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DDRE REPORT

Exploitation of Polarimetric Target Decomposition for Coastal Remote Sensing

Final Report
U.S. Office of Naval Research
NICOP Contract No. N00014-97-C-0408

by
Ernst Krogager

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Approved:

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ABSTRACT

Techniques for processing polarimetric SAR data have been considered in relation to applications in coastal and littoral environments. A comprehensive set of data from the Danish EMISAR has been acquired and exchanged with other NICOP partners. The two scenes covered by these datasets are the Great Belt Fixed Link (tunnel/bridge connection) in Denmark and the Oeresund tunnel/bridge connection between Copenhagen, Denmark, and Malmo, Sweden. Software for handling and analyzing the data has been developed. Notably, the sphere, diplane, helix decomposition has been applied in order to highlight the observed scattering mechanisms. The study has included collection of detailed and precision ground truth for supporting the analyses. This ground truth collection has been made by means of a digital camera and a differential GPS receiver capable of measuring position at a resolution of approximately 1 m. The scenarios and the techniques under consideration are illustrated by a number of examples of SAR images and digital photos.

1. INTRODUCTION

During the winter of 1996/1997, a proposal for a project under the ONR Naval International Cooperative Opportunities in Science and Technology Program (NICOP) was submitted, involving the present author as well as Dr. Shane Cloude, Applied Electromagnetics (AEL), Scotland, and Dr. Jong-Sen Lee, Naval Research Laboratory (NRL), Washington, D.C., with NRL as the provider of 'matching funding'. The title of the proposal was '*Exploitation of Polarimetric Target Decomposition for Coastal Remote Sensing*', and the proposal was approved in early 1997. The award was implemented as a contract with the Danish Defence Research Establishment (DDRE), and the present final report is for the fulfillment of this contract.

The original contract was extended after a second round of awards in 1998, and the deadline for the final report extended to 31 December 1999. For various reasons, this deadline could not be met, and after a clarification of a no-cost extension and the availability of funding beyond the deadline, the due date for the final report was ultimately changed to 30 April 2001.

This report marks the completion of the *NICOP contract N00014-97-C-0408*. The activities are being continued under a follow-up grant, *Award No. N000140110309*, entitled '*Application of Coherent Decomposition to High-Resolution Polarimetric and Interferometric SAR Data*'.

2. PROJECT CONTENT

2.1 Work content

The content of the DDRE contribution to the first phase of the project was the following

1. Interact with other members of this project to establish a common set of selected polarimetric SAR data for different scenes and from different SAR systems. If possible, EMISAR measurements with deployed targets in scene and collection of ground truth will be conducted.
2. Apply sphere, diplane and helicity decomposition to the common database, and analyze the results. Interact with other members in the evaluation of the effectiveness of decomposition algorithms.
3. Development / adaptation of software tools. Delivery / exchange of such tools (algorithms / source code). Exchange of obtained results - electronically and during laboratory visits.

In the extended project, the following items were added

4. Obtain high resolution polarimetric EMISAR C- and L-band data from the Danish Center for Remote Sensing, and relevant ground truth, if it is available, and distribute to other partners.
5. Ships in the EMISAR data will be refocused by considering ship motions and applying ISAR motion compensation techniques. Polarimetric decompositions will be applied to the refocused polarimetric SAR (ISAR) target response in order to assess the target recognition potential of such data. By reducing ship motion induced artifacts, "true" motion-compensated polarimetric signatures will be obtained.
6. Refocused polarimetric SAR images will be analyzed jointly with other partners by applying the various target decomposition theories that have been developed. Extension and or modification of known polarimetric decomposition theories will be considered, if the current theories are found insufficient to deal with this kind of data.
7. The benefit of using dual frequency SAR system on the target classification will be investigated. In particular, coastal features, such as bridges, inlets, harbor facilities and some ocean features will be analyzed.

2.2 Labor content and budget

Phase 1

	k$
Labor and overhead	30.5
Travel	5
Computing and materials	2
Total	37.5

Phase 2

	k$
Labor and overhead	15.75
Travel	3
Computing and materials	1.25
Total	20

3. SOFTWARE TOOLS

3.1 Programs developed at DDRE

The basic tools available at the initiation of the project were mostly tools developed by Krogager during the doctoral studies, [1], and the subsequent analyses of EMISAR data. In addition, the processing of EMISAR data was facilitated by software made available by the *Danish Center for Remote Sensing (DCRS)*, notably the program *'util'* which has been made available via the Internet for basic handling of EMISAR datasets.

Originally, the intention was to extend the user-interface for the existing processing tools in order to bring the programs into a form suitable for delivery together with the final report. However, due to recruitment problems, no supporting manpower has been available for this purpose, and the developments have therefore been directed at obtaining the desired results. On the other hand, the simultaneous participation in the European network on Radar Polarimetry, initiated April 1998, has provided an opportunity for pursuing this goal. Therefore, the delivered software tool for handling and processing polarimetric SAR data, has been developed so as to serve the dual purpose of the EU network activities and the present ONR sponsored project.

Due to the severe time pressure, the focus has been on implementing the basic functionality, to test various algorithms and processing techniques. Program structure, style, and documentation have therefore been of secondary importance. The following tools are available to participating partners.

1. *util.c*
   C program supplied by DCRS for reading, converting, and scaling a broad range of data formats, and for generating basic raw single-channel image files.

2. *decomp.c*
   Subroutines for computing various decomposition techniques and polarimetric parameters.

3. *polsar.pro*
   IDL program package based on subroutines developed in connection with EU network project on radar polarimetry. This program contains a basic menu-like user interface for specifying input and output files as well as all relevant processing parameters. Output is in the form of screen graphics or data/image files.

4. *gps.pro*
   Rudimentary IDL program for processing GPS data from a differential GPS receiver. The program looks for periods where the receiver has been stationary, i.e., where the position does not change from sample to sample. The further perspective is to correlate the time-stamps of the extracted positions with the time-stamps of simultaneously taken digital photos.

3.2 Programs supplied by other partners

In addition to the above programs that have been used for the DDRE contributions, a number of software routines have been supplied by the other partners. A list of the routines in this library follows, while further information about these routines should be acquired from the respective partners.

3.2.1. IDL programs supplied by NRL (Drs. T. Ainsworth and J.-S. Lee)

1. *byte_swap.pro*
2. *emisar_pp_to_pc.pro*
3. *selectfile.pro*
4. *sub_apt_emisar.pro*

5. *sub_read_byte.pro*
6. *window_emisar.pro*

3.2.2. MATLAB programs supplied by AEL (Dr. S. Cloude)

1. *airsarHR.m*
2. *airsar.m*
3. *classget.m*
4. *desy.m*
5. *emisar_SM.m*
6. *entropy3.m*
7. *filterim.m*
8. *haplot.m*
9. *hebhist.m*
10. *hebhist2.m*
11. *imzoom.m*
12. *JPEG.m*
13. *lamvecs.m*
14. *menus.m*
15. *mueller.m*
16. *noisefilt.m*
17. *pauli.m*
18. *subsamp.m*
19. *subsamp1.m*
20. *viewcoh.m*
21. *viewphase.m*

4. AVAILABLE DATA

In the initial phase of the project, the partners exchanged several datasets to be analyzed by the various techniques under consideration.

4.1 JPL AirSAR data

These data have been distributed via an ftp-site provided by NRL. The file sizes are in the order of 12 MB each.

4.1.1. Classical San Francisco scene with Golden Gate bridge

ggate.dat
sanfranl.dat

4.1.2. Malaysia scene in L-band and C-band.

One dataset (L- and C-band) for coastal area (land) and one for ocean area (sea):

Malaysia_C-band_land.dat
Malaysia_C-band_sea.dat
Malaysia_L-band_land.dat
Malaysia_L-band_sea.dat

4.2 EMISAR data

These data, delivered by the Danish Center for Remote Sensing (DCRS), have been distributed via EXABYTE tapes and/or CD-ROMs. File sizes are up to almost 1 GB per polarimetric channel. CPOL refers to C-band fully polarimetric, FPOL C-band fully polarimetric with flush-mounted antenna, L-POL L-band fully polarimetric. RTI refers to Repeat Track Interferometry. These data are subject to a data agreement which prevents redistribution without explicit permission by DCRS.

4.2.1. Great Belt area

fl043_m1048_storebaelt	96.06.19	CPOL	159°	
fl044_m1344_grbelt_l	96.07.17	LPOL	90°	
fl065_m0948_greatbelt_c	98.06.16	FPOL	159°	
fl065_m0948_greatbelt_l	98.06.16	LPOL	159°	0 m RTI offset
fl065_m1001_greatbelt_l	98.06.16	LPOL	-21°	20 m RTI offset

4.2.2. Øresund / Copenhagen Airport area

fl076_m1546_oerestad_l	99.06.09		
fl075_m1513_oerestad_c	99.06.09	FPOL	117°
fl075_m1523_oerestad_l	99.06.09	LPOL	-63°

5. GROUND TRUTH

A collection of ground truth based on the campaigns mentioned below is included on the CD-ROM.

5.1 Great Belt area

5.1.1. Digital photos from ferry

A series of photos with analog and digital cameras was taken by DDRE photographer S.M. Larsen on December 1, 1997, and distributed on CD-ROMs.

5.1.2. Digital photos from the archives of www.bridgephoto.dk

A collection of photos from the archives of the Great Belt and Øresund connections has been acquired.

5.1.3. Digital photos and waypoints from ground truth collection campaigns

Several campaigns for ground truth collection in selected areas of the Great Belt scene have been conducted. Notably, the following campaigns were conducted.

29 MAY 1999 Ernst Krogager, collection of *digital photos* in Halsskov area north of Korsør on Eastside of the Great Belt

04 JUL 1999 Ernst Krogager and Wolfgang-Martin Boerner, *collection of digital photos and GPS waypoints* in area north of Knudshoved on Westside of the Great Belt

06 JUL 1999 Ernst Krogager and Wolfgang-Martin Boerner, *collection of digital photos and GPS waypoints* in Halsskov area north of Korsør on Eastside of the Great Belt

30 JUL 1999 Ernst Krogager and Johanne Krogager, *collection of digital photos and GPS waypoints* in the old Knudshoved ferry harbor area on Eastside of the Great Belt

5.1.4. Maps

Digital maps from *Kort & Matrikelstyrelsen* (www.kms.dk) have been utilized, including sections of maps from *Det levende Danmarkskort*, which contains a special theme about the Great Belt area with navigation maps and detailed maps in scales down to 1:10000.

5.2 Øresund / Copenhagen Airport area

5.2.1. Digital photos from the archives of www.bridgephoto.dk

A collection of photos from the archives of the Great Belt and Øresund connections has been acquired.

5.2.2. Maps

Digital maps from *Kort & Matrikelstyrelsen* (www.kms.dk) have been distributed, including sections of maps from *Det levende Danmarkskort*, which contains a special theme about the Great Belt area with navigation maps and detailed maps in scales down to 1:10000. In one of the maps, named *Halsskov_groundtruth_positions.jpg*, the positions where digital photos were taken on 29 May 1999, have been marked with the numbers of the corresponding digital photos.

6. BRIEF REVIEW OF DECOMPOSITIONS

The main categories of decompositions considered in the NICOP project are the following:

1. Direct use of linear basis HH, HV, VH, VV, or circular basis RR, RL, LR, LL elements
2. Pauli spin matrix decomposition
3. Coherent decomposition of 2x2 Sinclair matrix into sphere, diplane, and helix components; Krogager 1990
4. Incoherent decomposition of 3x3 coherency matrix into three components based on eigenvalues; Cloude 1985 and subsequent related approaches

6.1 Direct use of scattering matrix elements

The most straightforward way of generating RGB color images from high-resolution polarimetric data is to use the elements of the (symmetric) scattering matrix directly, e.g., red~HV, green~HH, blue~VV, in a linear Horizontal-Vertical basis. This is a useful way to obtain a quick overview of the data, but because of the orientation dependence of these parameters, they are not suited for a more detailed assessment and interpretation. A better approach in this respect is to use the elements of the matrix in the circular (Right-Left) basis, whereby red~RL, green~RR, blue~LL. These parameters are independent of orientation (roll-invariant), and thus give a more stable characterization of a target.

6.2 Pauli decomposition

The Pauli decomposition is based on the fact that the three Pauli spin matrices can represent any given complex, symmetric scattering matrix as follows,

$$[S] = k_1[S]_{sphere} + k_2[S]_{diplane(0^\circ)} + k_3[S]_{diplane(45^\circ)}, \tag{1}$$

where k_1, k_2, and k_3 are complex coefficients.

More explicitly, in vector form,

$$\underline{k} = [k_1 \quad k_2 \quad k_3] = \frac{1}{\sqrt{2}}[S_{HH}+S_{VV} \quad S_{HH}-S_{VV} \quad 2S_{HV}]^T. \tag{2}$$

in which HH, HV, and VV refer to the elements in an H-V linear basis. The three components are usually interpreted in terms of a sphere, an un-rotated dihedral and a dihedral rotated 45° about the line-of-sight, respectively.

6.3 Sphere, diplane, helix decomposition

The sphere, diplane, helix decomposition is based on the fact that any 2x2 complex, symmetric scattering matrix can be represented in terms of the three component as follows,

$$\begin{aligned}[S] = e^{j\varphi}\{&e^{j\varphi_s}k_s[S]_{sphere} \\ &+k_d[S]_{diplane(\theta)} + k_h[S]_{helix(\theta)}\}\end{aligned} \tag{3}$$

In the circular basis, the following expressions for the parameters of the decomposition may be found,

$$\begin{aligned}
k_s &= |S_{RL}| \\
k_d^+ &= |S_{LL}|; \quad k_d^- = |S_{RR}| \\
k_h^+ &= |S_{RR}| - |S_{LL}|; \quad k_h^- = |S_{LL}| - |S_{RR}| \\
\varphi &= \tfrac{1}{2}(\varphi_{RR} + \varphi_{LL} - \pi) \\
\theta &= \tfrac{1}{4}(\varphi_{RR} - \varphi_{LL} + \pi) \\
\varphi_s &= \varphi_{RL} - \tfrac{1}{2}(\varphi_{RR} + \varphi_{LL})
\end{aligned} \tag{4}$$

Thus, S_{RR} (if $|S_{LL}| > |S_{RR}|$) or S_{LL} (if $|S_{RR}| > |S_{LL}|$) represents the diplane component directly. Correspondingly, the helix component is of either right or left sense. In comparison with the direct use of RR, RL, and LL parameters, this decomposition thus incorporates an interpretation, in that the even bounce component is ascribed to either RR or LL on a pixel-by-pixel basis.

