CONCEPTS FOR AN EO LAND CONVOY MISSION

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ABSTRACT

ESA are undertaking three studies investigating possible synergistic satellite missions flying in formation with the operational Copernicus Sentinel missions and/or the METOP satellites.

These three studies are focussed on:-

a) ocean and ice
b) land
c) atmosphere

Surrey Satellite Technology Ltd (SSTL), the University of Leicester and Astrium Ltd are undertaking the second of these studies into the synergetic observation by missions flying in formation with European operational missions, focusing on the land theme.

The aim of the study is to identify and develop, (through systematic analysis), potential innovative Earth science objectives and novel applications and services that could be made possible by flying additional satellites, (possibly of small-class type), in constellation or formation with one or more already deployed or firmly planned European operational missions, with an emphasis on the Sentinel missions, but without excluding other possibilities.

In the long-term, the project aims at stimulating the development of novel, (smaller), mission concepts in Europe that may exploit new and existing European operational capacity in order to address in a cost effective manner new scientific objectives and applications. One possible route of exploitation would be via the proposed Small Mission Initiative (SMI) that may be initiated under the ESA Earth Explorer Observation Programme (EOEP).

The following ESA science priority areas have been highlighted during the study [1]:-

- The water cycle
- The carbon cycle
- Terrestrial ecosystems
- Biodiversity
- Land use and land use cover
- Human population dynamics

The study team have identified the science gaps that might be addressed by a "convoy" mission flying with the Copernicus Sentinel satellites, identified the candidate mission concepts and provided recommendations regarding the most promising concepts from a list of candidates. These recommendations provided the basis of a selection process performed by ESA. This final selection will be followed by a detailed technical study of the selected concepts.

The paper will present the results of the gap analysis, the potential convoy concepts, and the latest conclusions derived from the study.

1. INTRODUCTION

Satellite constellations and formations are a means to accomplish complex scientific objectives, exploiting the synergies among different types of missions. The most notable in-orbit examples of this kind of configuration are the Afternoon Train (A-Train) comprising a number of satellites operated by multiple agencies.

Several dedicated European operational missions called Sentinels are being developed for launch in the 2014 time frame for the Copernicus programme. The aim of these Sentinel missions is to provide reliable and stable long-term EO data streams, including data on the ocean and ice, the land domain, and the atmosphere.

In the land domain, the three Sentinel missions of particular relevance are Sentinels-1, 2 and 3. A brief summary of the capabilities of these missions is as follows:-

Sentinel-1 is a C-band synthetic aperture radar (SAR) imaging mission comprising two satellites. Sentinel-1A is scheduled for launch in 2014 and Sentinel-1B is planned for launch in 2015. Sentinel-1 will be placed in a dawn-dusk orbit (18:00 LTAN) at 693 km with a 12-day repeat cycle. Sentinel-1 has four operational modes: interferometric wide swath mode (250 km swath), strip

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map mode (80 km swath), wave mode (sampled images of 20 x 20 km at 100 km along the orbit) and extra-wide swath mode (400 km swath). Sentinel-1 will operate predominantly in interferometric wide swath mode.

Figure 1. Sentinel-1

Sentinel-2 is a multispectral optical imagery mission comprising two satellites aimed at providing global and systematic medium resolution optical imagery. The Sentinel-2A mission is scheduled for launch in 2014 and a Sentinel-2B is planned to be launched in 2016. Sentinel-2 shall be placed in a sun-synchronous orbit at 786 km with a LTDN of 10:30 am. Each Sentinel-2 satellite will carry a multispectral imager (MSI) with a swath of 290 km. The MSI comprises 13 spectral bands (443 nm – 2190 nm) with spatial resolutions of 10, 20 and 60m. In full operation the two satellites will have a maximum revisit time of 5 days (at the equator, and assuming cloud free conditions).

