Initial testing of ERS Tandem data quality for InSAR applications

Examples from Taiwan, Madagascar, Zaire, Ivory Coast, Mali and Greenland

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1 Introduction

1.1 General

After one year of ERS-1 and ERS-2 performing repeat acquisitions with a one day separation (the so-called tandem acquisition phase) there are around 100 000 repeated frames of data covering areas all over the world. At the present time, most of the acquisitions by ESA and by national stations within Europe and North America have been made available to the user community.

Terrain and terrain cover (vegetation, ice, snow etc) are some of the most important factors which affect the potential usefulness of tandem data within particular applications. Early results from the Tandem phase [1] show that forest stands and snow melting cause a drastic reduction on the signal coherence over the one day time interval between successive acquisitions. Additional factors such as complex topography also reduce the interpretability of InSAR results due to an increased loss of coherence and fragmentation of the interpretable areas. A further problem with the tandem results is that data have currently been acquired and analysed only over a limited region of the Earth's surface. This can lead to possible doubts as to the generality of any findings regarding the application of tandem data. The limited coverage is due to the difficulty in handling the large amounts of data involved in processing the InSAR acquisitions.

1.2 Scope

The work presented here covers certain aspects of the use of data acquired under the ERS Tandem phase. In particular, the examples are intended to illustrate the application of InSAR techniques for the provision of information related to various geophysical phenomena. In addition the examples allow a certain degree of analysis and assessment regarding the suitability and performance criteria for InSAR techniques within a particular set of applications and for different geographic locations.

The analysis of the Tandem InSAR data required the execution of a number of distinct tasks including:

- the ordering of data from selected geographical areas not covered by data already stored at ESRIN (including South America, West Africa, Eastern Europe and Greenland)
- the processing of data which were either already available at ESRIN when the analysis started or which were delivered to ESRIN during the execution of the project
- the use of a prototype InSAR Quick Look (Q-L) processor to allow the processing of full acquisition strips. This required extensive collaboration with a consultant from Politecnico di Milano, Dipartimento di Elettronica e Informazione familiar with the processor operations and capable of implementing ad-hoc improvements and repairs as and when required
- the use of a high performance Power Onyx workstation to ensure that the large amounts of data to be processed could be handled within the time available for the project

For a variety of reasons, mainly due to problems with the delivery of data from the various acquisition stations, only a few test sites were analysed. The table below gives details of the data used in the evaluation.

Scene name	acquisition station	dates	orbits	30km strips
Taiwan_1	Taiwan	960221 / 22	24975 / 4402	5
Taiwan_2	Taiwan	960224 / 25	24118 / 4445	9
Madagascar	Johannesburg	951209 / 10	23018 / 3345	19
Zaire	Johannesburg	960401 / 02	24644 / 4971	16
Ivory Coast	Maspalomas	960427 /28	25025 / 5352	24
Mali	Maspalomas	960423 / 24	24960 / 5287	36
Greenland_1	Kiruna	960125 / 26	23693 / 4020	35
Greenland_2	Kiruna	960211 / 12	23932 / 4259	14

Table 1: data used in the project

1.3 Document structure and contents

The document is arranged as follows:

- section 2 is a background on SAR interferometry (InSAR), the various applications of InSAR, the potential contribution from the tandem phase of the ERS platforms and a statement of the current status of tandem acquisitions
- section 3 is a description of the Quick Look processor used to produce the interferogrammes
- section 4 presents a summary of the conclusions that can be drawn regarding the use of tandem data for producing interferogrammes and the applicability of tandem interferometry within particular disciplines in geophysics
- section 5 is a bibliography of references cited within this report
- appendix A provides example InSAR composites from tropical forests covering mountainous terrain
- appendix B provides example InSAR composites from tropical forest and savannah areas close to the equator
- appendix C provides example InSAR composites from arctic and sub-arctic Greenland

2 SAR Interferometry

2.1 Introduction

Radar interferometry is a technique for extracting information about the Earth's surface using the phase content of the radar signal as an additional information source derived from the full complex radar signal. Initial development of the technique was carried out during research projects using radar to map the surfaces of Venus and the Moon. The initial terrestrial applications started with airborne Side Looking (SLAR) and Synthetic Aperture (SAR) radar. With the availability of satellite borne SAR instruments, particularly the ERS platforms, considerable development in the technique (known as InSAR) has resulted.

The basic idea is that the height of a point on the Earth surface can be reconstructed from the phase difference between two signals arriving at two antenna. This is because the phase difference is directly related to the difference in path lengths traversed by the signal between the point on the Earth surface and the two antennae. If the positions of the antennae are known accurately then the path difference can be used to infer the position of the target point on the Earth surface.

The basic requirements for a repeat pass interferometric system (such as the use of ERS-1 or tandem ERS-1 / ERS-2) can be stated as:

- stable terrain backscatter (ie slowly changing)
- similar atmospheric conditions during acquisitions
- stable viewing geometry
- preservation of inherent phase information within the SAR processor

Unfortunately, in practice, the accurate determination of the terrain height over the InSAR dataset is difficult. This is due to a number of reasons which arise at different points in the generation, processing and application of interferogrammes and result in one or more of the criteria listed above not being met. In order to categorise these effects it is necessary to know precisely how InSAR can be used to generate height information and to what uses this information can be put.

There are four stages to the reconstruction of height information from the raw images:

① coregistration of the complex SAR images: as the second image is acquired from a different viewing point to the first reference image, the data in the second image must be resampled so that the second image can be projected on to the first image.

② interferogramme formation: this is calculated by multiplying the second image by the complex conjugate of the first image.

The fact that the image data retains both amplitude and phase information means that the file size is somewhat larger than the more familiar intensity images. The interferogramme is a method for illustrating the variation of phase difference over the image although there is an ambiguity of $\pm 2N\pi$ where N is an integer.

Interferogrammes are conventionally visualised using a Red-Green-Blue composite image where different information is assigned to each of the channels. One typical scheme is to assign the red channel to the coherence estimate (which can be calculated using a variety of methods), the green channel to the phase difference between pixels in the two images and the blue channel to the average intensity.

③ phase unwrapping: The problem of adding the correct number of multiples of 2π to the interferogramme in order to extract height information is referred to as phase unwrapping. There are a number of methods for attempting this stage of the processing including:

- the Goldstein branch cut method
- the fringe detection method of Lin et al
- knowledge injection

④ DEM construction

At each processing stage, there are various problems that must be overcome. Some of the problems are outlined below:

noise: the major sources of noise lead to problems mainly in the coregistration of the images and the phase unwrapping. Noise values lead to a loss of coherence and a degradation of the observed fringes.

atmospheric effects: local variations in atmospheric properties lead to differences in the path lengths between the two antenna positions and the target area giving rise to spurious phase variations which are superimposed on to the phase variations generated by the target area.

environmental effects: effects such as layover lead to discontinuities in the phase variations . In addition changes in environmental conditions (eg wind direction) alter the backscattering properties of the target areas between successive acquisitions leading to loss of coherence and subsequent difficulties in the production of the interferogrammes.

In addition to the effects outlined above which give rise to degradation effects in the images and interferogrammes, there are several parameters which must be optimised for useful InSAR data acquisition. These include the time between acquisitions and the interferometric baseline:

temporal decorrelation: excessive time periods between successive acquisitions of SAR scenes can result in a reduction of coherence preventing the generation of interferogrammes due to a temporal variation in backscattering properties of the target area. The time scales vary depending on the nature of the target (Eg for a glacier during the summer period when excessive melting may occur, successive scenes acquired one day apart may not exhibit sufficient coherence to generate interferogrammes. In other cases, acquisitions several years apart may allow the generation of high quality fringes.

baseline limitations: above a critical length of baseline (approximately 1100m for ERS-1) there is a complete loss of coherence. The degree of this coherence significantly influences the accuracy of the phase and hence the height measurement. In practice, there are limitations on length of baseline for which useful interferogrammes can be calculated. For mapping, the optimal baseline length is between 50m and 300m. Shorter baselines can yield useful information regarding glacier properties but tend not to yield useful datasets for height estimation. The upper practical limit is around 600m.

The availability of satellite borne SAR data has allowed InSAR to develop at a considerable rate. Current SAR missions include Radarsat and JERS-1 as well as the ERS programme. Analysis by the Canadian Centre for Remote Sensing has concluded that the large incidence angle and fine resolution operating modes should allow the generation of high quality interferogrammes from Radarsat data. Unfortunately, the Radarsat repeat cycle of 24 days leads to a significant degree of temporal decorrelation between acquisitions and the tracking and orbit maintenance is less precise than for the ERS missions making the processing of interferogrammes laborious and difficult.

2.2 Applications of InSAR

InSAR techniques can provide useful information within many application fields. Depending on various factors (eg the area under study, the time between repeat acquisitions, the time of year etc) it is possible to extract very different categories of information. Some of the applications are mutually exclusive (ie when a dataset is suitable for one application it is unsuitable for another) whereas other applications can extract different signature information from the same dataset. This can cause additional problems as the signature of one type of phenomena contained within an interferogramme can be regarded as noise contaminating the signature of a different phenomena. Examples are:

- **DEM generation and land cover mapping:** vegetation causes a strong temporal decorrelation between acquisition dates (due to changes in environmental conditions) preventing the extraction of reliable height information from the interferogramme and the subsequent construction of a DEM. On the other hand, vegetation can be categorised by the degree of decorrelation caused and thus enable the identification of different land cover types.
- **Glacier movement and topographic mapping:** separation of effects due to glacier movement induced decorrelation and topographic effects can be difficult but is a necessary step in the extraction of glacier information from the interferogrames.

In addition, components of the interferometric signal such as anomalous signal path lengths introduced by atmospheric effects are currently treated as pure noise. This is because there are currently no applications exploiting such information.

At the present time there are five major applications of InSAR. These are:

- DEM generation: this involves the reconstruction of terrain heights from the unwrapped phase information derived from the InSAR dataset and has numerous applications including mobile telecommunications network planning, exploration geology and urban planning. An additional application is in the improved terrain correction of SAR imagery for applications in remote areas where cartographic data are out of date or unavailable.
- Land use classification and forest monitoring. Forest canopy height information can be extracted in suitable terrain if the coherence is sufficiently high. Different crop types can be identified based on their effects on the spatial variation of coherence within the InSAR dataset. In general, forested areas exhibit low levels of coherence (due to changes in wind conditions between acquisitions) allowing the identification f forest cover from other land cover classes.
- Geophysical hazard analysis (earthquakes, volcanoes, landslides and subsidence), prediction and quantification There are three principle application areas in geophysical hazard analysis:
    - measurement of dislocation extent at the source of an earthquake
    - measurement of small height variations due to the filling and drainage of magma chambers under volcanoes
    - monitoring of subsidence resulting from extraction activities such as coal mining.

  Each of these applications require a more advanced technique known as *Differential Interferometry*, in which very small land surface movements can be detected. The idea is to use an existing DEM or a stable (no movement) interferogramme to remove topographic effects by subtracting the terrain generated fringes from an interferogramme. The resulting fringes are due to smaller motion effects. Differential Interferometry allows the measurement of movements on the scale of millimetres.
- Glacier motion measurement: InSAR data are used for the measurement of glacier motions and topography changes. This is important information for assessing glacier mass transport rates and changes in glacier volume which is, in turn, essential for the validation and improvement of hydrological models. In addition, such information may have significant implications for global climate change assessment.
- Hydrological modelling: there are two aspects to the use of InSAR data in hydrological applications:
    - determination of ground cover and run off paths in arid regions in order to optimise run-off interception structures
    - measurement of ground motion associated with the filling and drainage of underground reservoirs

In addition to the five applications described above, there are several application areas which are currently the focus of attention regarding future applications of InSAR. These include:

- coastal zone and inter-tidal zone monitoring
- snow melt measurement

These last two applications are at a less advanced stage due to particular difficulties in extracting the signal of interest from decorrelations arising due to variations in surface moisture levels.

2.3 InSAR and the ERS Tandem operations

The orbit maintenance and measurement strategy is such that the ERS platforms are unique in their capability to be exploited for the generation of interferometric SAR data sets. However, the ERS orbit configuration, designed before interferometry was considered as an operational technique, is not ideally suited to the production of interferometric datasets. In particular, the repeat cycle of 35 days for the major part of the ERS lifetime means that the level of coherence between successive SAR acquisitions is, in many cases, insufficient to allow the generation of interferogrammes. The launch of ERS-2 however, changed the situation drastically. With the potential to simultaneously operate two platforms in tandem, the time between acquisitions can be reduced to ensure an adequate coherence between successive SAR scenes while maintaining each platform in an orbit configuration that ensures a maximum possible coverage of the Earth's surface.

The ERS Tandem Mission was approved in April 1995 by the ESA Council for an operation period of 9 months following the ERS-2 Commission Phase. The objectives have been primarily focussed on the collection of SAR data pairs for exploitation in interferometry together with the synergistic use of instruments on the two platforms. ERS-1/ERS-2 SAR pairs with an offset of one day have been acquired covering large parts of the global land surfaces. Close and efficient cooperation among all the ERS ground-segment entities enabled the collection of this unique data set which offers a chance to scientists and operational organisations to derive medium to high resolution DEMs for a variety of applications.

The tandem objectives were met by accurately adjusting the orbital positions of the two satellites. During ERS-2 Commissioning Phase and the Tandem Operations Phase the two satellites have been maintained in same orbital plane. ERS-2 following ERS-1 30 minutes later. This means that the same swath on ground is acquired by ERS-2 one day after ERS-1. In coordination with the global network of national and foreign receiving stations, a background acquisition plan was set up matching within the constraints of satellite resources the availability period of the station with specific orbit maintenance procedures. For example in the period 15-Jan to 25-March (Polar Campaign) the orbit was maintained to meet baseline requirements (cross track separation of 70-170 meters) at latitudes above 60 deg. while orbit cross over points were at equatorial latitudes. During this period maximum acquisition was scheduled over the stations of O'Higgins, McMurdo, Syowa, Alaska, Prince Albert and Kiruna. In contrast, full coverages of S-America (Cuiaba) have been acquired in April/May, when the orbit maintenance was focused on meeting a 50-200 meters cross track separation at the equator.

Loss of SAR tandem coverage due to late availability of certain receiving stations and conflicts caused by the completion of the ERS-2 WSC commissioning activities during the Tandem Phase could be compensated for by extremely precise orbit maintenance, The high frequency of in-plane manoeuvres especially towards the end of the tandem mission ensured that nearly every acquired data pair met the stringent specifications in terms of cross-track separation.

First Results of ERS SAR Interferometry using data from both satellites have been summarized in a document prepared by ESRIN and presented to the DOSTAG delegates. A preliminary investigation was performed of the potential of tandem interferometry within a variety of application areas, including glacier motion studies, forest and land cover mapping, land surface motion related to volcanism and neotectonic forcing as well as DEM production.

In order to further strengthen the exploitation of the ERS Tandem Mission, an Announcement of Opportunity dedicated to the scientific exploitation of the data collected was released in January and resulted in some 60 projects focussing on ERS INSAR techniques and complementary use of ERS-1 and ERS-2 instruments.

2.4 Tandem acquisition status

After 9 months of operating the ERS-1 and ERS-2 spacecraft in tandem together with the ERS-2 commissioning phase, the objectives of the ERS Tandem Mission have been successfully completed. The table below shows the current acquisition status.

Baseline range	number of frame pairs	% of total
$\mathbf{B}_{\mathbf{perp}} < 50$m	22181	20
50m $\leq \mathbf{B}_{\mathbf{perp}} \leq$ 300m	81619	73
300m $< \mathbf{B}_{\mathbf{perp}} \leq$600m	6221	6
600m $< \mathbf{B}_{\mathbf{perp}}$	1028	1

Table 2: Tandem acquisition statistics

The data acquired during the Tandem phase with values of $\mathbf{B}_{\mathbf{perp}}$ between 50m and 300m are of particular interest for InSAR applications. These are shown in greater detail in Table 3 below.

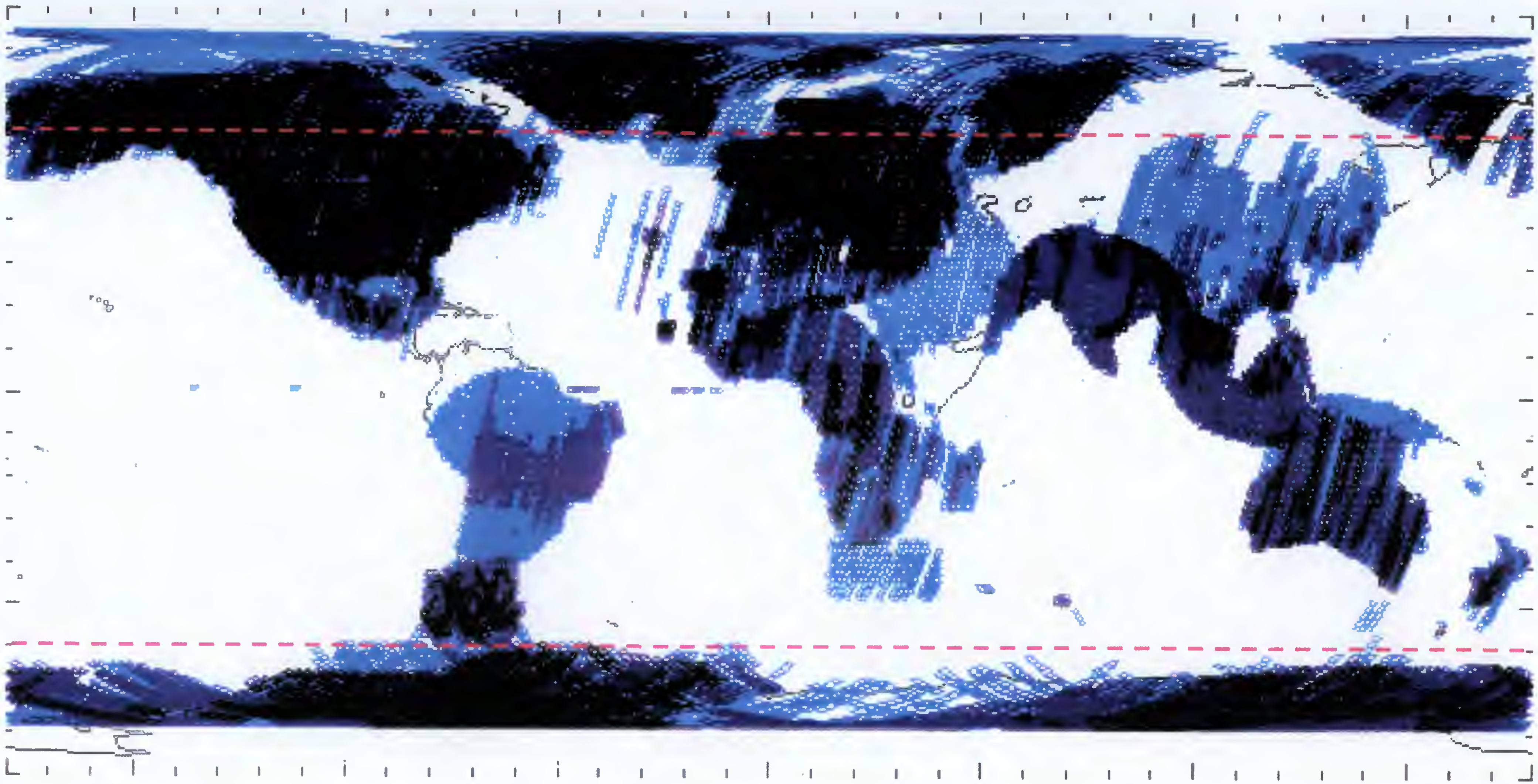
Baseline range	number of frame pairs	% of total
50m $\leq \mathbf{B}_{\mathbf{perp}} \leq$ 130m	45681	41
130m $< \mathbf{B}_{\mathbf{perp}} \leq$ 215m	26637	24
215m $< \mathbf{B}_{\mathbf{perp}} \leq$300m	9301	8

Table 3: Tandem acquisitions with baseline values between 50m and 300m

The geographical distributions of the acquisitions for baselines between 50m and 300m are illustrated on the following pages both in mercator projection and polar projection. The colour coding is explained in each image caption.

