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FINAL REPORT
Simultaneous Implementation of a Synthetic Aperture Radar and a High-Resolution Optical Imager (Phase B)

(Volume 1 of 2)
Executive Summary

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EXECUTIVE SUMMARY

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ABSTRACT

In this work, which was managed by GEC-Marconi Research Centre under contract to ESTEC, an investigation has been performed into the temporal variation and contemporality of SAR and optical, high resolution remote sensing data. The primary aim of the study is to investigate the combination of SAR and optical data to determine, in the application areas of the cryosphere and hydrology, the so-called 'synergistic' temporal sampling requirements, i.e. the time interval within which both optical and SAR data must be recorded in order to derive a particular ground parameter or give a specified improvement. Given that the different viewing geometries of SAR (side-looking) and optical (nadir-pointing) sensors would prevent the same area from being imaged simultaneously from the same platform, the resulting temporal sampling requirements are analysed to assess whether single-platform satellites combining SAR and optical sensors would be feasible in future missions for the various application areas considered. The results indicate that single-platform satellites could be used for such application areas in all cases except for the most stringent (1 day) sampling requirements.

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CONTENTS

1. Introduction

High resolution, spaceborne, optical satellite sensors (e.g. SPOT, LANDSAT) have been in use for many years in the field of Earth Observation monitoring. Now that Synthetic Aperture Radar ('SAR') data is becoming routinely available, both from ERS-1/2 and the anticipated launch of further SAR systems (e.g. ENVISAT, RADARSAT), 'synergistic' studies for the retrieval of ground-based, geophysical parameters are appropriate. The different characteristics of data recorded by sensors operating in different parts of the electromagnetic spectrum in principle enable additional information to be derived, beyond the capabilities of one type of sensor by itself. Thus, the high sensitivity of microwaves to water content and surface roughness may enable the differentiation of land-use classes not distinguishable in the visible spectrum alone.

In the first Phase ('A') of the study, the synergistic temporal sampling requirements were investigated in four main application areas (vegetation, hydrology, cryosphere and geology / pedology), for a number of selected key parameters. These were then assessed by reference to various one- and two-platform mission analysis scenarios. This report presents the results of Phase 'B' of the study, which concentrates in more depth on the temporal sampling requirements of the two application areas of the cryosphere and hydrology. For the cryosphere application, two sub-application areas are considered : snowmelt runoff and Greenland Ice Sheet monitoring. Temporal sampling requirements are again assessed with reference to various mission analysis scenarios, in this Phase also taking account of typical cloud cover incidence.

The work (also referred to as the 'ESA Complementarity Study' or 'ECS') has been managed by GEC-Marconi Research Centre ('MRC') under contract to ESTEC. Two Sub-Contractors (University of Innsbruck and ESYS Ltd.) were involved in this Phase of the study. The assistance of Yann Kerr ('LERTS') in the provision of HAPEX-Sahel data for the hydrology study is gratefully acknowledged, as well as the contribution of the Rutherford Appleton Laboratory ('RAL') in the processing of ERS-1 ATSR data.

2. Principal Aims and Strategy

The primary aim of this study is to investigate the combination of SAR and optical data to determine, for a number of application areas, the so-called *synergistic* temporal sampling requirements, i.e. the time interval within which both optical and SAR data must be recorded in order to derive a particular ground parameter or give a specified improvement. In Phase 'A' of the study, four main types of synergy were defined :

A. No synergy (must use data from one particular sensor type).
B. Data from either type of sensor can be used.
C. Strong requirement for data from both sensor types.
D. Weak requirement for data from both sensor types (one data-set supports the other, but is not essential).

In synergy case 'C', the optimum situation is for observations to be as close together in time as possible in order to obtain the information required, whilst in case 'B', spacing the observations out evenly in time will minimise the time gaps between observations. For case 'D', the optimum situation is likely to be part way between these two extremes. Factors which will affect the rate at which the ability to retrieve geophysical information decreases with increasing time separation between SAR and optical measurements include the underlying rate at which the geophysical variable may be varying, the spatial scale over which the parameter is retrieved, and the effect of discrete events such as rain-storms. For synergy case 'A', the synergy that may exist from combining parameters within some broader model should also be considered.

The present study is essentially an empirical approach, and undertaken as three distinct tasks. The three main application areas of interest within the study are Snowmelt Runoff (Institute of Meteorology and Geophysics, University of Innsbruck), Hydrology (ESYS Ltd.) and Greenland Ice Sheet monitoring (GEC-Marconi Research Centre).

In Task 1, a survey is performed in each of the three applications areas in order to establish an appropriate test site(s) for which both SAR and optical image data are available for the specific application of interest, as well as supporting ground-truth data for validation.

In Task 2, an assessment is made (based on the data sets identified in Task 1) of the temporal variations inherent in each of the three application areas of interest to the study for a selected number of ground parameters for which validation data are available. By the use of various simulation, class separability and correlation techniques, the time margins can be established beyond which complementary optical and microwave data do not provide meaningful information (synergy types 'C' and 'D' above). The individual effects on SAR backscatter and optical reflectance (synergy types 'A' and 'B' above) have also been investigated as part of the study.

Finally, in Task 3, a summary is presented of the work undertaken in the current study, highlighting major problems encountered, and providing a list of recommendations for future work. Through a Mission Analysis task, the temporal sampling requirements derived in Task 2 are analysed in order to assess whether single-platform satellites combining SAR and optical sensors would be feasible in future missions for each of the application areas considered, or whether separate spaceborne platforms are necessary. For the orbit calculations, near-circular, sun-synchronous orbits are considered.

3. Data Survey

A survey was performed in each of the application areas in order to establish suitable test sites for which both SAR and optical, high-resolution, image data were available, as well as supporting ground-truth data for validation. The main application areas of interest within the study are shown in Figure 1, along with the key parameters selected as appropriate for investigation. Factors influencing the choice of these parameters are : their importance to the particular sub-application under consideration, their sensitivity to determination by remote sensing data, and whether their determination is likely to be enhanced by a combination of microwave and optical data.