For computing the circular basis quantities from linear basis quantities, the following relations apply,

$$\begin{aligned} S_{RR} &= j\,S_{HV} + \tfrac{1}{2}(S_{HH} - S_{VV}) \\ S_{LL} &= j\,S_{HV} - \tfrac{1}{2}(S_{HH} - S_{VV}) \\ S_{RL} &= \tfrac{j}{2}(S_{HH} + S_{VV}) \end{aligned} \tag{5}$$

This decomposition is particularly suited for analysis of high-resolution SAR data, because it operates on the individual pixels on a coherent basis, and thereby provides a means for fully utilizing the intrinsic coherent nature of polarimetric SAR data. It further characterizes objects in terms of frequently encountered, physically appealing concepts of odd- and even-bounce scattering.

In terms of scattering mechanisms, this approach has the advantage that even-bounce scatterers show up in only one of the components, irrespective of the incidental orientation angle, unlike the above decomposition based on the Pauli spin matrices, where two dihedrals of different orientation angles (but identical scattering *mechanism*) are involved.

It should also be noted, however, that in the sphere, diplane, helix decomposition (SDH), two of the components, the diplane and the helix, are not mutually orthogonal, while all three components of the Pauli decomposition are orthogonal. Nevertheless, SDH has the advantage of being roll-invariant, and of being able to give a clear overview of the type of scattering *mechanisms* within a given resolution cell. Although the helix component is a rather peculiar type of scatterer, it is not without practical significance, because helix scattering can be produced by two or more dihedrals. Thus, two dihedrals with a 45° difference between their orientation angles and 1/8 wavelength range separation between their phase centers will exhibit the scattering matrix of a helix.

For practical targets, like ships, one may often find several double bounce contributions within one resolution cell. One role of the helix component could therefore be to serve as a measure of the purity of a double-bounce (dihedral) scatterer. Absence of helix scattering could indicate that the diplane component is due to a single even-bounce scattering mechanism. For motion compensation purposes this could be of great significance, since a stable phase history is mandatory for obtaining a well-focused image. By assessing the purity of the reference points along these lines, interference problems associated with the reference phase could perhaps be reduced considerably.

The question about the number of orthogonal components is also related to the actual information content in the kind of data under consideration. Mathematically, the matrices can be projected along three orthogonal component matrices, like in the Pauli decomposition. However, in terms of scattering mechanisms, no approach has yet been shown to represent the complex 2x2 scattering matrix in terms of three fundamental, orthogonal mechanisms. In this sense, one could say that the Pauli expansion offers *two mechanisms* while SDH has the unique property that three elementary single scatterers (sphere, dihedral, and helix) show up in only *one out of three components*, even though two of them are not represented by mutually orthogonal matrices. In other known decompositions, including the Pauli decomposition, a maximum of two different scatterers will show up in only one out of three components, while other scatterers will show up in at least two out of the three components.

6.4 Decomposition based on the coherency matrix

In cases dealing with the statistics of fluctuating targets, other formulations are usually preferred. From the above vectorization along the Pauli spin matrices, a coherency matrix, $[T]$, can be formed as follows,

$$[T] = \underline{k} \cdot \underline{k}^{*T} \tag{6}$$

[*T*] is a 3x3 Hermitian matrix which can be readily subjected to standard eigenvalue and statistical analyses, like multi-looking and averaging to obtain a local estimate of [T] from complex, high-resolution scattering matrix data,

$$\langle [T] \rangle = \frac{1}{N}\sum_{i=1}^{N} \underline{k}_i \cdot \underline{k}_i^{*T} = \frac{1}{N}\sum_{i=1}^{N} [T_i]. \tag{7}$$

From such an estimate, the eigenvectors and eigenvalues of <[*T*]> can be found, and in fact, the vast majority of current work in the field of radar polarimetry for remote sensing is based on this approach. Several decomposition approaches based on the eigenvalues of <[*T*]> have been developed. In recent years, the so-called '*Entropy, anisotropy, alpha*' decomposition has been introduced, and has been quite widely used for classification of terrain, crop, and other remote sensing applications where resolution is not a major concern.

In relation to the application of the Pauli spin matrix expansion of [*S*] for statistically fluctuating targets, the interpretation of the Pauli components is often extended, e.g., linking the cross-polarized terms to so-called '*volume scattering*'. In such a concept, designations like '*surface*', '*double bounce*', and '*volume*' scattering components are sometimes met. However, the fact that two of the Pauli components are directly related to double bounce contributions means that such interpretations must be applied with quite some care.

In the present report these techniques are not considered any further, since that has been the task of other partners, who are leading experts on such techniques.

7. HIGHLIGHTS OF OBTAINED RESULTS

During these studies, a large number of scenes have been processed, and it is not feasible to include all the examples that have been considered. Thus, only some highlights will be shown, while more images are to be found on the CD-ROM.

Due to the large size of the EMISAR datasets, subsets have been blocked out by means of the above-mentioned programs.

A discussion of some examples may be found in the attached publications. Also, an impression of the progression of the project and the evolvement of ideas and approaches appears from the progress reports included in Appendix I. However, some specific examples with a few explanations are in order at this place.

7.1 Great Belt Eastbridge June 1996 and June 1998

A very instructive example of the peculiarity of radar imagery, which was encountered during this work, is the scene shown in Fig. 1. This is the Eastbridge of the Great Belt Fixed Link that was opened to the public in June 1998. During the construction phase, the bridge was imaged by EMISAR on June 19, 1996 (C-band) and July 17, 1996 (L-band), while only the main cables were in place, as seen in Fig. 5. Hence, the straight line in Fig. 1 is not due to any road deck or the like, but rather to double bounce reflections from the main cables. This may be readily understood by comparing with the reflection from a dihedral, for which the phase centre appears to be at the intersection of the sides. If one assumes that only a fraction of one side of the dihedral is present, corresponding in Fig. 1 to the suspension cables, then the reflection from this structure via the other side (the water surface) must therefore also have its phase centre along the water surface. For comparison and illustration of the extra amount of information contained in fully polarimetric data, an image of the HH channel is shown in Fig. 2, which corresponds to what would be seen by traditional single polarization radar.

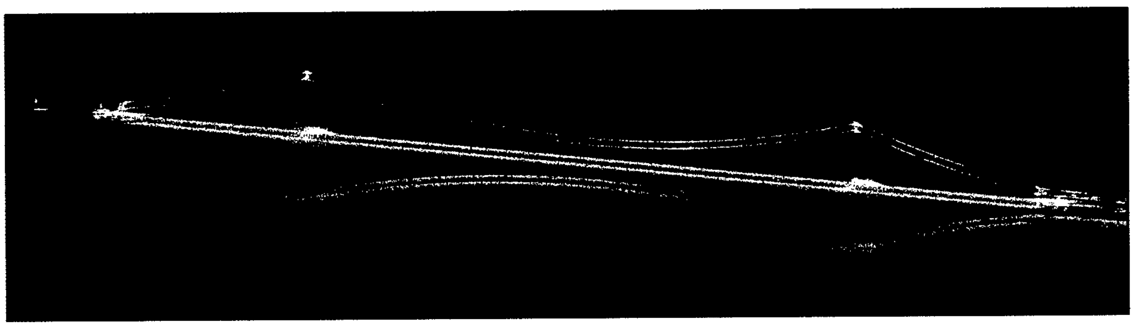


Fig. 1 Great Belt Eastbridge 1996. C-band, red=sphere, green=diplane, blue=helix.

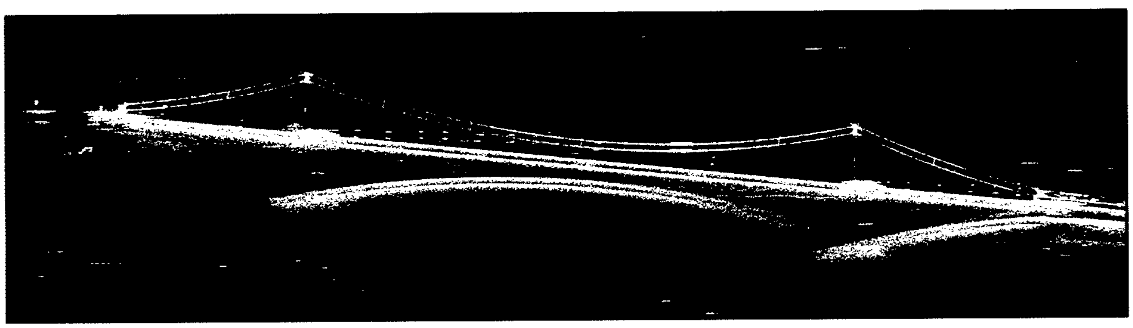


Fig. 2 Great Belt Eastbridge 1996. C-band, HH channel only.

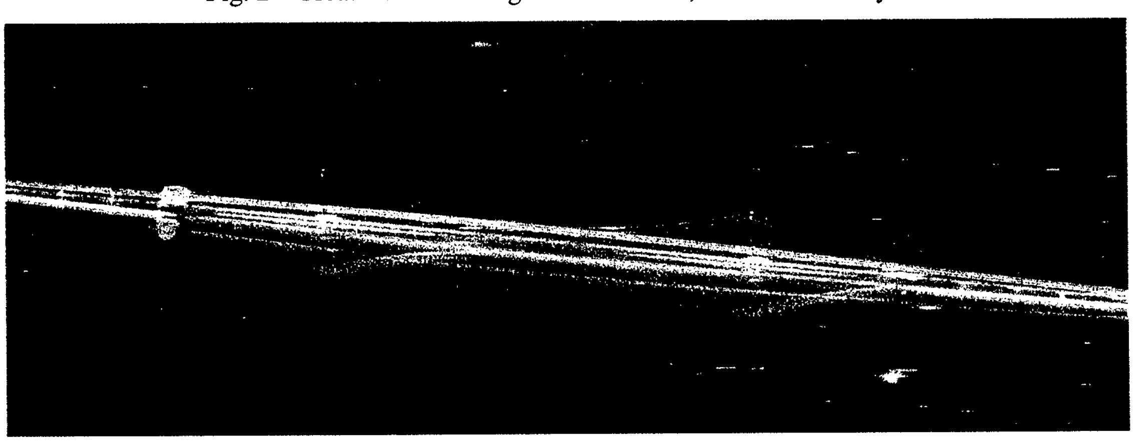


Fig. 3 Great Belt Eastbridge 1998. C-band, red=HH-VV, green=HV+VH, blue=HH+VV.

Fig. 3 shows the bridge after completion, imaged by EMISAR on June 16, 1998, two days after the opening to the public. The pixel resolution in Fig. 3 is app. 1.5 m x 1.5 m, while the effective resolution in Fig. 2 is only 3 m due to a used bandwidth of 50 MHz instead of 100 MHz.

Naturally, Fig. 3 contains a lot of additional scattering contributions, as compared to Fig. 1, and a multitude of reflections in the water surface are found. Note how the color-coding offers a direct interpretation in terms of even and odd number of bounces. That the main cables in Fig. 3 appear as dots is due to the fact that the finished cables are encapsulated and hence only reflect weak signals back towards the radar, except from the areas where the suspension cables are attached to the main cables. In 1996, the cable bundles were not yet encapsulated, and in addition catwalks etc. were mounted. However, reflections via the water surface appear rather strongly in some areas.

In Fig. 3, several scattered, mostly green spots are seen. The cause of these spots is not immediately obvious, however, from the navigation map shown below in Fig. 4, one can see how most of the spots in the SAR image can be ascribed to buoys marking areas of no admittance.

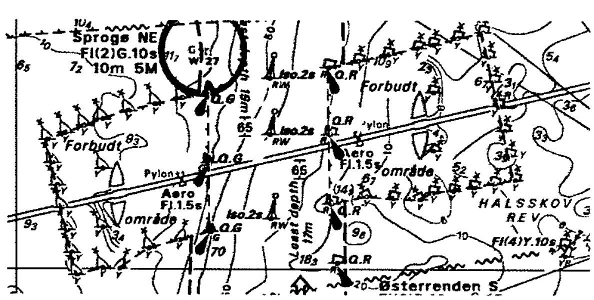


Fig. 4 Buoys around bridge. (Copyright Kort & Matrikelstyrelsen)

Fig. 5, Fig. 6, and Fig. 7 show some aerial photos taken in the summer of 1996, where the SAR data of Fig. 1 were also collected. The photos were acquired from the Photo Archives of the Great Belt Fixed Link at a cost of app. $100 each.

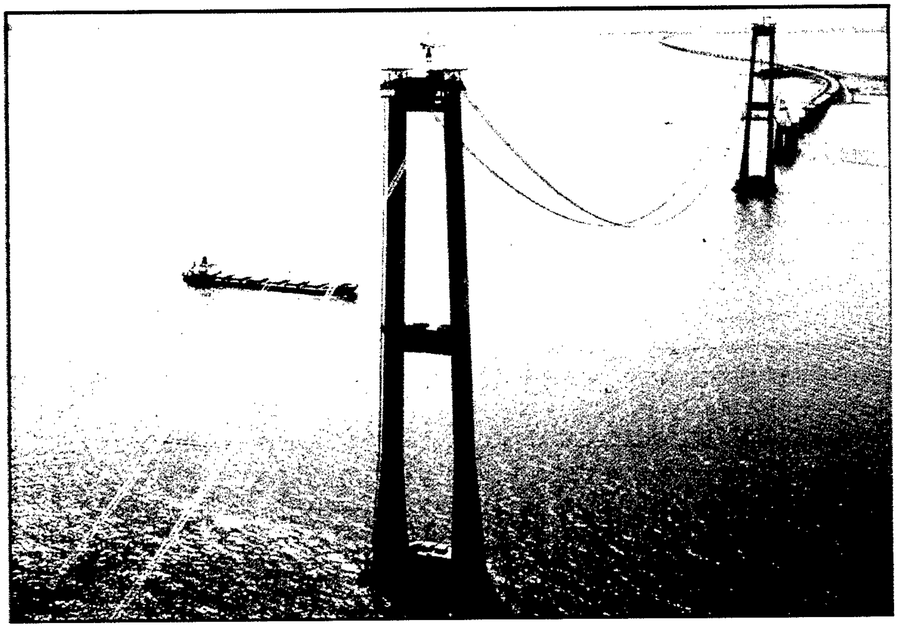


Fig. 5 Aerial photo of Great Belt Eastbridge. 15 June 1996. Photo: Jan Kofod Winther.