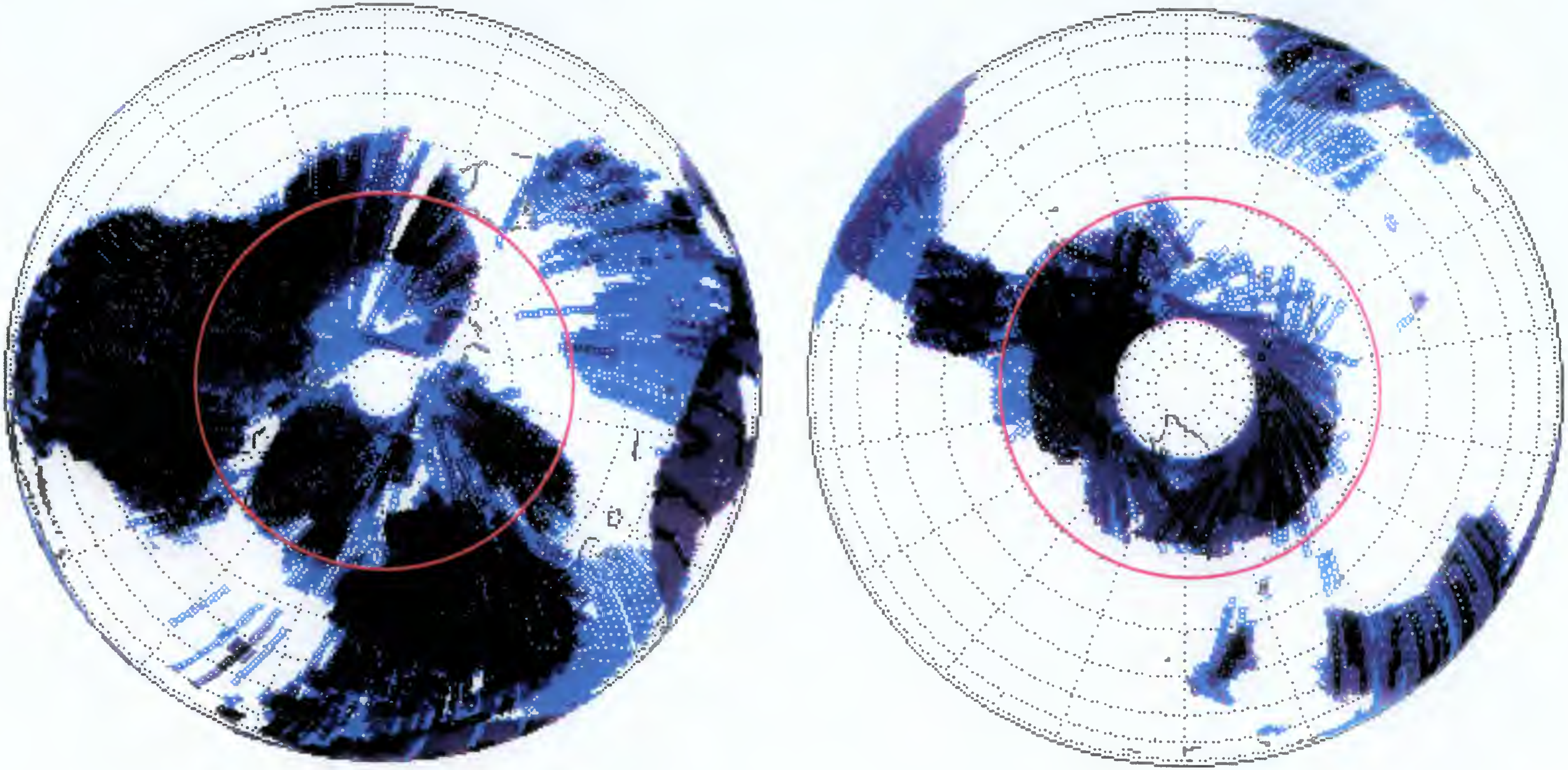
For reference, the red lines indicate the limits of the Shuttle orbit.

Mercator projection of tandem acquisitions with baseline between 50m and 300m



White = No tandem acquisitions, Turquoise = One tandem acquisition, Blue = Two tandem acquisitions, Black = Three or more tandem acquisitions.

Polar projection of tandem acquisitions with baseline between 50m and 300m



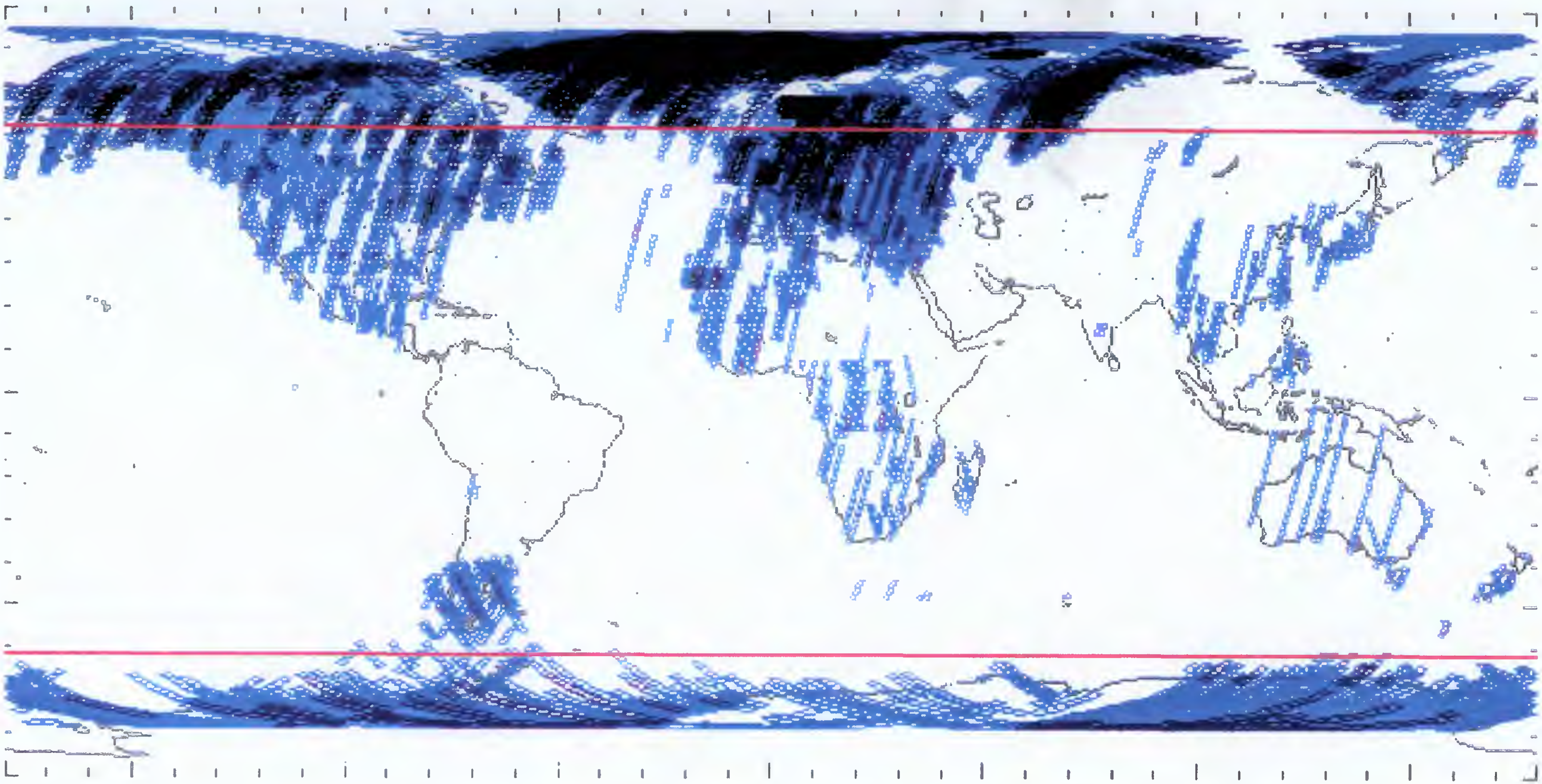
White = No tandem acquisitions, Turquoise = One tandem acquisition, Blue = Two tandem acquisitions, Black = Three or more tandem acquisitions.

A number of observations can be made regarding the Tandem acquisition status

- The majority of land areas have already been covered. In particular (apart from Siberia) latitudes above 60^{o} N and S are covered by at least one acquisition.
- For large areas of Antarctica, only one acquisition pair is available. The overlap between neighbouring tracks however, assures three acquisitions for all areas south of 63^{o} which includes the entire Antarctic continent.
- For Greenland, there are two to three acquisitions over most areas of the island. The area north of 70° has three full coverages due to partial overlap between neighbouring tracks.

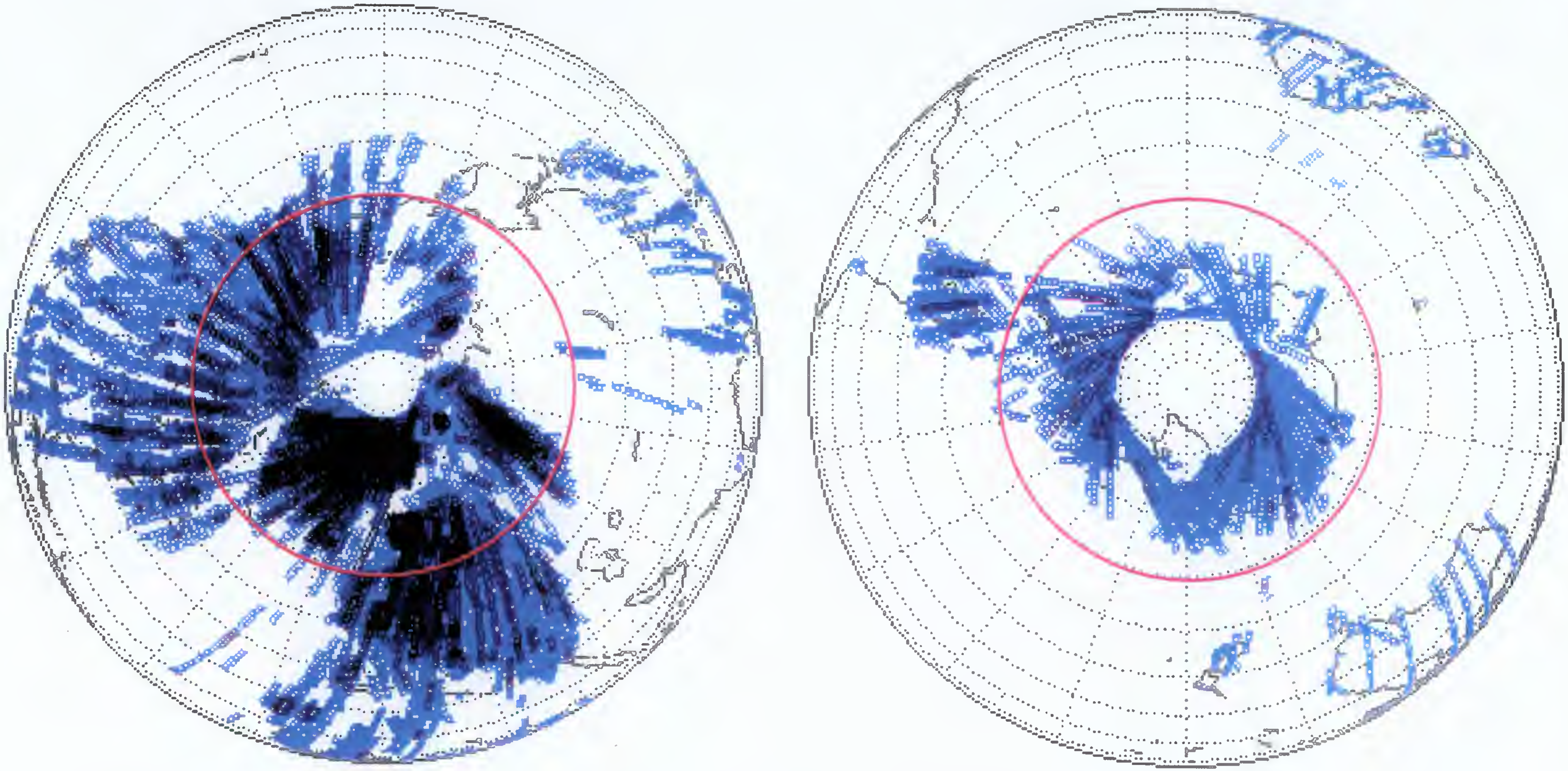
In addition to the pairs of SAR scenes acquired for baseline values between 50m and 300m, a number of tandem acquisitions have also been made for baselines less than 50m. While a separation of less than 50m is normally too small for mapping purposes, it can allow the separation of glacier movement effects and static topographic effects within interferogrammes generated over Arctic and Antarctic regions. Acquisitions for which the baseline is less than 50m are illustrated both in a mercator projection and a polar projection. Again, the colour coding is explained within each image caption.

Mercator projection of tandem acquisitions with baseline lower than 50m



White = No tandem acquisitions, Turquoise = One tandem acquisition, Blue = Two tandem acquisitions, Black = Three or more tandem acquisitions.

Polar projection of tandem acquisitions with baselines lower than 50m



White = No tandem acquisitions, Turquoise = One tandem acquisition, Blue = Two tandem acquisitions, Black = Three or more tandem acquisitions.

3 The InSAR Quick-Look Processor

3.1 Overview

With InSAR processing involving several work intensitive tasks, the large scale generation of the output products quickly becomes prohibitively time consuming and processing power demanding. During the last few years the industry standard computing has manyfold increased its processing power through new development of i.e. parallel processing. To efficiently exploit such a computer architecture it is important to separate the different tasks of the data processing into independent blocks which can be processed independently of each other.

The concept of the InSAR Quick-Look prototype processor which was used in this work is to reduce the amount of computations necessary at the same time as the processing becomes more easy to parallelise. This has been achieved through reducting the resolution of the input data. This results in a small reduction in the quality of the end product as well as lower resolution in the output products. This resolution and quality reduction should be limited to a level where the exploitation of the output products in user applications is still feasible. One of the principal benefits of using reduced resolution input data is that it leads to a reduction of the output product data volume, which is important for limiting the cost and complexity of the subsequent user data handling.

3.2 Structure

The prototype processor [3] is performing the following processing steps:

- Estimate parameters for the subsequent processing such as the baseline, the doppler centroid and the geolocation of the image.
- Time domain filtering of the two acquisitions raw data in range extracting a part of the common ground reflectance spectrum. This process decreases end product quality variation for baselines smaller than 600m and reduces the quantity of raw data by a factor two.
- Time domain filtering of the azimuth spectrum to generate 1, 3, 5 or 7 (normally 3 or 5) new raw datasets for each acquisition. Each of them reduced in size by a factor 8.
- Process the reduced raw datasets into SAR images. The reduction of the resolution simplifies the processing steps needed to generate high quality images.
- Coregister the images from one acquisition to the images from the other.
- Calculate the coherence with an estimator working on the intensity images. This avoids the need of estimating the local slopes from the interferogram and greatly reduces the processing load.
- Generate the interferogram.
- Remove the range fringes for flat terrain projection.

The processing is done on 30km blocks which allows efficient use of quick FFT operators in the image synthesis. After all the separate blocks in a strip have been processed they are catenated and the output products are generated.

The output products are:

- Coherence image
- Interferogram
- Multilooked intensity image.

3.3 Performance

The typical processing time for a strip of 30km is between 90 and 120 seconds on a 8 CPU Power Onyx Silicon Graphics Unix workstation. The time is scene dependent due to time variable processing e.g. in the coregistration. This is around 1/24th the real time data rate and allows large scale processing of the tandem data for generation of browse and low-resolution user products. However, the algorithms need to be further improved and an operational version of the processor need to be developed before such operations can be initiated.

4 Conclusions

4.1 Introductory remarks

The scope of this work has been twofold:

- Testing the InSAR Quick-Look processor on a variety of datasets to learn more about its performance over different terrain and carry out some assessment of the effect of the different terrain on the performance of the processor.
- Making a quick assessment of the quality of the tandem data from remote areas of the world for applications use.

The conclusions drawn can be separated into the following categories:

- general conclusions regarding Tandem data
- conclusions regarding the availablity of Tandem data
- conclusions regarding the QL processor itself
- conclusions regarding the use of Tandem data within different applications and over a restircted category of geographical zones

Two of the main points emerging from this (limited) study are:

- there seems to be a clear correspondence in tropical reigons between high values of the AVHRR NDVI and low coherence (and hence poor quality fringes) in the Tandem data
- low resolution "browse" products such as those analysed during the work are extremely useful indicators of the quality of the data with regard to the generation of interferogrammes. This would allow users to determine whether it is worthwhile processing datasets at a higher spatial resolution

4.2 General conclusions

A follow on project with large scale generation of InSAR quick-looks from diverse areas of the world is needed before any definitive conclusions can be taken as to the usability of the tandem dataset for different InSAR applications. However this study indicates that an important application like DEM generation may be expected to be possible over large parts of the Earth surface. Only the presence of dense forests seem to be out of range for these interferometric techniques. As has been clear from the start of interferometry with ERS, there is a need for complementing the coverage in mountainous areas with the use of both ascending and descending acquisitions.

The tandem dataset is promising to be a major source of application information for a variety of applications ranging from DEM generation in various parts of the world through derivation of velocity fields over fast moving glaciers to land use mapping of a range of land use classes.

It seems also to be clear that an effort should be done to valorise the tandem dataset. This effort should start with actions to make the dataset available regardless of the station where the data were acquired in the first place. The availability of a browse and a low resolution InSAR product from ESA could also be considered a priority. This will enable the value adding companies and end users to reduce their initial investment in SAR processing capability and focus the effort on making use of the data in applications.

4.3 Availability of tandem data

Tandem data, having been acquired over most parts of the world, are often not available outside the country of origin. This analysis has been limited to a few datasets that were already available. A serious effort needs to take place to make sure that the tandem data is made available consistently. One possible method of ensuring this availability might be the generation of a tandem archive within the ESA ground segment.

4.4 InSAR Quick-Look processor performance

The prototype processor used in this work has allowed the generation of large amounts of InSAR data in a relatively short time. The concept of reducing the computational load through sacrificing spatial resolution and to a lesser degree the accuracy has been proven to be a good approach for large scale generation of InSAR products.

During the course of this work, several changes to the prototype InSAR Quick Look processor have been implemented to make it more adapted to the processing of full acquisition strips. In addition, some effort has been expended to make the processor more robust for use over different kinds of terrain and vegetation. Several algorithmic shortcomings have been identified which will be investigated in the immediate future to allow the generation of consistently high quality interferometric quick-look products.

During the work it has become clear that the timely supply of raw data to the processor is now the major obstacle for an eventual large scale generation of InSAR products on the ERS-1 and ERS-2 datasets.

4.5 Applications of tandem data

4.5.1 Tropical mountain forests: Taiwan, Madagascar

The topography in combination with often dense forest makes the interferogrammes difficult to use for applications other than land use classification. In particular, the fragmentation of the unwrappable areas seems to be an obstacle to the further exploitation of InSAR techniques over densely vegetated mountains. Through the use of a combination of ascending and descending pass interferogrammes it will be possible to increase the area exploitable by other InSAR applications.

Over the lowland regions where most human activities take place, the fringes obtained are of high quality and InSAR applications are feasible without major problems.

4.5.2 Tropical forests and savanna: Zaire, Ivory coast, Mali

There seems to be a clear correlation between the NDVI and the attainable coherence and resulting fringe quality. Where the forest is very dense, very little or no coherent signal remains. Depending on the type of forest and climate there should be seasonal variations in the coherent signal which could increase the areas where. for example, DEM generation may be possible. To address the limits of ERS C-band interferometry over this kind of vegetation it is necessary to identify the acquisitions which are expected to yield the highest coherent signal and perform a large scale evaluation to find out if the results can be generalised. This was not possible within this exercise due to the limited amounts of available data and the short time frame.

For areas which are only sparsely forested it seems likely that most of the acquired tandem data can be used for InSAR applications like DEM generation.

4.5.3 Arctic coasts and inland-ice: Greenland

The results from Greenland show that during the Arctic winter it is probable that almost all the acquired tandem data should have high value for InSAR applications. There are some indications that eolean transport of snow may reduce the coherence. Further studies have to take place to determine if this is a real subject of concern before any conclusions can be taken on the effect on the expected usability of the tandem dataset.

