Science potential for advanced EO missions in convoy with operational satellites

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(ESA contract number 4000100620/10/NL/FC)

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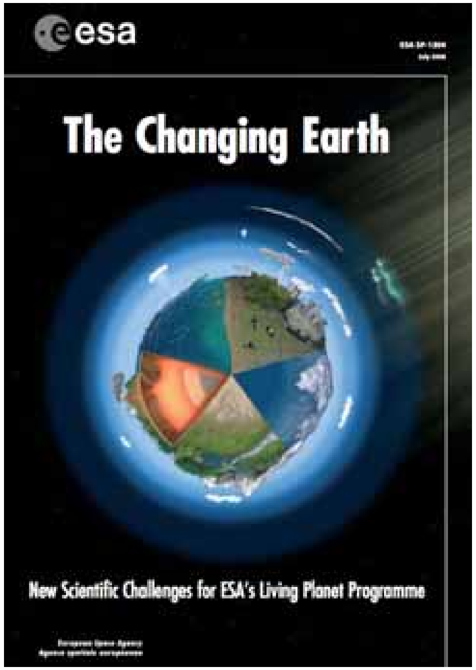
Introduction

- ESA study 'EO Sentinel Convoy – Ocean & Ice theme'
  - Opportunities for flying new missions in formation with operational missions for synergistic EO
  - Part of the Support to Science Element (STSE), a new element in ESA's Earth Observation Envelope Program (EOEP-3) which aims to reinforce the scientific component of the ESA Living Planet programme



- First of three studies to respond to scientific challenges set out in the ESA Living Planet Programme:
  - Study 1 - Ocean & Ice Theme
  - Study 2 - Land Theme
  - Study 3 - Atmosphere theme

Ocean & Ice themed study

- Objectives of Study
  - Review current and future European EO capabilities, formation flying and scientific gap analysis
  - Identify new applications and services and mission concepts flying in formation with European Operational Missions
  - Perform scientific/engineering analysis and preliminary assessment of several concepts in collaboration with the scientific community
  - Select most promising mission concepts and detail scientific requirements, observational principles and preliminary architectures
  - Perform a preliminary assessment of scientific and technological feasibility and develop mission roadmaps

Study Status

- Study has completed Mid-Term Review
  - Definition of three selected mission concepts is ongoing

Ocean & Ice study

Review current and future EO missions and perform Gap Analysis

What is possible with formation flying?

What Scientific measurements are not currently available?

Identify and develop Preliminary Mission Concepts

What missions could be considered to fill the identified gaps?

Scientific analysis and preliminary assessment of mission concepts

Decide on selection criteria
Assess missions and select up to THREE concepts

Mission Concepts Definition

Determine Preliminary system and mission requirements

Payload Analysis, Mission Performance

Develop Mission Roadmaps

What are the critical system requirements?

Identify technology options, TRLs and required developments

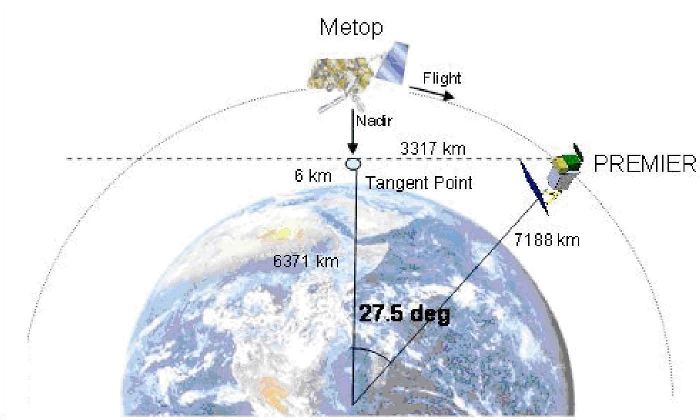
Study Kick-off

Mid-Term Review

Final Review

Synergistic mission examples

- NASA A-train
  - Combining data sets from instruments gives better understanding of parameters affecting climate change
- PREMIER (infrared limb sounder & mm-wave limb sounder)
  - Earth Explorer 7 Candidate mission
  - Will fly ahead of nadir viewing MetOp satellite
  - Synergy of atmospheric observations down to Earths surface (without cloud)
- Sentinel-5 Precursor (S5p)
  - Will fly with NPP/JPSS
  - Atmospheric chemistry, with cloud data provided by NPP/JPSS
- Earth Explorer 8 candidates
  - FLorescence Explorer (FLEX) and CarbonSat flying with Sentinel-3



