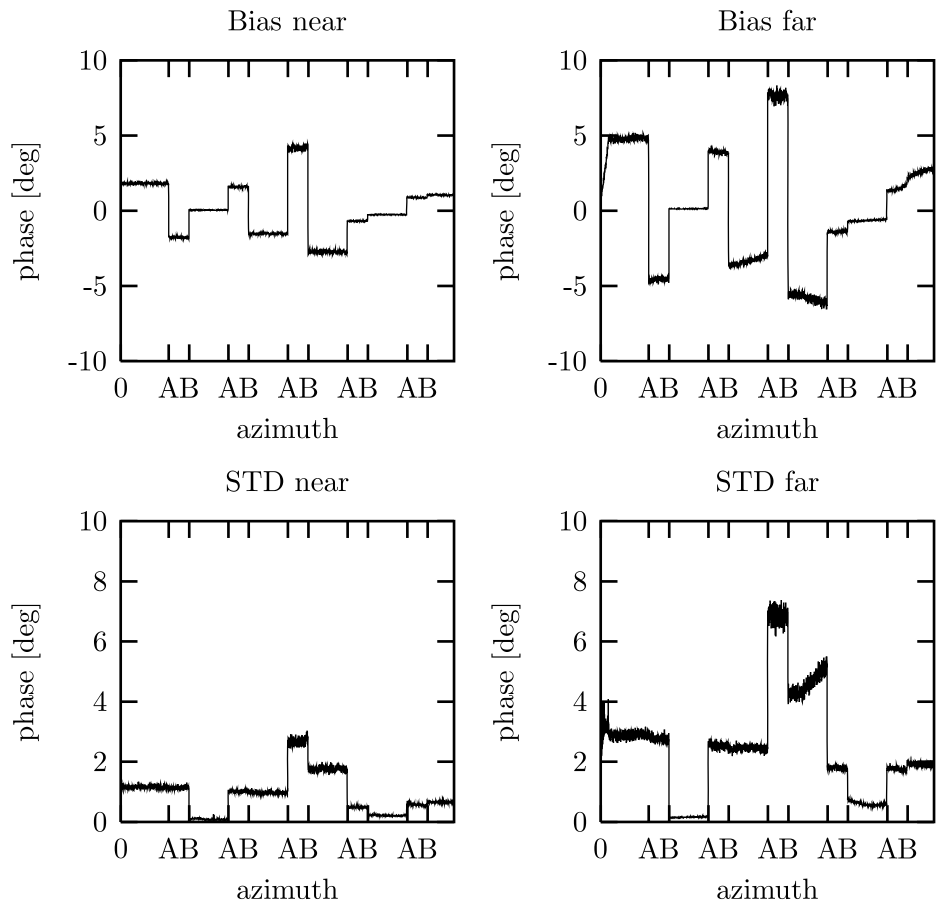


Figure A.3: *Phase preservation test 3 for 277. Block size 4096; "PRF over v" updated for each block; elevation angle updated for each pulse.*

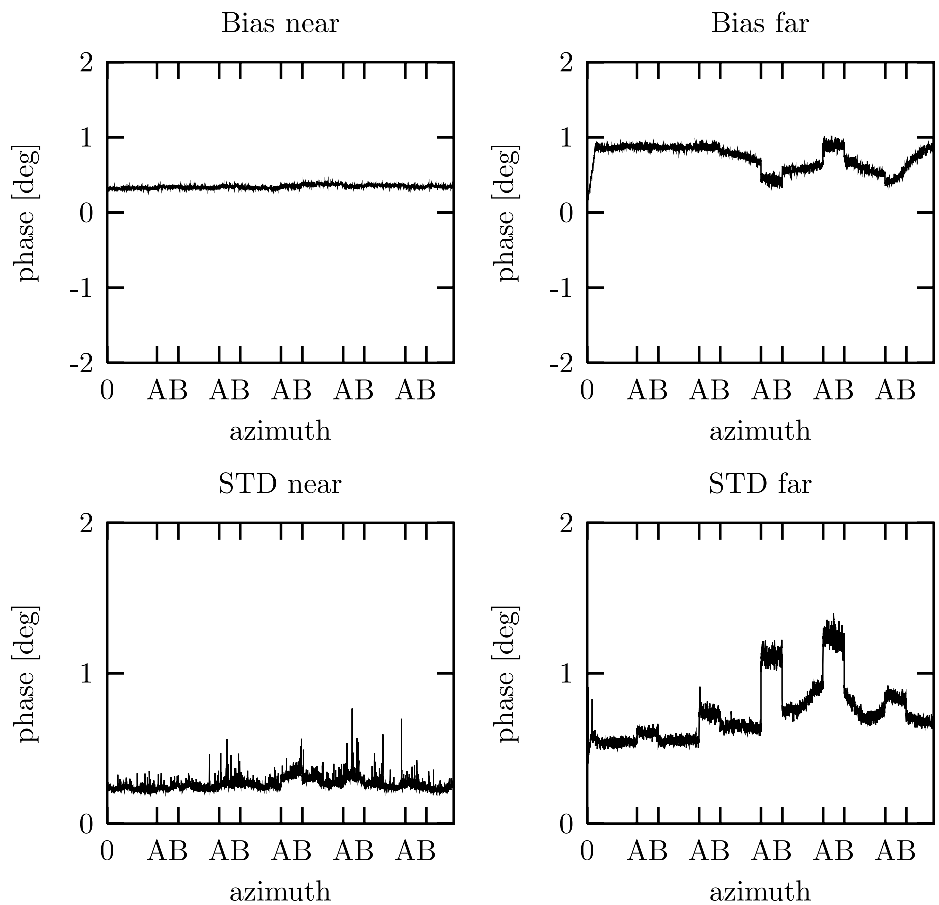


Figure A.4: *Phase preservation test 4 for 277. Block size 4096; mean "PRF over v" used; elevation angle updated for each pulse.*

This page intentionally left blank.

Annex B: CHASP Processing Examples

Three processing examples are shown in this report. The data were acquired during the CoCoNaut trial on 23-Sept.-2004 off the west coast of Vancouver Island. Two vessels, observed under different conditions, are analyzed. The first vessel, CCGC *Cape St. James*, is small and at a rather low incidence angle. Because of this, the signal-to-clutter ratio is rather low and the integration time is short. The other ship, a bulk oil tanker, is large and is at a higher incidence angle. Therefore, its signal-to-clutter ratio is higher and integration time is longer. *Cape St. James* was equipped with a GPS device. The Tanker is a ship of opportunity; its identity, position, and velocity are available from coastal radar traffic logs. The Tanker is detected in two passes so velocity can also be estimated from its displacement between the two acquisition times.