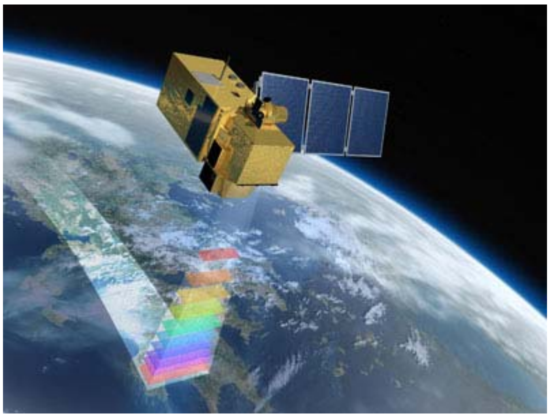

Figure 2. Sentinel-2

Sentinel-3 is a multi-instrument mission comprising two satellites. The Sentinel-3A satellite is scheduled for launch in 2014 and a Sentinel-3B is planned for launch in 2016 the following year. Each Sentinel-3 shall be placed in a sun synchronous orbit (10:00 LTDN) at 814 km with a 27-day repeat cycle. The Sentinel-3 payload includes: an altimetry suite (comprising a dual-frequency (Ku/C-band) altimeter, a radiometer and a precise orbit determination package), an Ocean and Land Colour Instrument (OLCI), which has 21 bands (covering the spectral range 0.4 to 1.02 μm) with a spatial resolution of 300 m and a Sea and Land Surface Temperature instrument (SLST), which has 9 bands (covering the spectral range 0.5 to 12 μm) with a spatial resolution of between 500 and 1000 m.

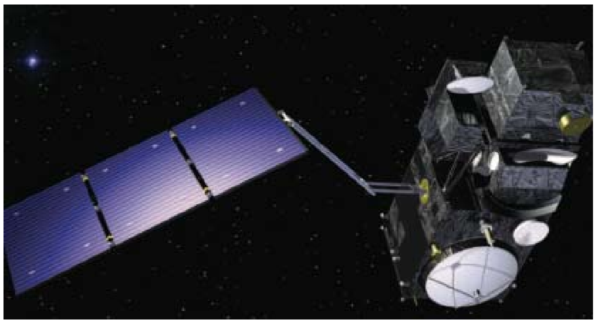

Figure 3. Sentinel-3

The three ESA Convoy studies are based upon the assumption that additional cost-effective missions, flown in conjunction with these operational Sentinel missions, offer far-reaching possibilities for meeting new Earth science and application objectives, e.g. fulfilling observational gaps; multi-static observations of a given location; multi-sensor measurements of specific Earth system phenomena.

2. CAPABILITY GAP ANALYSIS

Scientific and operational needs were captured at the beginning of the study via a dedicated land surface user consultation workshop, attended by a number of International experts in the principal sciences areas. Following this workshop the science needs were aggregated, (broadly in accordance with the observational priority areas listed in the abstract above), as illustrated below. These results were published in [3].

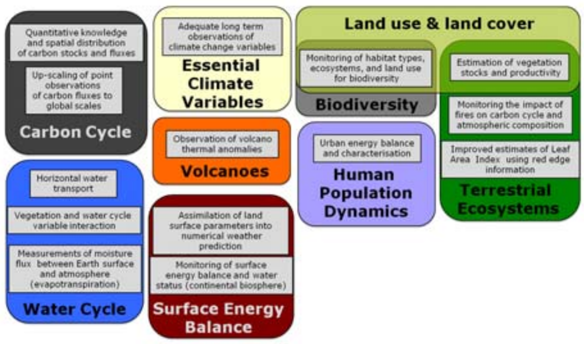

Figure 4. High-Level User Need Areas identified in the Land Domain [3]

These needs were assessed against present and near future satellite missions, and a number of measurement capability gaps were identified [3], as tabulated in Table 1.