GMES and Associated Missions

- Global Monitoring Environment Security (GMES): Sentinel 1-5
  - Sentinel 1 –SAR imaging, all weather & day/night, 2 satellites, 693 km SSO dawn-dusk
  - Sentinel 3 – Wide-swath ocean colour, vegetation, sea/land surface temperature and altimetry, 2 satellites, 815 km SSO LTDN 10:00

- Associated MetOp and MetOp-SG
  - MetOp, Suite of instruments dedicated to operational meteorology including VIS/IR and MW radiometers and IR and MW sounders. 3 satellites, 817 km SSO LTDN 09:30.
  - MetOp-SG follow on mission in same orbit as MetOp
  - Other missions: RadarSat-2, TanDEM-X, Cryosat-2…

Relevance of Sentinel missions

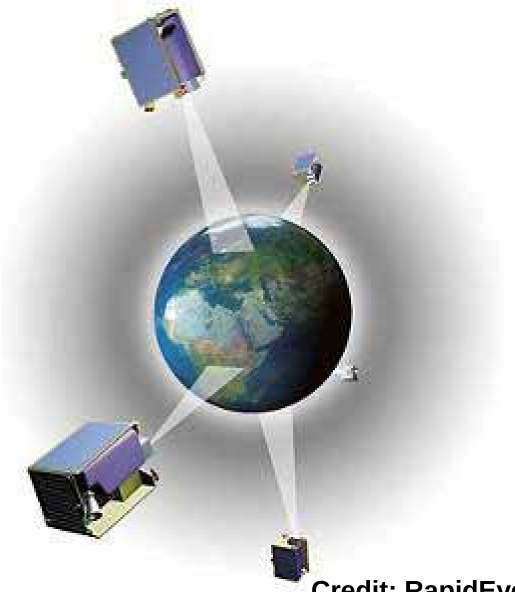
- For Oceans and Sea Ice… and Land Ice

Mission	Orbit	Instruments	Instrument type	Ocean Colour/Biology	Ocean Topography/ Currents	Ocean Salinity	Ocean Surface Winds	Sea Surface Temperature	Wave Height and Spectrum	Multi-purpose imagery
Sentinel-1	sun-synchronous	C-Band SAR	C-Band SAR		✓		✓		✓	✓
Sentinel-3										

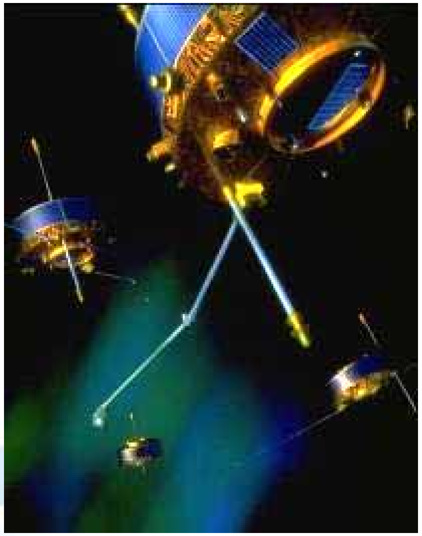
Sentinel Mission	Instruments	Ice Sheet Margin	Ice Sheet Topography	Grounding Line	Iceberg Calving	Diagenetic Facies	Ice Sheet & Glacier Surface Motion	Glacier Front & Area	Glacier Topography	Lake & River Ice Extent	Total Snow Cover Area	Snowmelt area (on land & ice sheets)	Snow & Ice Albedo	Snow & Ice Surface Temperature	Permafrost Surface Morphology	Perfmafrost Surface Deformation
S-1	C-Band SAR	✓		✓	✓	✓	✓	✓	(✓)	✓		✓			✓	✓
S-2	Multi Spectral Instrument (MSI)	✓						✓		✓	✓		✓		✓	
S-3	Ocean & Land Colour Instrument (OLCI)	✓			✓					✓	✓		✓			
	Sea & Land Surface Temperature (SLST)	✓									✓			✓		
	Sentinel-3 Ku/C Band Radar Altimeter (SRAL)		✓						(✓)							