Of primary importance in the selection of data is the requirement for 'contemporality' between the SAR, optical and ground-truth data, i.e. data of each type must be recorded within a time interval less than the frequency of underlying change in the parameter under consideration. A sufficient number of 'contemporaneous' measurements are required of a given parameter in order to investigate the main underlying variation, as well as the rate at which any synergy between SAR and optical measurements changes over time. Data should therefore be available that cover the periods of greatest underlying change (e.g. over critical periods of crop growth), though it is not within the scope of the current study to consider the effect of unpredictable 'events' such as forest fires or earthquakes. Ground data must, of course, be available which cover the key parameters identified.

The test data sites selected for the study are shown in Figure 1, full details of which are given in the appropriate Appendices ('A' - 'C'). A brief description of the datasets used in each application area is given below. Satellite and airborne instrument surveys were performed by Matra Marconi Space U.K. and GEC-Marconi Research Centre respectively in Phase 'A' of the study, providing the main system and orbit parameters required for the Mission Analysis task (c.f. Section 5.2).

Snowmelt Runoff

For the snowmelt runoff application (Institute of Meteorology and Geophysics, University of Innsbruck), the area of investigation includes the two drainage basins Rofenache (98 km^2) and Venter Ache (165 km^2) in the Ötztaler Alps, Austria. Approximately 40% of the basin Rofenache and 38% of the basin Venter Ache are covered by glaciers. 13 ERS-1 SAR images of the Ötztal test site were acquired over the period April 1992 to March 1993, covering a wide range of snow cover conditions at various altitude zones. Landsat 5 TM quarter-scenes were acquired close to two of the SAR image acquisitions, in August and September 1992. Auxiliary data available includes runoff measurements from the basins acquired daily (Rofenache) and at 15 minute intervals (Venter Ache), air temperature and precipitation measurements from the climate station at Vent (located at an elevation of 1906 metres near the two runoff gauges), and digital elevation data over a 25 metre grid.

Hydrology

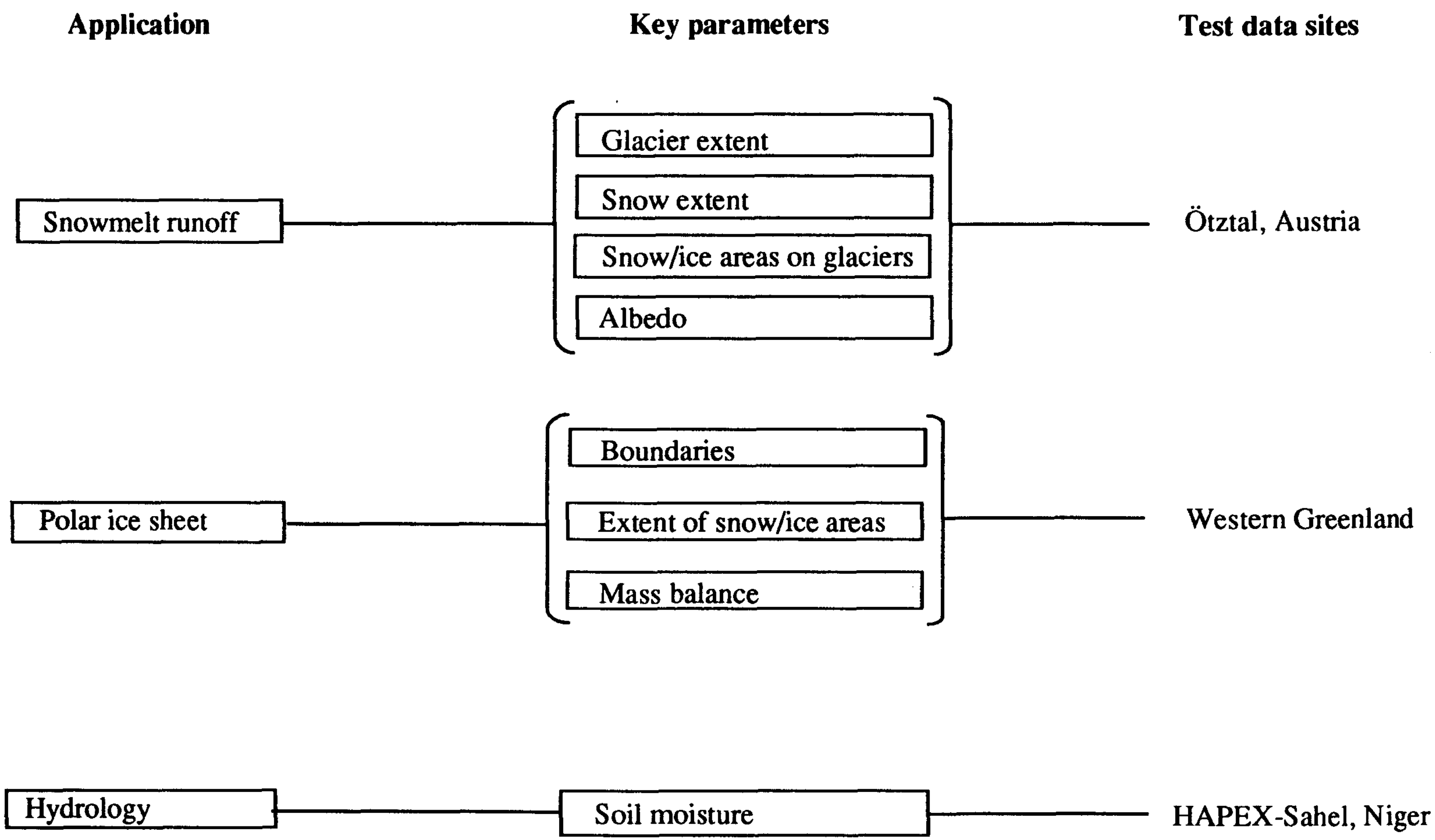
For the Hydrology application, SPOT and ERS-1 data are analysed for the area of the HAPEX-Sahel experiment (13°N, 02°E to 14°N, 03°E), covering two supersites. The Niger river flows south-easterly through part of the area. Due to the relatively light nature of the soils in the region, the response to rainfall inputs in terms of infiltration and evaporation is expected to be rapid. The highest temperatures occur at the end of the dry season in April and May, followed by a considerable reduction in the wet season lasting until October. The rainfall during the wet season generally results from relatively short periods of heavy rainfall associated with thunderstorms, predominantly in the late afternoon. In 1992, there was an early start to the rains, followed by a dry spell from early June to mid-July, and then above-average rainfall in August and early September. The rainfall total over the whole study area was 537 mm (787 mm at the southern supersite and 410 mm at the central eastern supersite), just below the 1950 - 1990 average of 550 mm.