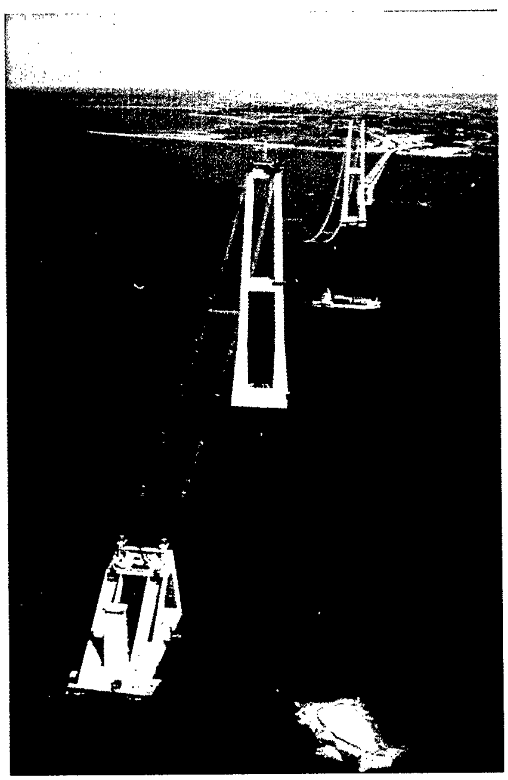


Fig. 6 Aerial photo of Great Belt Eastbridge. 15 June 1996. Photo: Jan Kofod Winther.

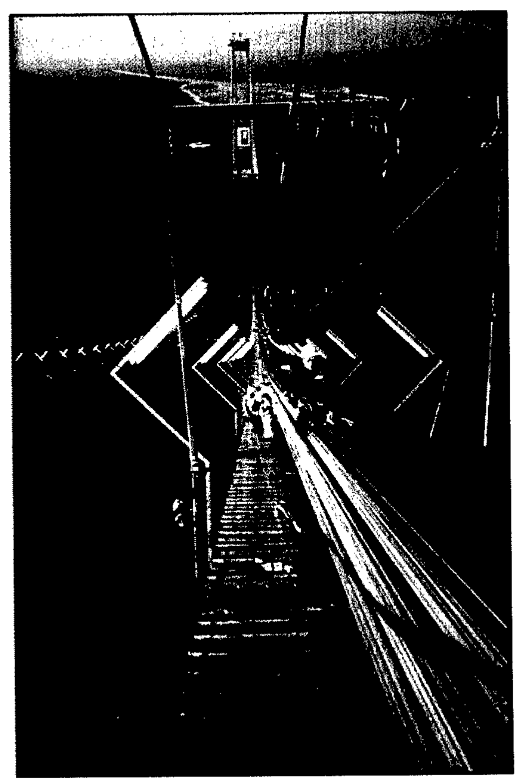


Fig. 7 Catwalk mounted on Great Belt Eastbridge. 15 July 1996. Photo: Søren Madsen.

7.2 Knudshoved Ferry Harbor July 17, 1996

It should be emphasized at this point that the SAR images shown in this report are scaled according to the slant range resolution of the radar system. To obtain a true ground-range scaling suited for geo-coding, the slant range images would have to be interpolated and rescaled.

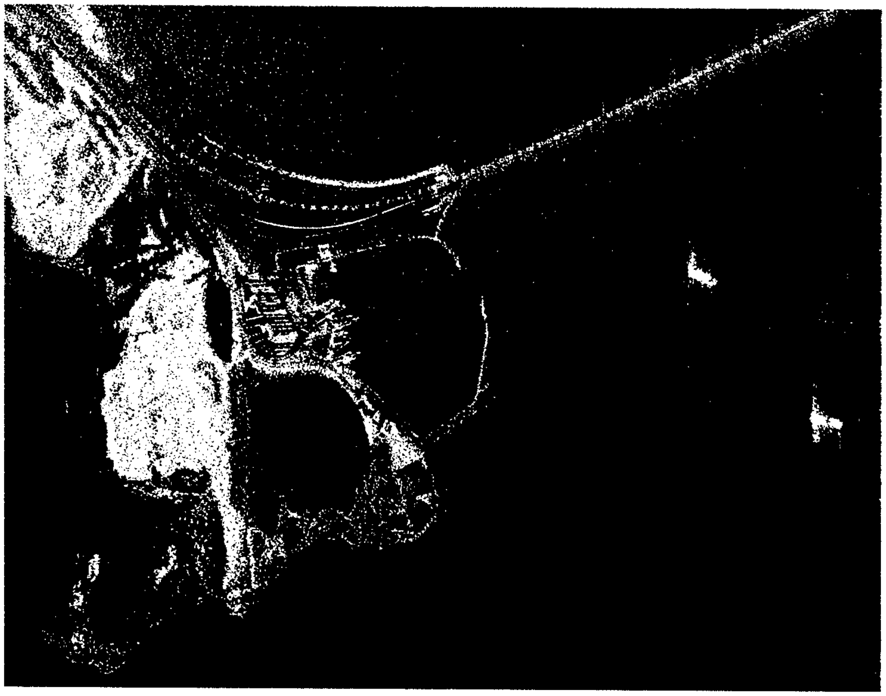


Fig. 8 Knudshoved Ferry Harbor. L-band, July 17, 1996, with the radar looking from the left. SDH decomposition: red=sphere, green=diplane, blue=helix.

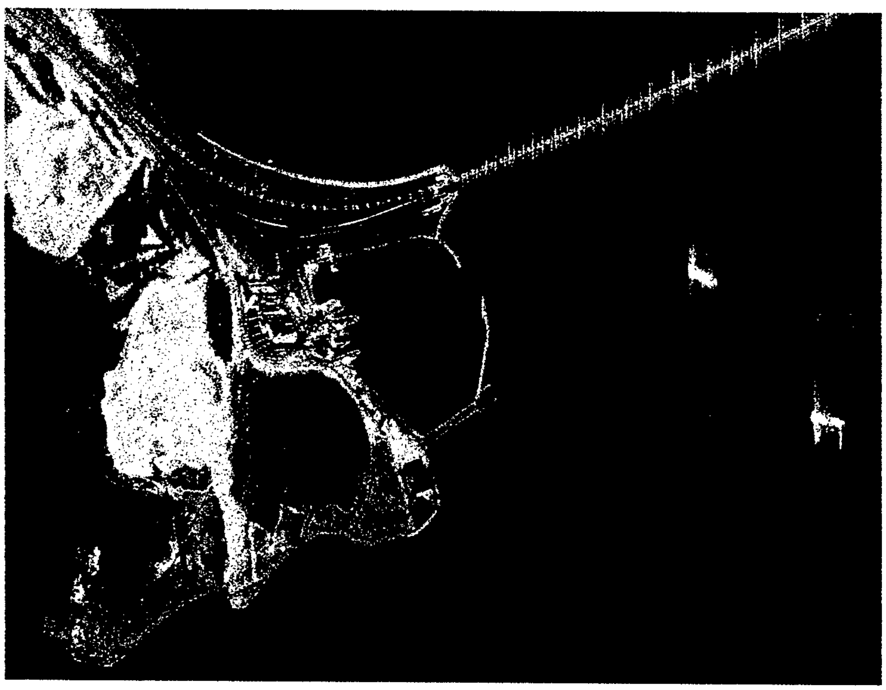


Fig. 9 Knudshoved Ferry Harbor. L-band, July 17, 1996, with the radar looking from the left. Pauli decomposition: red=HH-VV, green=HV+VH, blue=HH+VV.

7.3 Knudshoved Ferry Harbor June 16, 1998

Radar looking from above, pixel resolution 3 m.

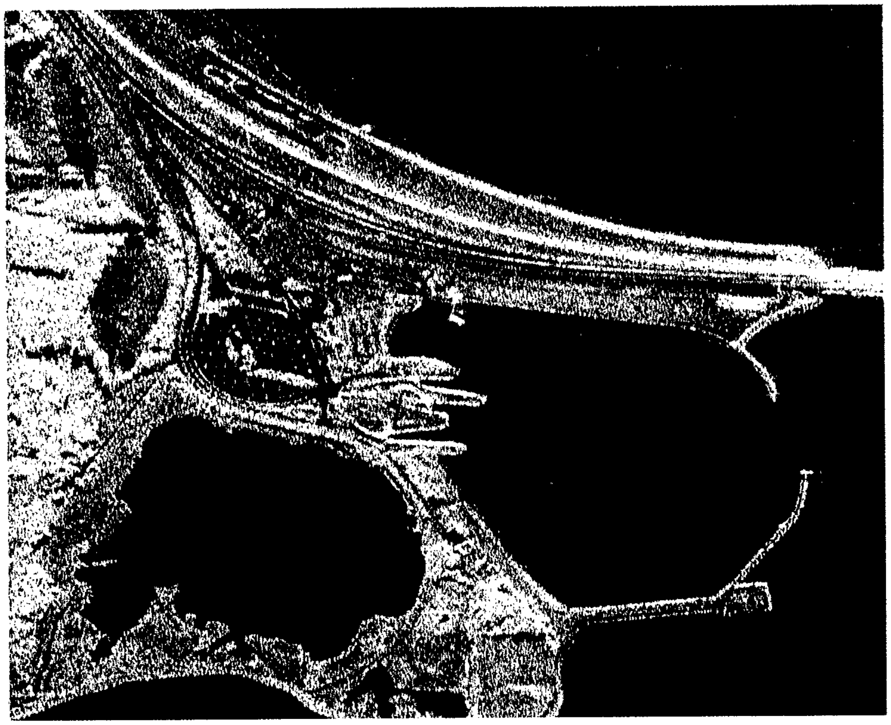


Fig. 10 Knudshoved Ferry Harbor. C-band, June 1998, red=sphere, green=diplane, blue=helix.

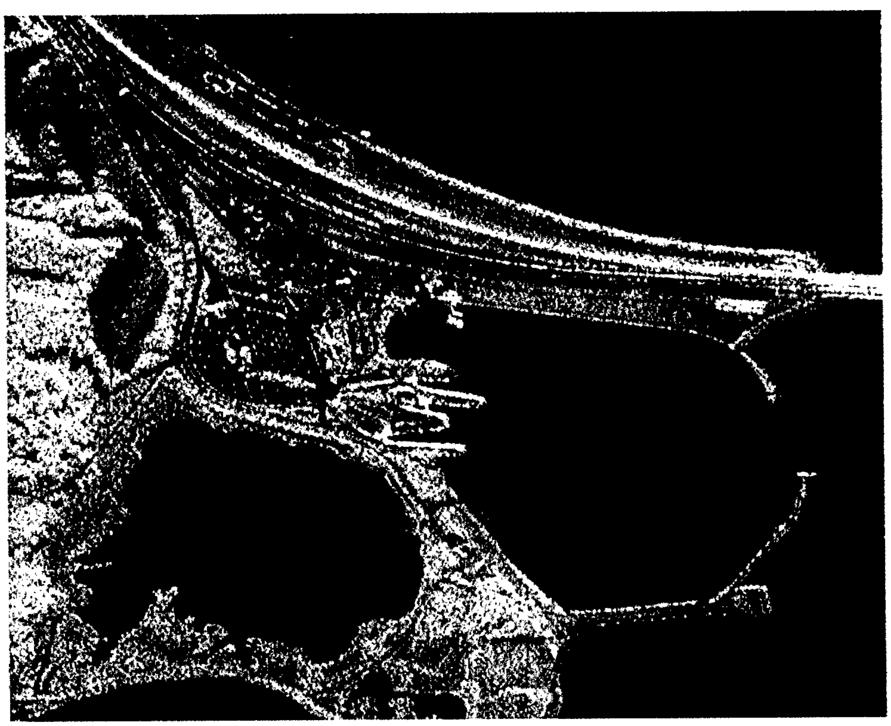


Fig. 11 Knudshoved Ferry Harbor. C-band, June 1998, red=HH-VV, green=HV+VH, blue=HH+VV.

7.4 Knudshoved Ferry Harbor June 16, 1998

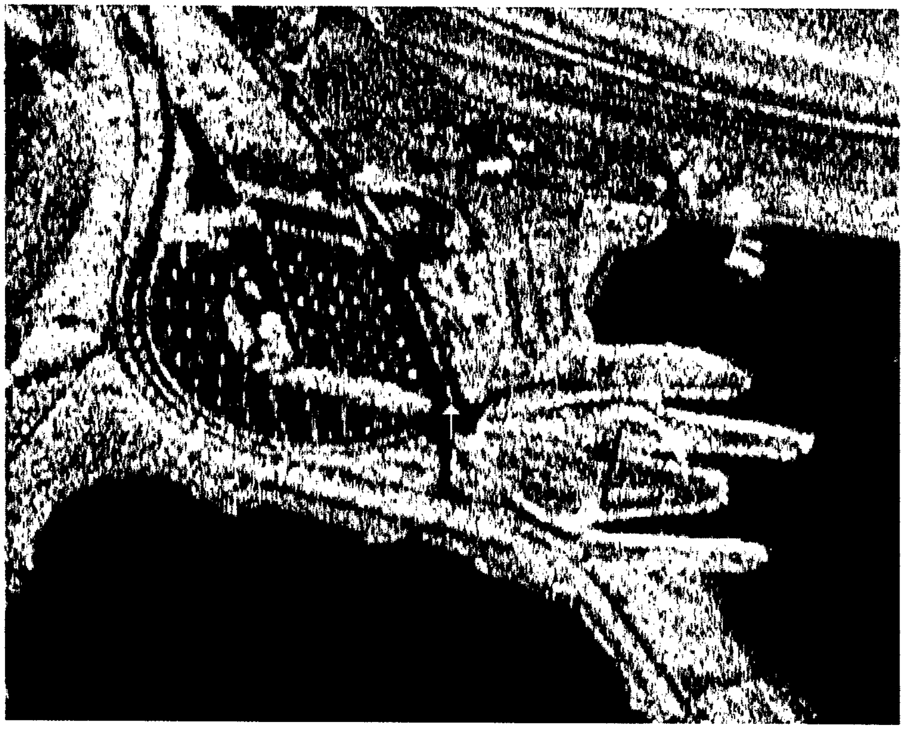


Fig. 12 Knudshoved Ferry Harbor. C-band, June 1998. Radar looking from above, pixel resolution 3m. SDH: red=sphere, green=diplane, blue=helix. Ground truth point of Fig. 14 is indicated.