Velocity Estimation Results

EC CV-580 SAR and vessel parameters are shown in Table B.1. True and estimated velocities are presented for *Cape St. James* in l1p8 and for the Tanker in l1p8 and l1p9 based upon GPS measurements and Marine Communications and Traffic Services (MCTS) coastal radar, as available. The airplane track was from North to South for l1p8 and from South to North for l1p9. Thus, V_East, the eastwards component of the vessel velocity, is also the cross-track component and V_North, the northwards component of the vessel velocity, is also the along-track component.

In all three cases, the vessels were georeferenced and various CHASP algorithms were applied to estimate velocity. the Tanker is observed in two consecutive passes; the time interval between the acquisitions was 994 seconds; which corresponds to the first velocity estimate in Table B.1 (georeferenced displacement). This type of estimation is not available for *Cape St. James*.

Cross-track (V_East) estimates shown in the table are based on the procedures described in Section 7.1. Cross-track velocity based on ghost minimization is not shown for *Cape St. James* because there were no visible ghosts for a large interval of DC values around 0. Cross-track velocity estimate for the Tanker based only on ghost minimization over the baseband DC interval (-0.5 to 0.5) would have been wrong; the ambiguity is resolved using the contrast improvement technique, confirmed by the range misregistration technique. Corrections of the initial DC estimates, based on tracking and contrast refinement, as discussed in Section 7.1, are also shown.

Along-track (V_North) estimates are based on a contrast improvement procedure, as discussed in Section 7.2 and on the two procedures discussed in Section 7.3.

Diagnostic Plots

As shown in Figs. 8 and 9, it is possible to generate diagnostic plots associated with various CHASP procedures. Such plots illustrate the applied techniques very well. Some examples

Table B.1: *Velocity estimation results for CoCoNaut data, 23-Sept.-2004.*

SAR	*l1p8*	*l1p8*	*l1p9*
track angle [deg]	179.50	179.50	359.50
incidence angle [deg]	45.54	61.40	70.63
integration time [s]	3.77	5.52	8.19
Vessel	*Cape St. James*	*Tanker*	*Tanker*
length [m]	14.6	183	183
time [UTC]	19:20	19:24	19:41
ground truth	GPS@1s	MCTS@360s	MCTS@360s
V_East [m/s]	**0.00**	**7.49**	**6.65**
georeferenced displacement	N/A	7.40	7.40
ghosts	?	7.28	7.49
range misregistration	0.00	8.03	8.63
tracking offset	-1.27	6.69	6.66
contrast refinement	-0.64	7.82	6.10
V_North [m/s]	**9.76**	**-2.72**	**-2.16**
georeferenced displacement	N/A	-2.30	-2.30
multi-look	8.23	-2.37	-2.16
tracking	8.93	-2.58	-2.30
contrast	10.46	-2.09	-2.70

are shown in this section.

Fig. B.1 illustrates the ghost minimization technique in the example of the Tanker in pass l1p8, channel HH. From the series of presented plots, it is clear that the ghosts become symmetric at a relative DC of between 0.3 and 0.4; the minimum value found in the CHASP header is 0.3. User might want to refine the search step in this interval.

Fig. B.2 illustrates the inter-look misregistration in range and azimuth for the Tanker in l1p8, channel HH. Range misregistration is due to an ambiguity of -1. The plot is created assuming that the relative DC is 0.3. User may correct for the ambiguity and repeat the procedure for a new value of DC set to -0.7. Then, the peak would appear at or very close to zero. This confirms the result obtained by measuring the contrast for ambiguity hypothesis 0 and ± 1. At the same time, the azimuth misregistration is measured as also shown in Fig. B.2. Azimuth misregistration is caused by the uncompensated along track velocity. Similarly, if the along track velocity is adjusted and the procedure reiterated, the peak should move to zero.

Fig. B.3 llustrate inter-look misregistration in range and azimuth, for the *Cape St. James*. In this case, no cross-track velocity component is revealed, but the along-track velocity component is strong. Local maxima and lower main peak of the azimuth cross-correlation sequence illustrate some of the problems encountered when estimating motion of small vessels, especially at ranges closer to nadir.

Multilook analysis is illustrated in Fig. B.4 for the Tanker in pass l1p8, channel HH. Similar