Nine ERS-1 SAR images were acquired of the test site over the period May to November 1992. Cloud-free, SPOT HRV, multi-spectral images were acquired for the area on two dates in August and September 1992 (each within 7 days of an ERS-1 SAR measurement). Supporting ground-truth data include vegetation type and cover, soil moisture (the key parameter for this application), and daily meteorological data (temperature, humidity and precipitation).

Greenland Ice Sheet study

For the Greenland Ice Sheet study, the key parameter is the position of the different snow facies boundaries, related to changes in accumulation and ablation (and hence mass balance) across the ice sheet. Two sources of data (ERS-1 SAR and ATSR) are used to monitor an area of western Greenland between 71°N, 53°W and 76°30'N, 43°W. ERS-1 SAR data was available on 5 dates during the period April 1992 to March 1993 and ATSR data on 7 dates during the period April to September 1992. Supporting data includes daily air temperature and dew point measurements, and a 1:250,000 scale topographic map.

Figure 1 - ECS (Phase B) Applications and Datasets



4. Investigation of Contemporality

Following the identification of appropriate data sets and key parameters as described in Section 3, an assessment is made of the temporal variations inherent in each of the three application areas of interest to the study (snowmelt runoff, hydrology, and Greenland Ice Sheet mapping), with the aim of establishing the time margins beyond which the combination of optical and microwave data does not provide meaningful information (i.e. in deriving a particular ground parameter or giving a specified improvement). The temporal sampling requirements are considered both in terms of the acquisition of 'added-value' synergistic data (i.e. assuming no change in the underlying ground parameters), and in order to observe genuine change detection (e.g. the movement of the transient melt line across an ice sheet).

As in Phase 'A' of the study, within each application area the main steps undertaken in the investigation of contemporality can be summarised as follows :

• An empirical investigation to determine how quickly the key parameters change in both the optical and radar data.

• Determination of how quickly cross-correlation between optically- and SAR-derived parameters reduces as a function of increasing the time interval between acquisition of SAR and optical data.

• Tabulation of the optimum and maximum time interval between SAR and optical data acquisition for each parameter for which 'synergistic' information may be derived.

• A theoretical investigation of the underlying dynamics of the key parameters, based on an analysis of the field data. This can then be compared with the measured response in the remote sensing data.

Full details of the results of the investigation of contemporality for each application area are given in the appropriate Appendices ('A' - 'C'), a summary of the main findings within each application area being given below. A summary of the results in terms of the temporal sampling requirements derived for the various application areas is given in Section 5 ('Synthesis of Results and Recommendations').

4.1 Snowmelt Runoff Application (Institute of Meteorology and Geophysics, University of Innsbruck)

For the snowmelt runoff application, the satellite-derived information is used as input to a Snowmelt Runoff Model, which calculates for every day the water produced from snowmelt and from rainfall and adds this to the recession flow. As defined in Appendix 'A', on day (n+1), the runoff, Q, is calculated according to :

$$Q_{n+1} = [c_{sn}\alpha_n(T_n^+ + \Delta T_n)S_n + c_{rn}P_n] \, . \, [A.10000/86400].[1 - k_{n+1}] + Q_n k_{n+1} \quad (1)$$

where : Q = average daily discharge in m^3s^{-1};

c = runoff coefficient expressing losses due to snowmelt, 's' , and rain, 'r';

α = degree-day factor (cm/°C/day), indicating snowmelt depth resulting from 1 degree-day;

T^+ = degree-days (°C days), positive degrees of mean daily air temperature;

ΔT_n = adjustment (°C) by temperature lapse rate between temperature at recording station and average elevation of basin or altitude zone;

S = ratio of snow-covered area to total area;

P = precipitation contribution to runoff (cm);

A = area of basin or altitude zone (km^2);

k = recession coefficient, indicating (and determined from) decline of discharge in a period without snowmelt and rainfall;

n = number of days during discharge computation period;

(10000/86400) = conversion factor (cm km^2 d^{-1} to m^3 s^{-1}).

Due to the wide range of elevations (from 1800 to 3800 m.) and the different runoff from glacier surfaces and snow-covered areas in ice-free regions, the runoff is calculated separately for ice-free and ice-covered areas in different altitude zones. Altogether, the runoff calculations were made for 8 sub-zones per drainage basin, with the meteorological input variables, degree-days T^+ (determined from the mean of daily maximum and minimum air temperatures, corrected for altitude) and precipitation 'P', derived from measurements at the climate station Vent. Different values of degree-day factor ,'α', were derived for snow and glacier ice. The average altitude dependence of precipitation was taken account of by increasing the runoff coefficient for rain, 'c_r', with altitude.