Flying spacecraft together

- Different methods- no single definition
- Constellation: multiple spacecraft flying together as a system to meet spatial and temporal coverage not possible with single satellite
  → S/C not linked
- Formation flying: two (or more) S/C fly in a geometrical arrangement to synthesise a larger, virtual S/C
  → S/C directly linked
  - Ground Track orientated: same area observed with time delay e.g. A-train
  - Geometry orientated: instrument distributed, S/C maintain geometery suited to observation e.g Cluster-2



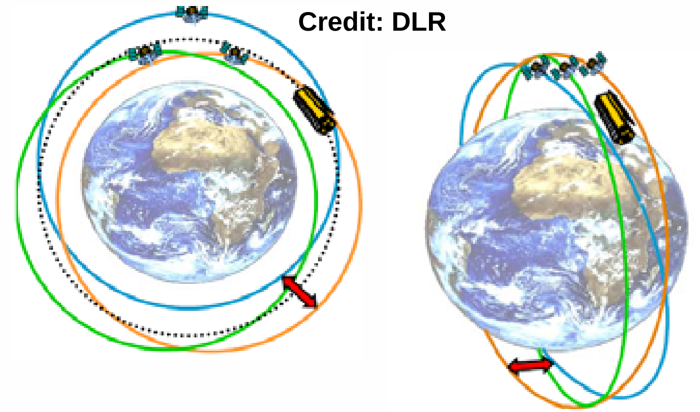
Credit: RapidEye



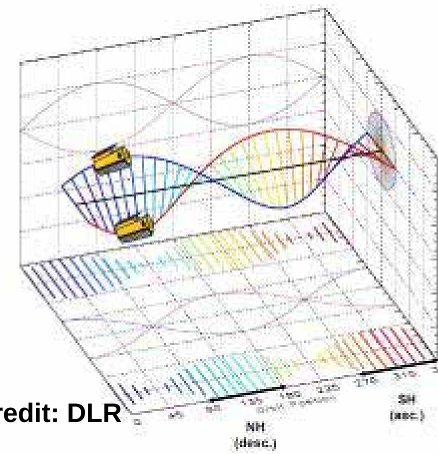
Credit: ESA

Formation flying

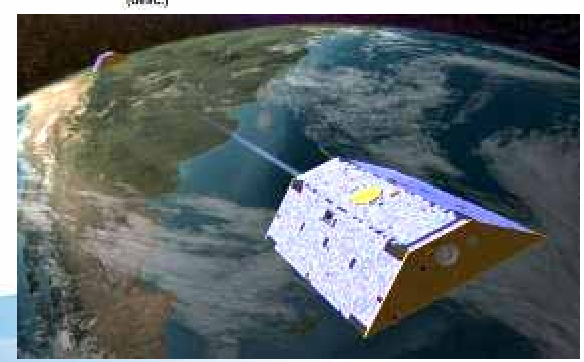
- Geometry orientated formations
  - Relative motion of S/C described by Hills equations, varying a,i,e,Ω
  - **Cartwheel:** Allow single pass interferometry (avoid scene decorrelation) but variations in along track baselines result in temporal decorrelation in dynamic scenes
  - **Pendulum:** Overcome cartwheel issues at expense of additional maintenance fuel
  - **Helix formations:** No crossing of orbits allows shift between satellites without need for autonomous control
  - **Leader-follower:** same orbit plane with some along track separation