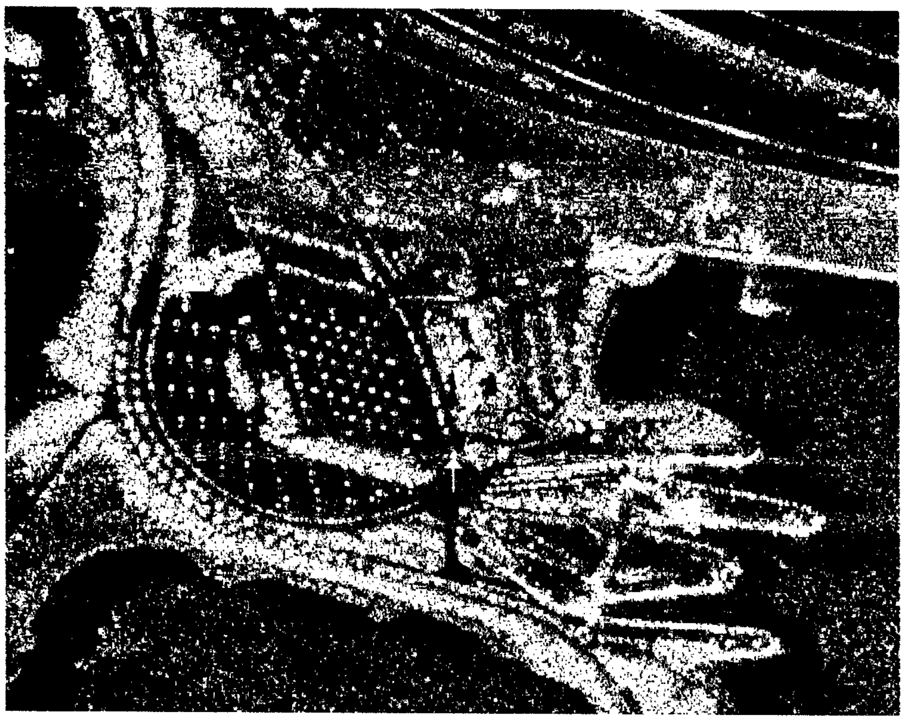


Fig. 13 Knudshoved Ferry Harbor. L-band, June 1998. Radar looking from below, pixel resolution 1.5m. SDH: red=sphere, green=diplane, blue=helix. Ground truth point of Fig. 14 is indicated.

7.5 Ground truth from Knudshoved Ferry Harbor

Fig. 14 Ground truth collection at Knudshoved Ferry Harbor 30 July 1999. Photo: EK. The position is indicated in Fig. 12 and Fig. 13 by a white arrow.

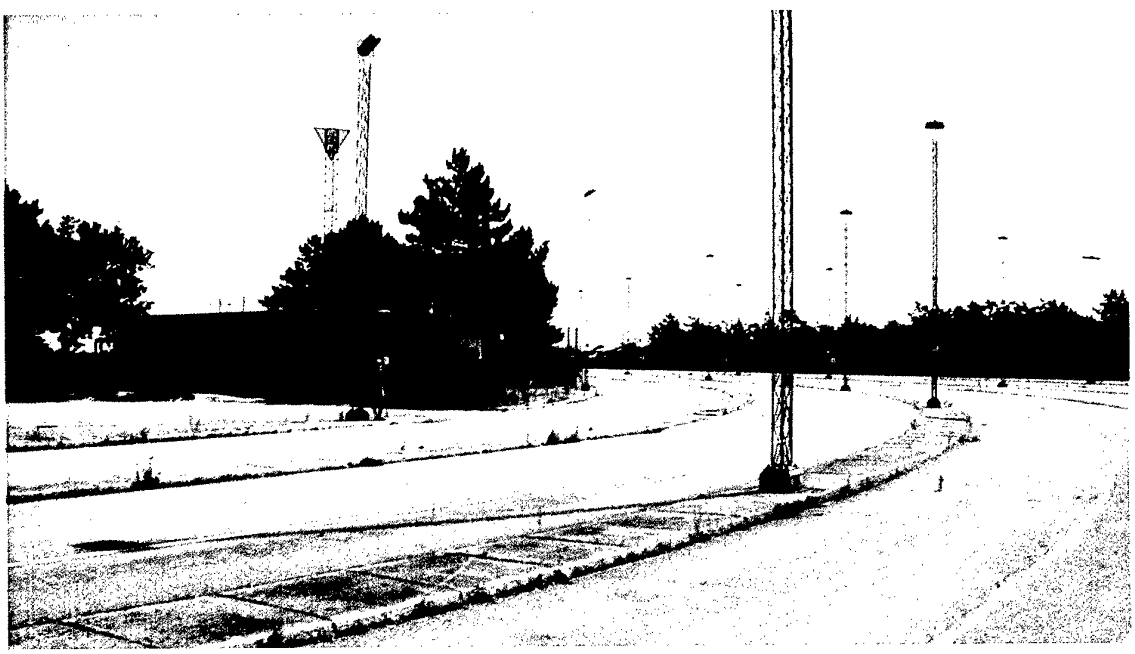


Fig. 15 Ground truth collection at Knudshoved Ferry Harbor 30 July 1999. Photo: EK.

7.6 Halsskov/Korsør June 16, 1998

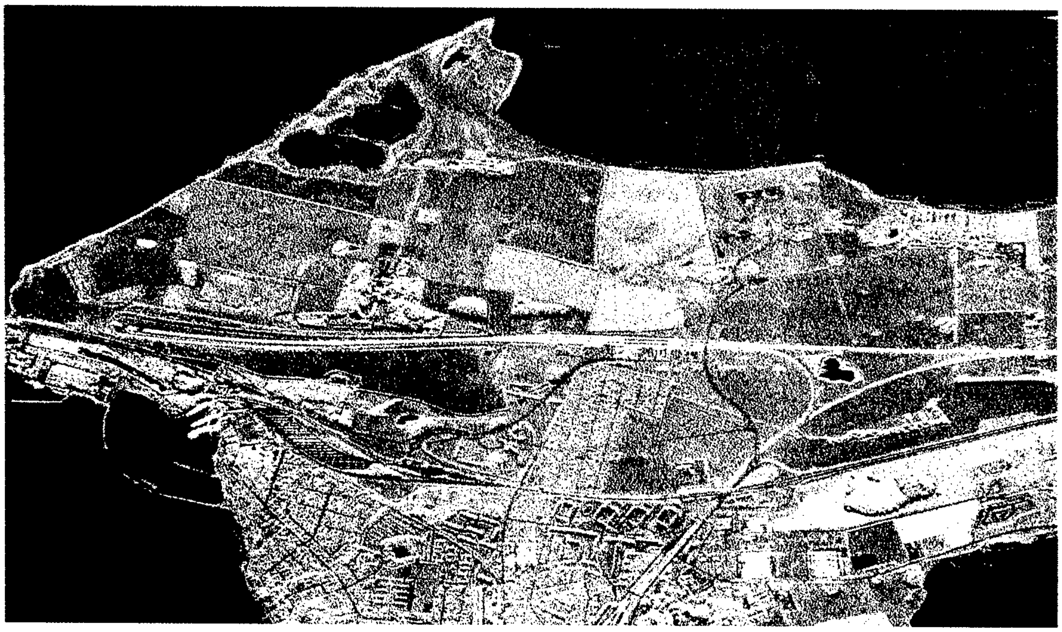


Fig. 16 Halsskov/Korsør, east of the Great Belt connection. C-band, June 1998, red=sphere, green=diplane, blue=helix.

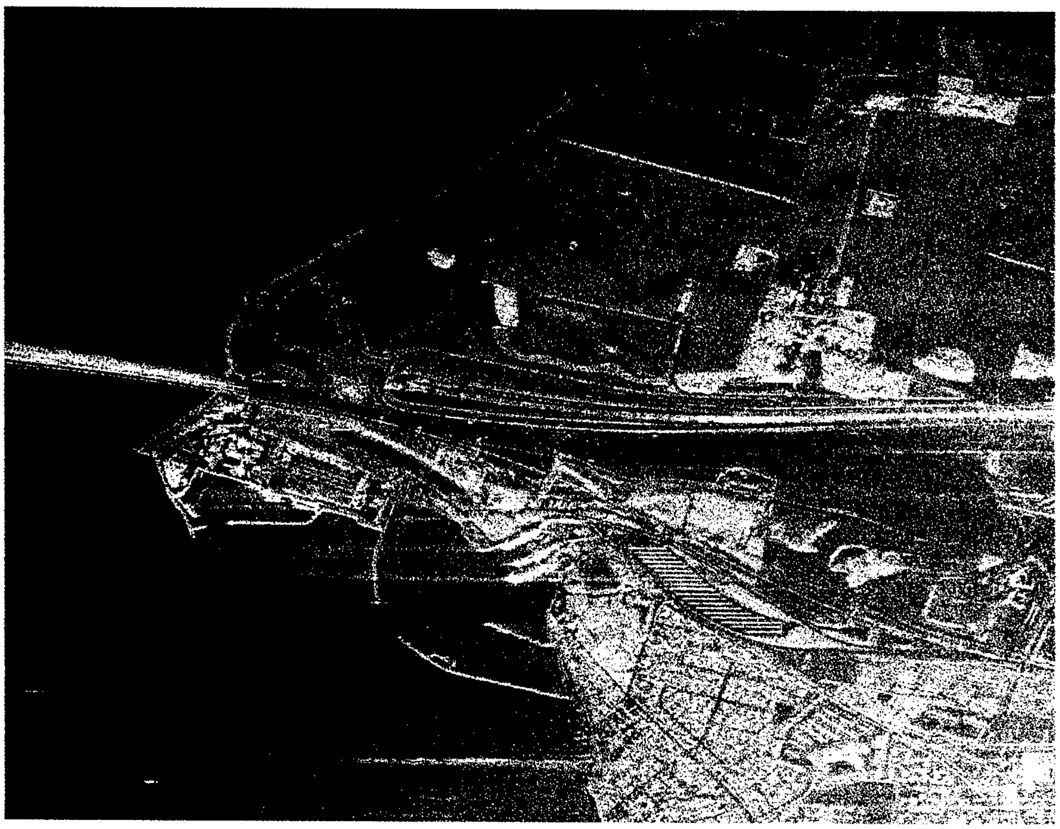


Fig. 17 Knudshoved Ferry harbor. C-band, June 1998, red=HH-VV, green=HV+VH, blue=HH+VV.

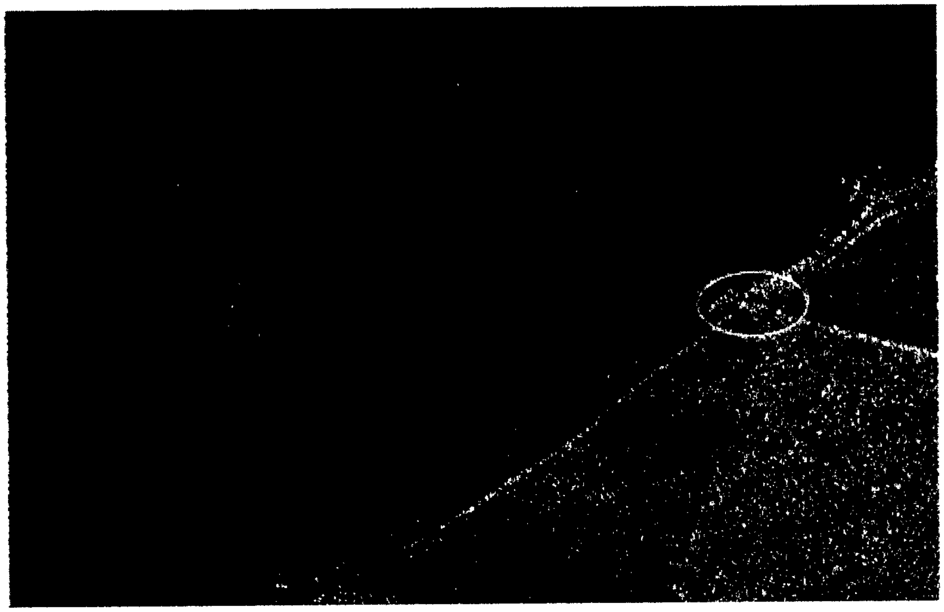


Fig. 18 Fishing nets and beacon location. L-band, red=sphere, green=diplane, blue=helix. The encircled area marks the location of the ground truth collection point of Fig. 20.

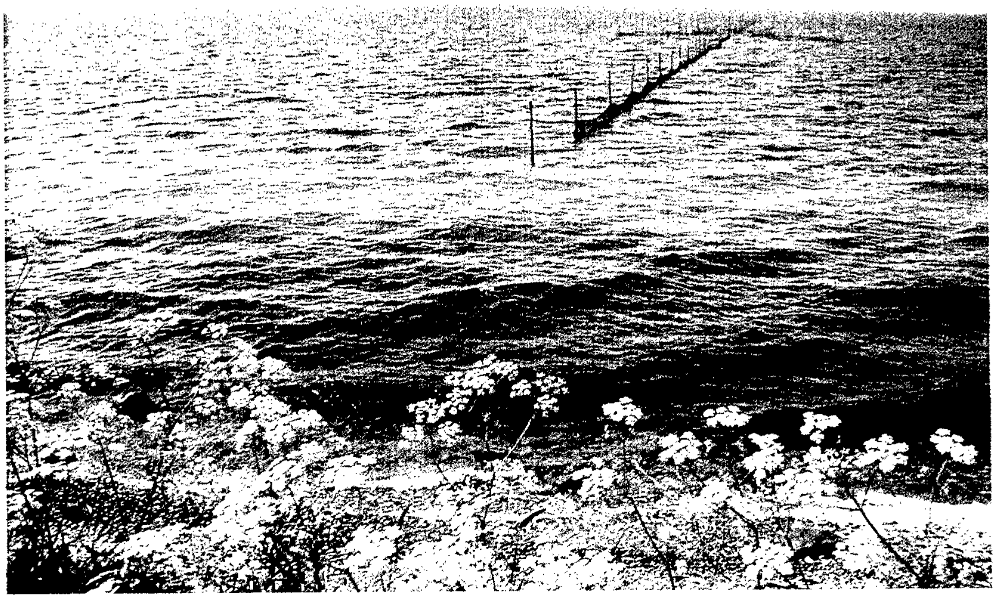


Fig. 19 Fishing stakes and nets in the Great Belt, May 29, 1999. Photo: EK. The configuration is seen in Fig. 18 above as mostly green strips.

Fig. 20 Beacons at location indicated in Fig. 18. July 6, 1999. Photo: EK.

It is noted that the L-band image shown in Fig. 17 exhibits many spurious contributions which may be due to interference and/or saturation, as well as side-lobes. The causes are not known, but these problems tend to be typical in the L-band channel. Part of the problem may be RF interference, which poses a general problem at the lower frequencies with current frequency allocations.

7.7 Øresund bridge June 9, 1999

Fig. 21 Øresund bridge June 9, 1999. C-band, radar looking from the south. Pixel resolution 3 m. SDH decomposition: red=HH-VV, green=HV+VH, blue=HH+VV.

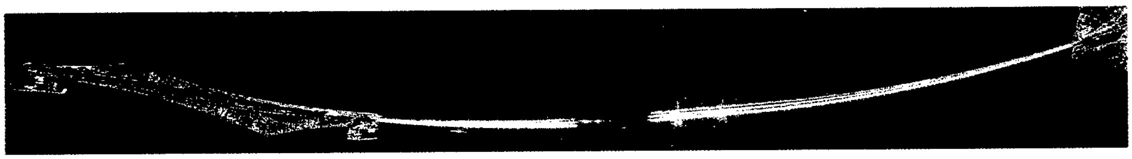


Fig. 22 Øresund bridge June 9, 1999. L-band, radar looking from the north. Pixel resolution 1.5 m. SDH decomposition: red=HH-VV, green=HV+VH, blue=HH+VV.