5 References

1 Tandem Early Results: report to the DOSTAG committee meeting, May 1996

2 R Gens J L Van Genderen, "*SAR interferometry - issues, techniques and applications*", Int J Remote Sensing 17 10 pp 1803-1835 1996

3 InSAR Quick-Look Processor Algorithm Specification, Contract report, ESA Contract C10179/93/YT-I(SC)

Appendix A:

Tropical forest in mountanous terrain

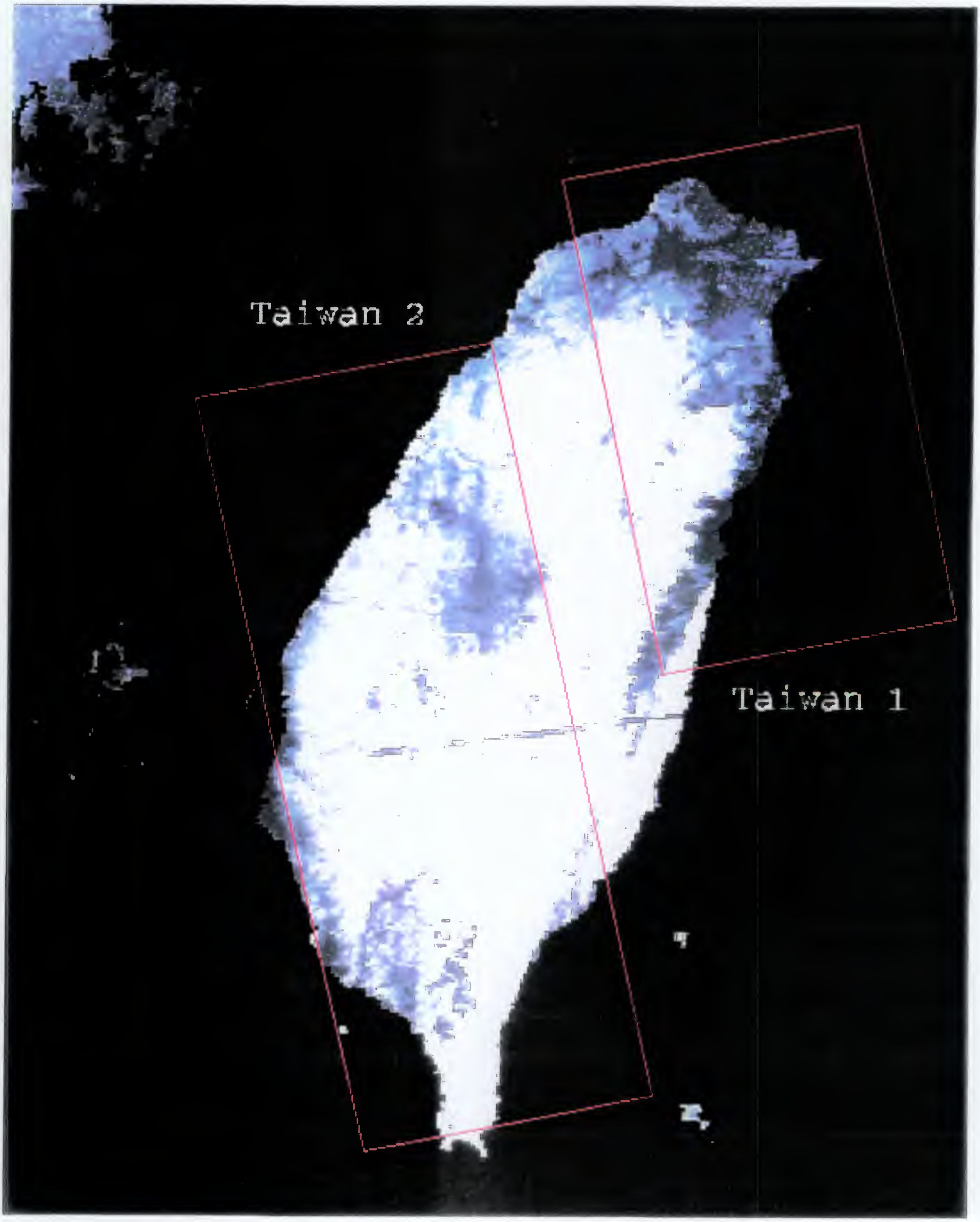
A.1 Taiwan

Climate	tropical; marine; rainy season during southwest monsoon (June to August); cloudiness is persistent and extensive all year
Terrain	eastern two-thirds mostly rugged mountains; flat to gently rolling plains in west
Land cover	arable land: 24% permanent crops: 1% meadows and pastures: 5% forest and woodland: 55% other: 15%

Taiwan AHVRR NDVI

This image shows the maximum NDVI value over a two month period between 1 April to 30 May 1992. Darker areas correspond to low NDVI while lighter areas correspond to high NDVI values. In some areas, cloud signatures may remain, especially over the Eastern region of the island where mountains can block the passage of humid air coming inland from the ocean. The red rectangles show the areas covered by the example colour composite images, the first from the Northern end of the island (Taiwan1), the second over the Southern and Western regions (Taiwan2).

Taiwan AVHRR-NDVI



Taiwan1

There are two obvious areas that can be identified within the colour composite:

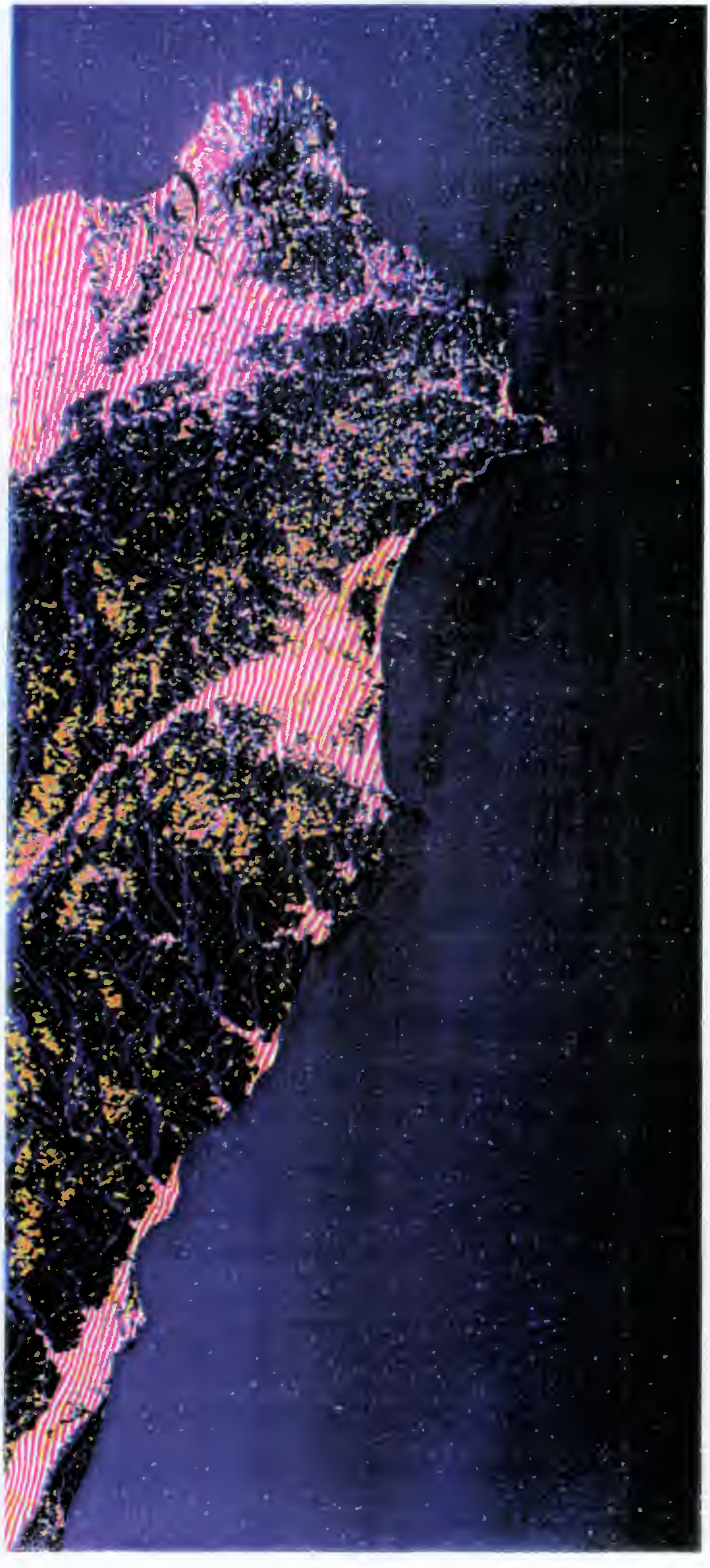
- agricultural areas with a high coherence where fringes can be observed
- mountainous forest regions with very low coherence showing up in blue-black colours depending on the range intensity and medium to low coherence areas showing up in green

Between the two major mountain forest features, a dry river bed can be identified.

Fringes in the coastal regions correspond to imperfect flattening during the processing rather than any geomorphological structure. The high coherence over the agricultural areas leads to the possibility of using a higher resolution processor to provide valuable information on crop coverage.

The lack of coherence over the mountainous forested areas is a useful aid to the identificaiton of such heavy forestation but prevents any further analysis of the forest parameters (eg canopy height, biomass etc)

Taiwan 1



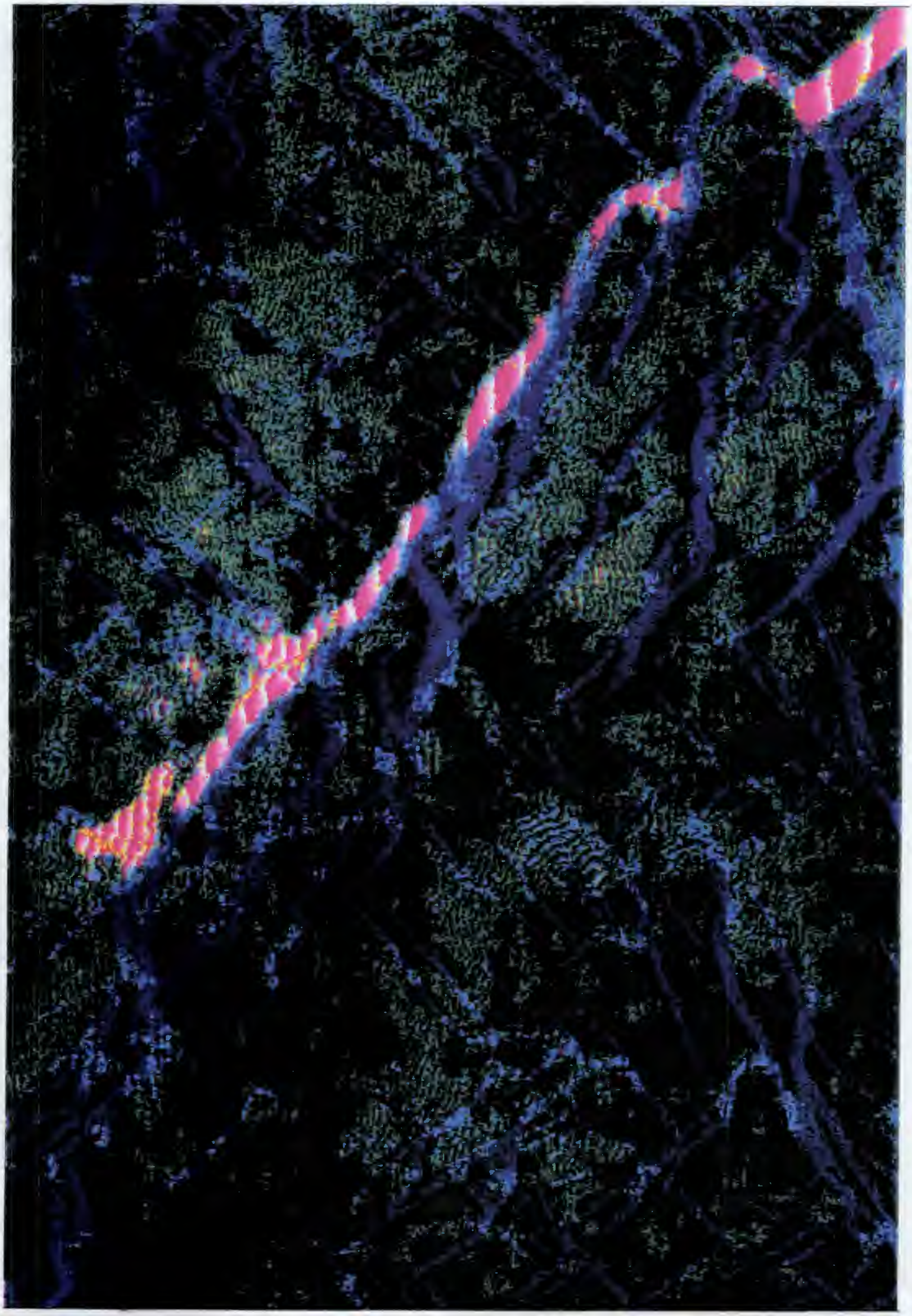
Taiwan1 close up

This colour composite focuses on the area around the dry river bed and allows a more detailed analysis of the coherence. Areas with low coherence are coloured in dark green due to the channel assignment whereas high coherence areas are coloured in bright green, yellow and red. Areas with very low coherence (less than 0.2) are masked out in black.

High intensity areas show up in blue. The close up better highlights the typical layover and foreshortening effects found in SAR data acquired over mountainous terrain. Black areas on the mountain slope (coherence less than 0.2) can be interpreted as being dense forest cover.

The fringes along the river valley are again generated by imperfect flattening within the processing, giving rise to spurious topographic effects.

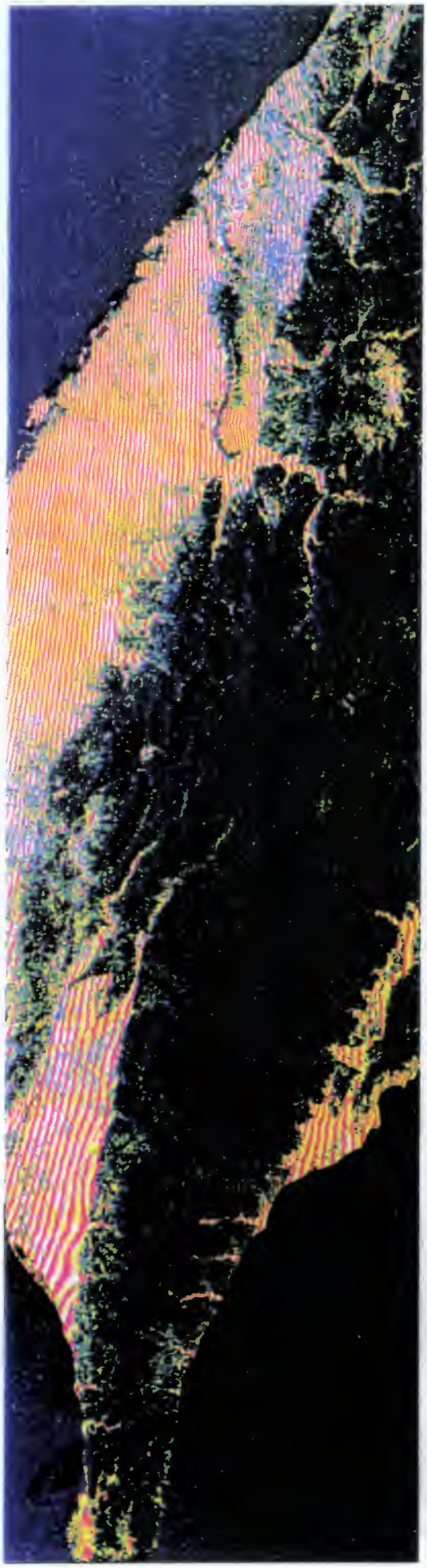
Taiwan 1, close-up



Taiwan2

As with the data acquired over the North Eastern part of the island, there are two generic classes observable within the colour composite, namely the coastal region exhibiting a high level of coherence and very low coherence areas corresponding to the mountainous and densely forested regions. Again, problems with the image flattening give rise to the fringe structure that can be observed over the coastal region, masking some of the actual signatures relating to the coastal land cover. In addition, the flattening error is not constant over the image giving rise to a difference in the fringe pattern between the northern and southern parts of the island. However, it is still possible to detect certain features. One example is the terrain structure as the coastal plain rises up to the mountains in the southern end of the island. The broadening of the fringe pattern together with the appearance of cusp like structures are related to the geomorphology. In addition, structure is discernible within the region where two river valleys emerging from the mountain regions meet in the central part of the colour composite..

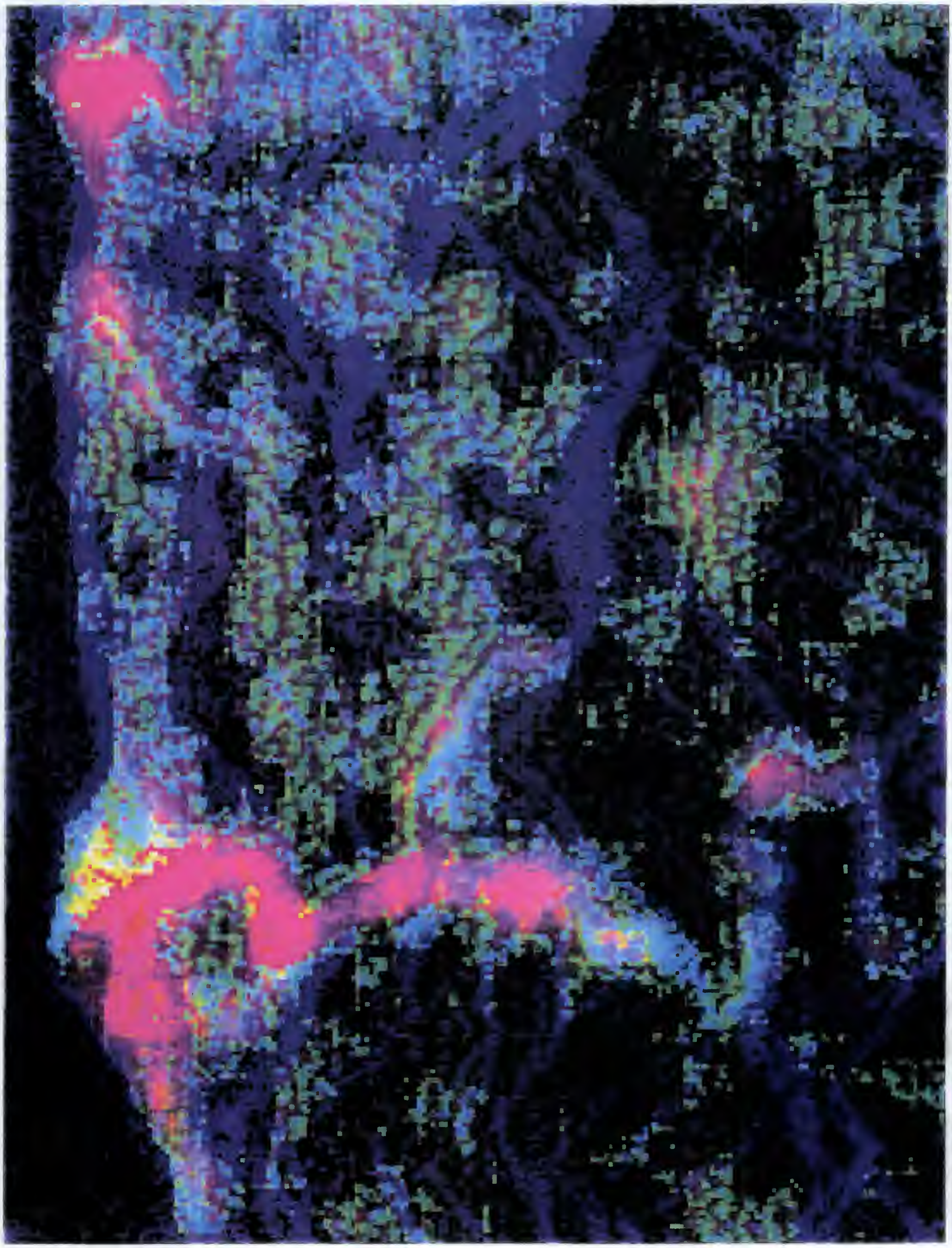
Taiwan 2



Taiwan2 close-up

This is over the south-western coastal area of Taiwan where the mountainous regions fall abruptly to the coast. The steep mountainsides in this area generate significant foreshortening and layover effects and there are very few areas exhibiting an adequate coherence where fringes of sufficient quality can be generated. Areas of low coherence, which can be observed in blue and black, again correspond to foreshortened and densely forested steep mountain areas. At the southern part of the image, a dry river bed can be detected between the areas of low coherence. Mountain areas where coherence is greater than 0.2 correspond to deforested regions or less dense vegetation.

Taiwan 2, Close-up



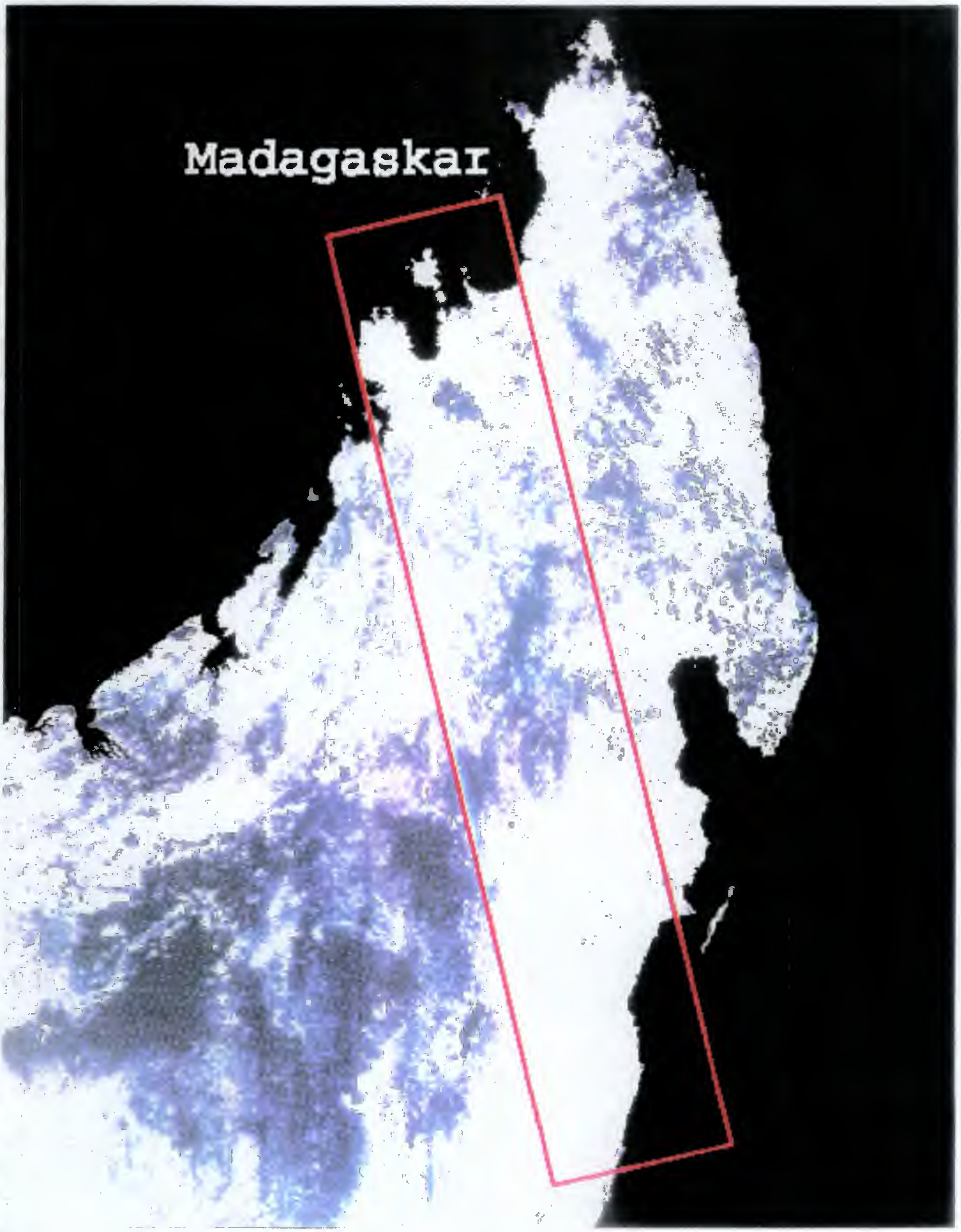
A.2 Madagascar

Climate	tropical along coast, temperate inland, arid in south
Terrain	narrow coastal plain, high plateau and mountains in centre
Land cover	arable land: 4% permanent crops: 1% meadows and pastures: 58% forest and woodland: 26% other: 11%

Madagascar AHVRR NDVI

The maximum value of the NDVI over the two month period 1 April to 30 May 1992 is illustrated for the Northern part of Madagascar. Comparison of the NDVI values with the composite InSAR image shows a clear correlation between areas with high vegetation index and areas of low coherence except for areas along the coast. The reason for this discrepancy is that the vegetation along the coast is such that it allows SAR penetration to ground level and probably corresponds to cultivated areas.