Credit: DLR



Credit: DLR

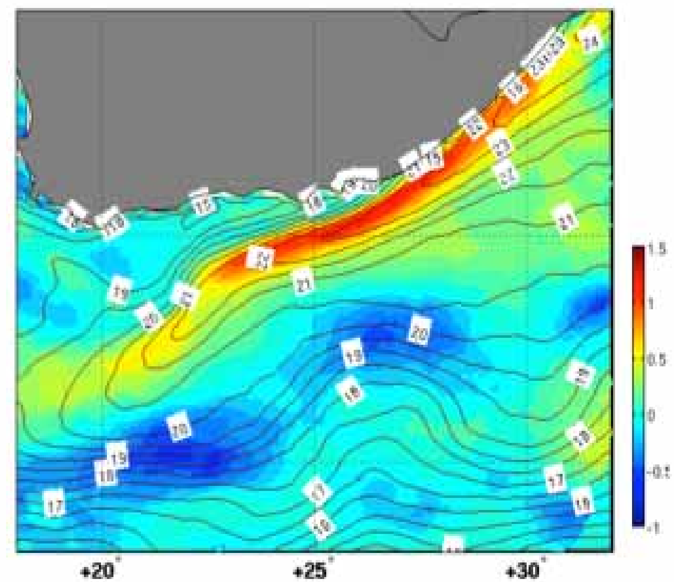


Credit: ESA

Credit: ESA

Science Gaps: Ocean

- Some identified Gaps:
  - Surface current and frontal dynamics (convergence/shear)
  - Absolute surface current
  - Detailed surface salinity
  - Sea state bias correction
  - O_2 and CO_2 and aerosol fluxes, role and influence of acidification
  - Absolute surface current
  - CO_2 uptake and transport (inc. influence on biological pump and acidification)
  - Colour dissolved organic matter and freshwater relationship



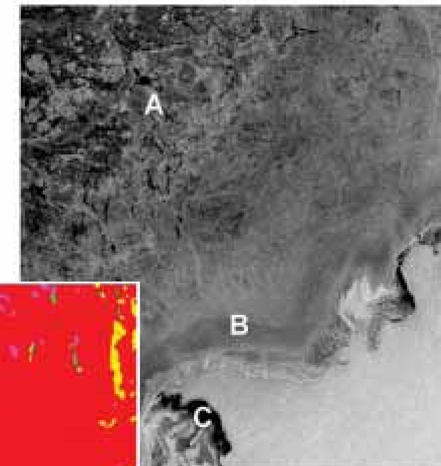
Agulhas current – SST and range doppler velocity averaged 2007-2009 (NERSC)

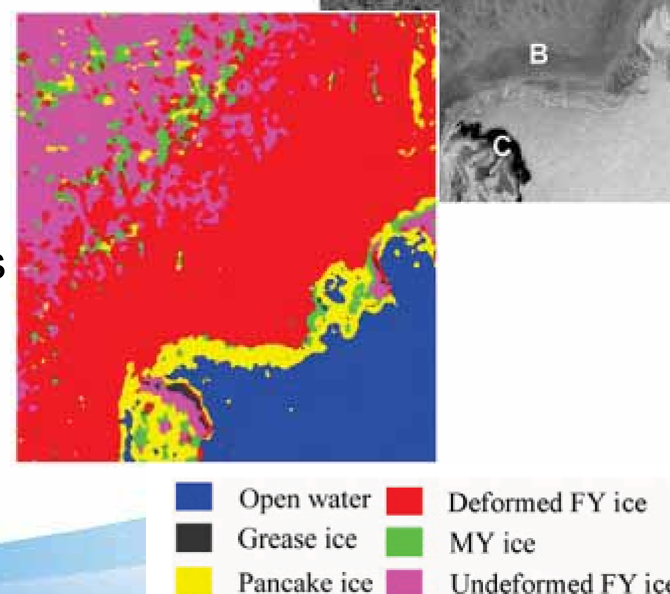
Identified Gaps: Sea Ice

- Some identified Gaps
  - Reduction in ice type ambiguity (particularly in marginal zone)
  - Young ice biases
  - Reduce ambiguities in margin ice concentration
  - Improved information on ridges and deformation zones (type, density, thickness, orientation)
  - Melt stage observations
  - Improvement in surface temperatures under cloudy conditions
  - Mesoscale dynamics measurement
  - Systematic and routine iceberg observation