Both the SAR and optical data can be used to measure snow extent, and optical data to additionally determine surface albedo (from which the degree-day factor is derived). The ERS-1 data are geocoded using digital elevation data with 25 metre grid size to eliminate terrain-induced distortions, and low-pass filtered (adaptive Frost filter) to reduce speckle effects. The extent of melting snow areas is then derived (following the method described in Phase 'A' of the study) by thresholding on a pixel by pixel basis the ratio of backscatter power from the SAR image to a reference (dry snow) image, the ratio compensating for the angular variations of backscatter due to topography. Snow maps derived from SAR images of ascending and descending orbits at a given date were combined in order to reduce the loss of information due to layover and foreshortening. In the Landsat data, surface reflectivity, 'R_S', was calculated according to a simplified radiative transfer model, with discrimination of snow and glacier areas based on thresholding the ratio of the surface reflectivities in TM bands 3 and 5 (again, as described in Phase 'A' of the study).

The model calculations were carried out on data from 1 May to 30 September 1992, the period of snow and glacier melt, for the two basins Rofenache and Venter Ache. Between dates of actual measurements, snow extent and albedo were interpolated linearly, zone by zone. Upto mid-August, when no optical data were available, albedo was estimated either using albedo data from previous years or data on extent of snow and ice areas in the glacier zones derived from the SAR images. As shown in Appendix 'A', good agreement is observed with the actual runoff measurements both when the model is run in 'simulation mode' (i.e. runoff calculations initiated with daily discharge on 30th April, and no other measured runoff data used), and in 'forecast mode' (i.e. runoff predictions made 3 days ahead of measured runoff). Requirements for contemporality of SAR and optical data were determined from the time interval over which keeping albedo and snow extent constant in the model calculations did not increase the error in the runoff above 2.5% (optimum case) and 5% (maximum), results being given in Section 5.

4.2 Hydrology Application (ESYS)

For the hydrology application, ERS-1 SAR and SPOT HRV data were obtained co-incident with two supersites of the HAPEX-Sahel experiment. The ERS-1 data were averaged over an area of 500 pixels in order to derive calibrated backscatter, centred on points at which soil moisture measurements were available. The SPOT data were first converted to top-of-the-atmosphere radiance values using standard calibration factors for each band, and then corrected for atmospheric effects by subtracting out the response from an area of low reflectance.

From the temporal variation in SAR backscatter as determined at different locations, each with a different type of vegetation cover, it is noted that in addition to a general rise in backscatter during the wet season consistent with an observed increase in soil moisture, there additionally appears to be a vegetation effect such that (for instance) a stronger dependence is seen at the Southern Supersite for millet than for the denser tiger bush cover. The contrast in backscatter between millet and tiger bush is found to be generally higher in the wet season than in the dry season. Correlation of ERS-1 SAR backscatter with 'in situ' soil moisture measurements also indicates a strong relationship, particularly in conditions of higher soil moisture (above 0.02 cm^3/cm^3). A multi-temporal composite of ERS-1 SAR data recorded in dry soil moisture conditions reveals that tiger bush, fallow and millet cover types may all be identified.

Analysis of the SPOT data again shows that there are marked differences in reflectance between the wet and dry seasons. However, the extent of this change differs substantially between sites, indicating that the reflectance is primarily sensitive to vegetation (type, condition and growth) rather than to soil moisture changes. Thus, at the Southern Supersite (millet, tiger bush and fallow), the range of reflectance values is approximately double that at the Central Supersite, where there is a greater similarity of cover type. Additionally, no relationship is apparent in scatterplots of SPOT reflectance with soil moisture, although changes in soil moisture will produce a delayed effect in the vegetation growth.

Thus, it is believed that the real synergy for this application derives from the potential for using information obtained from the optical data on the type and condition of vegetation cover to correct the soil moisture estimate from the SAR data. Recommendations for temporal sampling requirements based on this approach are given in Section 5.

4.3 Greenland Ice Sheet Application (GEC-Marconi Research Centre)

For the Greenland Ice Sheet application, multi-temporal ERS-1 SAR and ATSR datasets were formed covering the area of interest over both the winter and ablation seasons. For the ATSR data, the 1.6 μm channel was used, with cloud-clearing performed based on intensity thresholding. Radiance values were normalised for solar elevation angle, solar elevations below 5° not being used. A multi-temporal composite of ATSR data from the pre-melt, mid-ablation and end of ablation periods was found to enable separation of the ice- and snow-covered areas.

Multi-temporal analysis of the calibrated ERS-1 SAR data for the same periods shows clear features related to the boundaries of diagenetic zones and the transient melt line. By looking at the diference in backscatter between June 1992 and January 1993 from the dry snow zone, it can be seen that the variation is extremely small (generally 0.1 to 0.2 dB), well within the specification for the instrument stability. This result is in good agreement with the less than 1 dB temporal variability reported by University of Innsbruck in Phase 'A' of the study based on ERS-1 AMI wind scatterometer measurements made over the period February to October 1992 of the Amery Ice Shelf in the Antarctic.

Analysis of synergy is based on the relative separability of the various diagenetic zones in the ice sheet using one and both instruments. The data were first spatially averaged and 'cropped' so as to have the same areal coverage and pixel size (1 km. x 1 km.), and a cloud mask applied to both data types. The calibrated ERS-1 SAR data were analysed in the form of mosaics of 6 images along a swath in order to increase the areal coverage. A simple intensity threshold was applied to the SAR winter imagery in order to delineate the dry snow and equilibrium lines, and merged with a segmentation of the full multi-temporal SAR image data. This segmentation could then be applied to the ATSR data in order to derive attributes for the same regions as the SAR data.

Separability of the diagenetic zones was assessed from the Jeffries-Matusita measure (normalised to a value between 0, indicating no separability, and 1, indicating 'clear' separability), calculated from the mean backscatter / reflectance of the segmented regions in the multi-temporal data. The results show that the dry snow line and transient melt line are better determined in the SAR data, and the equilibrium line in the ATSR data, with improved delineation in each case by a combination of data from the two sources. Implications for temporal sampling are given in Section 5.