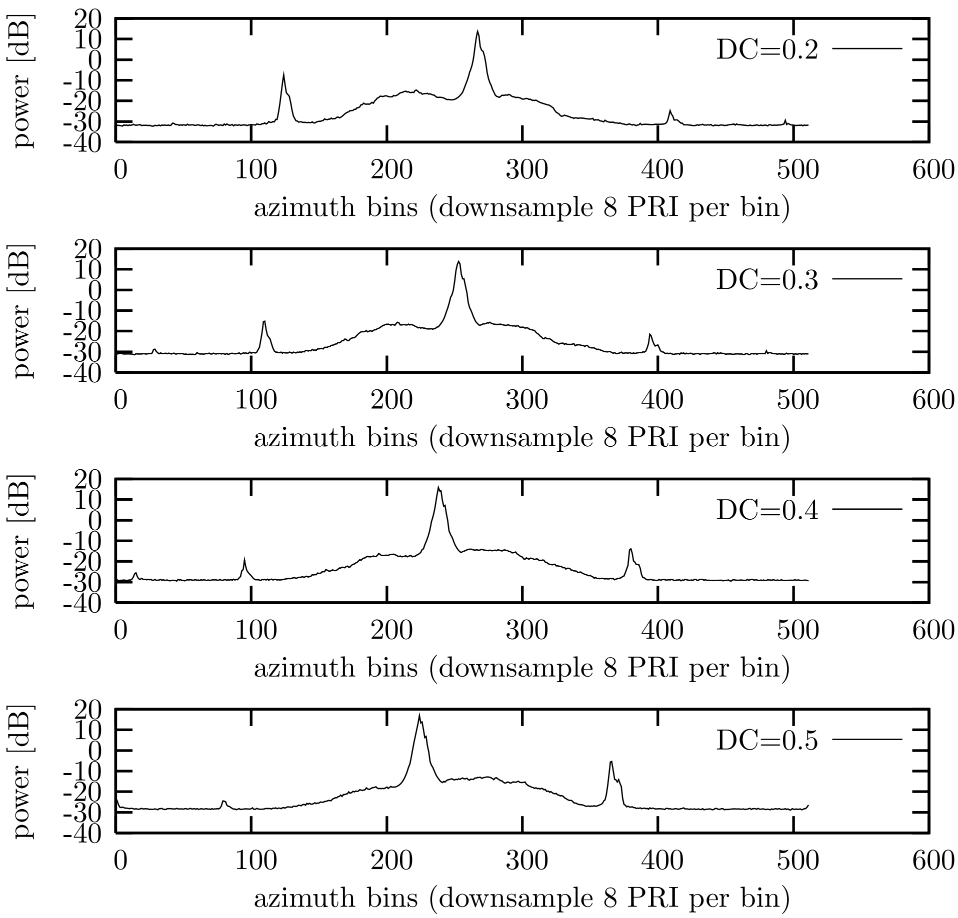


Figure B.1: *Power profiles for different DC values for the Tanker.*

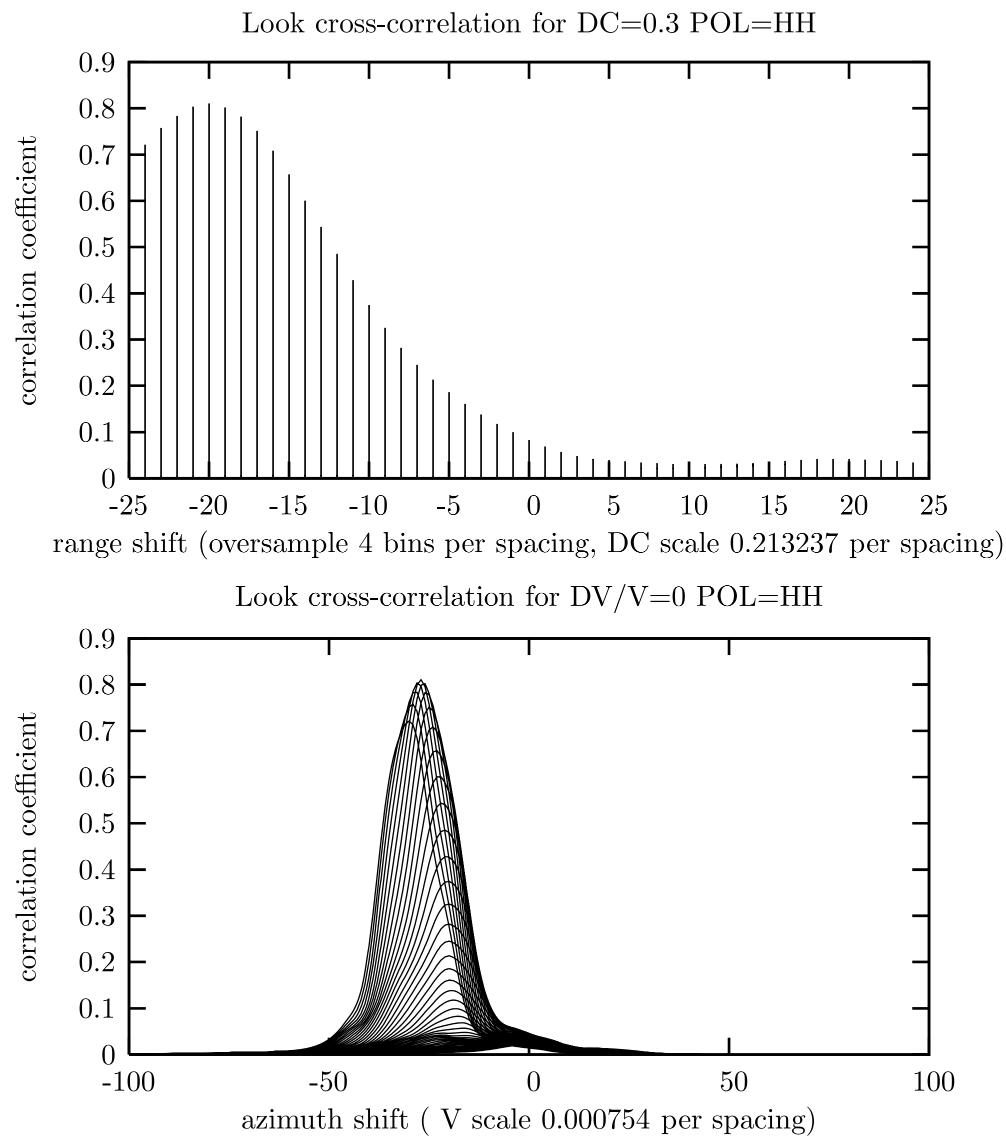


Figure B.2: *Look cross-correlation as a function of range and azimuth for the Tanker.*