Credit: NASA

ERS-1 SAR i the Barents Sea March 1992 (NERSC)

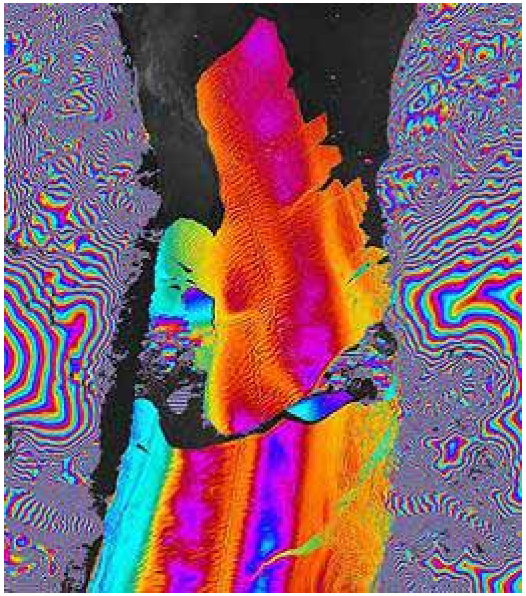




Identified Gaps: Land Ice

- Some Science Gaps
  - Precise topography & temporal changes of glaciers, ice caps and outlet glaciers of ice sheets
  - Very precise ice sheet surface topography & temporal changes
  - Surface velocity fields of glaciers and ice streams
  - Snow accumulation on ice sheets
  - Snow mass on land (Snow water equivalent, SWE)
  - Improvement of freeze/thaw soil cycle monitoring
  - Improved snow albedo measurements
  - Ice sheet internal layer depth at better spatial and vertical resolution

Credit: NASA



TanDEM-X single-pass interferogram (pursuit-monostatic mode) Petermann Glacier, Greenland (DLR, 2011)

Mission Concept Candidates

- 18 Concepts in total, 11 evaluated in depth
- Some concepts eliminated early due to repetition, lack of formation flying or not feasible