I.D.	Variable	Gap	Identified User Needs
Carbon Cycle			
G-CC-01	Biomass (direct measurement)	Sensitivity to biomass at spatial scales of < 10 km	100-200 m < 1-2 years revisit < 10 tonnes/hectare or 20 % accuracy All forest types, full range of biomass, at least 300 tonnes/hectare in tropical rainforest
G-CC-02	Vegetation Height	Better observations of vegetation structure to improve biomass estimation	10 m to 100 m < 1 – 2 years revisit < 4 m accuracy
G-CC-03	Leaf Area Index (LAI)	Bi-directional Reflectance Distribution Function (BRDF) data needed At present only effective LAI can be derived	< 100 m < 15 days revisit < 20 % accuracy Multi-angle observations for BRDF (G-SE-01)
G-CC-04	Fire Radiative Power (FRP)	Sensitivity to small fires < 250 m	< 250 m > 500 K accuracy Morning observations not optimum. Afternoon preferred. MIR needed for fire observation
G-CC-05	Veg. Fluorescence	Measurements < 500 m	< 500 m 5 to 10 days revisit < 5% radiometric accuracy
Surface Energy			
G-SE-01	Surface albedo & BRDF	Higher spatial resolution and multi-angle BRDF measurement for vegetation structure	10 m to 50 m < 1-30 days revisit < 5-10 % accuracy
G-SE-02	Land surface temperature (LST)	Higher spatial resolution < 100 m	~ 50 m to 100 m, 5 day revisit < 0.5 K accuracy, NeDT < 0.2 K > 1 TIR channel
Water Cycle			
G-WC-01	Soil Moisture	High spatial & temporal resolution measurement for crop monitoring	< 100 m < 1 week revisit < 10g/kg or 5% accuracy
G-WC-02	Land surface temperature (LST)	High spatial resolution < 100 m to avoid LST anomaly	~ 50 m to 100 m, 5 day revisit < 0.5 K accuracy, NEdT < 0.2

I.D.	Variable	Gap	Identified User Needs
		confusion	
Land Use and Land Cover			
G-LC-01	Land cover change	Regular and continuous global coverage (high resolution)	10 m to 1 km, < 1 week revisit < 5 % accuracy
G-LC-02	Land surface topography	Lack of wider swath higher spatial resolution measurements	10 m to 250 m, < 10 years update < 10 m accuracy, swath > 100 km
Human Population Dynamics			
G-HD-01	Urban LST Urban Emissivity Urban albedo Urban land cover	Higher spatial resolution for urban planning and energy efficiency applications Higher spatial and temporal resolution for environmental quality and urban scale meteorology	< 25 m (< 500 m sufficient for environmental quality & urban meteorology applications) < 1 month revisit (< 1 day for environmental quality and urban meteorology applications) < 0.5 K accuracy (LST) < 5-10% accuracy (albedo) > 1 TIR (improved emissivity measurements leading to improved LST retrieval)
Volcano and Thermal Anomaly			
G-VO-01	Measurement of pre-eruptive thermal anomalies	TIR (higher resolution and improved accuracy)	< 60 m < 1 week temporal resolution < 1K accuracy for temperatures up to 360 K
G-VO-02	Lava temperature	Medium to high-resolution infrared measurement of temperatures up to 1500 K	< 100 m Observations required over target site several times a day during eruptions

Table 1. Identified Capability Gaps

For the purposes of the study, the above capability gaps were assumed to have equal priority.

3. MISSION CONCEPTS

There are two classical observation schemes for Earth observation missions, which can drive constellation / formation design are:-

- Co-located Observations: In which several satellites pass over the same ground track with short but (approximately) fixed time intervals between their observations e.g. the A-Train
- Distributed Observations: In which contemporaneous measurements from multiple satellites are made from different locations and different geometries of a given phenomenon.

Both types were considered to be within the scope of the Land Convoy study. During the Workshop [3], some consideration was given to the possibility of following the Sentinel satellite ground trace with a larger time separation for change detection applications. An example of the potential application of such an approach is an IR sensor in a sun-synchronous orbit with a mid-afternoon local imaging time to provide measurements of fire intensity. It was considered that such systems could legitimately be included within the relatively broad definition of the term "Convoy" used in this study.

A listing of the principal concepts addressed in the study (and the gaps in observational capability to which they are relevant) is provided in Table 2.

Mission Concept Number	Concept Name	Gaps Addressed	Concept Application and Focus
1	Passive C-band SAR	G-CC-01 G-CC-02	Improvement in observations of vegetation 3D structure, specifically canopy height above the ground
2	Conventional L-band SAR	G-CC-01	Improvement in observations of vegetation 3D structure
3	Wide swath LWIR/MWIR multispectral imager	W-G-SE-02	High spatial resolution LST observations needed to model surface energy balance and water cycle Both LST and emissivity are required both to provide complete variables and also to obtain accuracy of LST
4	L-band radar in sparse array configuration	G-CC-01	Improvement in observations of vegetation 3D structure
5	W-band conical scanner	G-CC-03	True retrieval of LAI requires multi-directional observations
6	Thermal Feature Measure concept (at a higher spatial resolution than existing sensors)	G-CC-04 G-VO-01 G-VO-02	Fire sensing, volcanic fumaroles and lava temperatures. Higher spatial resolution (< 250m) to ensure that small fires are correctly sampled. Sensitivity to high temperatures up to 1500K to enable observations of volcanic thermal features.
7	Multi-angle imager	G-CC-03 G-SE-01	Bi-directional Reflectance Distribution (BRDF) sampling to provide true retrieval of leaf Area Index (LAI).
8	S-band SAR	S-CC-04	Interaction of vegetation with water cycle variables
9	Active C-band SAR interferometer	G-CC-01 G-CC-02	Improvement in observations of vegetation 3D structure, specifically canopy height above the ground