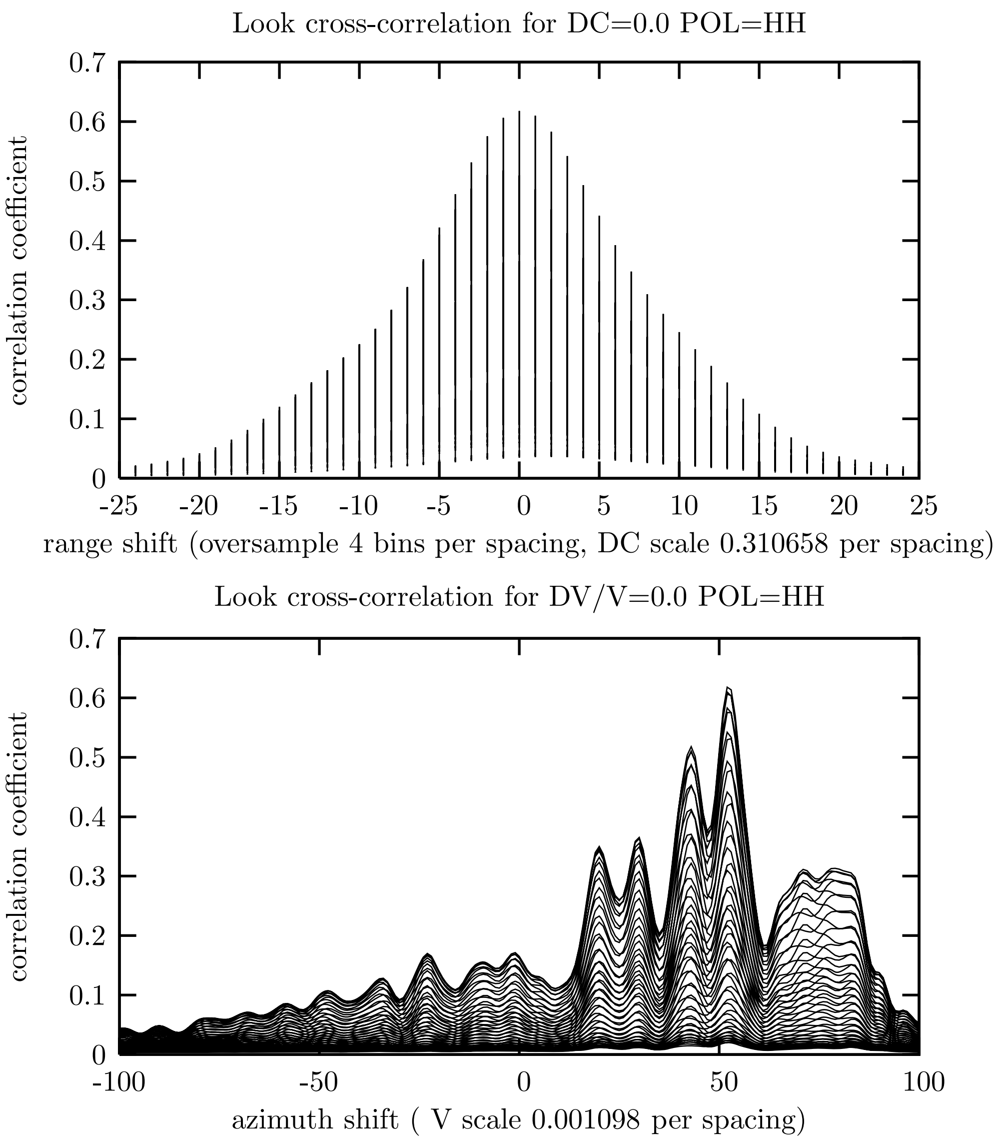


Figure B.3: *Look cross-correlation as a function of range and azimuth for* Cape St. James.

plots are made available for all channels. The assumed relative DC is 0.7, the relative look bandwidth is 0.2 and along track velocity is set to 0. The look frequency offset is varied in steps of 0.1, creating 5 pairs of adjacent looks. The cross-correlation plots are shown in descending order of frequency offsets. All plots indicate that there is a negative along-track velocity error; the intensity of the error decreases slowly towards negative frequency offsets.

The multi-look results are in good agreement with the frequency tracking results shown in Fig. B.5 also for the Tanker in pass l1p8. The central part of the plot, between lines 3000 and 5000, belongs to the Tanker. All four channels are represented and tracking is done forward and backward in time. The slope of the tracking curves corresponds to misregistrations in figure B.4; increasing time corresponds to decreasing frequency offset. The tracking algorithm is an adaptive notch filter. Signal power extracted by this filter is also presented in Fig. B.5 for all channels in forward and backward tracking. Due to a very high signal-to-clutter ratio for the Tanker, the extracted power is almost equal to the input power (not shown). This measured power is used to locate the uncompressed ship response and then to compare it to the location of the compressed image. It is clear why this method cannot be very precise; the power plot differs significantly from the ideal shape expected for a point target.

Tracking applied to the *Cape St. James*, is depicted in Fig. B.6. The duration of tracking is between lines 1500 and 2500, shorter than for the Tanker. The signal power driving the adaptive filter is lower; estimating its position in the raw data is even more difficult.

Fig. B.7 illustrates the contrast improvement method. Contrast is shown as a function of relative along-track velocity for *Cape St. James* in pass l1p8, for all channels and for a synthetic channel derived by polarimetric filtering. It is clear that the contrast metric depends on the choice of polarization. Generally, the channel with the highest contrast leads to the best results. Contrast optimization via polarimetric filtering usually agrees with the results for the single, highest contrast, channel.

RCS Results

RCS estimation results are shown in Table B.2 for the three analyzed cases. They are compared to a rule-of-thumb model for the RCS of a ship according to the formula [7]:

$$\sigma = 10 \log_{10}(0.08 L^{7/3}(0.78 + 0.11\, \alpha_i)) \tag{B.1}$$

where L is the ship length in metres, α_i is the incidence angle expressed in degrees, and the resulting cross section is in dB relative to 1 m^2. The measured values compare favorably with the rule-of-thumb model. The estimated ocean clutter values are also shown. The clutter level is very low in this case since the winds were light during data acquisition.

Refocused Images

Fig. B.8 shows the *Cape St. James* before (Fig. 8(a)) and after (Fig. 8(b)) CHASP processing.