X = necessary

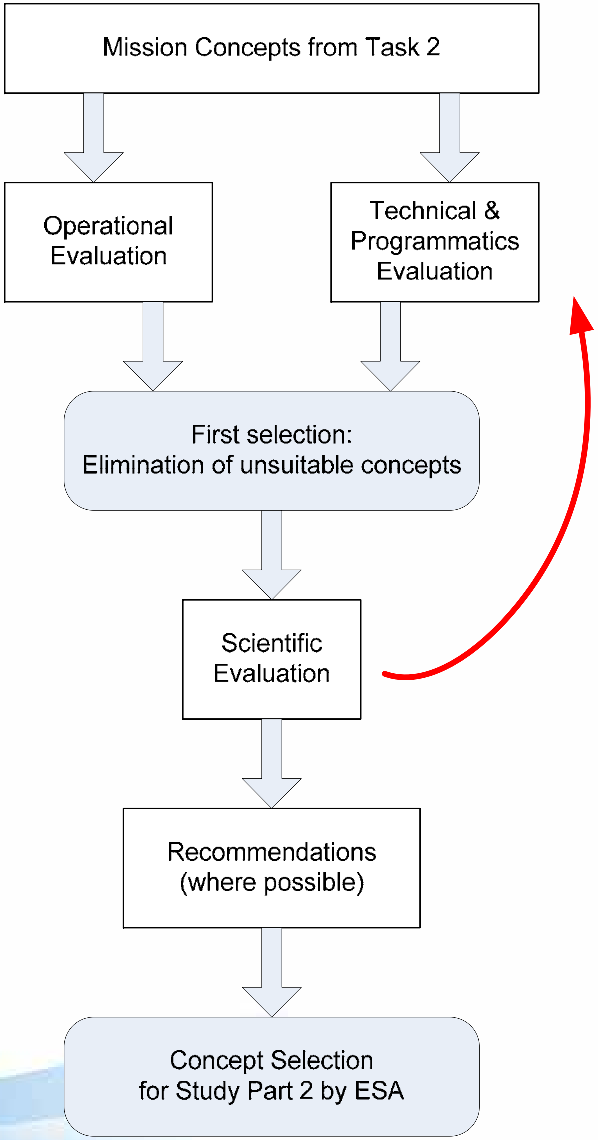
U = useful

* passive microwave radiometer
** microwave imager

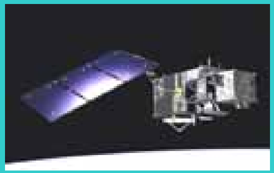
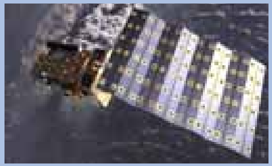
	Additional Sensors		European Operational Satellites	OCEAN									SEA-ICE											LAND-ICE								
				Ocean surface wind	Sea state parameters	Sea level	Ocean topography	Ocean currents (geostrophic & doppler range)	Sea surface temperature	Sea surface salinity	Ocean biogeochemical variables	Mesoscale fronts, eddies, internal waves	Ice edge	Ice concentration	Leads and polynyas	Ice type	Ice drift	Ice thickness	Ridge height & concentration	Snow cover	Melt onset & duration	Surface characteristics	Icebergs	Glacial surface topography & ice caps	Ice sheet topograpghy changes	Glacial & ice stream surface velocity	Ice sheet snow accumulation	Snow mass on land (SWE)	Permafrost surface topograpghy	Soil freeze & thaw cycles	Snow albedo	Snow microphysical properties
1	C-band SAR	+	Sentinel-1	u	u		u	u				u	u		u	u	x	u	u		u	u	u	u	u	x	u		u			
2	Passive SAR constell.	+	Sentinel-1	u	u		u	u				u	u		u	u	u	u	u		u	u	u	x	u	u	u		x			
3	VNIR + SWIR Imager	+	Sentinel-1	u	u		u	u			u	u	u		u	x			u		u	u	u								u	x
4	TIR	+	Sentinel-1	u	u		u	u	u		u	x	u		u			u			u	x								u		
5	L-band SAR	+	Sentinel-1	u	u		u	u				u	x		u	x			x		u	u	u									
6	PMR (L-band) *	+	Sentinel-1	u	u		u	u		x		u				x		u				u				u	u					
7	Laser altimeter	+	Sentinel-3		u	u	u	u				u						x	u	x				u	x							
8	PMR (L-band) *	+	Sentinel-3	u	u	u	u	u	u			u		x																		
9	MWI **	+	Sentinel-3																									u				x
10	Ku-band Scat + (TIR)	+	MetOp 2G	x					u					u		u				u	u	u					x	x		x		u
11	PMR (L-band) *	+	MetOp 2G	u					u			u		u							u	u					u					

Mission Selection

- **Three** most promising mission concepts selected from those identified
- Selection based on criteria:
  - **Operational**: includes Availability (P/L Duty cycle, Orbit corrections etc.), P/L reliability, Data handling and complexity
  - **Technical & Programmatics**: including Feasibility (Payload TRL, Requirements on P/F etc.) and Cost (Launch Vehicle, Space segment, Ground Segment)
  - **Science**: including User Needs (Scientific and operational) and Merit (Usefulness, Uniqueness and Complementarity)
- Adapted during the course of assessment:
  - Initially, some valuable scientific concepts were not selected because of programmatics (cost deemed too high)
  - Instead, consider “value-for-money”
- Recommendation made to ESA
  - Only represents view of small study team!