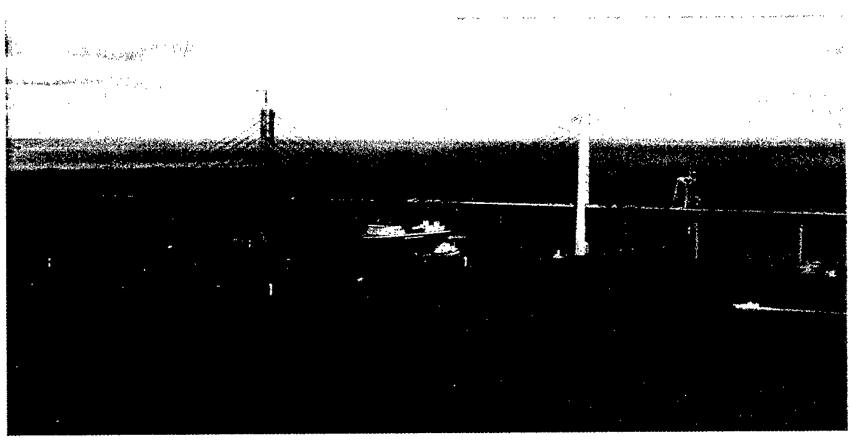


Fig. 23 Øresund bridge June 21, 1999. Photo: Pierre Mens.

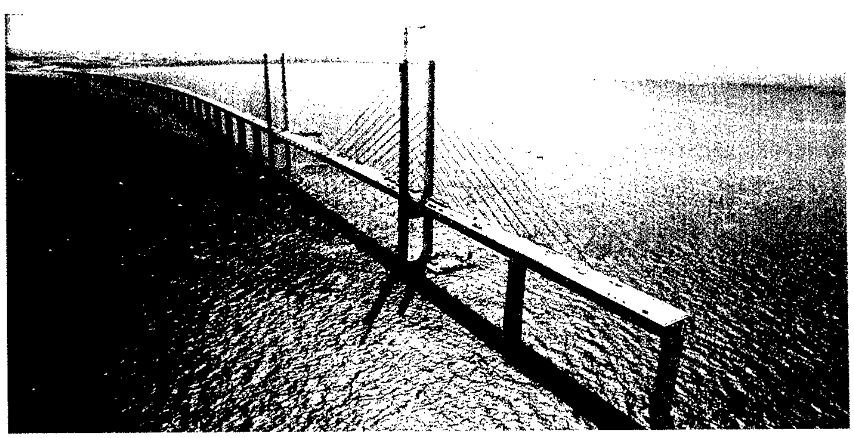


Fig. 24 Øresund bridge June 21, 1999. Photo: Pierre Mens.

7.8 Copenhagen Airport June 9, 1999

An illustrative comparison of the Pauli and the SDH representations is shown in Fig. 25 and Fig. 26. These figures show the upper part of the scene with Copenhagen Airport at L-band and a resolution of 1.5 m. Note how double bounce reflections stay green in the SDH representation, while they fall in the red and green channel of the Pauli representation, depending on the incidental orientation angle.

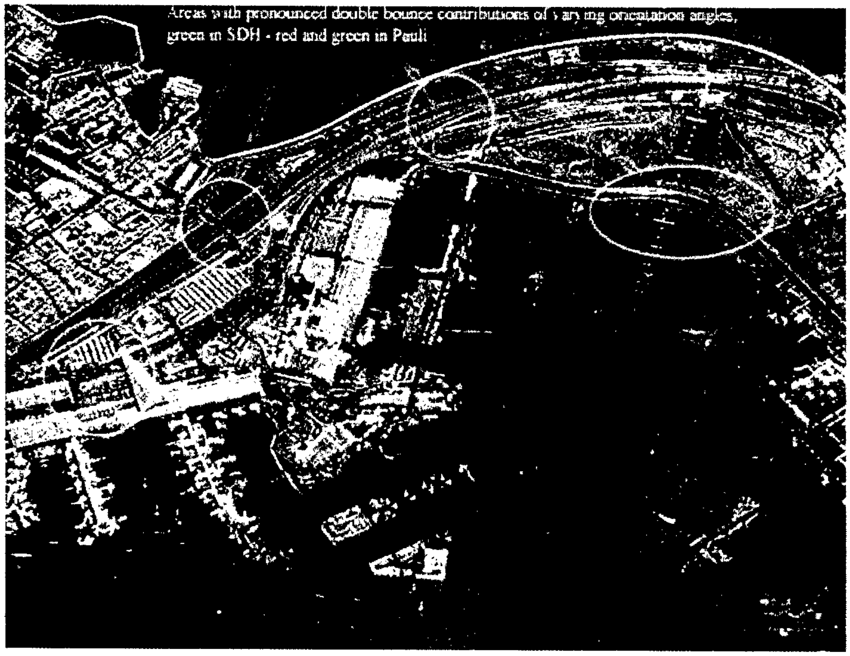


Fig. 25 Part of Copenhagen Airport. L-band, SDH: red=sphere, green=diplane, blue=helix.

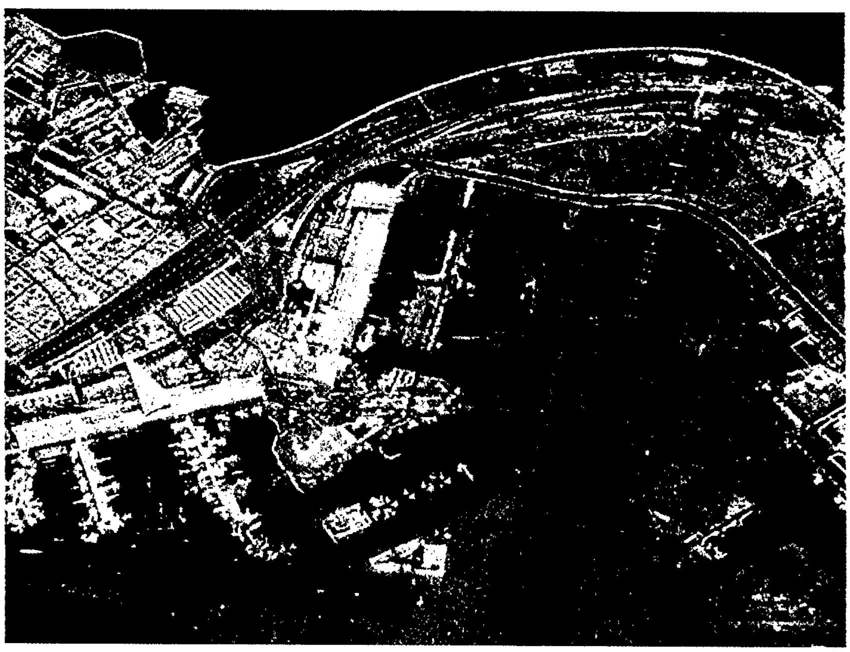
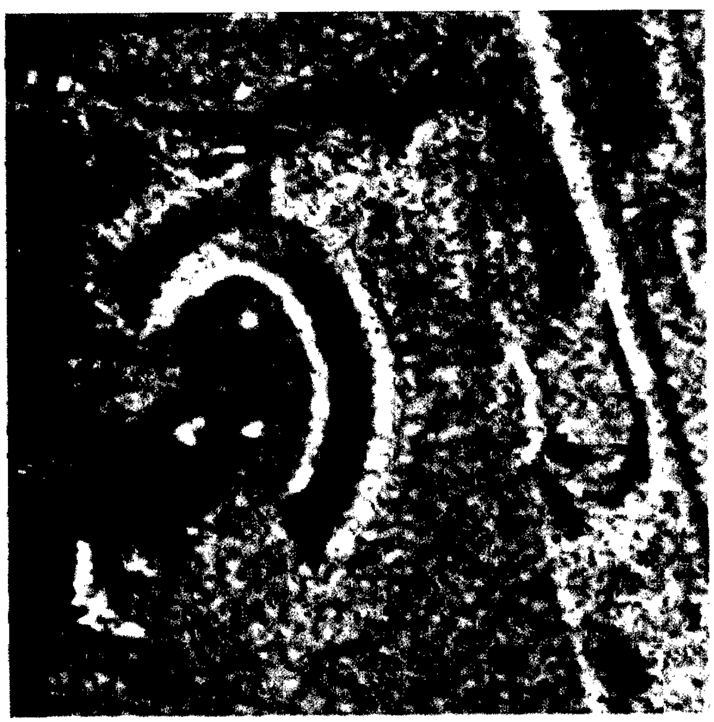


Fig. 26 Part of Copenhagen Airport. L-band, Pauli: red=HH-VV, green=HV+VH, blue=HH+VV.

L-band, 1.5 m x 1.5 m



C-band, 3 m x 3 m

Fig. 27 Parked plane at remote corner of Copenhagen Airport June 9, 1999. SDH: red=sphere, green=diplane, blue=helix. L-band seen from the left, C-band from the right.

8. PUBLICATIONS RELATED TO NICOP AWARD UNDER CONTRACT NO. N00014-97-C-0408

The following list represents the publications authored and co-authored by E. Krogager, DDRE, under the NICOP contract.

1. E. Krogager, S.R. Cloude, J.-S. Lee, T.L. Ainsworth, and W.-M. Boerner, Interpretation of high resolution polarimetric SAR data, *Journées Internationales de la Polarimétrie Radar, JIPR'98*, Nantes, France, 13-17 July, 1998.
2. T. L. Ainsworth, J. S. Lee, and E. Krogager, High-resolution Polarimetric SAR for Littoral Remote Sensing, *Journées Internationales de la Polarimétrie Radar, JIPR'98*, Nantes, France, 13-17 July, 1998.
3. T. L. Ainsworth, J. S. Lee, R. W. Jansen, R. Fiedler, and E. Krogager, Sub-aperture Processing of High-resolution Polarimetric SAR Imagery, *Progress of Electromagnetics Research Symposium*, Taipei, Taiwan, 22-26 March 1999.
4. E. Krogager, W.-M. Boerner, T. Ainsworth, J.-S. Lee and J. S. Verdi, Interpretation of High-Resolution Polarimetric SAR Data Using Detailed Ground Truth Information, *Proc. of the European Synthetic Aperture Radar Conference (EUSAR 2000)*, Munich (GE), May 2000.
5. Lee, J.-S., M.R. Grunes, T.L. Ainsworth, E. Pottier, E. Krogager, and W.-M. Boerner, Quantitative Comparison of Classification Capability: Fully-Polarimetric Versus Partially Polarimetric SAR, *Proc. of the European Synthetic Aperture Radar Conference (EUSAR 2000)*, Munich (GE), May 2000.
6. Lee, J.-S., E. Krogager, D.L. Schuler, T.L. Ainsworth, D. Kasilingam and W.M. Boerner, "On the Estimation of Slope Induced Shifts of Polarization Orientation Angles in Polarimetric Radar Images," submitted to the *IEEE Transactions on Geoscience and Remote Sensing*, Dec. 2000.
7. Krogager E., W.-M. Boerner, J.-S. Lee, T. Ainsworth and J. S. Verdi, Studies of Polarimetric SAR Imagery of the Great Belt Connection, *Proc. International Geoscience and Remote Sensing Symposium (IGARSS 2001)*, Sydney, Australia, July 2001.

9. SUMMARY AND RECOMMENDATIONS

The support from the U.S. Office of Naval Research for these activities has provided excellent conditions for conducting the reported investigations. A vast amount of high quality SAR (Synthetic Aperture Radar) data has been made available for the project, in part thanks to the fact that payment could be justified by the ONR NICOP award.

Thus far, the efforts have been mostly focused on establishing a solid basis for exploiting the utility of polarimetric techniques. This objective has been met via the following main steps: 1. Establishment of an extensive library of high-resolution fully polarimetric SAR data. 2. Development of software tools for analyzing such data. 3. Generation of a large number of image examples. 4. Exercising the interpretation and assessment of such imagery and the applied techniques.

A natural continuation of the work would be to conduct some direct, quantitative comparisons of the various techniques by automated, unbiased procedures. Furthermore, there is a strong need for more work in the direction of utilizing detailed, precision ground truth information for analyzing and utilizing this kind of data. As has been demonstrated in the reported work, radar imagery can be very tricky to interpret due to the highly complicated nature of the underlying scattering and reflection of electromagnetic waves in the microwave domain. To eliminate guesswork in the interpretation of actual applications, the availability of detailed ground truth is of paramount importance.

On the basis of the previous work, specific applications should be addressed in order to elucidate the potential of the techniques under consideration and development. Such work is of course being pursued at many research institutions worldwide, but for the express purpose of advancing these techniques within the present framework of applications in Danish littoral zones and their vicinity, a number of topics could form the basis for specific projects. For example, the classification and identification of single objects as well as extended areas and installations are of great importance for both civilian and military applications. The considered techniques of radar polarimetry have high potential for solving such problems. During the work reported here, the issue of passability has been discussed at DDRE as a subject that could be of particular interest. The scenes covered by the established library of datasets contain many areas of potential interest in this respect. The varying conditions of wetlands etc., due to annual variations as well as variations in climatic conditions on a short-term basis, pose a problem in relation to assessing the possibility of passing through such areas with different kinds of vehicles in a given situation.

In continuing the work with application oriented issues like classification, identification, and passability assessment as mentioned above, a natural extension would be to combine polarimetric techniques with interferometric processing, which is now a subject for intense research worldwide. For the techniques dealt with here, it is important to note that like SAR in general, interferometry is inherently a coherent technique (enabling topographic imaging and high-sensitivity change detection), and to preserve resolution as well as the coherent nature of the data, it is of relevance to consider the application of coherent decomposition techniques in comparison and together with the more commonly applied techniques based on incoherent processing. The incoherent techniques are particularly suited for extended areas and targets, where resolution is of less importance (or even not desired). However, for looking at detailed target structures, the highest possible resolution is desirable, and the processing techniques should be developed accordingly.

In fact, a proposal by the present author for such studies has already been approved by ONR, and a project has been initiated under the title *'Application of Coherent Decomposition to High-Resolution Polarimetric and Interferometric SAR Data'*.

10. ACKNOWLEDGMENTS

The support from the U.S. Office of Naval Research is gratefully acknowledged. In particular, the author is indebted to the former Associate Director of ONR Europe, Mr. Otto Kessler, for the invaluable support and encouragements that led to the NICOP collaboration reported herein. Likewise, sincere thanks are due to the Program Officer at ONR, Dr. William J. Stachnik, for his continued support to these activities and his encouraging appreciation of the results. The matching funding for the NICOP collaborations provided by the U.S. Naval Research Laboratory, Washington, D.C., is also gratefully acknowledged. The obliging support and the active, open-minded participation from Head of Image Science Section at NRL, Dr. Jong-Sen Lee, has been a most stimulating and encouraging contribution to this project, and sincere thanks are extended to Dr. Lee. The extensive contributions of Dr. Thomas Ainsworth to the data processing and publication thereof are also highly appreciated, and further thanks are extended to Drs. Dale Schuler and Mitchell Grunes of NRL.