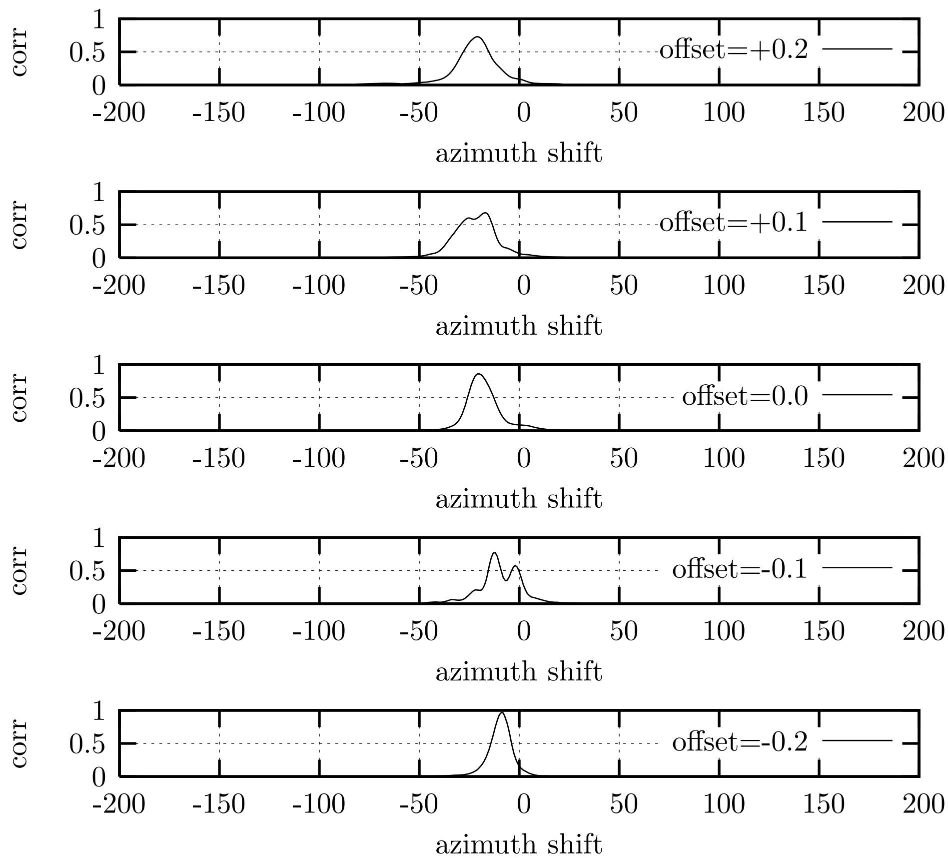


Figure B.4: *Multilook cross-correlation for the Tanker.*

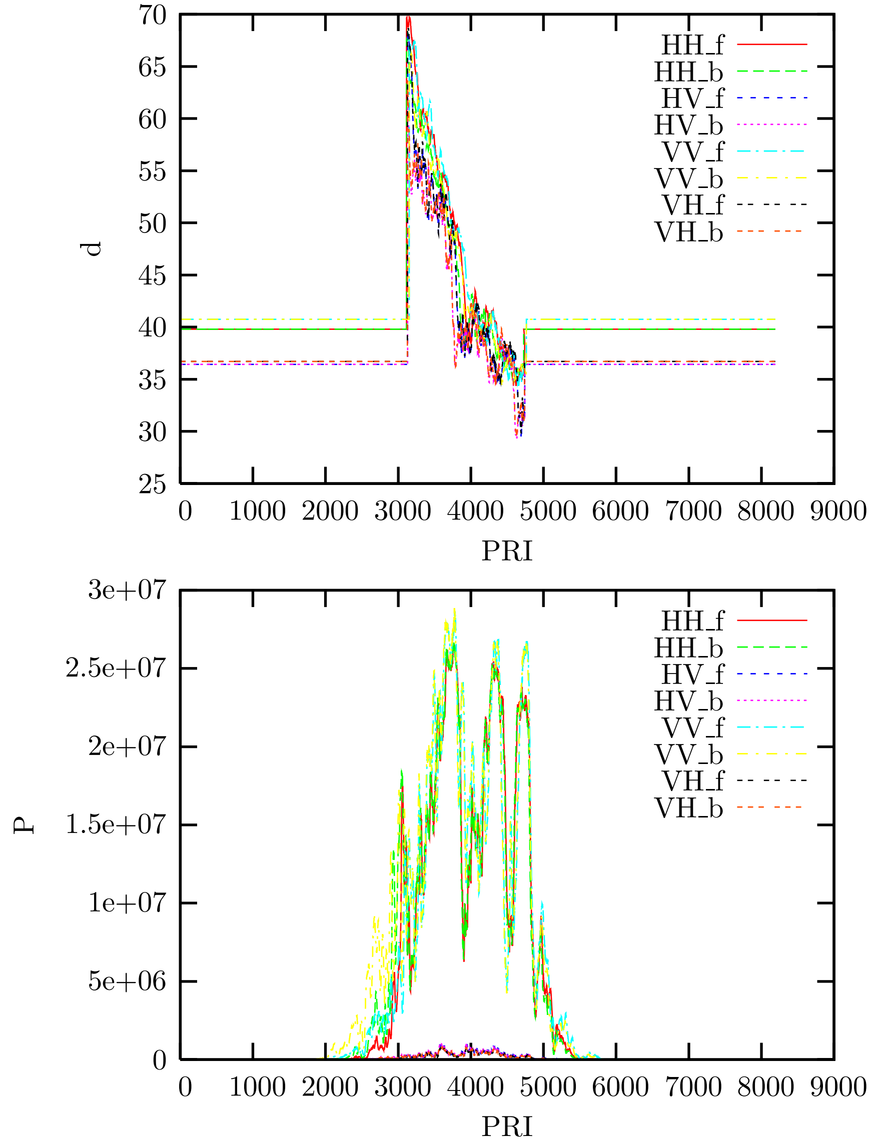


Figure B.5: *Azimuth frequency tracking for the Tanker.*

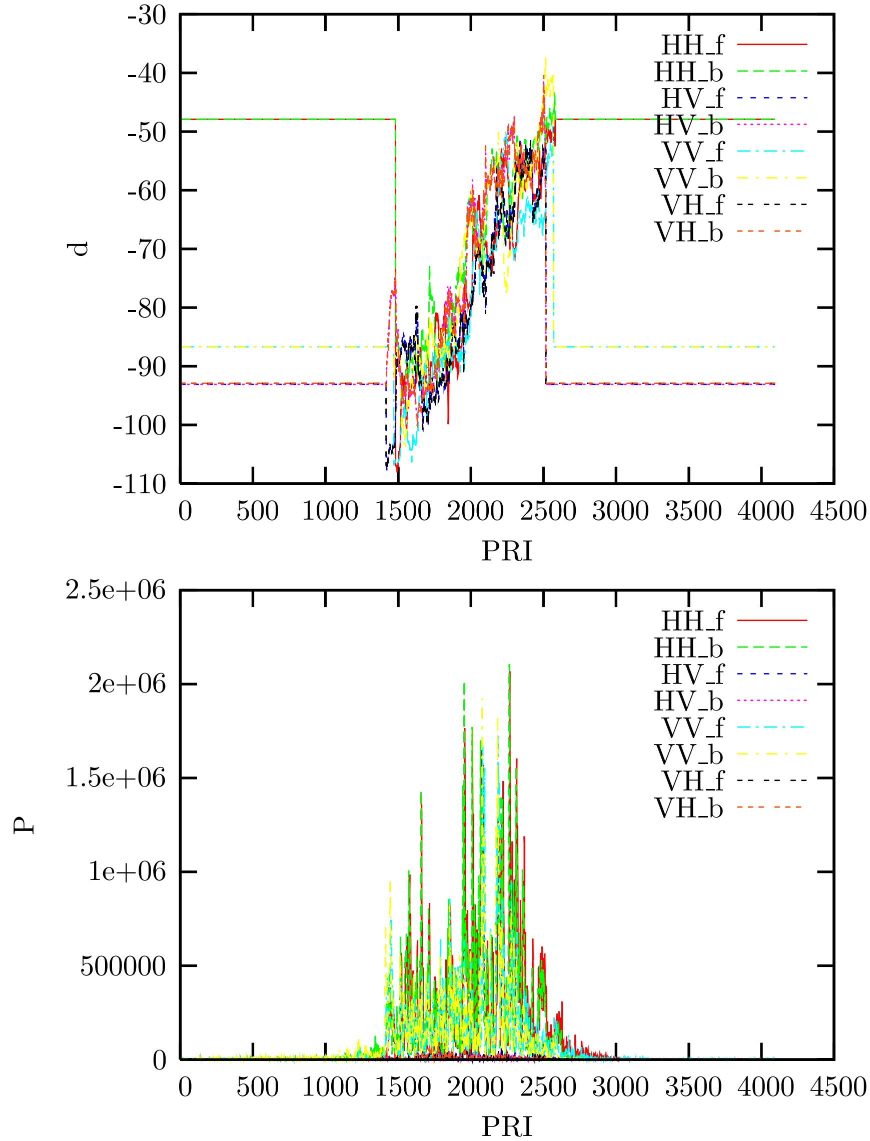


Figure B.6: *Azimuth frequency tracking for* Cape St. James.