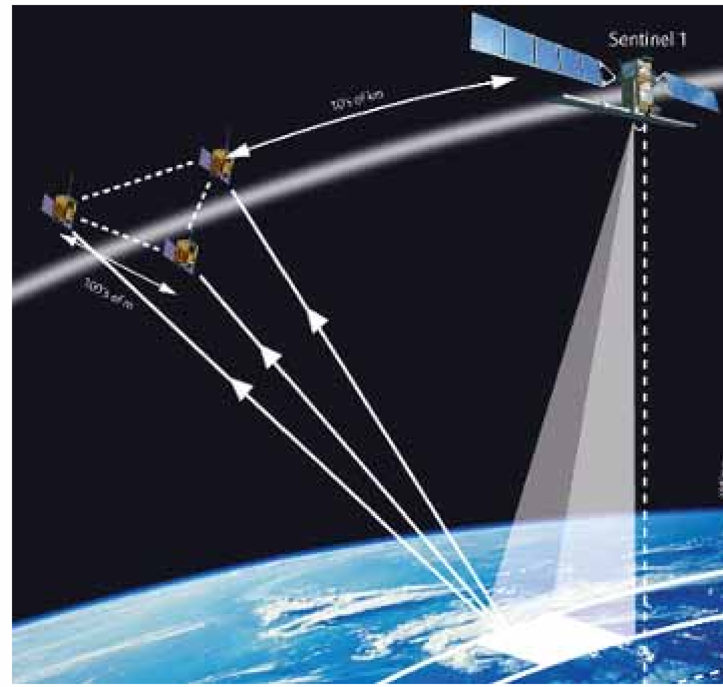


Missions selected for further study

Operational mission		Convoy mission	
Sentinel-1  C-band SAR	+	Passive C-band SARs C-Band SAR VNIR + SWIR TIR L-Band SAR PMR (L-Band)	→ **S-1+ Passive C-band SARs** Strong scientific interest lots of technical issues.
Sentinel-3 	+	Laser Altimeter PMR (L-Band) Microwave Imager	→ **S-3 SRAL + Laser Altimeter** Particular good for cryosphere (sea and land). Instrument complexity depends on acceptable vertical resolution
MetOp-SG 	+	Ku-band Scatterometer PMR (L-Band)	→ **MetOp-SG MWI + Ku Scatt.** Significant improvements for various snow products. No identified issues on technical side and realistic from a programmatic viewpoint

Concept 1: Passive C-band SARs with S-1

- Description
  - 2 or 3 passive SARs in cartwheel configuration follow by 50-100 km S-1 (illuminator)
  - Baselines of 100-400 m
- Purpose
  - Measure ocean and sea ice motion using along track inSAR
  - High accuracy Digital Elevation models (DEMS) from across track

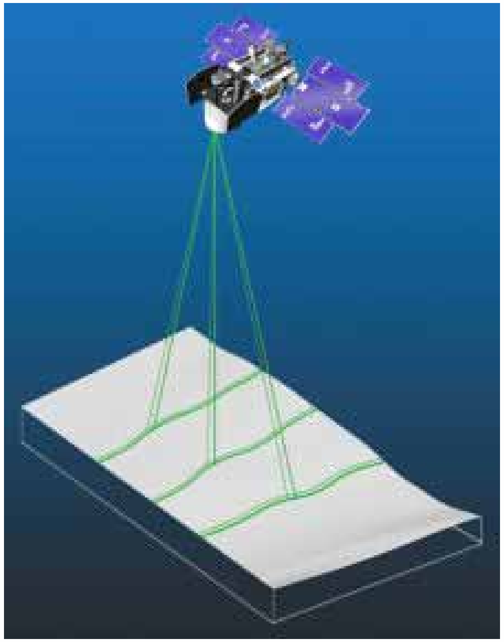


- Benefits
  - Single pass – avoids temporal decorrelation for interograms
  - Multiple interferograms in single pass avoids phase ambiguities in steep terrains
  - 3 SARs would Allow multi-baseline interferometry or after repeat orbits with 2.
- Considerations
  - Orbital control: maintaining baselines
  - Operational aspects: Collision avoidance, multi-satellite downlinks, Link between S-1 and passive SARs

Concept 2: Laser Altimeter flying with S-3

Description

- Combines S-3 Ku/C band synthetic aperture radar altimeter (SRAL) with Nadir-pointing laser altimeter