Professor Wolfgang-Martin Boerner, the University of Illinois at Chicago, has played a key role in coordinating and promoting the activities within this forum of radar polarimetry. The author is indebted to Prof. Boerner for his continued support during the years, and gratefully acknowledges the invaluable efforts of Prof. Boerner.

The author would also like to express his gratitude to the other European partners of these efforts, Profs. Shane R. Cloude, AEL, UK, and Eric Pottier, University of Rennes 1, France, for the fruitful interaction.

The report is based on EMISAR data from the Danish Center for Remote Sensing (DCRS), the Technical University of Denmark (TUD). DCRS takes no responsibility for the published results.

Thanks are due to Dr. Martin Hellmann and Mr. Martin Keller for contributions to the handling and processing of EMISAR data during their stays at DDRE within the EC TMR network.

11. REFERENCES

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[2] Krogager, E., and W.-M. Boerner, "On the Importance of Utilizing Polarimetric Information in Radar Imaging and Classification", *AGARD Conf. Proc. CP-582*, Apr. 1996, pp. 17.1-13.

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[9] Krogager, E., Polarimetric Decomposition for Radar Resolution Enhancement, *RTO MP-40, SET Panel Symposium on High Resolution Radar Techniques*, pp. 42.1-42.7, Granada, Spain, March 1999

[10] Martinez, C.L., X. Fàbregas Canovas, A. Broquetas i Ibars, and E. Krogager, Polarimetric Techniques for SAR Contrast and Resolution Enhancement, *Proc. European Microwave Conference*, Munich, Germany, Oct. 1999.

[11] Krogager, E., W.-M. Boerner, T. Ainsworth, J.-S. Lee and J. S. Verdi, Interpretation of High-Resolution Polarimetric SAR Data Using Detailed Ground Truth Information, *Proc. of the European Synthetic Aperture Radar Conference (EUSAR 2000)*, Munich (GE), May 2000.

[12] Lee, J.-S., M.R. Grunes, T.L. Ainsworth, E. Pottier, E. Krogager, and W.-M. Boerner, Quantitative Comparison of Classification Capability: Fully-Polarimetric Versus Partially Polarimetric SAR, *Proc. of the European Synthetic Aperture Radar Conference (EUSAR 2000)*, Munich (GE), May 2000.

Appendix I - Progress Reports

Progress Report No. 1

ONR NICOP Contract No. N00014-97-C-0408

Contractor: Danish Defence Research Establishment
Ryvangs Allé 1
DK-2100 Copenhagen Ø
Denmark

Contract Date: 30 SEP 1997

Report Due: 15 DEC 1997

SUBCLIN: 0001AA

Progress Report No. 1 to Program Officer:

Dr. William Stachnik
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, Virginia 22217-5660
USA

Other partners: Naval Research Laboratory (NRL), Washington, DC, Dr. Jong-Sen Lee
Applied Electromagnetics (AEL), St. Andrews, Scotland, Dr. Shane Cloude

Main activities for the period 15 SEP – 15 DEC 1997

1. Contract settlement
2. Data and software exchange
3. Ground truth collection
4. Software configuration and recompilation
5. Generation of initial results
6. Meeting at NRL

Re 1: Contract settlement took longer than originally expected, but no actual problems occurred.

Re 2: NASA JPL data for San Francisco Golden Gate Bridge and Malaysia scenes were made available by Dr. Jong-Sen Lee on NRL ftp site. Danish EMISAR data for Great Belt scene (C-band) distributed by Dr. E. Krogager on EXABYTE tape to Dr. Lee (hires data for the scene occupy app. 850 MB per polarimetric channel!), and on CD-ROM to Dr. Shane Cloude (covariance matrix data only, initially). Smaller blocks of hires data on CD-ROM, and full data sets on DAT tapes to be delivered to Dr. Cloude early 1998. L-band data expected next quarter as well. Utility program for basic handling of EMISAR data is available for download via the Internet. MATLAB utility program for reading JPL data has been made available by Dr. Cloude.

Re 3: Images of the Great Belt Bridge were collected by a DDRE photographer on DEC 1, 1997 from a ferry by analog and digital cameras. Digital images were distributed on CD-ROM to Dr. Cloude and Dr. Lee during meeting at NRL DEC 4-5, 1997.

Re 4: Data processing and analysis will for the major part be carried out on PC equipment. Programs that have been run in the past on UNIX and other systems are being modified and recompiled for use on DOS and Windows based PC's.

Re 5: The first examples of high resolution images generated from the EMISAR data were presented at the meeting at NRL DEC 4-5, 1997.

Re 6: The first progress meeting was held on DEC 4-5, 1997, at NRL. Participants in the meeting were the principal coworkers Dr. Cloude, AEL, Dr. Krogager, DDRE, and Dr. Lee, NRL, as well as the ONR sponsors Dr. Stachnik and Dr. Trizna, and others. Progress statements and examples of data analyses carried out so far were presented by the involved participants. Particularly noteworthy was the large poster prepared by Dr. Lee and his group at NRL, in which a mosaic of images was presented, representing different scenes from the Great Belt area, and different processing techniques. The meeting confirmed that the project provides an excellent basis for an assessment of various methods and techniques that are currently being developed for use in modern polarimetric radar.

In the next quarter, efforts will mainly be focused on further implementation of algorithms etc., on analyzing available data, as well as on the associated theoretical considerations.

Copenhagen, January 19, 1998

Ernst Krogager
Senior Scientist
M.Sc., Dr.Techn.

Progress Report No. 2

ONR NICOP Contract No. N00014-97-C-0408

Contractor: Danish Defence Research Establishment
Ryvangs Allé 1
DK-2100 Copenhagen Ø
Denmark

Contract Date: 15 DEC 1997

Report Due: 15 MAR 1998

SUBCLIN: 0001AB

Progress Report No. 2 to Program Officer:

Dr. William Stachnik
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, Virginia 22217-5660
USA

Other partners: Naval Research Laboratory (NRL), Washington, DC, Dr. Jong-Sen Lee
Applied Electromagnetics (AEL), St. Andrews, Scotland, Dr. Shane Cloude

Main activities for the period 15 DEC 1997 – 15 APR 1998

1. Exchange of data, results, and analyses
2. Software development
3. Generation of results with different techniques

Re 1: Several results have been generated by each partner and made available via an ftp site provided by Dr. Jong-Sen Lee, NRL. C-band EMISAR data has been used extensively, while delivery of L-band data for the same scene (Great Belt, Denmark) has been delayed due to heavy work-load on the Danish Center for Remote Sensing in connection with the search for a recent meteoric fall in Greenland. However, the L-band data should be ready for delivery around May 1.

Re 2: Significant progress has been made in implementing analysis software. Parts of new and existing programs for handling and analyzing high-resolution S-matrix data have been integrated and implemented for PC environments, and new features are currently being added.

Re 3: Some examples of the high-resolution images that have been generated from the EMISAR data are attached. The images show the East Bridge under construction, in four different RGB (red, green, blue) representations, denoted circ, lin, sdh, sighel, thus:

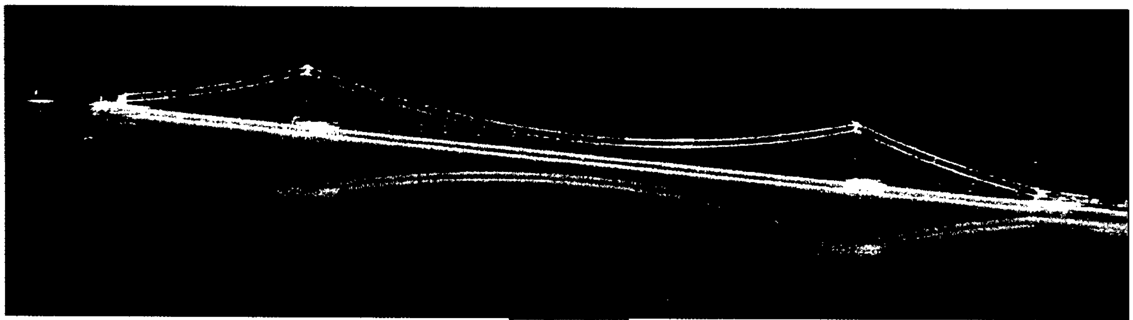
circ for circular basis (R=RL, G=RR, B=LL)
lin for linear basis (R=HV, G=HH, B=VV)
sdh for sphere, diplane, helix decomposition (R=ks, G=kd, B=kh)
sighel for signed helicity, i.e., signed helix component of sdh (R=left kh, G=right kh, B=0)

A detailed discussion of these images is without the scope of this report, but an interesting phenomenon could be mentioned. This is the double-bounce reflections from the suspension cables via the water surface, which appear as straight lines in the images, corresponding to the fact that all rays within a diplane appear to have the same phase center. It should be noted that at the time the data was recorded, the road elements were still not mounted, and only the vertical wires were hanging from the suspension cables.

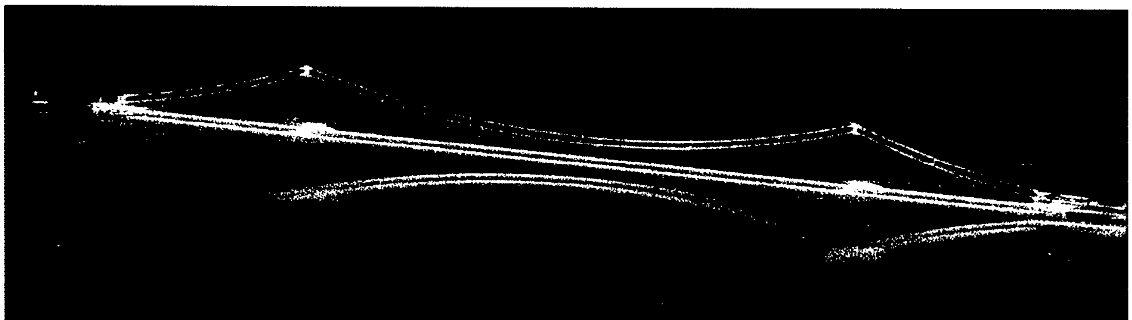
In the next quarter, the work will continue along these lines with more detailed analyses and characterizations of observable features and phenomena in the scene, and frequent communications with Dr. Cloude and Dr. Lee will take place in order to coordinate the efforts.

Copenhagen, April 15, 1998

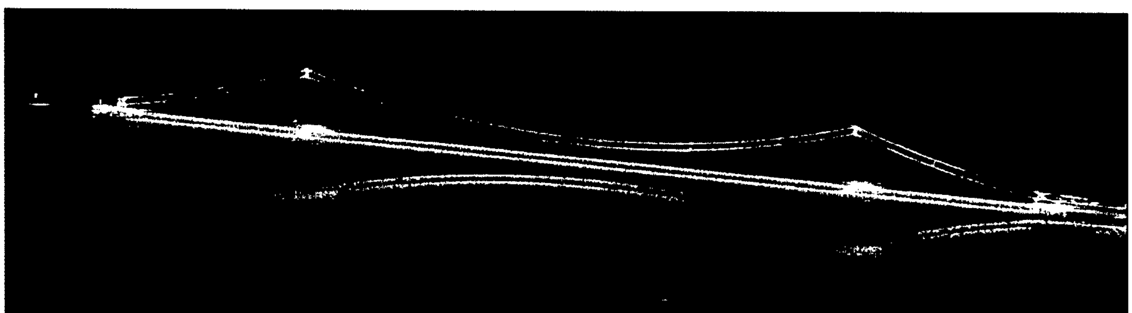
Ernst Krogager
Senior Scientist
M.Sc., Dr.Techn.



HV HH VV



RL RR LL



k_s k_d k_h

k_h^+ k_h^-

Progress Report No. 3

ONR NICOP Contract No. N00014-97-C-0408

Contractor: Danish Defence Research Establishment
Ryvangs Allé 1
DK-2100 Copenhagen Ø
Denmark

Contract Date: 30 SEP 1997

Report Due: 15 JUN 1998

SUBCLIN: 0001AC

Progress Report No. 3 to Program Officer:

Dr. William Stachnik
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, Virginia 22217-5660
USA

Other partners: Naval Research Laboratory (NRL), Washington, DC, Dr. Jong-Sen Lee
Applied Electromagnetics (AEL), St. Andrews, Scotland, Dr. Shane Cloude

Main activities for the period 15 APR 1997 – 15 JUN 1998

1. Exchange of data, results, and analyses
2. Software development
3. Generation of results with different techniques
4. Progress meeting at NRL, Washington, DC

Re 1: L-band EMISAR data has been made available by the Danish Center for Remote Sensing in early May as promised. Data has been distributed to other partners.

Re 2: Software development continues, especially with respect to plotting phase and angular parameters of the different representations.

Re 3: Particularly interesting areas of the scene under current consideration have been selected at both C- and L-band. In the L-band data, some peculiar phenomena have been observed, related to multiple reflections via a moving water-surface, which introduces Doppler shifts and hence smearing and shift of target position in the image. Also to be mentioned here are a couple of areas which stand out remarkably clear as having one specific sense of helicity. A visit to these areas has revealed that the areas are farm fields, but it is yet to be determined what was grown in these fields two years ago, when the data were taken.

Re 4: A progress meeting was held at NRL, Washington, DC, June 11-12, 1998, where the involved partners presented their most recent findings. A need for ground truth was expressed by all, especially related to the Great Belt bridges, which were under construction at the time the data were taken. For example, the scattering mechanisms observed for the suspension cables could not be explained without more detailed knowledge about the actual structures present, like catwalks on top of the suspension cables, etc.

Some of the findings related to this project were presented in two papers at PIERS'98, 13-17 July, 1998, Nantes, France. These papers are enclosed with this progress report.

In the following quarter, emphasis will be on more detailed interpretations based on relevant and traceable ground truth. Activities related to refocusing of ships in the scene will be initiated.

Copenhagen, July 28, 1998

Ernst Krogager
Senior Scientist
M.Sc., Dr.Techn.