5. Synthesis of Results and Recommendations

A full list of conclusions and recommendations is given in Appendix 'D'. In Section 5.1, a summary of the synthesis of results from the various application areas is given, in Section 5.2 the implications of these results are discussed in terms of mission analysis, and in Section 5.3 a number of recommendations are presented for future work.

5.1 Synthesis of Results

Results have been obtained for snowmelt runoff, ice sheet monitoring and hydrology applications which demonstrate in each case the synergistic potential of SAR and optical data. For the first two application areas in particular should be stressed the original nature of the research, with potential importance in areas of global climate monitoring, and (for snowmelt runoff) commercial possibilities in areas such as hydroelectric power generation. Associated temporal sampling requirements have been derived for each application, which are then assessed (c.f. Section 5.2) in terms of various mission analysis scenarios.

The main results in terms of the synergistic temporal sampling requirements derived for each application area considered in Phase B of the study are given in Table 1. These are specified both in terms of the maximum and optimum time interval between which SAR and optical measurements can be made in order to derive 'added-value' synergistic information.

For the Snowmelt Runoff application, separate requirements are specified for small and large drainage basins. Basins with large vertical extent are inherently more inert than basins which extend over small altitude zones. The sampling requirements in Table 1 refer to drainage basins for which the snowmelt period has a duration of at least a few weeks, as is the case for mountain and high latitude basins. In lowland basins at mid-latitudes, the snowmelt period and consequent synergistic sampling requirements will be generally shorter (as specified in Phase 'A' of the study). The different sampling requirements for use of the SAR and optical data are based on the results of keeping albedo and snow extent constant in the model calculations for a certain number of days. The fact that the temporal dynamics of snow extent are more pronounced than for albedo is reflected in the shorter sampling requirements for determination of snow extent from SAR or optical data rather than using the optical data to determine albedo.

For the Hydrology application, the synergistic sampling requirements for soil moisture estimation are specified both on the scale of daily and seasonal variation. The diurnal pattern of rainfall can vary markedly in West Africa, even between locations that are relatively closely spaced, the change of soil moisture after heavy tropical rainfall being an important indicator of the water-holding capacity of the soil. The rapid decrease of soil moisture after rainfall in semi-arid Africa occurs within a matter of days, especially where evapotranspiration from the soil is not restricted by vegetation cover. The strong seasonal variation in soil moisture derives from the fact that about 98% of the rainfall in the HAPEX-Sahel region occurs during the wet season from May to October, the precise duration and intensity of which is subject to the general movement of the inter-tropical convergence zone, which moves northwards in late spring, bringing the wet climates of coastal West Africa to the inland areas. From the end of October to the end of April, there are normally no more than 3 to 4 days of rainfall. The main use of the optical data in the determination of soil moisture is primarily to determine (and to help correct for) the effect of vegetation cover, and hence in Table 1 the optimum synergistic sampling requirement can essentially be interpreted as the sampling interval required between consecutive SAR observations and the maximum synergistic sampling requirement as the sampling interval required between SAR and optical measurements.

For the Greenland Ice Sheet application, no synergistic temporal sampling requirements are given for the dry snow line as this cannot be detected using the optical data. Using the SAR data, monitoring requirements are about once per year, ideally at the end of the ablation season. For the snow line, more research is required as to how well this can be determined in both the SAR and ATSR data (other visible frequencies may be optimum). A reference SAR or ATSR image would be required at the start of the ablation season, in conjunction with a time series of SAR and ATSR data at the specified sampling intervals towards the end of the ablation season. For the equilibrium line, the ATSR would act as the primary sensor and the SAR as the secondary sensor. The main sampling period required is at the end of the ablation season (perhaps a month starting in mid-August), detection of the maximum altitude of the bare ice zone being particularly important. For monitoring of the transient melt line, the primary sensor would be the SAR with sampling required over the whole duration of the ablation season.

Comparing the temporal sampling requirements determined in Phase 'A' and Phase 'B' of the study for the same application area (bearing in mind any differences arising from seasonal and geographic effects), there is good agreement in both the cases of relevance. For the polar ice sheet application, a maximum synergistic sampling interval of 5 days was specified in Phase 'A' for determination of the extent of snow and ice areas, in good agreement with the values obtained in Phase 'B' for identification of the snow and equilibrium lines. For soil moisture, the temporal sampling requirements estimated qualitatively in Phase 'A' of the study for the Mali test site (with similar climate characteristics to the HAPEX-Sahel site) are in good agreement with those obtained more quantitatively in Phase 'B' of the study.

Table 1 - Summary of ECS (Phase B) Temporal Sampling Requirements

Application	Sub-application	Measurement conditions	Optimum synergistic sampling interval (days)	Maximum synergistic sampling interval (days)
Snowmelt runoff	Small basin	Snow extent determined from SAR and albedo from optical data	5	10
		Snow extent determined from either SAR or optical data	3	6
	Large elevation range	Snow extent determined from SAR and albedo from optical data	5	10
		Snow extent determined from either SAR or optical data	5	10
Polar Ice sheet	Snow line	Late ablation season	5	10
	Equilibrium line	Late ablation season	5	10
	Transient melt line	Ablation season	1	3
Hydrology	Soil moisture	After rain	1	7
		Seasonal	7	30

5.2. Mission Analysis

The Mission Analysis work undertaken in Phase 'A' of the study using in-house software developed at GEC-Marconi Research Centre (reported in detail in Appendix 'G' of the Phase 'A' Final Report) showed that of the various SAR and optical instrument swath widths considered, only one enabled the majority of the synergistic sampling interval requirements to be met. This was for the 400 km. SAR swath (boresight look angle 29.0°) and the optical instrument with the ± 30° scanning capability, giving an effective optical swath width of 920 km. One of the assumptions made during the Phase 'A' Mission Analysis, however, was that cloud-free conditions prevailed.