Madagaskar, AVHRR-NDVI



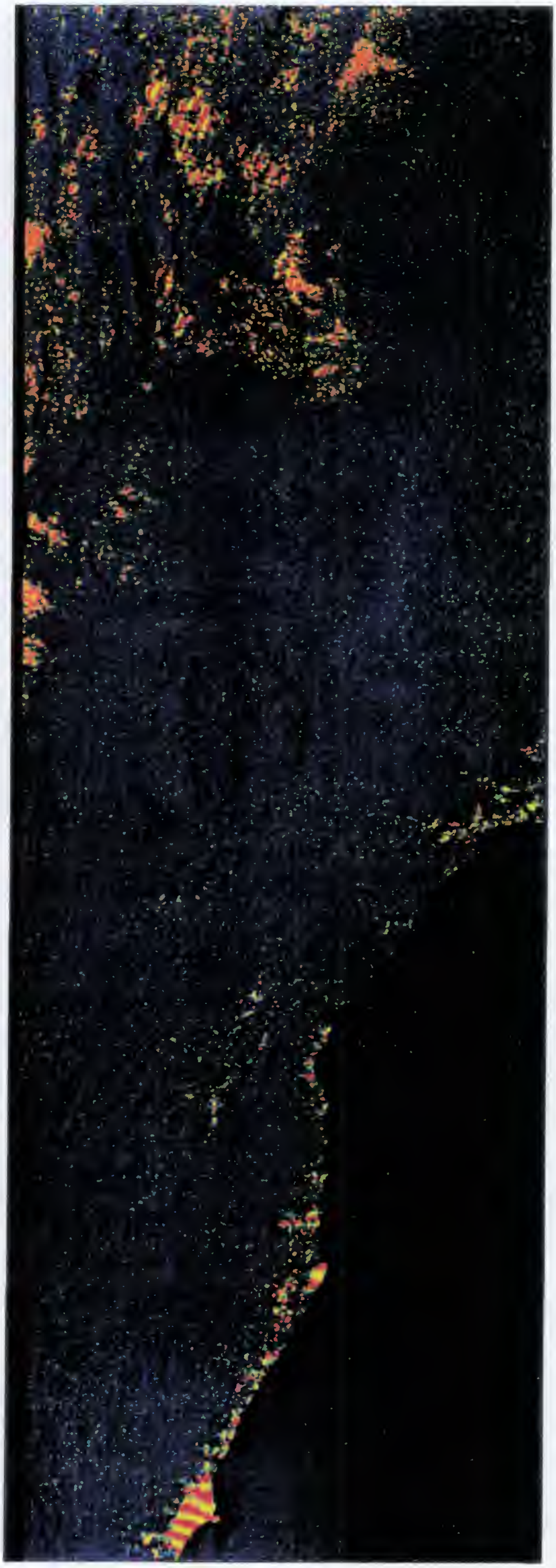
Madagascar

The acquisition strip has been divided into two segments due to the length. It is an ascending pass starting at the lower end of the right hand segment and ending at the upper end of the left hand segment.

Areas of very low coherence can be observed in blue. These correspond to mountain rain forest or tropical lowland forest. Areas shown in green, yellow and red correspond to savannah and non-forested mountians.

The interferogramme cannot easily be used to generate a DEM due to the fragmentation of areas with sufficient coherence levels to preserve the phase information. Some degree of land use classification, based on the coherence variation is possible.

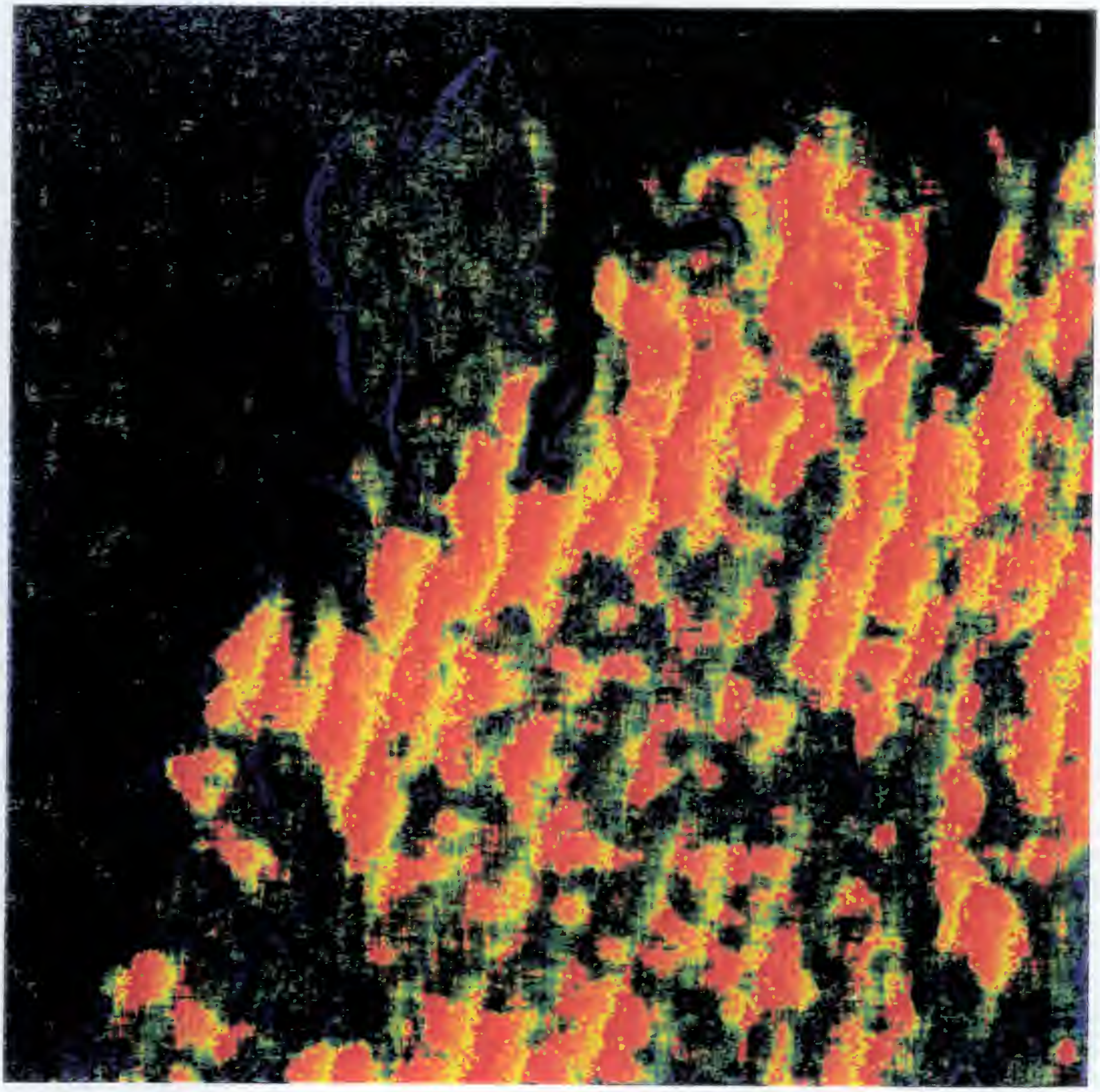
Madagaskar



Madagascar close-up

One of the principal features of the close-up, which is from the Northern end of the acquisition strip, is the blue rim around the coast, corresponding to a region of very high backscatter. These areas are mangroves which, due to the growth structure, exhibit a characteristically high backscatter. Inland, the terrain is savannah where variations in coherence probably correspond to variations in surface moisture levels.

Madagaskar, close-up



Appendix B:

Equatorial forest and savannah

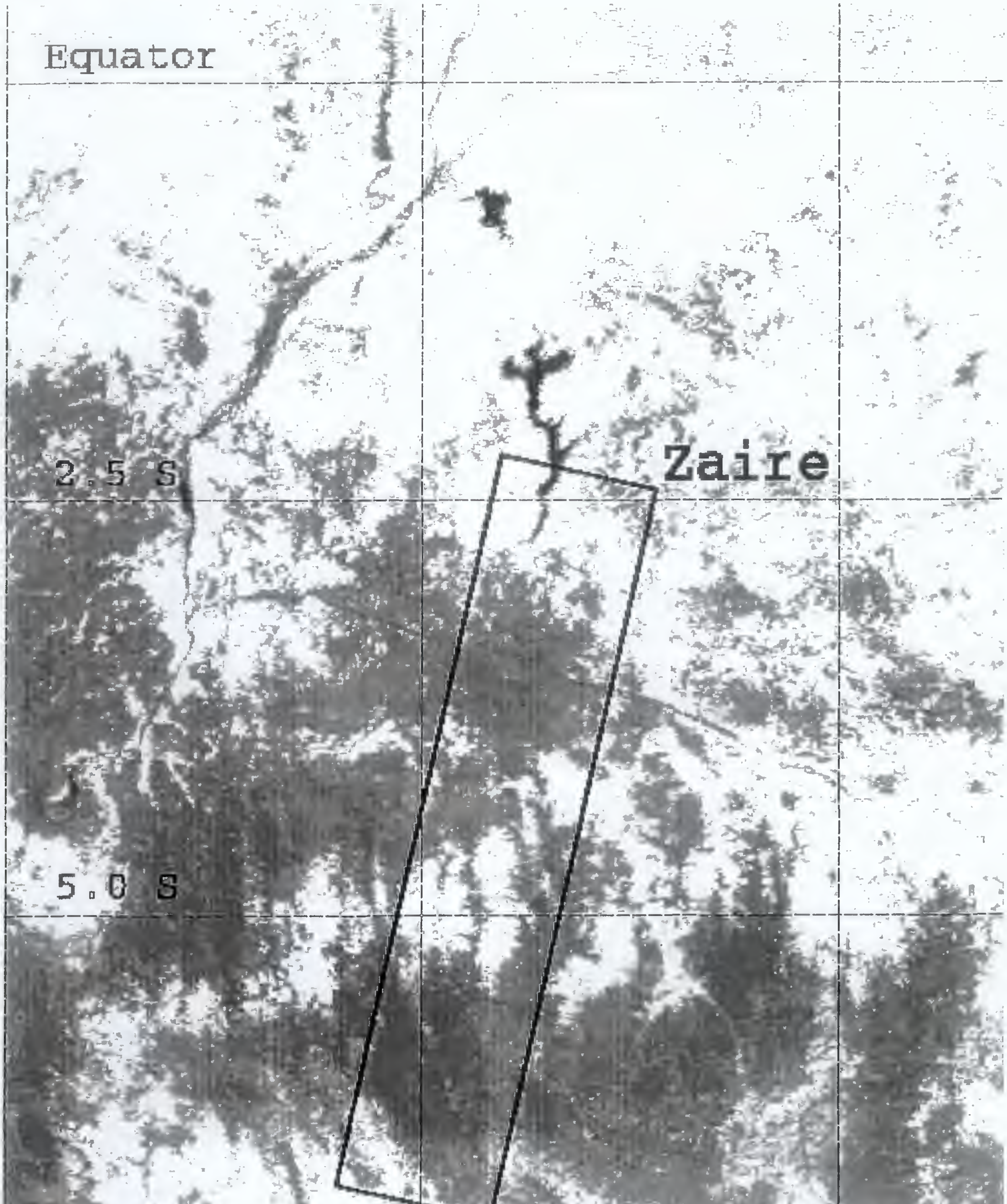
B.1 Zaire

Climate	tropical; hot and humid in equatorial river basin; cooler and drier in southern highlands; cooler and wetter in eastern highlands; north of Equator - wet season April to October, dry season December to February; south of Equator - wet season November to March, dry season April to October
Terrain	vast central basin is a low-lying plateau; mountains in east
Land cover	arable land: 3% permanent crops: 0% meadows and pastures: 4% forest and woodland: 78% other: 15%

Zaire AHVRR NDVI

The image shows the maximum value of NDVI over the period 1 April to 30 May 1992. Bright areas are high values of NDVI corresponding to dense vegetation and forest cover. By comparison with the InSAR colour composite, a correlation can be found between high values of the NDVI and low coherence values for the SAR acquisitions. This can be used as the basis for an extrapolation in estimating the coherence levels for areas outside the SAR acquisition strip.

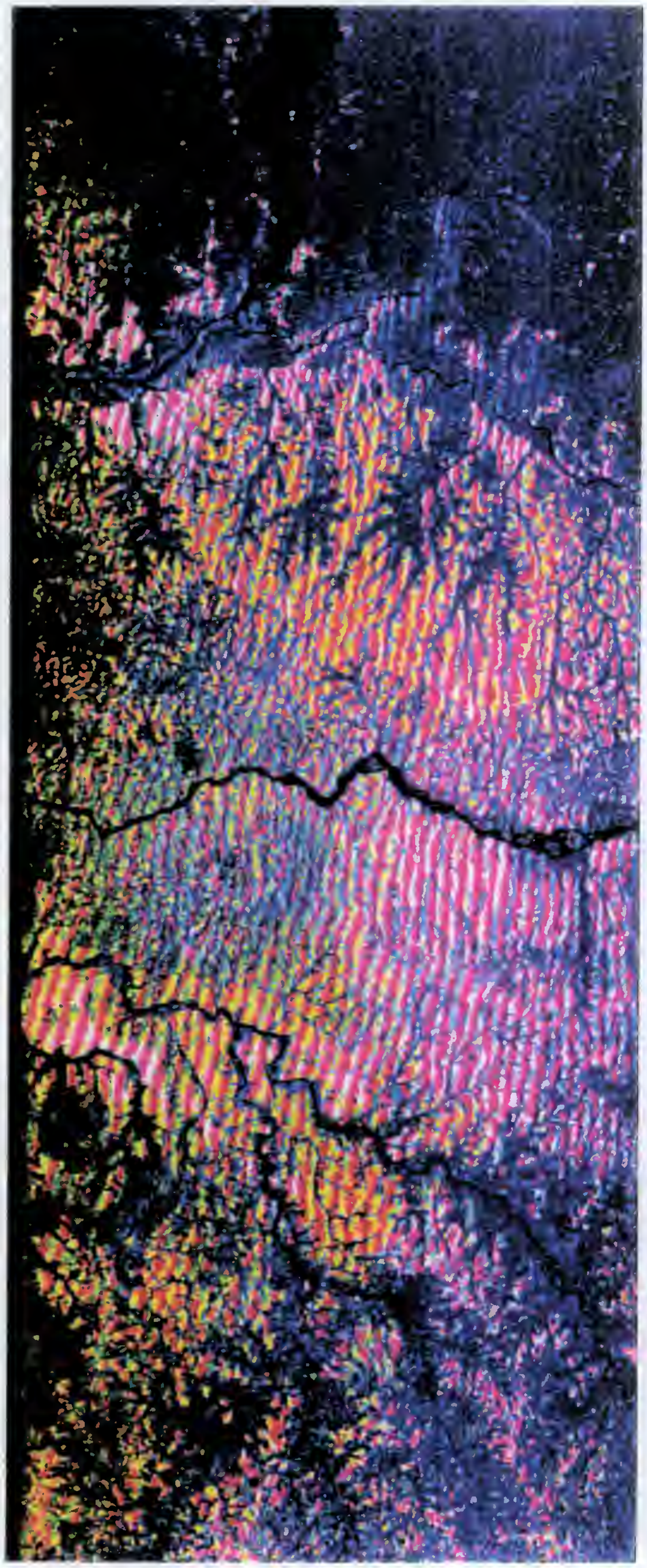
Zaire, AVHRR-NDVI

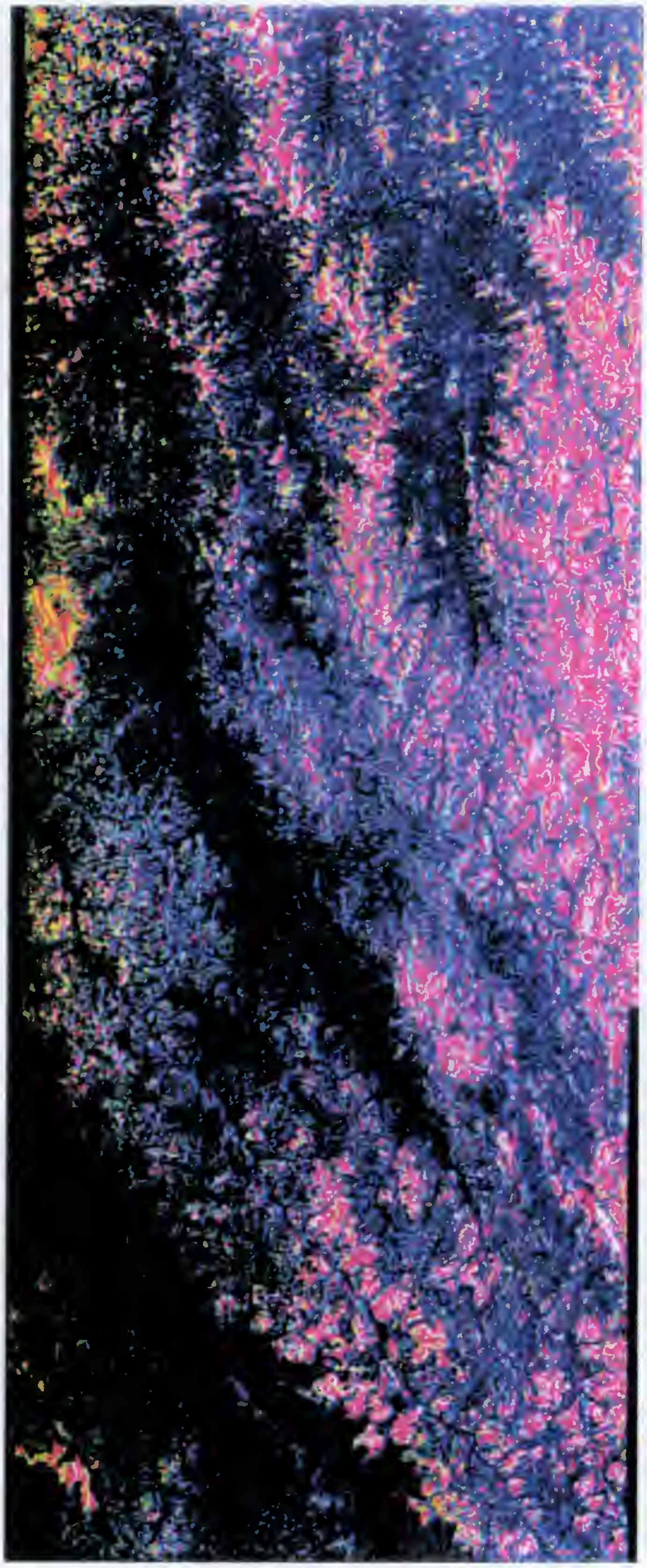


Zaire

The strip shown is a descending pass starting at top left and finishing at the bottom right. Again, the errors in flattening give rise to a set of parallel fringes over the first part of the image which are not related to any surface features. In the second part of the image however, the flatteneing has been performed correctly so that it provides a good example of the image quality to be expected from an operational processor. Dense vegetation exhibiting a correspondingly low level of coherence is visible in blue. The areas of high coherence probably correspond to savannah where the SAR signal can penetrate to the ground level. The low coherence area over the upper region of the image is the southern part of Lake Mai-Ndome.