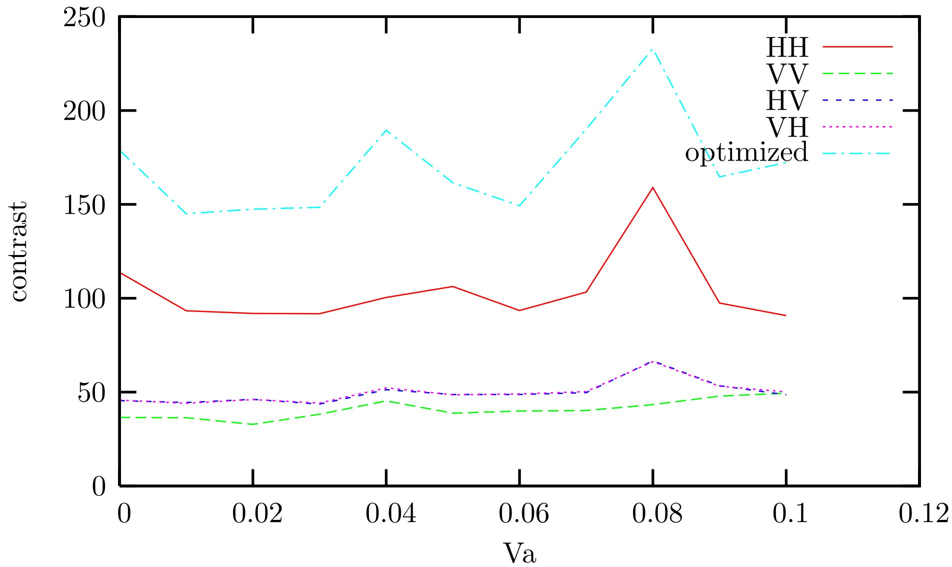
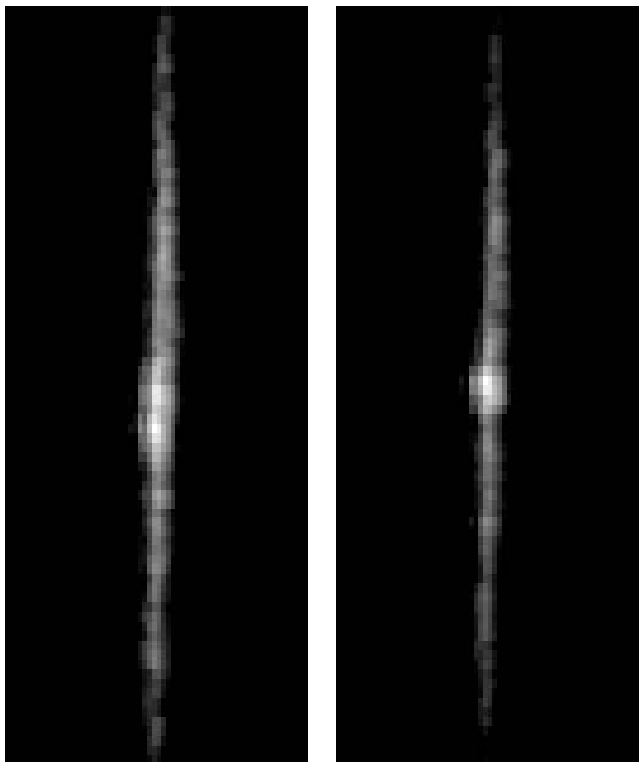


Figure B.7: *Contrast as a function of along track velocity for* Cape St. James.

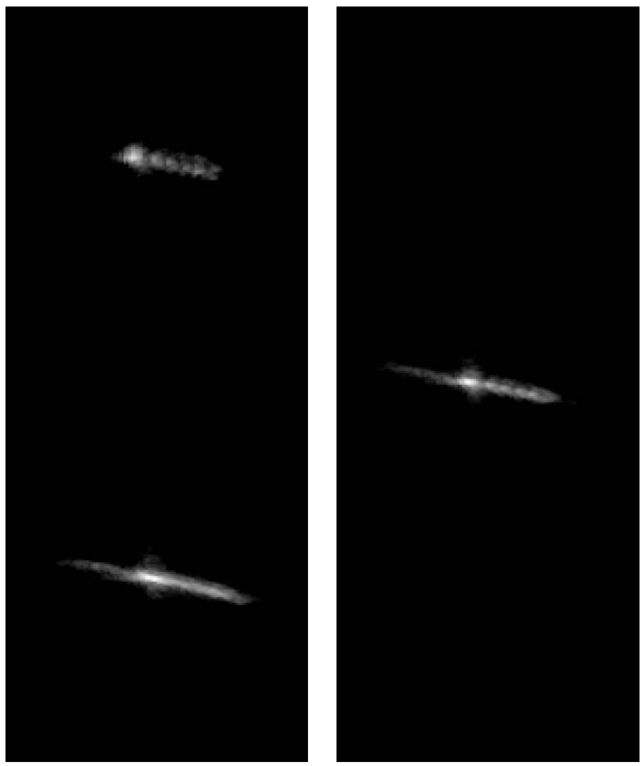
Fig. B.9 shows the Tanker in pass l1p8 before (Fig. 9(a)) and after (Fig. 9(b)) CHASP processing.