The further work undertaken in Phase 'B' of the study (described fully in Appendix 'D') includes simple cloud statistics for the optical instrument and considers the Phase 'B' synergistic applications. The cloud-cover statistics have been included in the analysis by aassuming (based on published data) a 40% cloud cover during the summer season and a 60% cloud cover during the winter. Each time a particular location on the ground has been imaged by the optical instrument, a random cloud-cover percentage has been generated, determining whether the location is taken to be cloud-free and thus included in the analysis. Only the single-platform case for both the SAR and optical instruments has been considered, with again a near-circular sun-synchronous orbit (repeat periods of 3, 14 and 35 days), and a minimum solar elevation of 15° for the optical data.

The applications described in Appendices 'A' to 'C' give requirements on the optimum and maximum synergistic sampling interval (i.e. return-times) which are acceptable for a given sub-application. To determine whether the synergistic temporal sampling requirements given in Table 1 can be achieved, the return time and percentage of longitude locations imaged have been analysed for a particular maximum return time. The maximum return times considered are 12 hours, 1, 3, 7, 14 and 28 days. The results of the analysis are then given in the form of plots showing as a function of latitude the percentage of longitude locations imaged by both the SAR and optical instrument for which the return time is less than the maximum return time at any point during the repeat period, and also the number (averaged over each longitude location) of return times less than the maximum return time at each latitude imaged. As expected, the results show a general reduction in the percentage of locations imaged (3 day repeat period) and in the number of return times (all repeat periods) due to the presence of cloud cover, especially away from the polar regions.

As previously, for each sub-application area, the synergistic temporal sampling requirements are assessed in terms of the degree of latitudinal coverage, longitudinal coverage and frequency of return times. Each of these three quantities has been categorised into three types. For the latitudinal and longitudinal coverage, the three types are (i) low (< 33%), (ii) moderate (33% to 66%) and (iii) high (> 66%) coverage. The number of return times quantity has been split into (i) insufficient number of return times to ensure that the required time interval is available throughout the repeat period, (ii) adequate number of return times and (iii) a large number of return-times. As an example of how an 'adequate number of return times' is defined, for a 35 day orbital repeat period and a 7 day synergistic sampling requirement, there needs to be at least 5 return times of 7 days duration or less to ensure that the combined coverage is fairly continuous. Taking the three quantities and the three ranges defined for each quantity together with the synergistic temporal sampling requirements in Table 1, Tables 2 and 3 show the suitability of the repeat period for each sub-application for the optimum and maximum synergistic sampling interval requirements respectively. When deriving these Tables, the latitude range appropriate to each application area has been taken into account (i.e. 47°N for Snowmelt runoff, 73°N for Polar ice sheet and 13°N for Hydrology), as well as whether the degree of cloud cover corresponds to summer or winter conditions.

From Table 2, for the optimum synergistic sampling interval requirements, there are no significant limitations imposed by the 400 km. SAR and 920 km. optical swaths except for the soil moisture (after rainfall, i.e. in the wet season) application which has a 1 day sampling interval requirement (discussed further in Section 5.3). During the winter season, the percentage of longitude locations and the number of return times are reduced compared to the summer season, though this reduction only impacts on the soil moisture (after rainfall) sub-application. The Polar Ice Sheet application is affected by the non-existence of any optical imagery in winter as the sun is below the minimum solar elevation of 15°. From Table 3, for the maximum synergistic sampling intervals, the maximum sampling requirements are less stringent than the optimum sampling requirements, with no significant limitations for all sub-applications. In all cases, there is at least moderate latitude and longitude coverage, and an adequate number of return times.

Application	Sub-Application	Optimum Sampling Interval (days)	3 Day Repeat Period Summer φ λ r	14 Day Repeat Period Summer φ λ r	35 Day Repeat Period Summer φ λ r	3 Day Repeat Period Winter φ λ r	14 Day Repeat Period Winter φ λ r	35 Day Repeat Period Winter φ λ r
Snowmelt runoff	Small basin[1]	5	√ √ √	√ √ √	√ √ √	√ • √	√ √ √	√ √ √
	Small basin[2]	3	√ √ √	√ √ •	√ √ •	√ • √	√ √ •	√ √ •
	Large elevation range[1]	5	√ √ √	√ √ √	√ √ √	√ • √	√ √ √	√ √ √
	Large elevation range[2]	5	√ √ √	√ √ √	√ √ √	√ • √	√ √ √	√ √ √
Polar ice sheet	Snow line[3]	5	√ √ √	√ √ √	√ √ √	x x x	x x x	x x x
	Equilibrium line[3]	5	√ √ √	√ √ √	√ √ √	x x x	x x x	x x x
	Transient melt line[4]	1	√ √ •	√ √ •	√ √ •	x x x	x x x	x x x
Hydrology	Soil moisture[5]	1	√ • x	√ √ x	√ √ x	√ x x	√ √ x	√ √ x
	Soil moisture[6]	7	√ • •	√ √ •	√ √ •	√ • •	√ √ •	√ √ •

(1) Snow extent determined from SAR and albedo from optical data, (2) Snow extent determined from either SAR or optical data, (3) In late ablation season, (4) In ablation season, (5) In wet season, (6) In dry season.

Table 2 Suitability of various repeat periods for application optimum sampling interval requirements. The symbols φ, λ and r refer to latitude coverage, longitude coverage and number of return times. The symbols x, •, and √ within the table refer to low latitude coverage, low longitude coverage or insufficient number of return times; moderate latitude coverage, moderate longitude coverage or adequate number of return times; and high latitude coverage, high longitude coverage or high number of return times.