Zaire, part 1 and 2

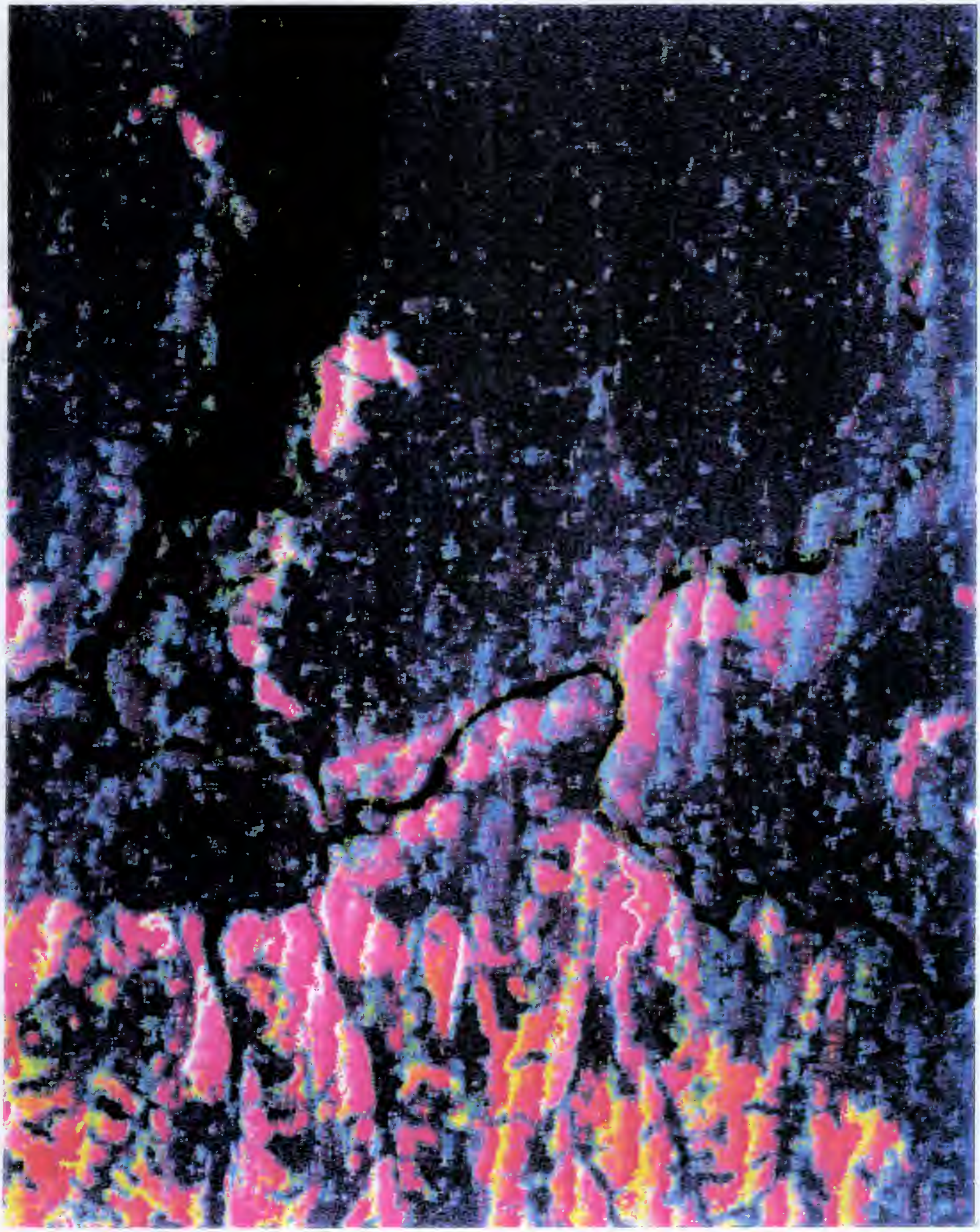




Zaire close-up 1

The first close up is over the upper part of the acquisition strip, around the Southern part of Lake Mai-Ndombe. This area is heavily forested giving rise to correspondingly low levels of coherence and preventing fringe generation. Areas of high coherence can be seen in the lower part of the image. Very high coherence areas are coloured pink and white whereas medium coherence areas are coloured in red and yellow. Once again, there are errors in the flattening giving rise to the parallel fringe structure over the image.

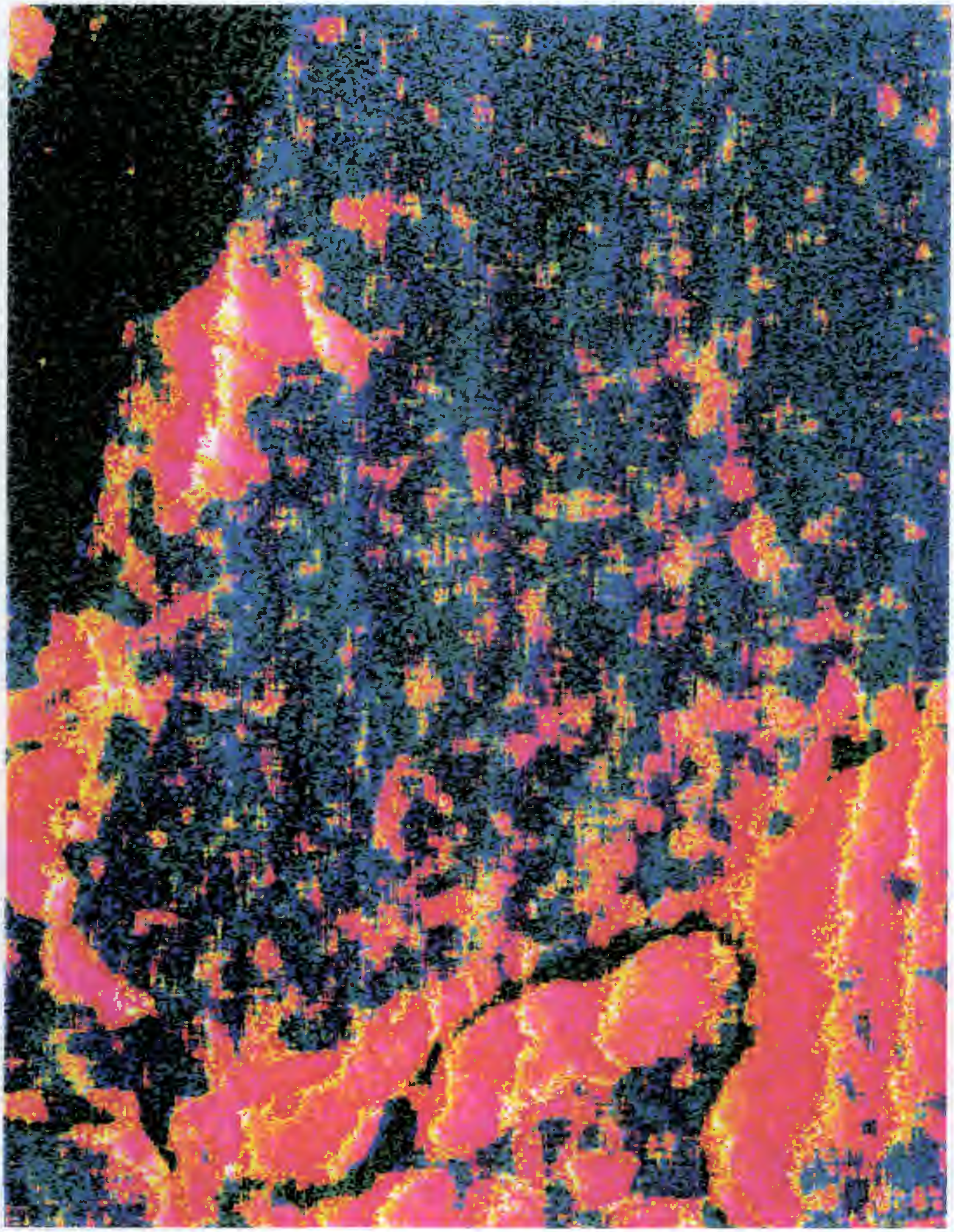
Zaire, close up 1



Zaire close-up 2

This second close-up is over an area at the South-Eastern part of Lake Mai-Ndombe. Large parts of the area have forest cover and hence exhibit a low degree of coherence (and so show up in green). In some parts of the image, it is possible to distinguish faint fringes although these are heavily contaminated by vegetation induced noise. Such fringes can be explained by the SAR signal penetrating to ground level due to a lower forest cover density. This can occur for a variety of reasons (eg soil quality changes, low water availability, selective logging activities).

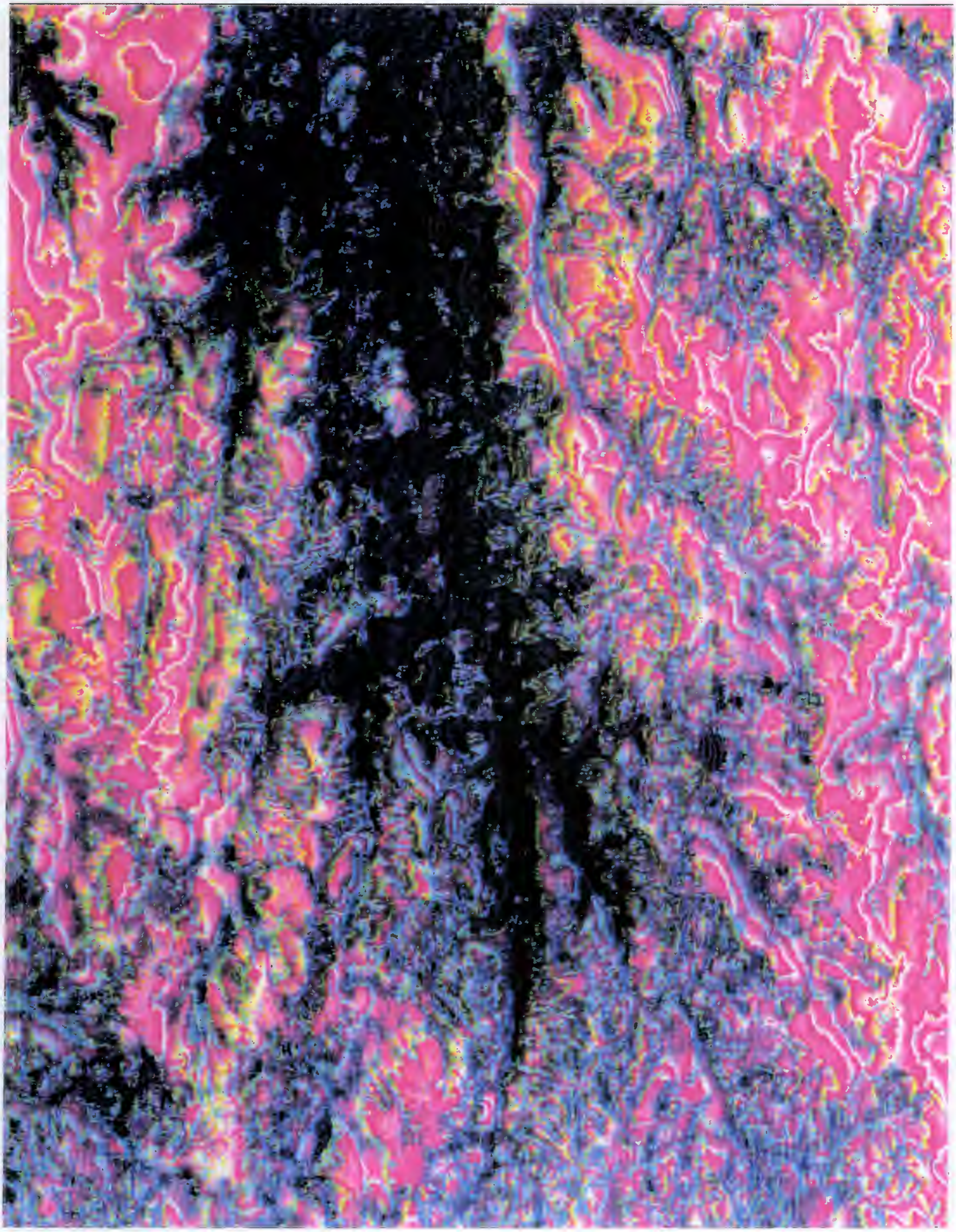
Zaire, close-up 2



Zaire close-up 3

This image is from the second part of the acquisition strip. In this area, the flattening was performed with a higher degree of accuracy and so the parallel fringes have been removed. Although there is a large area of low coherence in the centre of the image (due to heavy forest cover), terrain and vegetation structure can be inferred from the fringe structure on either side of the low coherence area. High quality fringes such as these can form the basis for the generation of DEMs without the need for complex unwrapping schemes.

Zaire, close-up 3



B.2 *Ivory Coast and Mali*

Ivory Coast

Climate	tropical along coast, semiarid in far north; three seasons - warm and dry (November to March), hot and dry (March to May), hot and wet (June to October)
Terrain	mostly flat to undulating plains; mountains in northwest
Land cover	arable land: 9% permanent crops: 4% meadows and pastures: 9% forest and woodland: 26% other: 52%

Mali

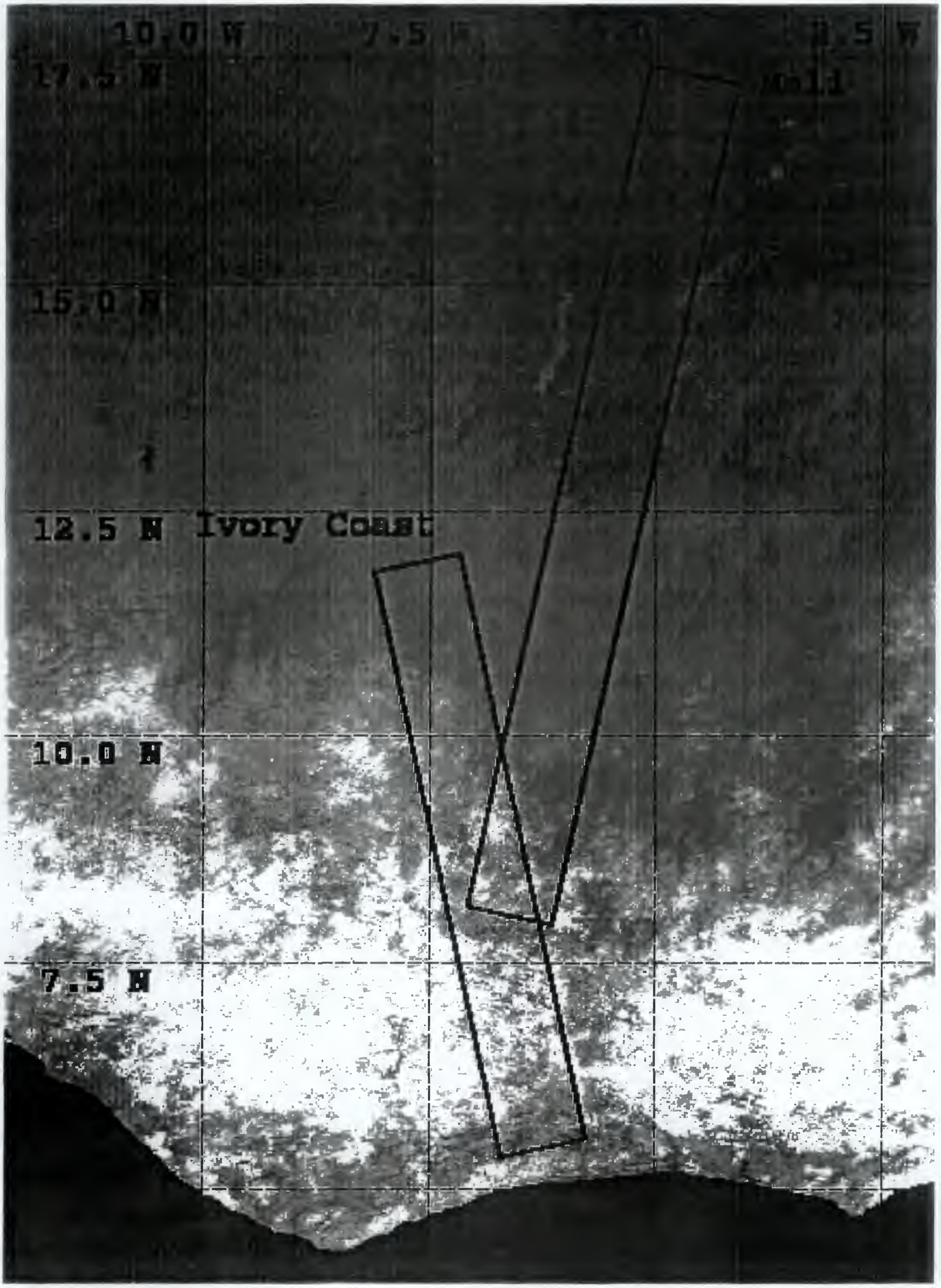
Climate	subtropical to arid; hot and dry February to June; rainy, humid, and mild June to November; cool and dry November to February
Terrain	mostly flat to rolling northern plains covered by sand; savanna in south, rugged hills in northeast
Land cover	arable land: 2% permanent crops: 0% meadows and pastures: 25% forest and woodland: 7% other: 66%

Ivory coast and Mali AVHRR

The image shows the maximum NDVI value over the period 1 April 1992 to 30 May 1992 with lower values in black and high values in white. The shorter strip is shows the InSAR acquisition over the Ivory Coast while the longer strip shows the acquisition over Mali.

In general, the values of the NDVI are lower than in Zaire although the high values are comparable with the highest values measured over Zaire. This would seem to suggest a potential for higher coherence values between the two tandem acquisitions.

Ivory Coast and Mali, AVHRR-NDVI



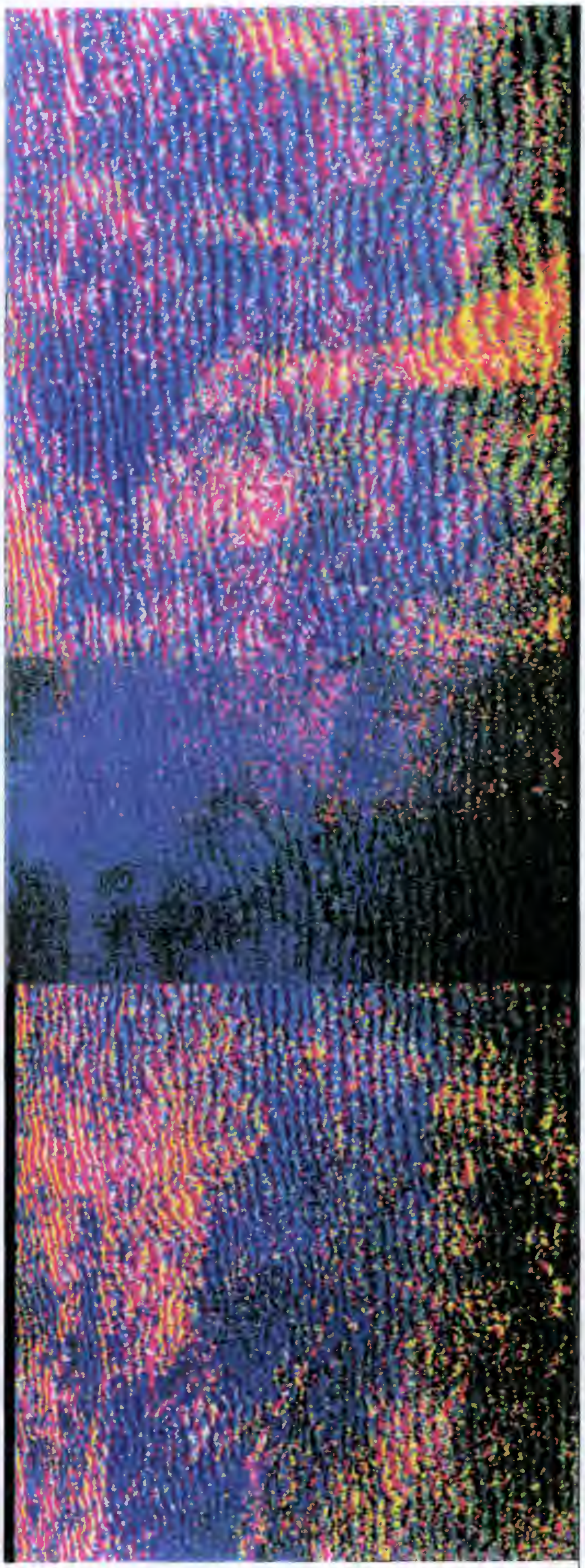
Ivory Coast

The image is split into three parts. The acquisition started at the lower end of the first image and finishes at the upper end of the third image. This corresponds to starting in the coastal area and ending in the Southern region of Mali.