Fig. B.10 shows the Tanker in pass l1p9 before (Fig. 10(a)) and after (Fig. 10(b)) CHASP processing.



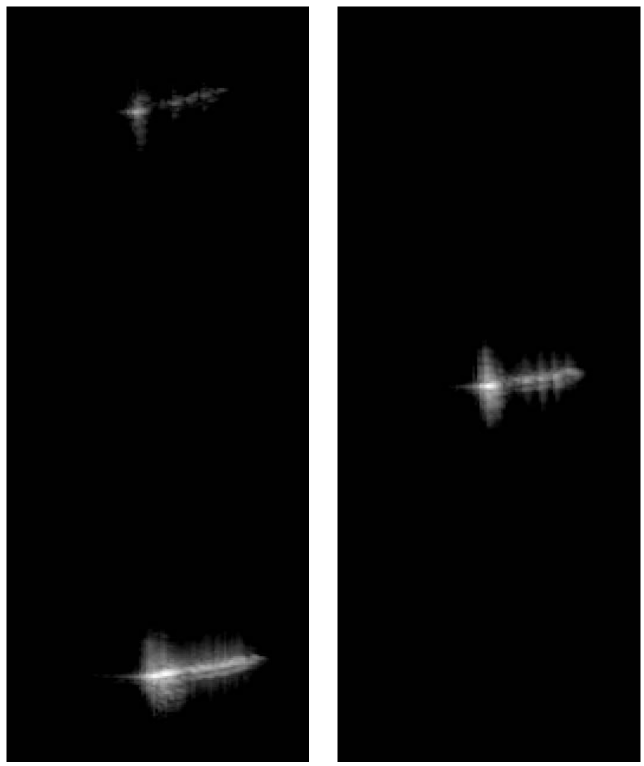
(a) COASP image (b) CHASP image

Figure B.8: *COASP and CHASP images of* Cape St. James, *HV, pass l1p8. Increasing azimuth is from top to bottom and increasing range is from left to right. The azimuth extent is 440 m and the ground range extent is 355 m.*



(a) COASP image (b) CHASP image

Figure B.9: *COASP and CHASP images of the Tanker, HH, pass l1p8. Increasing azimuth is from top to bottom and increasing range is from left to right. The azimuth extent is 1763 m and the ground range extent is 582 m.*

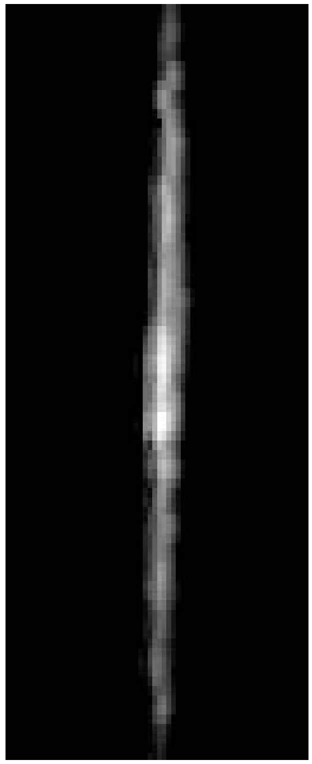


(a) COASP image (b) CHASP image

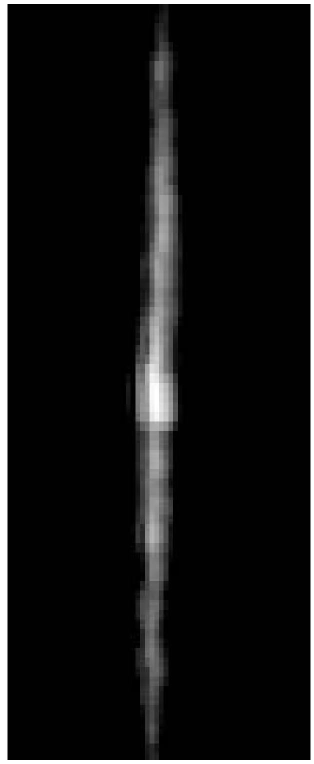
Figure B.10: *COASP and CHASP images of the Tanker, HH, pass l1p9. Increasing azimuth is from top to bottom and increasing range is from left to right. The azimuth extent is 1770 m and the ground range extent is 543 m.*

Table B.2: *RCS estimation results for CoCoNaut data, 23-Sept.-2004 expressed in decibels relative to 1* m^2 *for* σ.

SAR	*l1p8*	*l1p8*	*l1p9*
Vessel	*Cape St. James*	*Tanker*	*Tanker*
Model [dB]	**23.8**	**50.6**	**51.1**
σ_{HH} [dB]	29.7	47.8	47.4
σ_{HV} [dB]	16.0	32.8	30.9
σ_{VV} [dB]	27.8	48.0	44.9
σ_{VH} [dB]	15.0	31.8	29.9
σ^0_{HH} [dB]	-31.4	-46.1	-38.9
σ^0_{HV} [dB]	-49.2	-52.9	-44.5
σ^0_{VV} [dB]	-26.8	-45.6	-37.5
σ^0_{VH} [dB]	-50.8	-55.0	-46.8



(a) Nominal parameters



(b) CHASP parameters

Figure B.11: *COASP and CHASP magnitude coherence images of* Cape St. James, *HV, pass l1p8. Increasing azimuth is from top to bottom and increasing range is from left to right. The azimuth extent is 440 m and the ground range extent is 355 m.*

Coherence Images

Fig. B.11 shows *Cape St. James* coherence images created from two azimuth looks represented by their magnitude. Phase is ignored since complex coherence did not show good results in discriminating between the ship and the ocean. Coherence images are created using nominal processing parameters (Fig. 11(a)) and using processing parameters adapted by CHASP (Fig. 11(b)).