Application	Sub-Application	Maximum Sampling Interval (days)	3 Day Repeat Period Summer φ λ r	14 Day Repeat Period Summer φ λ r	35 Day Repeat Period Summer φ λ r	3 Day Repeat Period Winter φ λ r	14 Day Repeat Period Winter φ λ r	35 Day Repeat Period Winter φ λ r
Snowmelt runoff	Small basin[1]	10	√ √ √	√ √ √	√ √ √	√ • √	√ √ √	√ √ √
	Small basin[2]	6	√ √ √	√ √ √	√ √ √	√ • √	√ √ •	√ √ •
	Large elevation range[1]	10	√ √ √	√ √ √	√ √ √	√ • √	√ √ √	√ √ √
	Large elevation range[2]	10	√ √ √	√ √ √	√ √ √	√ • √	√ √ √	√ √ √
Polar ice sheet	Snow line[3]	10	√ √ √	√ √ √	√ √ √	x x x	x x x	x x x
	Equilibrium line[3]	10	√ √ √	√ √ √	√ √ √	x x x	x x x	x x x
	Transient melt line[4]	3	√ √ √	√ √ √	√ √ √	x x x	x x x	x x x
Hydrology	Soil moisture[5]	7	√ • √	√ √ √	√ √ •	√ • •	√ √ •	√ √ •
	Soil moisture[6]	30	√ • √	√ √ √	√ √ √	√ • √	√ √ √	√ √ √

(1) Snow extent determined from SAR and albedo from optical data, (2) Snow extent determined from either SAR or optical data, (3) In late ablation season, (4) In ablation season, (5) In wet season, (6) In dry season.

Table 3 Suitability of various repeat periods for application maximum sampling interval requirements. The symbols φ, λ and r refer to latitude coverage, longitude coverage and number of return times. The symbols x, •, and √ within the table refer to low latitude coverage, low longitude coverage or insufficient number of return times; moderate latitude coverage, moderate longitude coverage or adequate number of return times; and high latitude coverage, high longitude coverage or high number of return times.

5.3 Overall Conclusions of Study

The results of Section 5.2 show that apart from the soil moisture (after rainfall) application, all the temporal sampling requirements addressed in this study can be met by mounting both a SAR and an optical sensor onboard the same platform. Indeed, it should be pointed out that for the soil moisture (after rainfall) application, the dominant temporal sampling requirement is not between SAR and optical measurements but for repeated SAR sampling. Thus, for this application, two platforms each with a separate SAR sensor onboard are ideally required, with an optical sensor mounted onboard either or a separate platform.

In fact, although one platform would appear to be adequate to meet most of the temporal sampling requirements considered, both the soil moisture example and other applications not investigated in this study (e.g. flood monitoring, forest fires), emphasize the considerable advantages in flexibility of mission of having multi-platforms each with a dedicated sensor onboard. One example of the advantage of such flexibility arises for those applications such as soil moisture which require a virtually constant incidence angle in the SAR measurements. Apart from by maintaining a platform in a short orbital repeat period, giving limited longitudinal coverage, this could only be achieved within the temporal sampling requirements by a number of separate platforms.

Thus, the recommendations of this study in terms of future missions concern not only the question of the minimum number of platforms required to meet the SAR and optical sampling requirements for any one particular application. Instead a fully integrated mission is foreseen, including sensors capable of covering a complete range of frequencies and polarisations, able to meet competing sampling requirements simultaneously across a range of different applications. Such a level of multi-sensor mission integration might even be extended to include the next generation of meteorological satellites (e.g. MSG, METOP) in order to help schedule optical measurements or indicate the need for SAR data. In such a complex system, the benefits of flexibility of reaction time, system survivability and reduced launch costs (including for replacement platforms as required) suggests that a multi-platform approach is likely to be the most cost-effective and practical way forward.

Combining the results on optimum synergistic sampling requirement obtained in Phase A and Phase B of the study, it is possible to group applications together by sampling requirement, as shown in Table 4, in order to help determine the type of mission most appropriate to specific sets of applications (also taking account of the different optimum frequency and polarisation requirements of the individual applications). Thus a mission to monitor those applications with a synergistic sampling requirement of 14 to 30 days or greater might need less than half the number of platforms required to meet a synergistic sampling requirement of 1 to 7 days. Given the importance of the temporal sampling requirements to future mission design, recommendations are given in Section 5.4 for future work in refining the accuracy of the current estimates and for extending the work to other applications.

Table 4 - Classification by Synergistic Sampling Requirement

Sampling Interval	Application	Sub-application
1 - 7 days	Hydrology	Soil moisture (primary monitoring requirement with SAR data)
	Cryosphere	Seasonal snow cover extent
		Snowmelt run-off in mountain basins
		Snow and ice extent of mountain glaciers
		Snow and ice extent of polar ice sheets
	Pedology	Watercourse run-off
7 - 14 days	Agriculture	Crop area / classification / condition, LAI, canopy height
	Hydrology	Seasonal soil moisture
	Cryosphere	Mass balance of mountain glaciers
14 - 30 days	Cryosphere	Extent of surging glaciers
30 - 60 days	Cryosphere	Areal extent of mountain glaciers
		External boundaries of polar ice sheets
> 60 days	Forestry	Biomass
	Cryosphere	Ice motion of mountain glaciers
		Ice motion of polar ice sheets
	Geology	Geological boundaries / faultlines

5.4 Recommendations for Future Work

5.4.1 General Recommendations

Whilst for both the cryosphere applications investigated in this study the datasets were adequate (using model simulations where appropriate) to support determination of the major changes in ground parameters by a combination of SAR and optical data, for the hydrology application this was possible primarily at the extent of determining the seasonal rather than the diurnal variation in soil moisture. A general recommendation for land applications covering particularly vegetation and hydrology is to build up for an appropriate site a comprehensive set of measurements which includes both high and medium resolution, microwave and optical data, as well as ground-truth data representative of all the key parameters of interest. Data of each type should, of course, be recorded within a time interval less than the frequency of underlying change in the parameters under consideration, and this may vary over time. For soil moisture determination, for instance, daily remote sensing measurements need to be acquired, either by low resolution satellites, tandem operation of medium to high resolution satellites, or by a dedicated airborne campaign.