Table 2. Principal Mission Concepts

In addition to the above concepts, a limited degree of consideration was given to a laser altimeter, a polarimetric sensor, and a real aperture radar concept.

4. MISSIONS SELECTED FOR FURTHER STUDY

The nine principal preliminary convoy concepts were then assessed to determine which would be of greatest utility for further, more detailed study in Phase 2 of the study. This assessment was made according to the scientific and technical criteria listed below.

- Science Criteria
  - Relevance to ESA research objectives [1]
  - Science need, usefulness and excellence
  - Uniqueness and complementarity
  - Innovation and European capability
  - Science benefit of Convoy operation
- Technical Criteria
  - Technology Readiness Level (TRL) (How mature is the technical concept from an engineering perspective)
  - Schedule - Can the concept be fielded in the operational timeframe of the Sentinel missions
  - Cost - Is the cost of the mission equal to, or less than, the cost of the principal Sentinel mission
  - Mission Impact - Will the operation of the convoy asset affect the performance of the Sentinel mission

In collaboration with ESA, the selected concepts for further study were:

- Concept 1: A passive C-band SAR including multi-baseline considerations
- Concept 3: LWIR/MWIR Imager for LST flying with Sentinel-2/Sentinel-3
- Concept 6: Thermal Feature Measurement payload flying with Sentinel 2/ Sentinel-3

A top level description of these three missions can be seen below:

4.1. Concept-1 Passive C-band SAR flying with Sentinel-1

Sentinel-1 will have repeat pass interferometry capability. However, repeat interferometry suffers from temporal de-correlation, which limits its effectiveness to measure certain land related variables. The benefit of flying a passive satellite in close formation with the Sentinel is that use of data from both spacecraft enables interferogram generation with a much shorter time delay between echo acquisitions. Specifically, the time delay between echo acquisitions are on the order of microseconds.

High level system requirements for this application are considered in Table 3.

Parameter	Value	Comment
Time between repeat coverage measurements	1-2 years	6 months for deforestation
Maximum acceptable time interval between observations to ensure maintenance of coherence between observations	1 day (TBC)	C band dictated by operation with Sentinel-1
Terrain parcel size	< 1km x 1km	
Vegetation height accuracy	< 10%	typically in the order 4 m

Table 3 System requirements for Concept -1

The anticipated configuration of the convoy asset relative to the Sentinel satellite is as shown in the Fig. 6 below

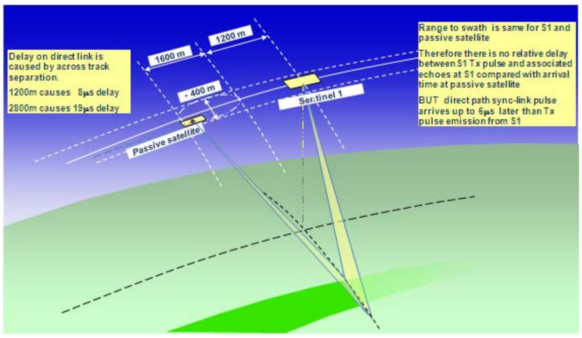

Figure 6. The relative configuration of Sentinel-1 and the convoy satellite

Key considerations of the concept are:-

- The need to establish synchronisation with Sentinel–1 master oscillator
- The need to coordinate beam pointing / tracking with Sentinel-1

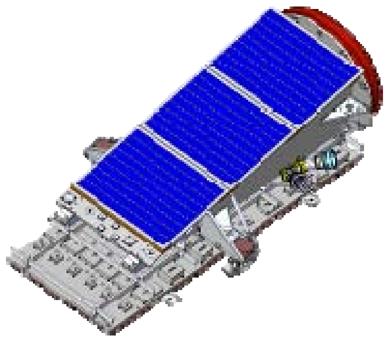

Figure 5. The Baseline Configuration for the Concept1 Satellite

The envisaged configuration of the satellite is based around a planar phased-array receiver antenna with dimensions of 4.8 m x 1 m. The baseline technical parameters, which will be further refined in the next study phase, are as shown in Table 4.