Progress Report No. 4

ONR NICOP Contract No. N00014-97-C-0408

Contractor: Danish Defence Research Establishment
Ryvangs Allé 1
DK-2100 Copenhagen Ø
Denmark

Primary investigator:
Dr. Ernst Krogager
Co-investigator:
Dr. Thomas Sams

Other partners: Naval Research Laboratory (NRL), Washington, DC, Dr. Jong-Sen Lee
Applied Electromagnetics (AEL), St. Andrews, Scotland, Dr. Shane Cloude
University of Nantes, (IRESTE), Nantes, France, Dr. Eric Pottier

Contract Date: 30 SEP 1997

Report Due: 15 SEP 1998

SUBCLIN: 0001AD

Progress Report No. 4 to Program Officer:

Dr. William Stachnik
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, Virginia 22217-5660
USA

Main activities for the period 15 JUN 1998 – 15 SEP 1998

1. Exchange of data, results, and analyses
2. Theoretical considerations
3. Software development
4. Generation of results with different techniques
5. Progress meeting/get-together at PIERS'98, Nantes, France
6. Contract extension

Re 1: Danish EMISAR C- and L-band data have been distributed to the new partner in the project, Dr. Eric Pottier, IRESTE, Nantes, France. In addition, some photos from the time the radar data were taken (June/July 1996) have been acquired and made available to the other partners via the ftp site at NRL. The photos have been very useful for explaining several observations in the SAR images.

Re 2: Alternative approaches to formulating and deriving polarimetric decompositions have been considered. In particular, the application of spherical tensor notation has revealed a close relation between this formalism and the circular basis representation of polarimetric quantities. Continued studies in this direction are ongoing, with the aim of a framework for implementation of more generalized decomposition approaches.

Re 3: Software development continues, especially with respect to the possible adaptation for the MATLAB environment.

Re 4: Continues. Geo-referencing of some data is currently being pursued. Thereby, distinct targets, such as buoys, may be conveniently traced in the SAR images.

Re 5: The involved partners discussed their most recent findings during a get-together during PIERS'98 at Nantes, France.

Re 6: An extended contract was signed in mid September this year, so that the project now runs until 31 AUG 1999 instead of 15 MAR 1999. Activities associated with the contract expansion took place between mid July and mid September.

In the following quarter, the activities outlined above will continue. Activities related to refocusing of ships in the scene could not be initiated in the past quarter, but are now planned for the following quarter.

Copenhagen, October 19, 1998

Ernst Krogager
Senior Scientist
M.Sc., Dr.Techn.

Progress Report No. 5

ONR NICOP Contract No. N00014-97-C-0408

Contractor: Danish Defence Research Establishment
Ryvangs Allé 1
DK-2100 Copenhagen Ø
Denmark

Primary investigator:
Dr. Ernst Krogager

Other partners: Naval Research Laboratory (NRL), Washington, DC, Dr. Jong-Sen Lee
Applied Electromagnetics (AEL), St. Andrews, Scotland, Dr. Shane Cloude
University of Nantes, (IRESTE), Nantes, France, Dr. Eric Pottier

Contract Date: 30 SEP 1997

Report Due: 15 DEC 1998

SUBCLIN: 0001AE

Progress Report No. 5 to Program Officer:

Dr. William Stachnik
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, Virginia 22217-5660
USA

Main activities for the period 15 SEP 1998 – 15 DEC 1998

1. Theoretical considerations
2. Software development
3. Generation of results with different techniques

Re 1: Polarimetric decompositions have become a very important factor in connection with polarimetric interferometry. Since interferometry is inherently a coherent technique, coherent polarimetric decomposition techniques have attracted quite some attention recently. Although interferometry is not a primary issue in this project, but rather in another NICOP project involving the co-investigator Dr. Shane Cloude, the current work with various decomposition techniques is also conducted with attention to potential uses in radar interferometry. Dr. Cloude and Mr. Kostas Papathanassiou, DLR, Germany, have developed a coherent decomposition approach based on eigenvalue analysis and coherence optimization of the covariance matrix, employing incoherent formulations and associated statistical assumptions. The general concepts, such as coherence optimization and polarimetric phase, associated with this kind of polarimetric decomposition, are of interest for the comparison of various decomposition approaches in this project. This further relates to the concept of coherent averaging of scattering matrices previously dealt with by Krogager (Thesis, 1993).

Re 2: The plans concerning software development have somehow changed, after the purchase in November 1998 of the software package ENVI (The Environment for Visualizing Images), which is a powerful package with many radar related utilities, and also such general features as various classification tools and georeferencing. Rather than adapting user routines for MATLAB, the plan is therefore now to adapt the routines for the ENVI package. Refocusing of moving targets mentioned in the previous progress report is now also planned to be developed for ENVI using IDL (Interactive Data Language).

Re 3: During this report period, no significantly new results have been obtained. However, preparations and tests using ENVI with the data have taken place.

A major objective for the next quarter is to have the above mentioned user functions incorporated into the ENVI environment, so that the general tools available there can be used jointly with our own techniques.

Copenhagen, January 7, 1999

Ernst Krogager
Senior Scientist
M.Sc., Dr.Techn.

Progress Report No. 6

ONR NICOP Contract No. N00014-97-C-0408

Contractor: Danish Defence Research Establishment
Ryvangs Allé 1
DK-2100 Copenhagen Ø
Denmark

Primary investigator:
Dr. Ernst Krogager

Other partners: Naval Research Laboratory (NRL), Washington, DC, Dr. Jong-Sen Lee
Applied Electromagnetics (AEL), St. Andrews, Scotland, Dr. Shane Cloude
University of Nantes, (IRESTE), Nantes, France, Dr. Eric Pottier

Contract Date: 30 SEP 1997

Report Due: 15 MAR 1999

SUBCLIN: 0001AF

Progress Report No. 6 to Program Officer:

Dr. William Stachnik
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, Virginia 22217-5660
USA

Main activities for the period 15 DEC 1998 – 15 MAR 1999

1. Theoretical considerations
2. Software development
3. Refocusing of ships in EMISAR images

Re 1. Determination of target orientation angle and other angles is important in many applications of radar polarimetry. In a correspondence with Dr. Jong-Sen Lee, NRL, the issue of orientation angle computation was considered in relation to current research to refine azimuth slope measurement. The diplane orientation angle associated with the sphere, diplane, helix decomposition has been found by Dr. Lee to be superior to other currently applied techniques for determining orientation angle. However, the range of the diplane orientation angle is limited to +/- 45 deg., and an approach for extending the range to +/- 90 deg. would be desirable. However, a closer analysis of the problem reveals that the restricted range of this angle is associated with the inability to measure the absolute phase of the elements of the scattering matrix. The correspondence with Dr. Lee triggered some actual calculations to compare the behavior of the overall (Huynen) orientation angle and the diplane orientation angle. The attachment illustrates this for a target composed of a sphere, a diplane, and a helix (any target can be thought of as being composed of these three components) with parameters varying as indicated in the attachment.

Re 2: Procedures for integrating user functions with the ENVI package are still under planning and consideration. However, due to defence budget negotiations which may result in significant cuts in the annual budget of DDRE for the coming years, the Director of DDRE had to impose a general stop for hiring new personnel of any kind in late January this year. This meant that a Ph.D. project within radar polarimetry could not be initiated this winter as otherwise expected. Consequently, extension of the efforts within radar polarimetry, and thereby also assistance for the development of user functions for the ENVI package etc. has not yet become possible.

Re 3: Refocusing is based on the determination of one or more suited single scatterers within the target of interest. The phase history of such individual contributions is used for phase (motion) compensation of the whole target. It is to be expected that polarimetric techniques can be used to enhance such motion compensation since more well-defined phase information can be used. The approach to be pursued in the present study will be largely based on the sphere, diplane, helix decomposition. Based on such a polarimetric technique, individual scatterers can be sorted by scattering mechanism rather than just by amplitude. A particular hypothesis to be tested is the usefulness of the helix component as a measure of the purity of a double-bounce (diplane) scatterer. Since helix-like scattering can be generated by two or more diplanes, absence of helix-scattering on the other hand could indicate that the diplane component is due to a single even-bounce scatterer. By assessing the purity of the reference points according to such criteria, interference problems associated with the reference phase should be reduced.

A major objective for the continued work is to have the above mentioned user functions incorporated into the ENVI environment, and to have the above mentioned procedure for refocusing of moving targets in SAR images implemented and tested.

Copenhagen, April 16, 1999

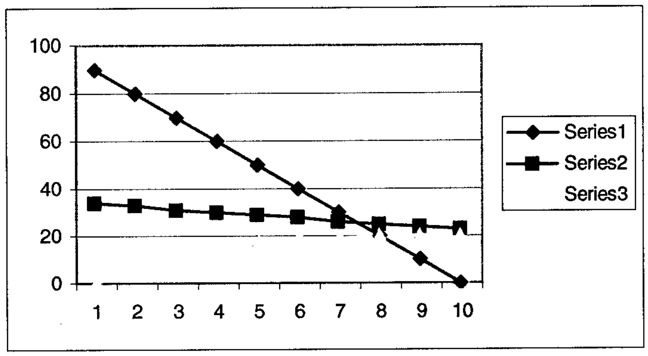
Ernst Krogager
Senior Scientist
M.Sc., Dr.Techn.

Diplane orientation angle and overall orientation angle vs. displacement of diplane phase center

Sphere: 1.0 **Diplane: 1.0** **Helix: 1.0** **E. Krogager - March 1999**

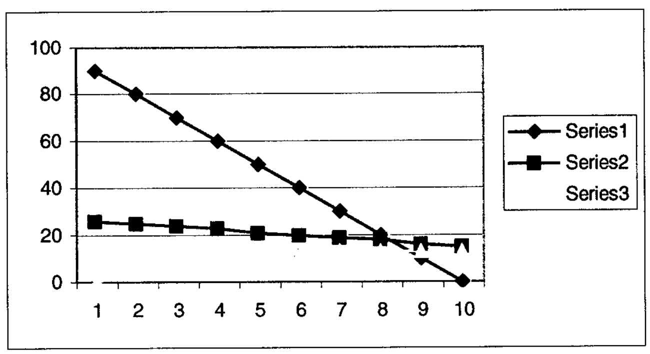
Dipl. orient. 30 deg.

Dipl. displ.	Dipl. orient	Huyn. orient.
90	34	0
80	33	7
70	31	12
60	30	15
50	29	17
40	28	19
30	26	19
20	25	20
10	24	20
0	23	20



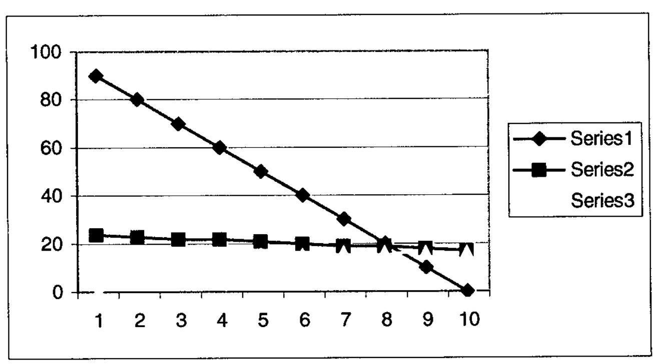
Dipl. orient. 20 deg.

Dipl. displ.		
90	26	0
80	25	5
70	24	8
60	23	10
50	21	11
40	20	12
30	19	13
20	18	13
10	16	13
0	15	13



Dipl. orient. 20 deg. **Helix 0.5**

Dipl. displ.		
90	24	0
80	23	8
70	22	12
60	22	13
50	21	15
40	20	15
30	19	16
20	19	16
10	18	16
0	17	16



Progress Report No. 7

ONR NICOP Contract No. N00014-97-C-0408

Contractor: Danish Defence Research Establishment
Ryvangs Allé 1
DK-2100 Copenhagen Ø
Denmark

Primary investigator:
Dr. Ernst Krogager

Other partners: Naval Research Laboratory (NRL), Washington, DC, Dr. Jong-Sen Lee
Applied Electromagnetics (AEL), St. Andrews, Scotland, Dr. Shane Cloude
University of Nantes, (IRESTE), Nantes, France, Dr. Eric Pottier

Contract Date: 30 SEP 1997

Report Due: 15 JUN 1999 (before no-cost-extension)

SUBCLIN: 0001AG

Progress Report No. 7 to Program Officer:

Dr. William J. Stachnik
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, Virginia 22217-5660
USA

Activities since last progress report

1. Theoretical considerations - refocusing of ships in EMISAR images
2. Ground truth collection by portable DGPS recording system
3. Data acquisition

Re 1.

The idea of improving motion compensation by the use of coherent polarimetric target decomposition techniques was transferred to Dr. Jong-Sen Lee (cc. Dr. Stachnik) by the following e-mail of 22 June, 1999:

Dear Jong-Sen,

One of the issues I am supposed to address in the extended NICOP project, is the problem of motion compensation in relation to refocusing of moving targets (especially ships) in SAR images. However, for various reasons it has not yet been possible to try various ideas in practice. Since you and your group have significant experience with these techniques as well as polarimetric decomposition techniques, I found it appropriate to pass a couple of suggestions on to you, to see if you should have any possibility of pursuing them in the near future within our NICOP network activities.

As you know well, a commonly used motion compensation technique is based on the determination of one or more suited single scatterers within the target of interest. The phase history of such individual contributions may then be used for phase/motion compensation of the whole target. The approach I'd like to pursue is based on the sphere, diplane, helix decomposition, by which individual scatterers can be sorted by scattering mechanism rather than just by amplitude (each of the components of the decomposition has associated with it a phase that allows for coherent processing). The helix component could be used as a measure of the purity of a double-bounce (diplane) scatterer, since helix-like scattering can be generated by two or more diplanes. Hence, absence of helix-scattering could indicate that the diplane component is due to a single even-bounce scatterer. By assessing the purity of the reference points along these lines, interference problems associated with the reference phase could perhaps be reduced considerably.

I look forward to our meeting in Hamburg in connection with IGARSS'99, where we can discuss these issues further.

Best regards,

Ernst

<u>Re 2</u>.

The following joint paper was published and presented at the European Synthetic Aperture Radar Conference (EUSAR 2000), Munich, 23-25 May 2000:

INTERPRETATION OF HIGH-RESOLUTION POLARIMETRIC SAR DATA USING DETAILED GROUND TRUTH INFORMATION, *by E. Krogager, W.-M. Boerner, T. Ainsworth, J.-S. Lee, J.S. Verdi*

The paper is attached, and the abstract and introduction are repeated here for easy reference:

ABSTRACT

Detailed ground truth information has been collected by the use of a digital camera together with a portable differential GPS data collection system. Thereby it becomes possible to precisely locate individual objects within a SAR image. The utility of such information for supporting the interpretation of high-resolution polarimetric SAR data is demonstrated through several examples based on data from the Danish EMISAR.

INTRODUCTION

High-resolution polarimetric SAR data make it possible to characterize and identify scatterers of limited physical extent. Thus, by polarimetric techniques, the physical properties of a scatterer can be described in terms of target characteristic parameters and features on a pixel-by-pixel basis [1, 2]. In order to analyze and interpret such data, detailed ground truth information is required [3, 4]. However, the available ground truth is usually very sparse compared to the information content of the SAR data, and most ground truth data takes aim at collecting large-scale data, applying to extended targets like forests, agricultural fields, etc., and applying to rather course radar resolutions.