Purpose:

- Land ice: surface topography and topographic changes of ice sheet
- Support mass balance estimation
- Sea ice: ridge height & deformation, snow cover on sea ice
  →Mission continues Cryosat-2/IceSat heritage

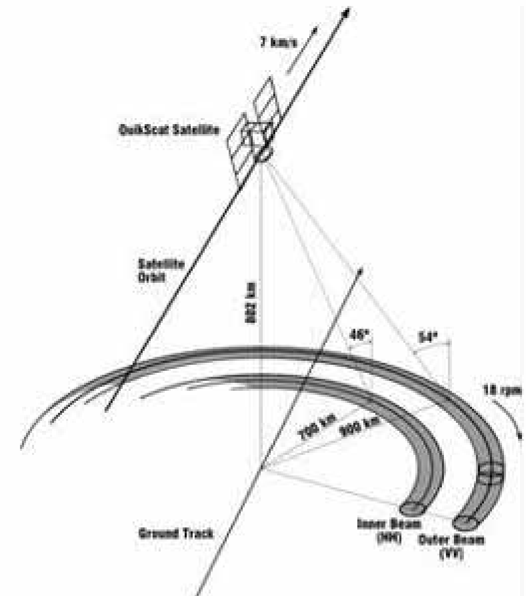
Benefits

- Biases can be reduced which will improve data product accuracy for ice sheet topography and change
- Different footprint sizes will help characterise sloping terrain

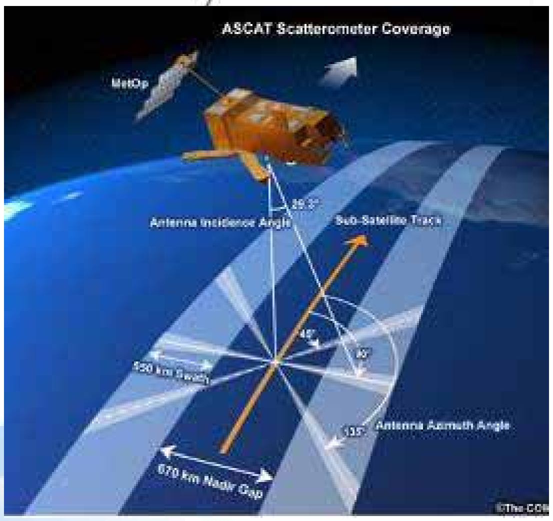
Considerations

- Limited European heritage in spaceborne lasers
- Timeframe given payload development would need to be with S-3B
- Sensor footprints must overlap→ orbit control requirements are high

Concept 3: Ku-band Scatterometer with MWI on MetOp-SG



- Description
  - Ku-band scatterometer with MWI on Metop-SG (817 km) in leader-follower configuration
  - Two scatterometer options: pencil beam or fan beam heritage- however currently considering hybrid…
- Purpose:
  - Measure snow accumulation on ice sheets
  - Snow mass on land at medium/low resolution
  - Observe freeze/thaw cycle of soil
- Benefits
  - Improves measurement of ice concentration and detection of large scale melt on-set
  - Improves the estimation of snow cover on ice, vector wind field and air-sea interaction observations
- Considerations
  - Two measurements must occur within short period (<30 min)
  - Formation flying not challenging



Conclusions & Acknowledgements

Conclusions

- Synergistic measurements can be achieved by flying spacecraft in formation
  → offer new possibilities for Earth observation.
- Demonstrated by the A-train and as proposed for Earth Explorer 8 missions
- Some of the concepts presented may form the basis for future Earth Explorer missions
- The study is expected to conclude in November and the final report should be available soon afterwards.

Acknowledgements

- Technical Officer: Amanda Regan (ESA)
- Study team: Nic Leveque, David Hall,
  Karl Atkinson (Astrium, UK)
  Johnny Johannessen, Stein Sandven (NERSC, Norway)
  Helmut Rott, Thomas Nagler (ENVEO, Austria)
  Kim Partington (Polar Imaging, UK)