4.2. Concept 3: LWIR/MWIR Imager flying with Sentinel-2/Sentinel-3

This concept is based on a small satellite ~150kg with a wide swath LWIR/MWIR multispectral payload, which would closely follow the Sentinel-2 or Sentinel-3 satellite and could compliment the Sentinel datasets with thermal data at 90m Ground Sample Distance (GSD) covering the same swath. The applications of this data are principally to provide support measurements relating to Land Surface Temperature (LST).

In order to achieve near contemporaneous data collection of a common swath, and to ensure a safe operational concept, the convoy asset is expected to maintain a separation of 1-2 minutes relative to the Sentinel mission.

The envisaged performance parameters for this mission concept are shown in Table 5.

The preliminary optical system design consists of two objective lenses (one for LWIR one for MWIR) each with an in field separated detector arrangement. A filter assembly positioned very close to the detector surfaces would provide waveband selection in 5 bands in the LWIR channel. MWIR channels are presently being investigated. The candidate optical configuration is shown in Fig. 6.

4.3. Concept 6: Thermal Feature Measurement Concept flying with Sentinel-2/Sentinel-3

This concept envisages a sensor operating in the IR, following either the Sentinel-2 ground trace, (but separated by 3 hours), or collocated with Sentinel-3. Both mission concepts have the principal objective of improving space-based surveillance of thermal features e.g. wild fire monitoring, volcanoes etc..

One application identified is fire monitoring. Fires are important indicators for understanding the carbon cycle and for monitoring and forecasting atmospheric composition. Global biomass burning is the second largest source of trace gases, the largest source of fine carbon particles in the troposphere.

Parameter	Value	Comments
Operating frequency	5405MHz ± 50MHz	Sentinel-1 SAR frequency
Antenna area	4.8m x 1.0m	sized for accommodation in VEGA
Antenna Polarisation	either single H or V or dual H + V	Commandable
Antenna steering	Full electronic in elevation Limited electronic in azimuth	to image in all swaths/sub-swaths to service TOPS ScanSAR
Collection Geometry	IWS mode, incidence angle 30° for IWS1	Full electronics steering to enable reception of all IWS sub-swaths
Payload Mass	~112 kg	
Payload Power	112W peak; 6.2 W orbit average	
Data Rate	< 200 Mbps	
Performance	NEσ0 ≤-23dB	(exclude Scan-in-Receive)
STALO synchronisation	by direct link from S1 to passive and by direct injection of a signal from the passive into the S1 SAR antenna	Result of trade-off Based on use of scattered signals from S1 SAR antenna
Sync-link antenna gain	3dB (to illuminate 180° x 50°)	Based on formation geometry
Event synchronisation	by command and reference to GPS lock	
Data downlink schedule	by command and reference to GPS lock	

Table 4 Summary of passive SAR design requirement

Parameter	Value
GSD	~ 90m
Sensor Type	Microbolometer
Spectral wavebands	8.125 – 8.475 μm 8.475 – 8.825 μm 8.925 – 9.275 μm 10.25 – 10.95 μm 10.95 – 11.65 μm
NEΔT, K (calculated at 243K ref temp)	0.2
Swath, km	290km
Absolute accuracy	Goal = 0.5K (calibration concept to be defined)
Focal length	300mm (dependant on detector selected)
Aperture	~150mm (dependant on MTF required)
Volume estimate (2 LWIR channels)	500mm (w) x 250mm (h) x 500mm (l)
Power estimate	20 – 30 W (duty cycle may be limited by platform OAP)
Data rate	~40Mbit/s assumes 5 bands in LWIR and multiple MWIR channel
Mass estimate	<30kg
Operational mode	Continuous Push broom if platform orbit average power (OAP) allows, pseudo TDI, instrument can be operated during eclipse although Sentinels 2 and 3 will not be imaging
Revisit frequency	Same as for Sentinel 2/3
Geo-location accuracy	Dependent on mounting of star tracker to instrument but could be < 100m

Table 5 Performance parameters for the envisaged Concept 3 Sensor

The system is being designed to operate in both the MWIR and LWIR. The MWIR spectral range is where the peak of thermal emission lies and together with the LWIR spectral range thermal feature characterisation can be performed. This combination of spectral bands enables discrimination of false signals caused by clouds and sun glint.