The present paper reports some experiments conducted with the purpose of collecting precision ground truth data for detailed interpretation of high-resolution polarimetric SAR data, and also for geocoding purposes. The ground truth information was collected in selected areas of a scene for which L- and C-band data from the Danish EMISAR system were available. Ground truth data were collected by a portable acquisition system consisting of a single-antenna battery-operated differential GPS (Global Positioning System) receiver installed in a rucksack together with a compact notebook computer. The antenna was mounted on a pole for easy carrying and positioning. Data from the GPS unit were recorded at a rate of one sample per second, while digital photos of areas of particular interest were taken.

Examples of the analysis of high-resolution SAR data using such detailed ground truth are shown. In a scene containing the Danish Great Belt bridges, some specific areas of interest for ground truth collection were selected. Using the ground truth information, it is possible to make a detailed assessment and interpretation of the appearance of distinct objects and scattering contributions in the SAR images.

Presently, software is being developed for automatically sorting the collected GPS data and digital photos, so as to automatically locate the positions of points of interest and the associated digital photos. Next, the positions thus determined may be used for geocoding the SAR data, enabling map overlay etc.

Re 3.

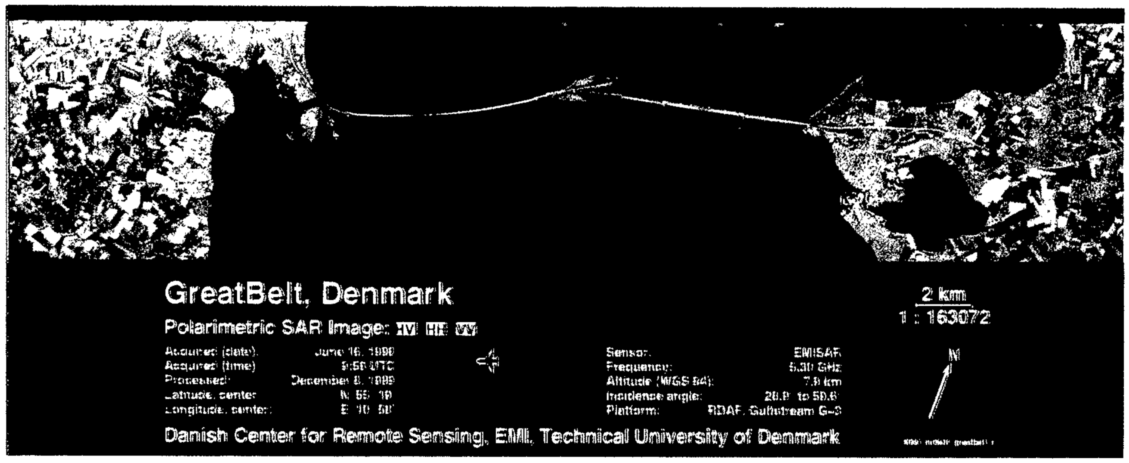
Since the last progress report, six more data sets have been acquired from the Danish Center for Remote Sensing (DCRS), containing images of the Great Belt and the Oeresund / Copenhagen Airport areas. The Great Belt data were taken after the opening of the bridge, unlike the data used hitherto. Among other interesting sites, the Oeresund scene contains the Copenhagen airport area as well as the new bridge between Denmark and Sweden, at the completion stage of June 1998 (to be opened to public traffic on July 1st, 2000).

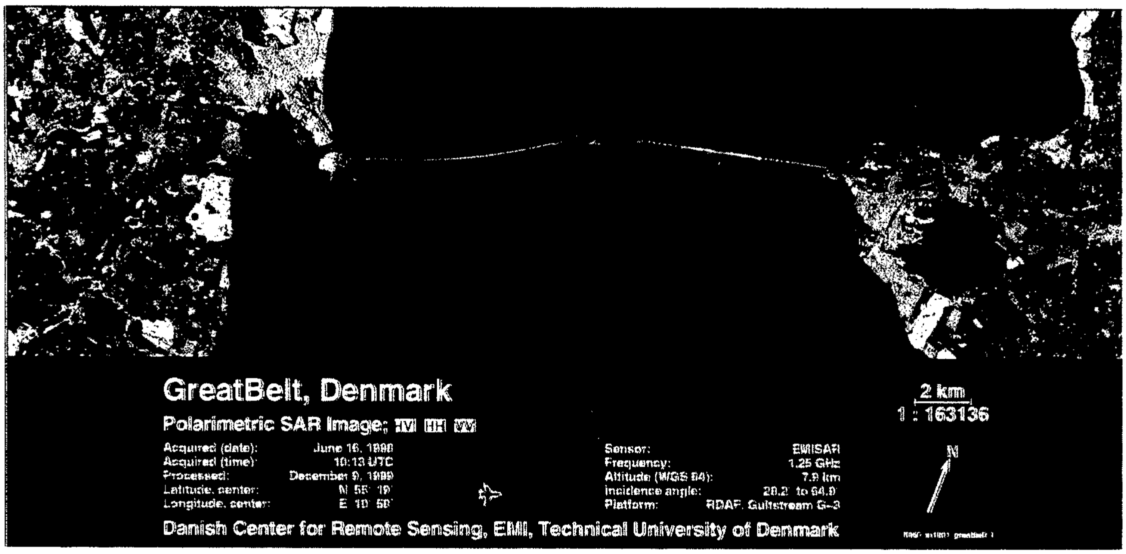
Copenhagen, June 27, 2000

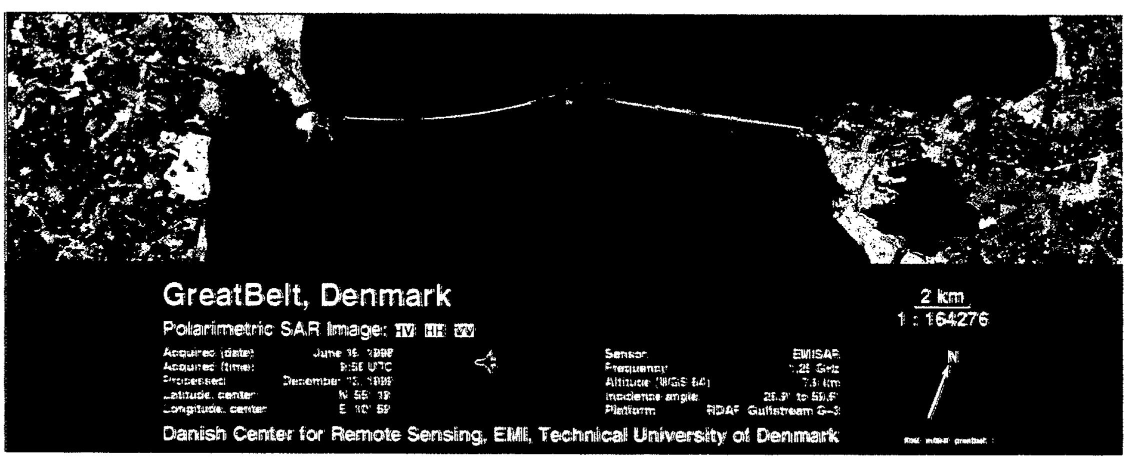
Ernst Krogager
Senior Scientist
M.Sc., Dr.Techn.

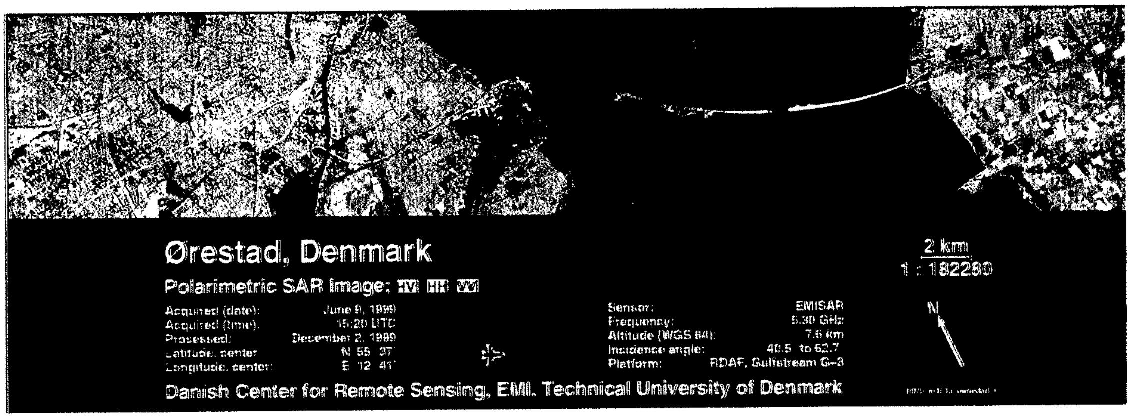
Appendix II - Overview of EMISAR datasets

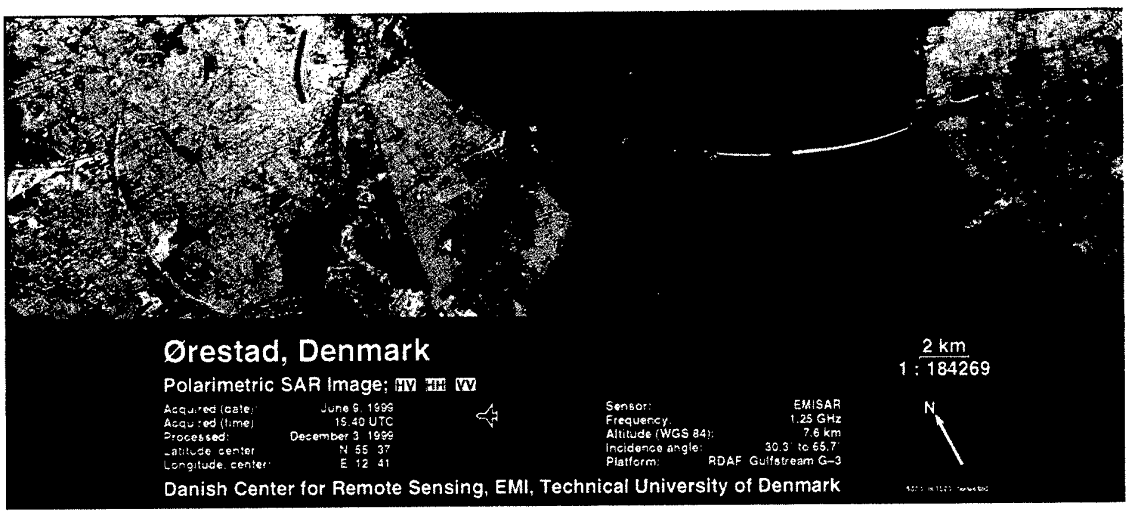
The following datasets were processed and delivered by the *Danish Center for Remote Sensing* in December 1999 against payment that was available thanks to the US ONR contract (Great Belt scenes, app. $3,500) and the EC TMR network contract (Ørestad scenes, app. $3,500).

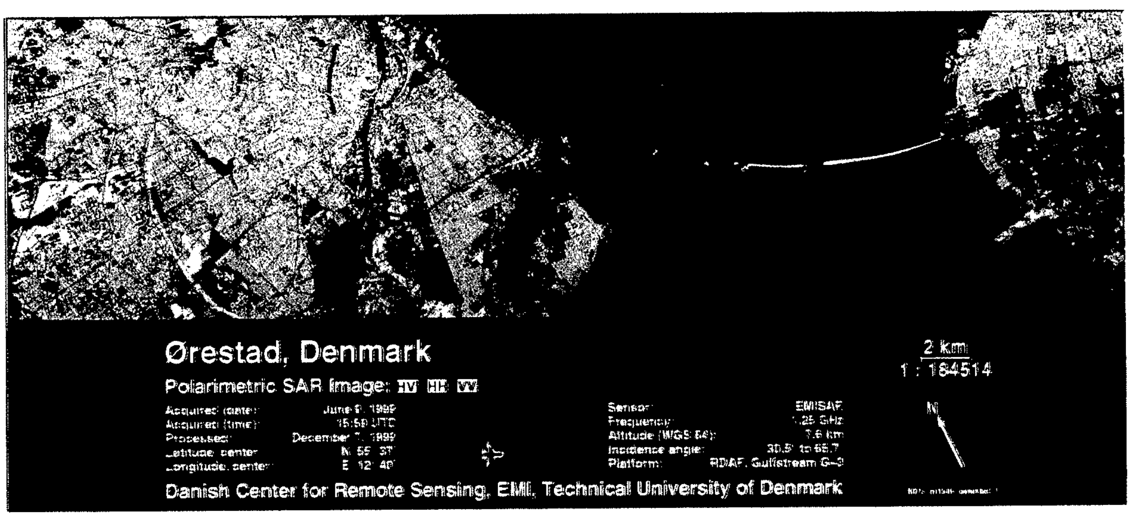







Ørestad, Denmark
Polarimetric SAR Image; HV HH VV
Acquired (date): June 9, 1999
Acquired (time): 15:20 UTC
Processed: December 2, 1999
Latitude, center: N 55 37
Longitude, center: E 12 41
Sensor: EMISAR
Frequency: 5.30 GHz
Altitude (WGS 84): 7.6 km
Incidence angle: 40.5 to 62.7
Platform: RDAF, Gulfstream G-3
Danish Center for Remote Sensing, EMI, Technical University of Denmark
2 km
1 : 182280
N


Ørestad, Denmark
Polarimetric SAR Image; HV HH VV
Acquired (date): June 9, 1999
Acquired (time): 15.40 UTC
Processed: December 3 1999
Latitude center: N 55 37
Longitude, center: E 12 41
Sensor: EMISAR
Frequency: 1.25 GHz
Altitude (WGS 84): 7.6 km
Incidence angle: 30.3° to 65.7°
Platform: RDAF Gulfstream G-3
Danish Center for Remote Sensing, EMI, Technical University of Denmark
2 km
1 : 184269
N


Ørestad, Denmark
Polarimetric SAR Image; HV HH VV
Acquired (date): June 9, 1999
Acquired (time): 15:58 UTC
Processed: December 7, 1999
Latitude, center: N 55 37
Longitude, center: E 12 40
Sensor: EMISAR
Frequency: 1.25 GHz
Altitude (WGS 84): 7.6 km
Incidence angle: 30.5° to 65.7
Platform: RDAF, Gulfstream G-3
Danish Center for Remote Sensing, EMI, Technical University of Denmark
2 km
1 : 184514
N

Appendix III - CD-ROM

The enclosed CD-ROM contains a PDF version of this report, as well as some ground truth data, papers and processed images. However, due to distribution limitations, software is not included on this CD-ROM.