Again, for each key parameter, the optimum SAR frequency / polarisation combination and optical frequency should be determined. For applications such as agriculture, forestry and hydrology, for instance, it is likely that a longer (e.g. L-band) wavelength and cross-polarisation (HV) may be optimal to the C-band, VV system onboard ERS-1. For the SAR instrument its use in interferometric mode might also be considered, albeit only for applications for which temporal coherence can be maintained over the orbital repeat period. SAR coherence information could then be used synergistically with optical data, for instance to derive improved land-cover classification.

Given the particular difficulty of obtaining cloud-free optical data, an investigation should also be made into the synergy between SAR and a medium resolution ('MERIS' type) optical sensor, as designed for ENVISAT. The improved repeat coverage of ENVISAT in both the optical (1500 km. swath width) and microwave (400 km. swath width) parts of the spectrum is of particular importance for applications in hydrology and water management. High spatial resolution is generally required for hydrological applications in complex terrain, and it may be possible for certain applications to improve the medium resolution (250 metres for MERIS) of optical data (for instance, to derive surface albedo) by reference to high resolution estimates of snow extent determined from SAR data. Due to the resolution differences of the SAR and optical data, more stringent sampling requirements may be needed than for synergy of data at similar spatial resolution. The improved synergistic potential of MERIS-type sensors due to high spectral resolution should also be investigated.

5.4.2 Application-Specific Recommendations

Snowmelt runoff application

The results obtained for the snowmelt runoff application were extremely encouraging in terms of the generally strong agreement found between the model calculations based on remote sensing measurements and actual runoff measurements made 'in situ'. However, the reliability of a number of inputs to the snowmelt runoff model would need to be addressed before the methodology adopted might be applied generally as part of an operational system :

• The estimation of representative precipitation is difficult for mountain basins, major errors being possible if for strong rainfall the precipitation measurements are not representative basin-wide. For runoff prediction, accurate and quantitative rainfall forecasts are needed, and these are not always reliable in mountain areas. The problem is reduced, however, where snow and glacier cover are significant due to the 'damping' effect of the cover on erroneous precipitation data.

• The runoff coefficient, 'c', (which accounts for the difference between available water volume (model input) and outflow from the basin) differs for snow-covered and snow-free areas, as well as with altitude, exposure and vegetation cover. In the study, the runoff was calculated separately for ice-free and ice-covered areas in different altitude zones, the average altitude dependence of precipitation being accounted for by increasing the runoff coefficient for rain, 'c_T', with altitude.

• Model parameters 'c' (runoff coefficient, determined separately for snow and precipitation), degree-day factor 'α', and the recession coefficient, 'k', may all be subject to a certain amount of seasonal variation. In the study, albedo data derived from optical measurements could be used to adjust for seasonal and spatial variations in determination of the degree-day factor, though due to the limited number of images it was not possible to account for short-term fluctuations of albedo caused by snow fall. The recession coefficient, 'k', may be determined from historical records.

Hydrology application

Whilst the study undertaken for the HAPEX-Sahel area was able to demonstrate the feasibility of combining SAR and optical data for determination of seasonal variations in soil moisture, the sampling requirements did not allow monitoring of the shorter-term variation in soil moisture that arises in such regions after rainfall. It is therefore suggested that the use of lower resolution data such as the ERS wind-scatterometer and NOAA AVHRR instruments is investigated in order to determine to what extent the poorer spatial resolution is acceptable for the anticipated improvement in temporal sampling.

It should also be investigated, by comparison with data at other sites, to what extent the temporal sampling requirements are influenced by local factors such as soil type, vegetation pattern and climate conditions. At the HAPEX-Sahel site, the relatively light, sandy nature of the soils means that the response to rainfall in terms of infiltration and evaporation is much more rapid than would be the case for soils with a larger water-holding capacity. The effect on the sampling requirements of the 'shielding' influence of different vegetation types, both water input to the soil and evaporation losses, also needs to be investigated.

Finally more work needs to be undertaken, both empirically and through application of microwave interaction models, as to the effects of both soil roughness and vegetation cover on the microwave backscatter for different frequencies, polarisations and incidence angles. Based on vegetation type, condition and development stage, as well as soil roughness and local incidence angle, it may then be possible to develop inversion algorithms for soil moisture retrieval applicable at least within locally well-defined areas.

Greenland Ice Sheet application

For the Greenland Ice Sheet application, promising results have been obtained for determination of the different snow facies boundaries. This work should now be supported by dedicated analysis of a glacial area where there are several campaigns on the ground, for instance at Jakobshavns Isbræ which drains roughly 6.5% of the total area of the Greenland ice sheet. ERS-1 and ERS-2 instruments might be used in tandem in order to give very fine (1 day) temporal sampling in both the SAR and ATSR data towards the end of the ablation season (i.e. from mid-August to the end of September), backed up by additional reference data obtained in mid-winter. Once the ability to reliably identify the positions of the particular diagenetic zones has been confirmed by the supporting ground data and appropriate sampling requirements further refined, the scope of the study should be broadened to an assessment of whether annual variations in mass balance across the ice sheet can be determined, with important implications for global climate monitoring.

The availability of ERS-2 data also needs to be assessed in terms of the visible wavelength channels onboard ATSR-2. It is believed that a shorter wavelength may be preferable for distinguishing between bare ice and snow surfaces to the 1.6 μm channel of the ERS-1 ATSR used in this work, thus helping to establish the position of the snow line.

Finally, an improvement is needed to the cloud-masking algorithm applied to the ATSR data, which was determined to be about 85% successful by visual inspection. The edges of clouds were often not adequately screened, and high, cold, relatively thin cirrus clouds were sometimes not identified, affecting in particular the ability to identify the position of the transient melt area.