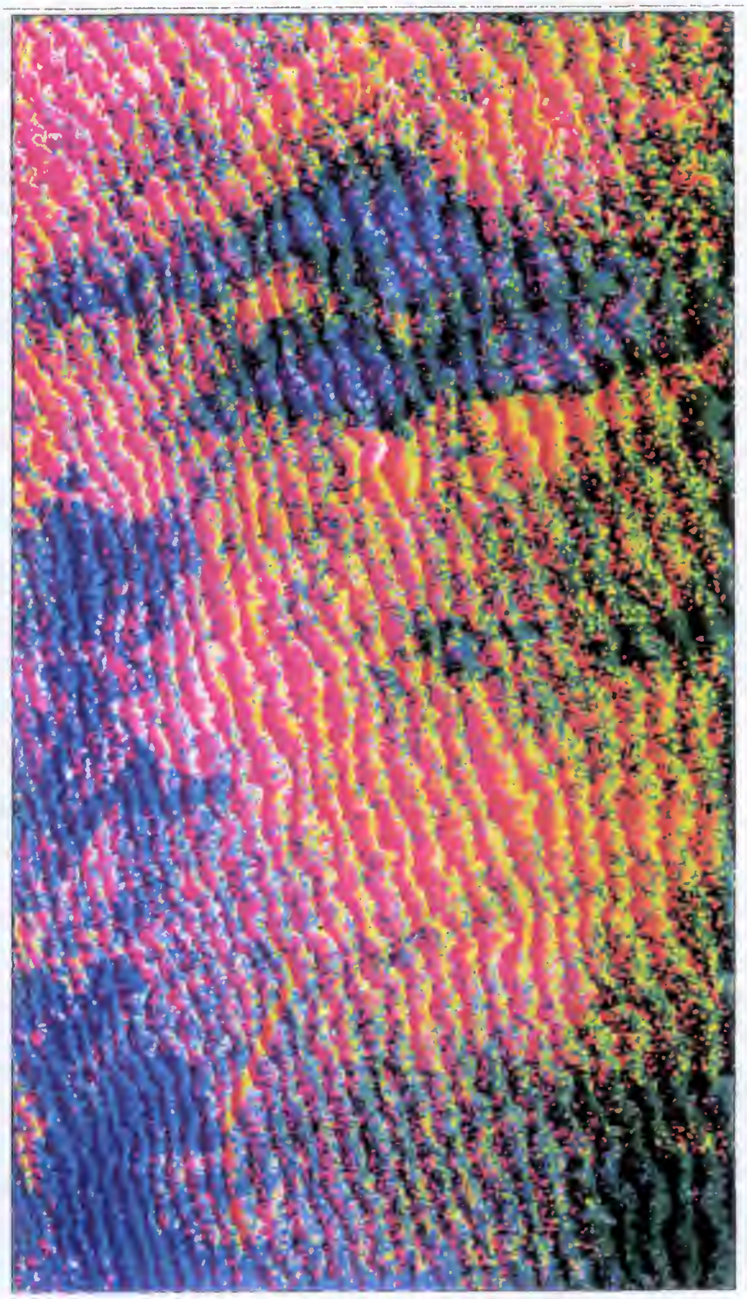
In this image, no mask has been introduced to remove very low coherence values in order to demonstrate the presence of fringes in the low coherence areas. Over the acquisition strip, land cover gradually changes from a tropical semi-deciduous rain forest to savannah in southern Mali. The terrain changes from coastal lowlands in the first part of the acquisition to gentle foothills of more rugged mountains in the inland region of the Ivory coast (in the second part of the image). Over Mali, the terrain becomes more regular once more. A further consideration is the change in dominant vegetation type. In the southernmost part, this is tropical rain forest whereas in the interior, the forest density decreases allowing a greater degree of SAR penetration and hence higher coherence values. Over the third part of the image, the forest has given way to savannah and the coherence increases still further. This is in marked contrast to the NDVI value which can be observed to decrease steadily from the coastal plain to the Savannah of Mali.

There are several areas where the InSAR Quick-Look processor has experienced problems and these have resulted in block discontinuities observable within the image. In addition, there are flattening errors within the image, resulting in the parallel fringes across range.

Ivory Coast, part 1 and 2



Ivory Coast, part 3

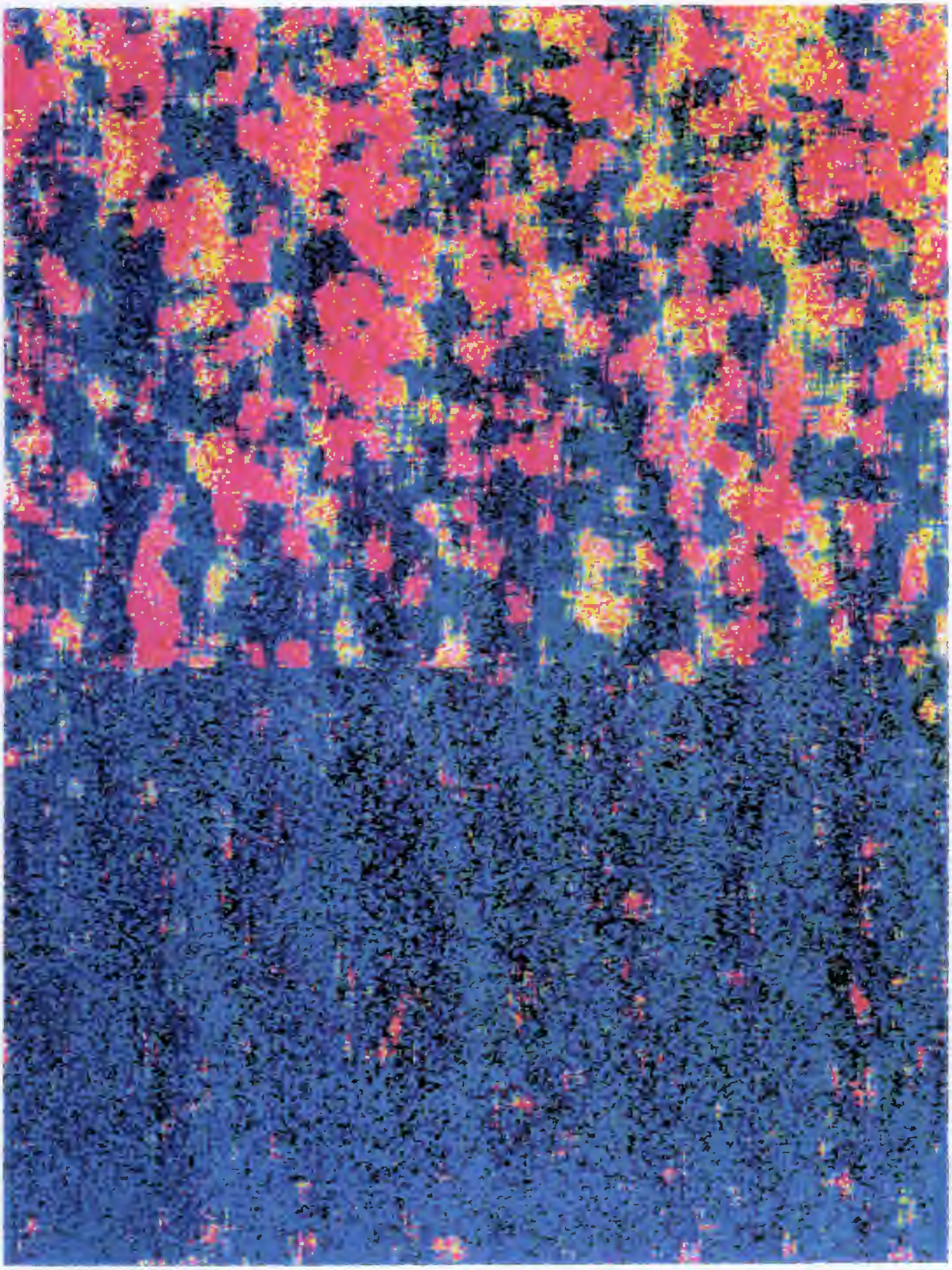


Ivory Coast close-up

This close-up is over the region where the block processing errors can be detected in the early part of the acquisition strip. One explanation for the problems is that the homogeneity of the forest cover caused a lack of suitable structure to enable accurate coregistration.

Modification of the coregistration scheme should generate an improved coregistration and hence a higher degree of coherence leading to the possibility of generating fringes of better quality.

Ivory Coast, close-up 1



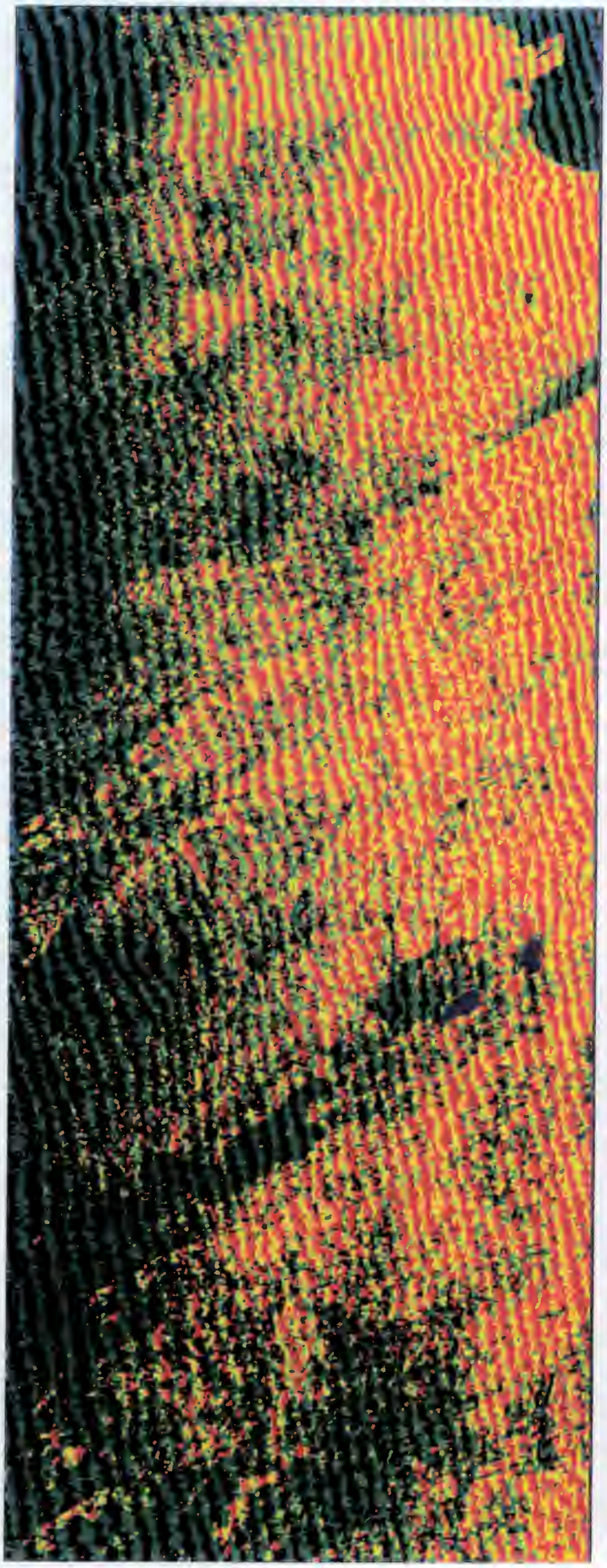
Mali

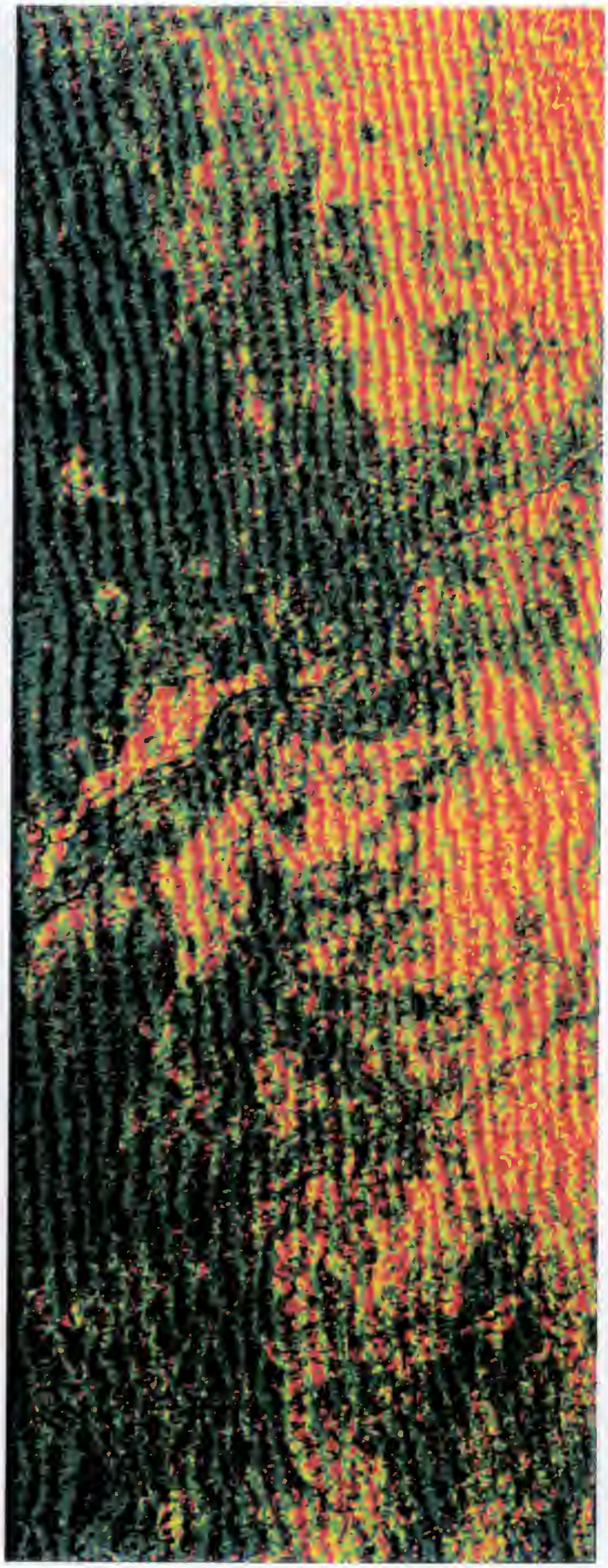
This strip has been split into four segments due to the length. The acquisition begins at the top of the first segment. The terrain varies over the acquisition strip from desert in the Northern part of Mali to savannah and forest in the southern regions.

Again, flattening errors within the processing have caused spurious fringe patterns over the entire image although significant structure can still be identified and related to surface features. One such feature occurs in the first segment where Lakes Tana and Kabara can be seen in blue. In the second segment, the River Niger can be observed crossing the strip from West to East.

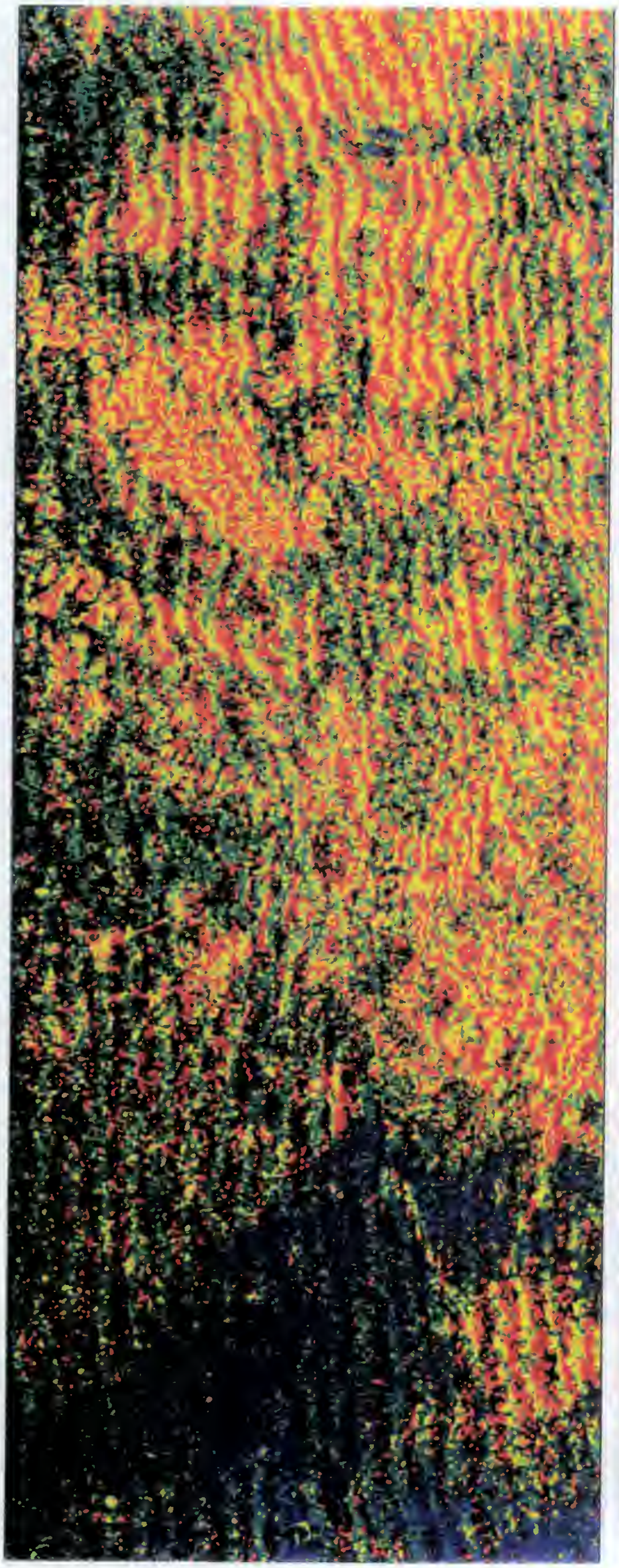
As the data start to be acquired over more heavily vegetated areas, coherence drops and the identification of fringes becomes problematic. The blue areas in the third and fourth segments correspond to forested areas. One predominant feature is the sharp change in vegetation along the border between Mali and the Ivory Coast where the land cover changes abruptly from savannah to relatively dense forest. In addition, several terrain features can be identified within the third strip including mountain structures on the upper right hand edge of the third segment and also, slightly to the North East of the forest regions.

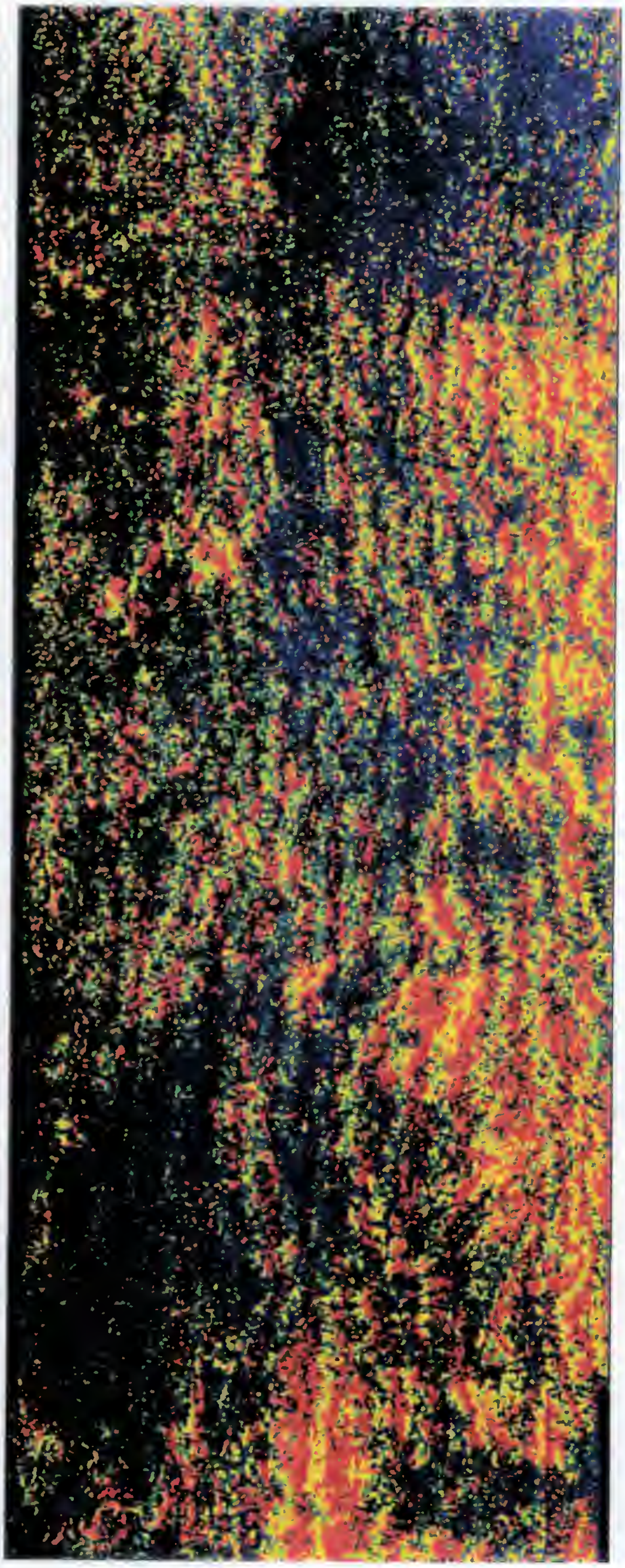
Mali, part 1 and 2





Mali, part 3 and 4



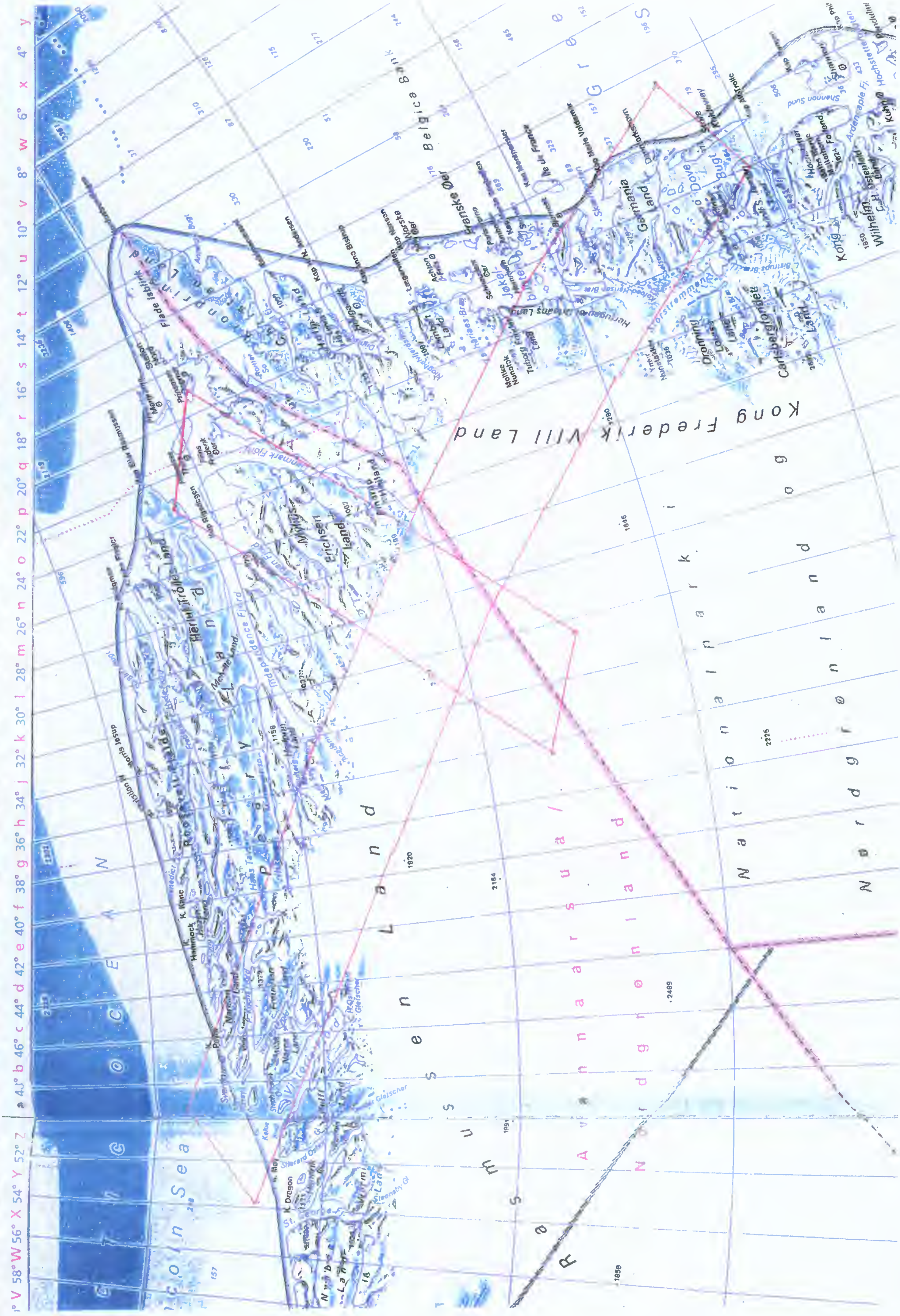


Appendix C:

Arctic and sub-artic regions

C.1 Greenland

Climate	arctic to subarctic; cool summers, cold winters
Terrain	flat to gradually sloping icecap covers all but a narrow, mountainous, barren, rocky coast
Land cover	arable land: 0% permanent crops: 0% meadows and pastures: 1% forest and woodland: 0% other: 99%



Lincoln Sea
Peary Land
Roosevelt Halde
Independence Fjord
Mylius-Erichsen Land
Kronprins Christian Land
Kong Frederik VIII Land
Germania Land
Dove Bugt
Belgica Bank
Danmarkshavn
Shannon Sund
Danmark Fjord
Nordgrønland
Nationalpark
Kap Morris Jesup
Kap Bismarck
Kap Hammack
Kap Kane
Kap Dragon
Frederik Øer
Kap Ammitsbøll
Sherard Osborn Fjord
Wulff Land
Nares Land
Kong Wilhelm Land
Storstrømmen
Dronning Louise Land
Lambert Land
Ile de France
Hochstetter
Kap Philip Broke
Carlsbergfondet Land
Nørrecamp Gletscher
Gleischer

Greenland 1

The entire acquisition starts from Germania Land in North East Greenland and finishes at Freuchen Land in North West Greenland. Germania Land can be observed at the right hand end of the first segment. The image has been split into five segments due to its length.

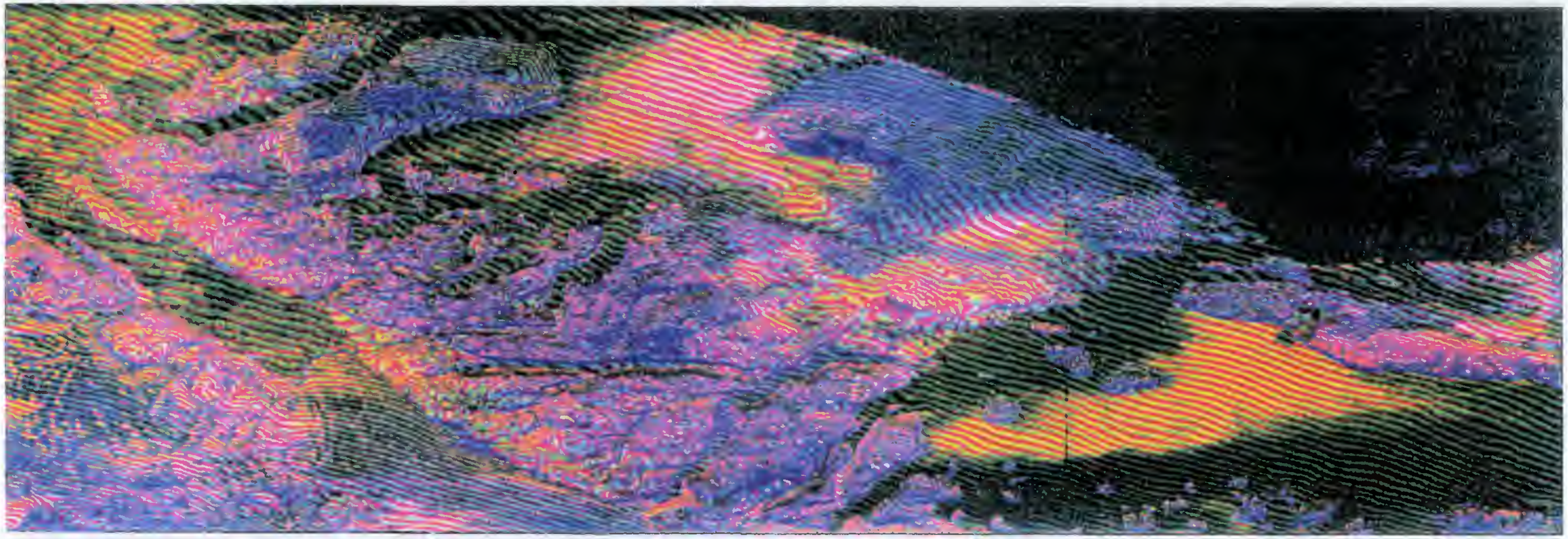
Imperfect flattening has caused the generation of spurious fringe structure throughout the entire acquisition strip making interpretation more difficult than might have otherwise been the case. In particular, sea ice areas off the coast of Germania Land could be mistaken for glaciers or land.

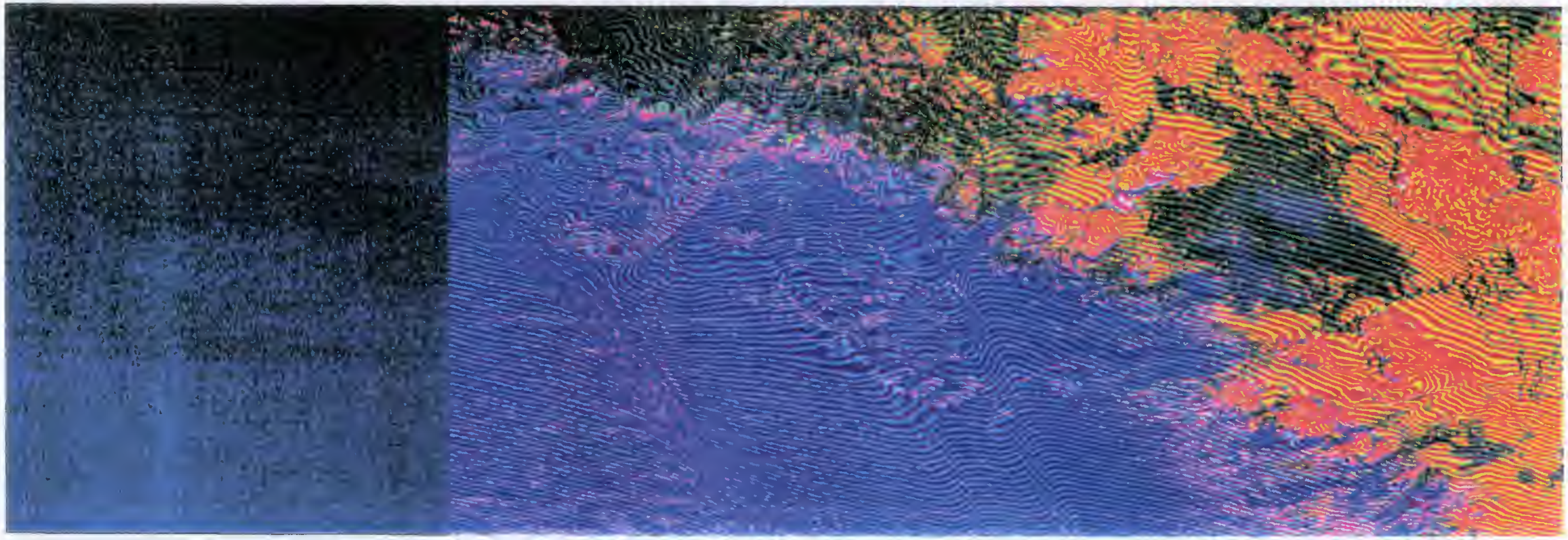
As with the tropical forest cover in Zaire, the homogeneity of the backscatter over the ice shelf has led to problems in the image coregistration algorithm employed within the InSAR Quick-Look processor. This can be seen as block discontinuities within the colour composite. This can be improved by using a more sophisticated coregistration scheme.

In the last segment, fringes on the drifting sea ice can be observed. This is due to the relatively low drift velocity which enables coherent coregistration. In addition, a large segment, almost completely separated from the coast can be seen. Most parts of the ice pack, in both the initial and final sections of the acquisition, are moving too rapidly for the preservation of the coherent signal.

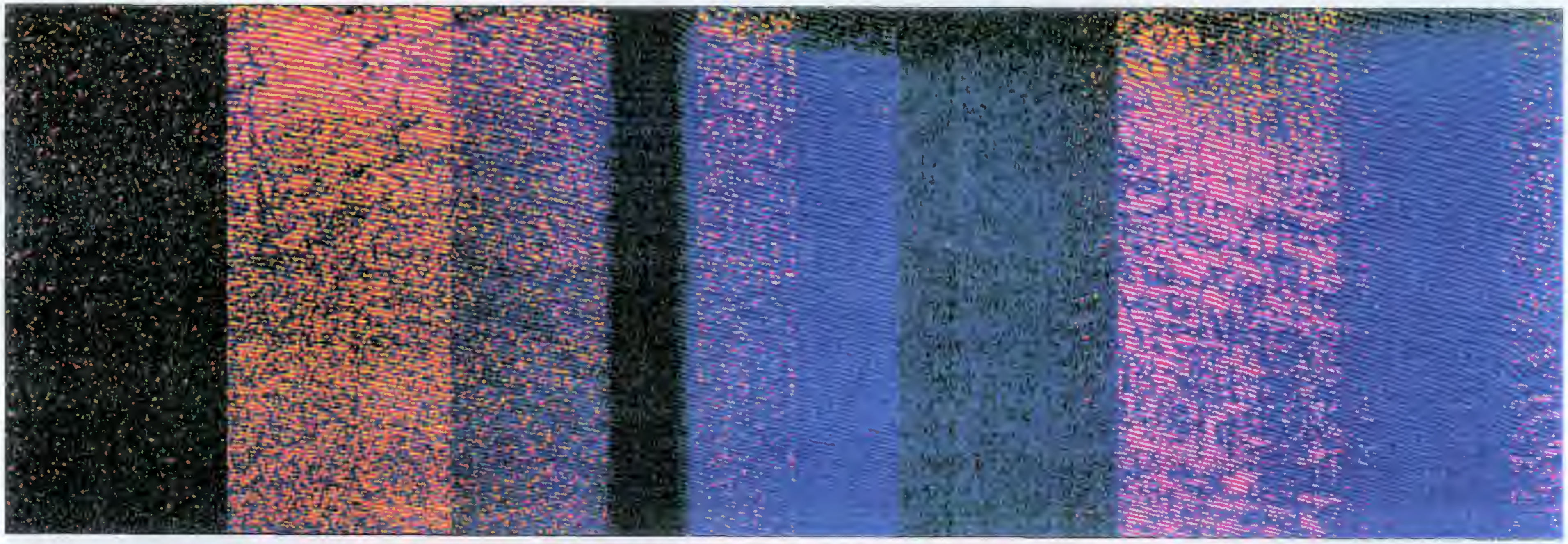
No coherence mask has been applied so it is possible to see the blue colours of the intensity channel in all areas of the image. As an example, the backscatter intensity from glaciers is higher than for areas of sea ice or exposed land. They therefore stand out as blue coloured areas within the images.

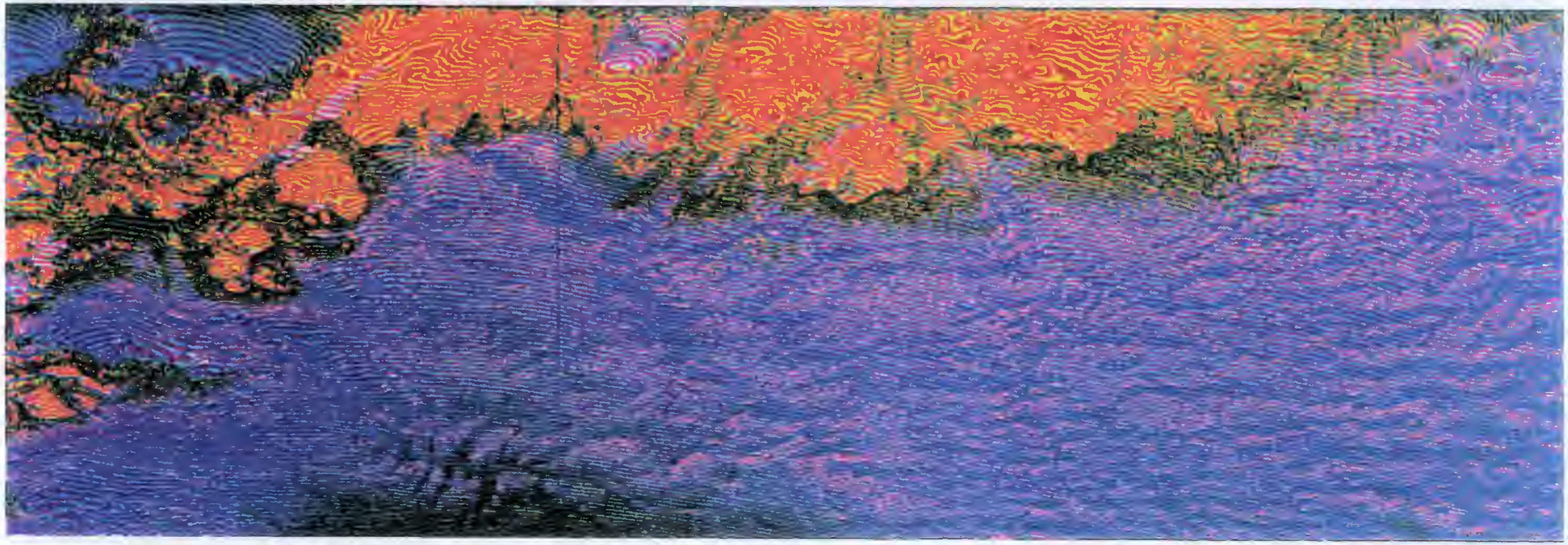
Greenland 1, part 1 and 2



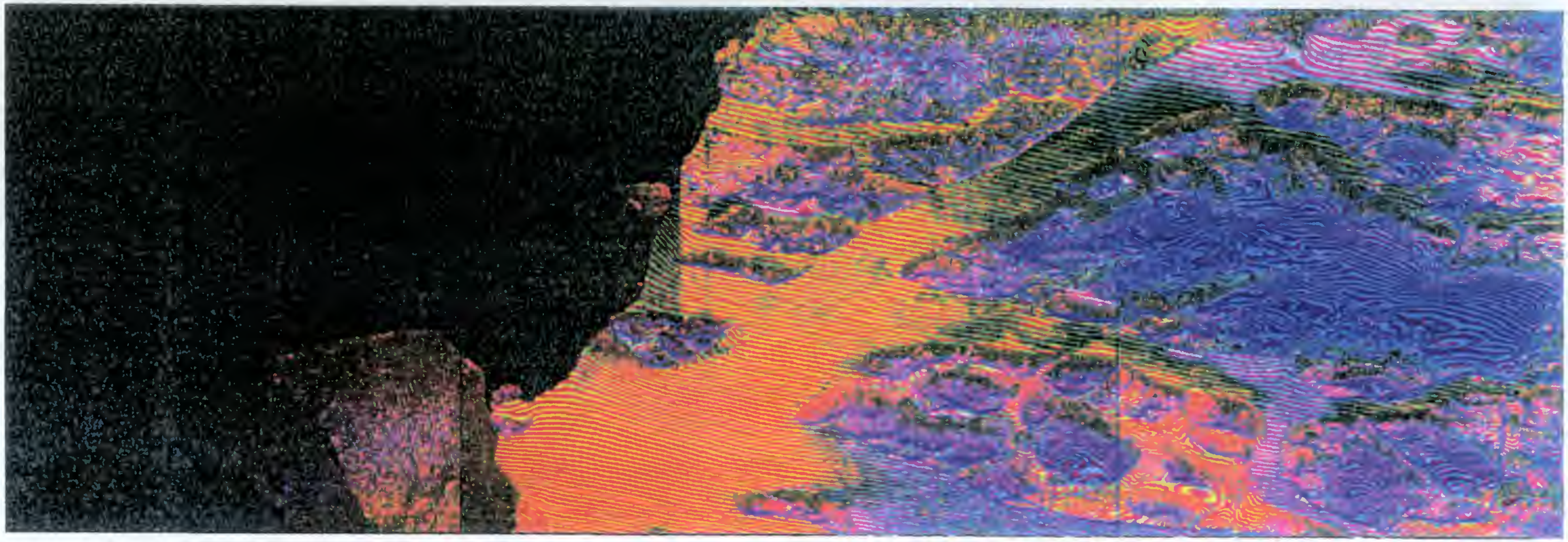


Greenland 1, part 3 and 4





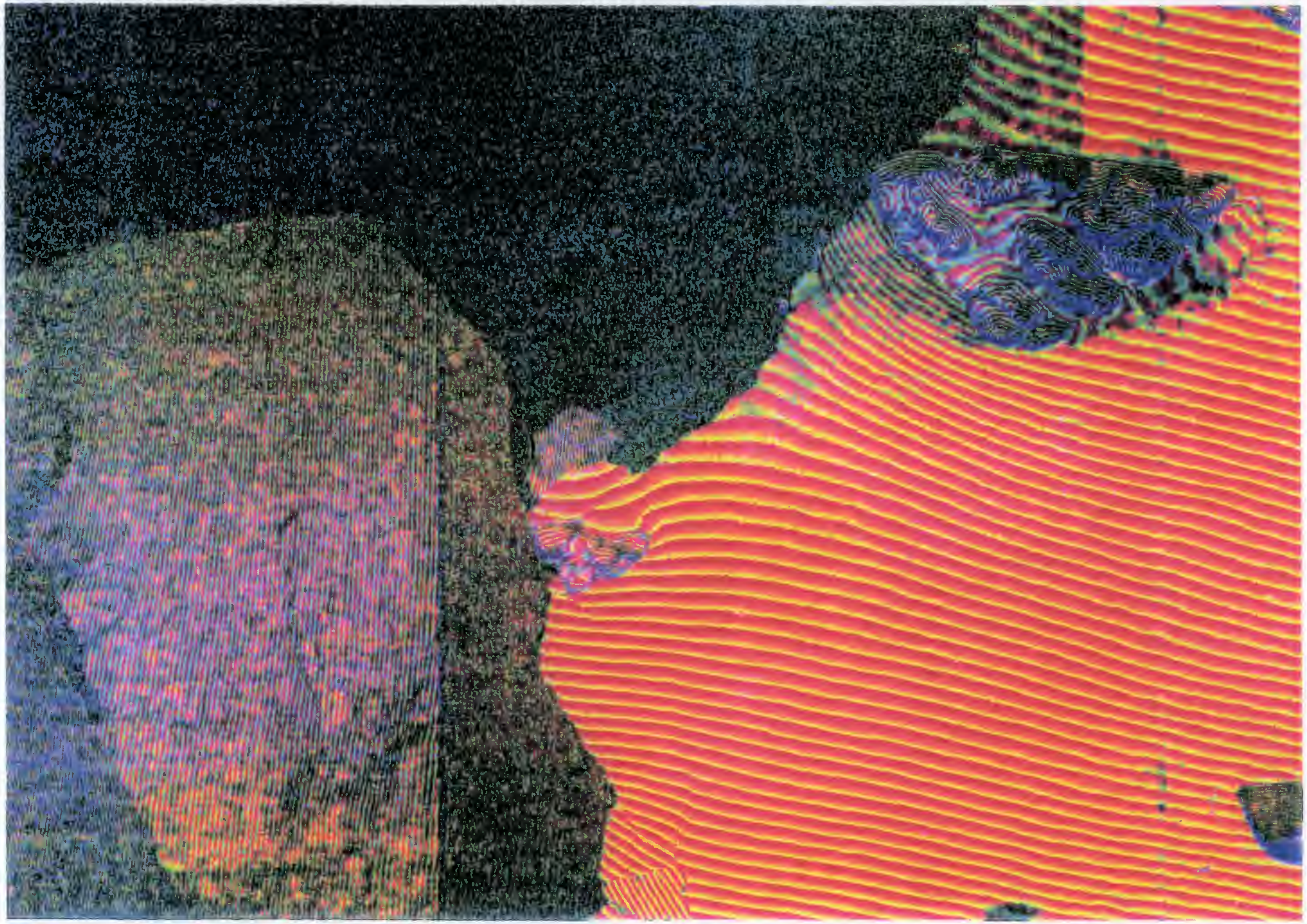
Greenland 1, part 5



Greenland 1 close-up 1

This close up is over the coastal region of Freuchen Land where John Murray Island, to the west of Freuchen Land can be seen surrounded by sea ice. The areas of red and yellow horizontal stripes are landfast ice which is, for the most part, stationary between acquisitions. Areas with vertical striping are free floating ice within the icepack which can be subject to a larger degree of movement.