List of Acronyms

A/D	Analogue-to-Digital
ARC	Active Radar Calibrator
ASCII	American Standard Code for Information Interchange
atan2	Princple value of the arctangent function in four quadrants
BITE	Built-In Test Equipment
CCGC	Canadian Coast Guard Cutter
CCRS	Canada Centre for Remote Sensing
CEOS	Committee on Earth Observation Satellites
CHASP	Chip Adaptive SAR Processor
COASP	Configurable Airborne SAR Processor
CPU	Central Processing Unit
CV-580	Consolidated Vultee Convair 580 (aircraft)
CVS	Concurrent Version System
DB	Doppler Bandwidth
DC	Doppler Centroid
dGPS	Differential GPS
DR	Doppler Rate
DRDC	Defence R&D Canada
EC	Environment Canada
ECEF	Earth Centre, Earth Fixed
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
GPS	Global Positioning System
HH	Horizontal transmit, Horizontal receive
HV	Horizontal transmit, Vertical receive
IEEE	Institute of Electrical and Electronic Engineers
IIR	Infinite Impulse Response
INS	Inertial Navigation System
InQC	Motion Compensation software developed at DRDC Ottawa
IPC	Inter-Process Communication
IR	Integrated Response
ISAR	Inverse SAR
LOS	Line-of-Sight
LP	Low Pass
LUT	Look-Up Table
MCTS	Marine Communications and Traffic Services
PCA	Point of Closest Approach
PGM	Portable Gray Map
PolGASP	Polarimetric Generalized Airborne SAR Processor
PRI	Pulse Repetition Interval
PRF	Pulse Repetition Frequency
PTR	Point Target Response
R&D	Research and Development

RCMC	Range Cell Migration Correction
RCS	Radar Cross Section
RDA	Range-Doppler Algorithm
RM	Range Migration
RW	Range Walk
SAR	Synthetic Aperture Radar
SAW	Surface Acoustic Wave
SGI	Silicon Graphics Inc.
SI	International System of Units
SLA	Service Level Arrangement
SMP	Symmetric Multiprocessing
SPECAN	Spectral Analysis
SRC	Secondary Range Compression
VV	Vertical transmit, Vertical receive
VH	Vertical transmit, Horizontal receive
xv	XView

List of Main Symbols

α	Incidence angle
a	azimuth coordinate
Δs	Azimuth sample spacing
b_c	Doppler rate
f_c	Doppler centroid frequency
f_p	Pulse repetition frequency
γ	Elevation angle
r	slant range coordinate
R	Slant range
ΔR	Slant range sample spacing
R_0	Slant range at point of closest approach
v_g	Ground speed

Distribution list

<u>LIST PART 1: Internal Distribution by Centre:</u>

4	Library DRDC Ottawa
1	Gary Geling
5	Paris Vachon
1	Marina Dragosevic
1	Bing Yueh
1	Jeff Secker
1	Chen Liu
1	Ramin Sabry
1	Terry Potter
1	Chuck Livingstone
1	Allan Meek
1	Mike Robson
19	TOTAL LIST PART 1

<u>LIST PART 2: External Distribution by DRDKIM</u>

1	DRDKIM
2	Library and Archives Canada
1	CISTI
1	LCol Jeff Howes, DPDOIS, Polar Epsilon
1	LCdr Robert Quinn, D Space D
1	LCdr Andy Samoluk, D Space D
1	Maj Peter Butler, D Space D
1	Jake Tunaley, DPDOIS, Polar Epsilon
1	Robert Hawkins, Canada Centre for Remote Sensing 588 Booth Street Ottawa, Ontario K1A 0Y7
1	Kevin Murnaghan, Canada Centre for Remote Sensing 588 Booth Street Ottawa, Ontario K1A 0Y7
1	Francois Charbonneau, Canada Centre for Remote Sensing 588 Booth Street Ottawa, Ontario K1A 0Y7
1	Carl Brown, Environment Canada 3439 River Road Ottawa, Ontario K1A 0H3
13	TOTAL LIST PART 2

<u>32</u> **<u>TOTAL COPIES REQUIRED</u>**

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) Defence R&D Canada – Ottawa 3701 Carling Avenue, Ottawa, Ontario, Canada K1A 0Z4	2. SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable). UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title).

COASP and CHASP Processors for Strip-map and Moving Target Adaptive Processing of EC CV-580 Synthetic Aperture Radar Data: Algorithms and Software Description

4. AUTHORS (last name, first name, middle initial)

Vachon, Paris W. ; Dragošević, Marina V.

5. DATE OF PUBLICATION (month and year of publication of document) May 2006	6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc). 128	6b. NO. OF REFS (total cited in document) 7

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered).

Technical Memorandum

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include address).

Defence R&D Canada – Ottawa
3701 Carling Avenue, Ottawa, Ontario, Canada K1A 0Z4

9a. PROJECT NO. (the applicable research and development project number under which the document was written. Specify whether project). 15ec06-01	9b. GRANT OR CONTRACT NO. (if appropriate, the applicable number under which the document was written).
10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique.) DRDC Ottawa TM 2006-066	10b. OTHER DOCUMENT NOs. (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

(X) Unlimited distribution
( ) Defence departments and defence contractors; further distribution only as approved
( ) Defence departments and Canadian defence contractors; further distribution only as approved
( ) Government departments and agencies; further distribution only as approved
( ) Defence departments; further distribution only as approved
( ) Other (please specify):

12. DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution beyond the audience specified in (11) is possible, a wider announcement audience may be selected).

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual).

DRDC Ottawa has been working with data from the Environment Canada (EC) CV-580 C-band polarimetric synthetic aperture radar (SAR) since the late 1990's in support of target detection and classification studies. Until recently, processing of data from this SAR system has been carried out in-house using the Polarimetrc Generalized Airborne SAR Processor (PolGASP) that was developed at the Canada Centre for Remote Sensing. As DRDC Ottawa interests began to focus on moving targets to improve Polar Epsilon maritime and land target detection and classification capabilities, PolGASP-processed data proved to be inadequate to support required downstream analyses. PolGASP uses a simple azimuth-oriented compression algorithm, fixed processing parameters over each flight line, and assumes that the target is static (i.e., not moving). Therefore, the COASP (Configurable Airborne SAR Processor) and CHASP (Chip Adaptive SAR Processor) processors have been developed to replace and augment PolGASP and to provide better focused imagery to support downstream analysis such as polarimetric decomposition of moving ship targets, ship velocity estimation, and to act as a test-bed for phase-based target detection algorithms. In this document, the COASP and CHASP processors are described from an algorithmic and software perspective. Test results for moving ship targets are presented; focus improvements are readily apparent and derived ship velocities are favourably compared with available validation data.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title).

Adaptive processing
Autofocus
EC CV-580 C-band polarimetric SAR
Moving target
SAR
SAR processor
Synthetic aperture radar