The spectral bands anticipated for this concept are indicated in Table 6

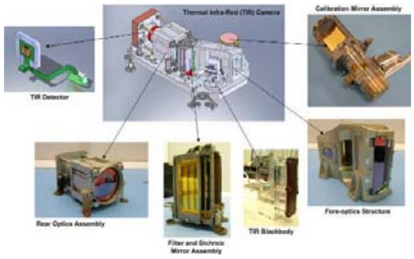

Figure 6. Concept 3 Baseline Optical Configuration

Instrument	Band	GSD (m)	Swath (km)
Thermal imager	MWIR (3.9 μm)	< 250 m	>100 km
	LWIR (11-12 μm)	< 250 m	>100 km

Table 6. Spectral bands for Concept 6 System

The particular focus here is on achieving a spatial resolution of less than 250 m in order to detect smaller thermal features such as fires, which despite their size, are nevertheless numerous enough to impact (via smoke generation) to local and regional scale atmospheric composition..

The sensor concept under consideration for this mission is an uncooled bolometric sensor working with appropriate spectral bands.

The mass of the instrument required is currently estimated to be on the order of 20 kg and so could readily be accommodated on a satellite with a mass of 150kg as illustrated below in Fig.7.

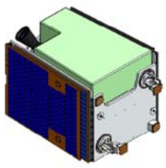

Figure 7 Proposed Platform for Concept 6

5. FUTURE WORK

The second phase of land convoy study will define the requirements for these three concepts in more detail – as well as the baseline parameters such as resolution and swath width, more sophisticated performance metrics relating to radiometric performance will also be specified.

The potential utility of these concepts might be enhanced if, for example, the passive SAR concept (Concept-1) involved multiple passive components, rather than a single convoy asset; or if, in the case of the IR concepts (Concept-3 and 6), both sets of mission requirements could be accommodated on a single satellite. Such design considerations will be addressed.

Top-level designs for the sensors will be developed, allowing mass and power budgets for the satellites to be created in more detail than was possible in phase 1.

Utilising this satellite design information, the final activity in the study will be to develop cost estimates and development schedules for the preferred concepts.

6. CONCLUSIONS

In the coming years, a number of new long-term operational EO satellite series will be launched by Europe. These satellites will provide a continuous, systematic and long-term capacity to observe and monitor the Earth surface, oceans and atmosphere to unprecedented accuracies. This long-term capacity represents an excellent opportunity to design novel focused missions exploiting suitable multi-satellite configurations.

To this end, three studies (known as EO-Convoy studies) have been defined focusing on ocean and ice, land and atmosphere. For the Land EO-Convoy study, several areas were identified where support from additional missions flying together with operational satellites could be beneficial. These areas included estimation of carbon stocks, water transport, estimation of surface energy balance and vegetation structure etc.

Based on the science objectives and measurement gap analysis a number of convoy mission concepts were identified comprising additional satellites flying with European operational missions. Two categories of convoy concepts were selected for further study (passive SAR and Infrared IR)) and the latest results have been presented. If flown, the passive SAR concept would have the potential to improve knowledge of vegetation structure and canopy height. If more than one passive SAR concept is considered leading to multiple baseline measurement then more applications become possible e.g. tomography etc. The IR concepts would enhance the understanding of land surface temperature, emissivity and the characterisation of high temperature events such as wild fires and volcanic eruptions and lava flow.

9.1. Sample References

1. 1. Changing Earth, ESA Publication SP-1304

2. A. Regan, et al, Sentinel Convoy: Synergetic Observations with Satellites Flying in Formation with European Operational Satellites, The 4S Symposium Conference, Portoroz, Slovenia, June 2012.

3. Study Workshop Report, www2.le.ac.uk/departments/physics/research/earth-observation-science/sentinel-convoy/documents/SCLfinalreport.pdf.