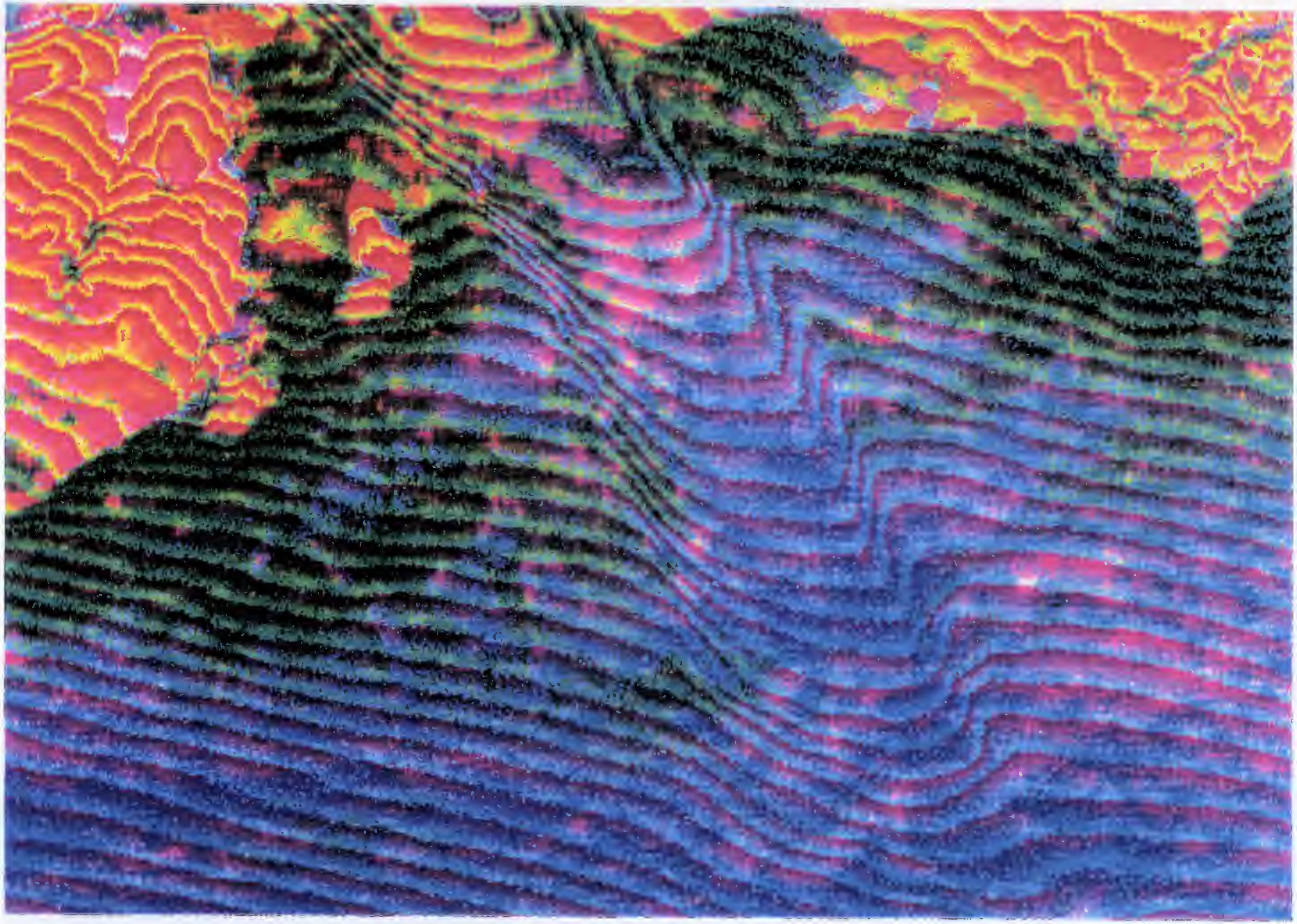
Greenland 1, close-up 1



Greenland 1 close-up 2

This second close-up is over the upper part of the Marie-Sophie glacier which has its outlet at the bottom of the Independence fjord in North Eastern Greenland. The distortion of the purple fringes across the image is partially caused by the rapid movement of this part of the ice shelf. In order to separate this information on ice movement from topographic effects in the fringe pattern, it is necessary either to use a very small baseline interferogramme or to apply sophisticated techniques such as the use of neighbouring tracks or combining ascending and descending pass data.

Greenland 1, close-up 2



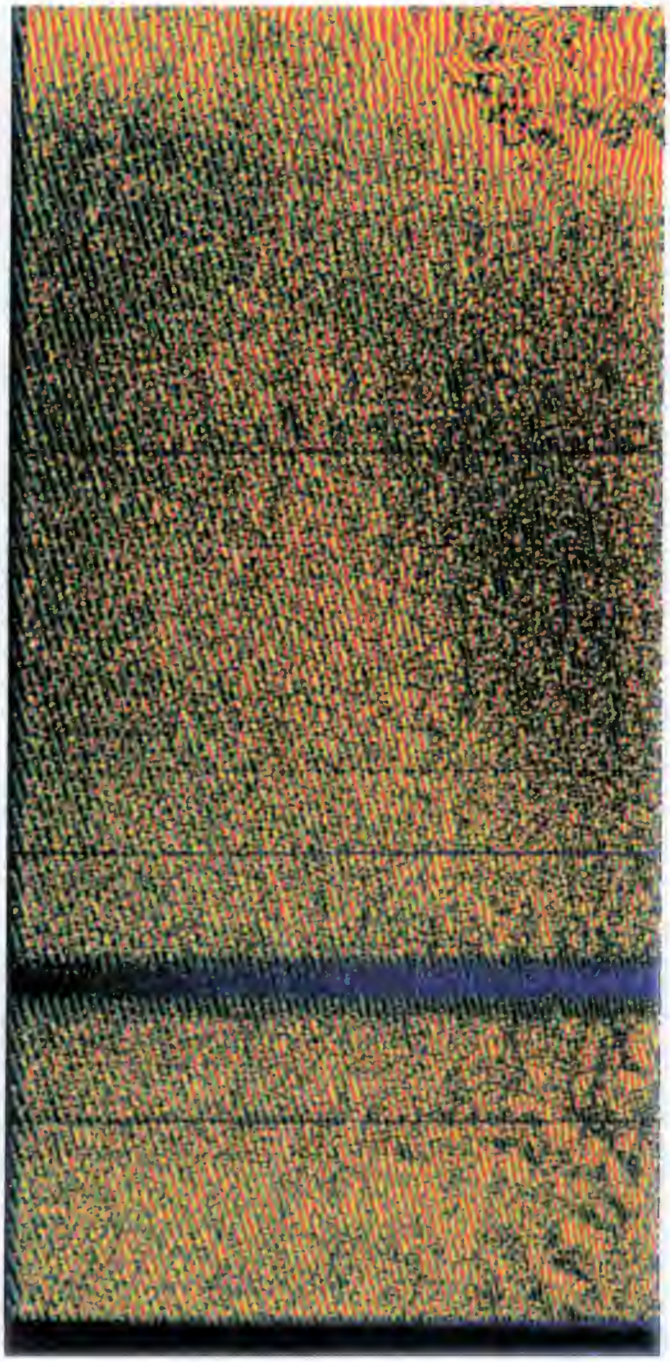
Greenland 2

This acquisition over Northern Greenland covers Mylius Erichsens Land with the surrounding fjords and part of the Greenland ice shelf. Again, lack of discernible structure on the ice shelf has caused problems in coregistration over the second part of the strip.

The variation in height is from sea level to around 2200m at the highest point of the ice shelf. Coherence is high although for an area at the outlet of the Hagen fjord and Kap Rigsdagen at the start of the strip coherence is somewhat lower than the other parts of the acquisition. This is probably due to snow transport in the one day interval between acquisitions. Imperfect flattening remains a problem although a significant degree of topographic structure can be detected.

Even if the flattening is far from perfect, the topographic features can be seen with great clarity. This image, more than anything else, proves the quality of the datasets since good results can be derived from a simple phase unwrapping scheme.

Greenland 2

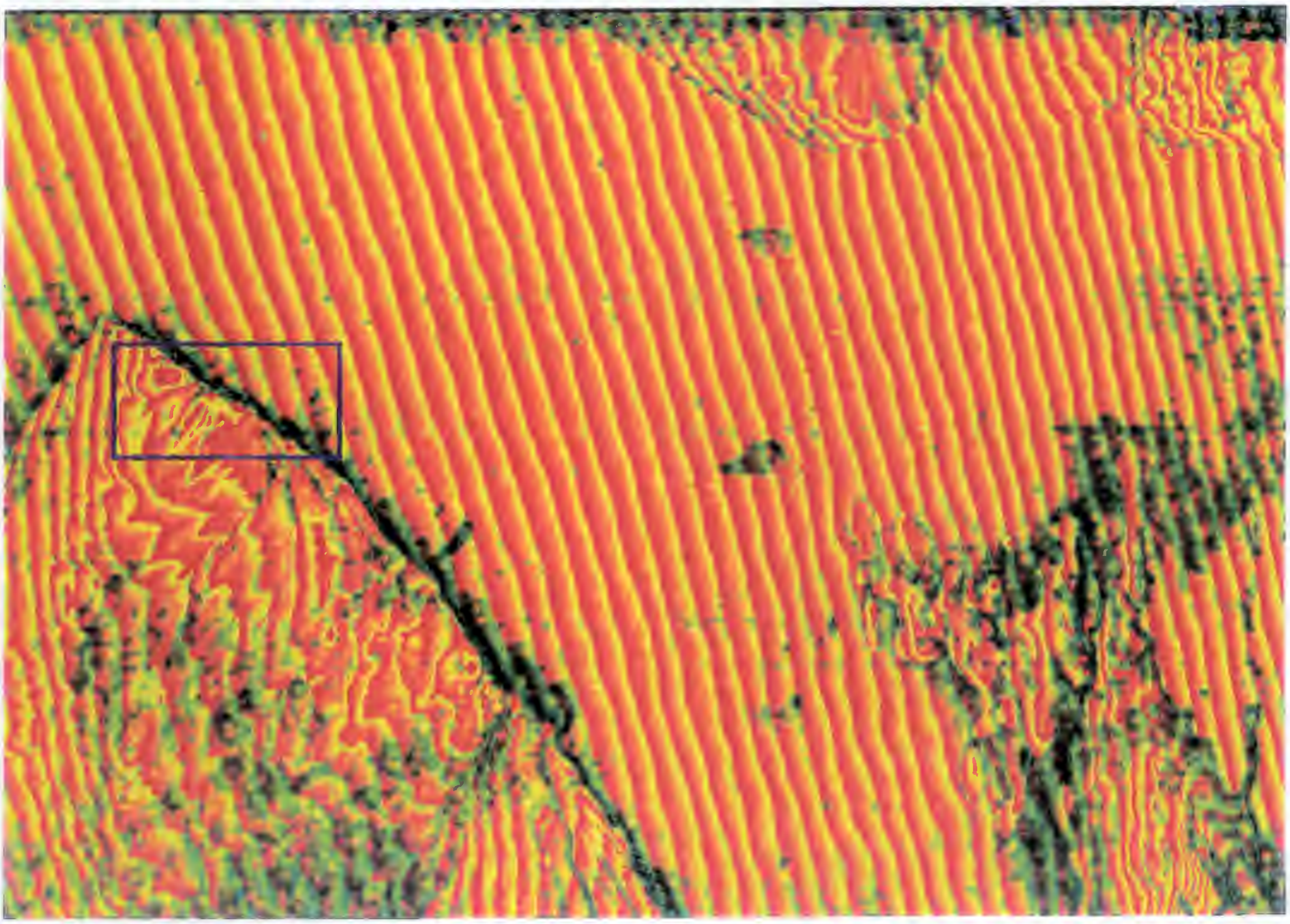


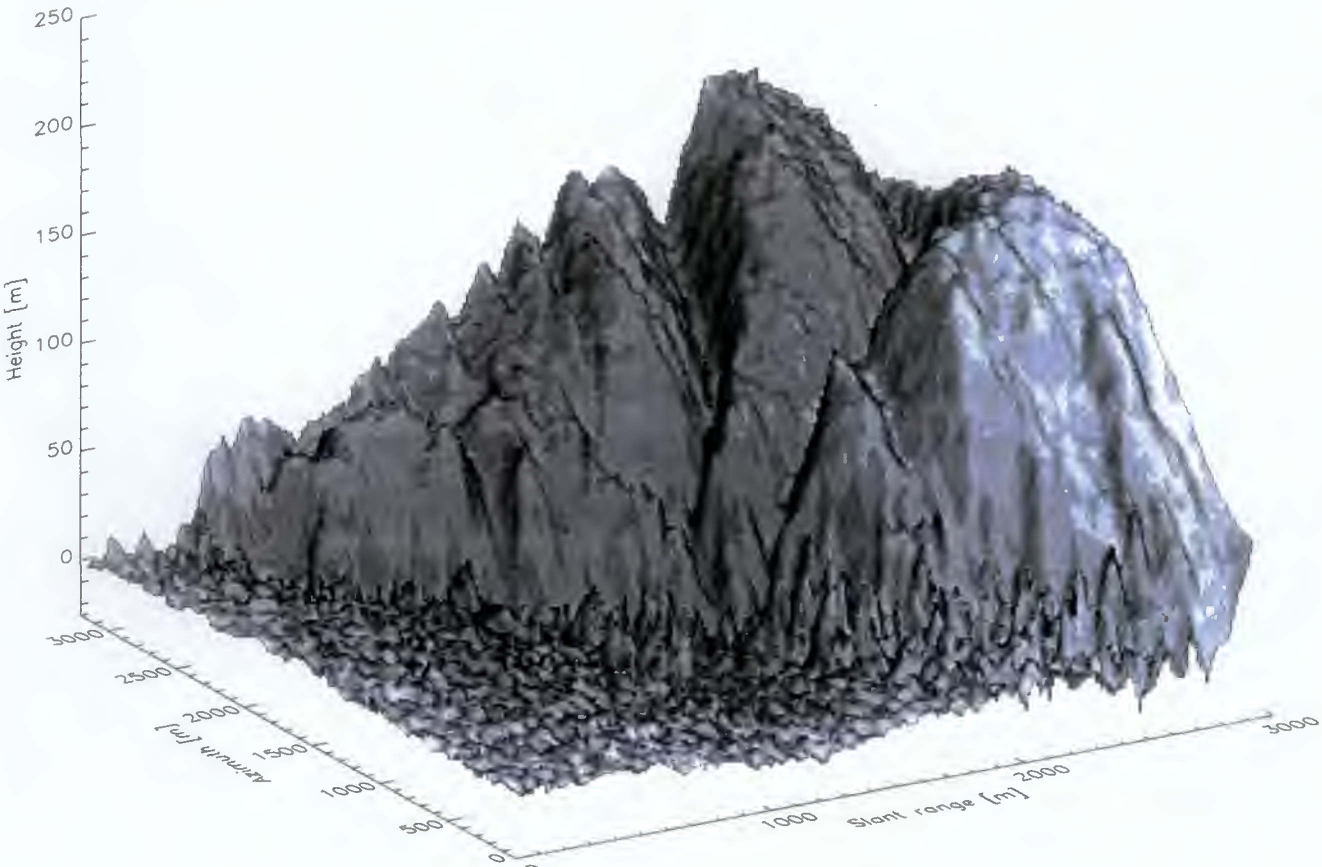
Greenland 2 close-up

This extract is a close-up from around Kap Rigsdagen and show the frozen Danmark Fjord together with some of the islands at the outlet. Even though the flattening is imperfect, generating spurious fringe patterns, it is still possible to distinguish topographic land features

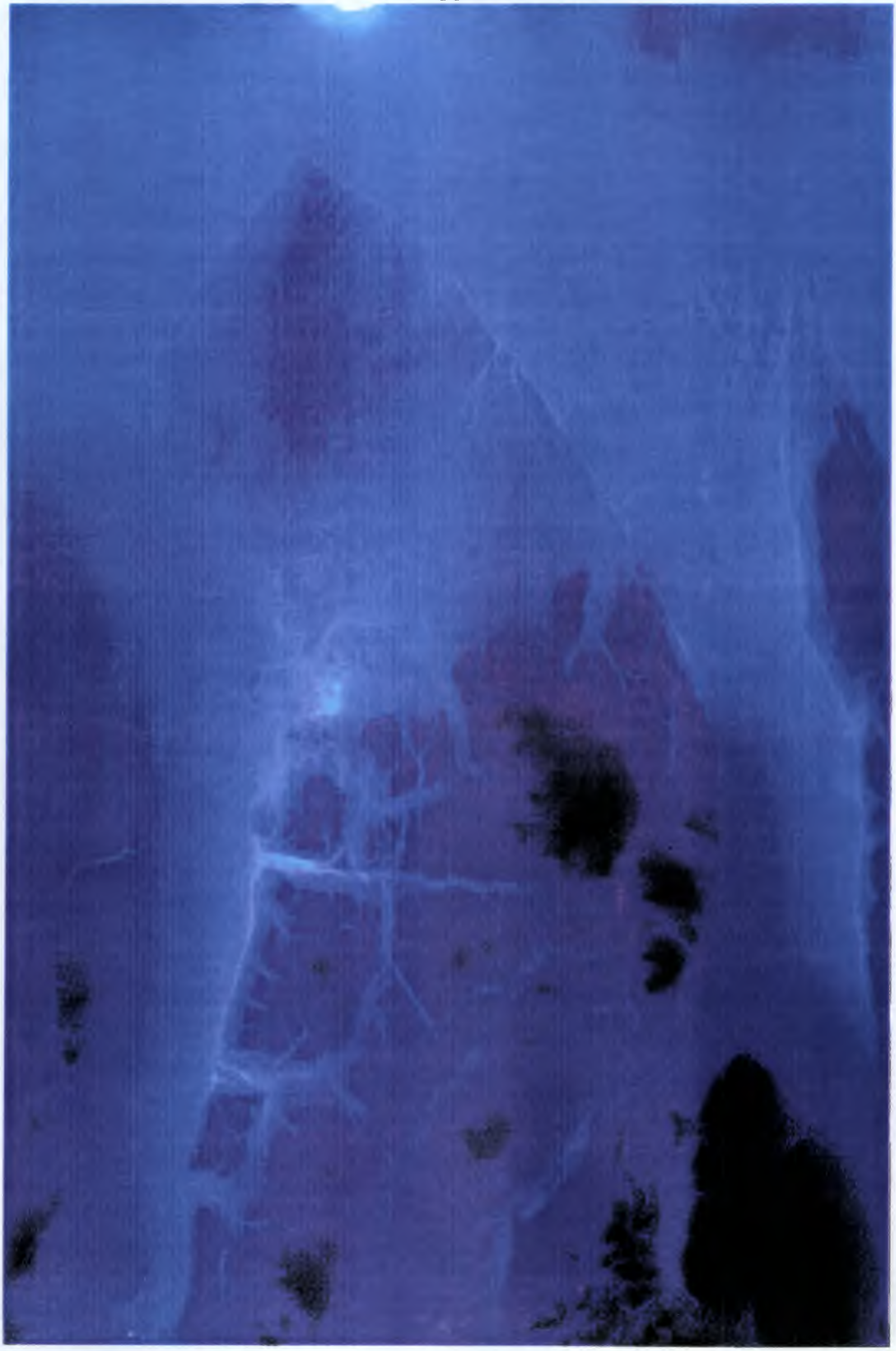
A 3D representation of the part of Kap Rigsdagen is illustrated where the fringes have been partially unwrapped using a simple algorithm. The area covered is shown as a blue rectangle on the close-up of the Danmark Fjord area.

Greenland 2, close-up 1 with unwrapped extract





Greenland 2, unwrapped 100 km * 200 km



Greenland 2, close-up 2 and 3